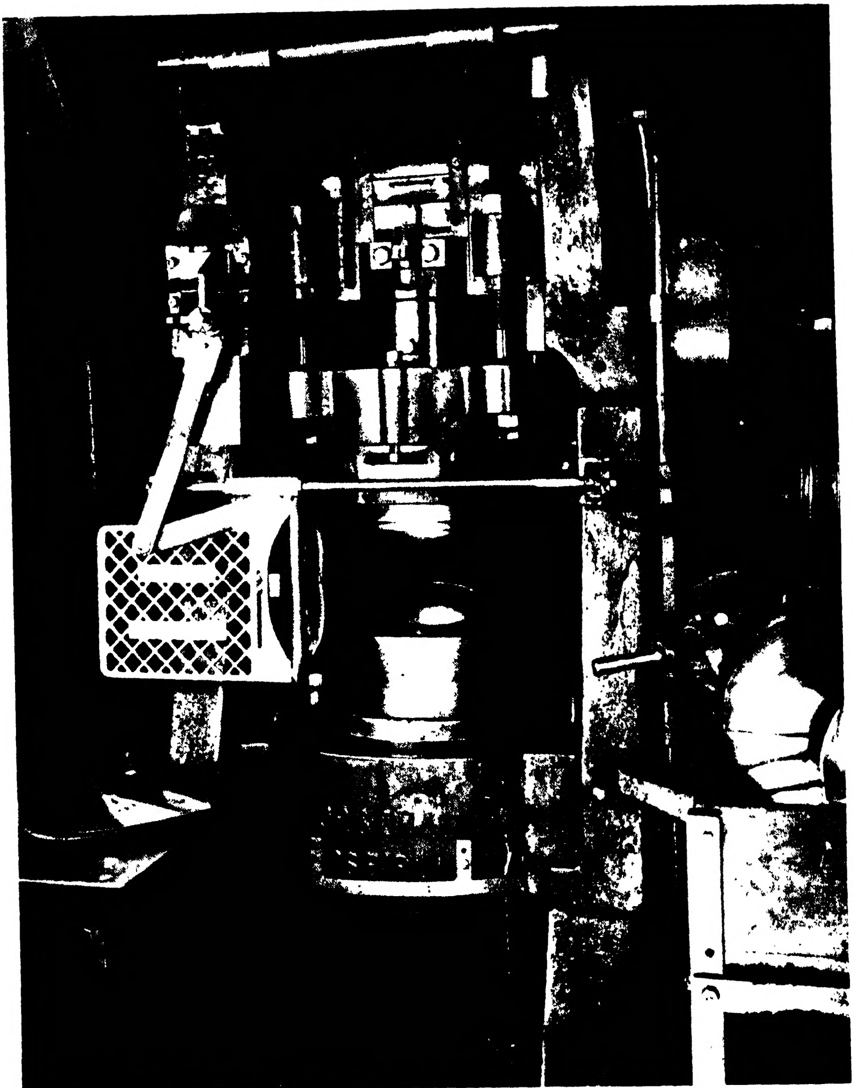
THE METALLURGY OF DEEP DRAWING AND PRESSING



[*By courtesy of Joseph Lucas Ltd*

A severe draw: automobile lamp bodies (*seen on right*) drawn in one operation from circular brass blanks 0·027-inch thick (*seen on left*) in double-action press.

[*Frontispiece.*

THE METALLURGY OF DEEP DRAWING AND PRESSING

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By J. DUDLEY JEVONS
Ph.D., B.Sc., A.I.C.

WITH A FOREWORD BY

H. W. SWIFT
M.A., D.Sc.
Professor of Engineering at Sheffield University

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TO

ALL CRAFTSMEN

STUDENTS

AND

INTELLIGENT

INDUSTRIALISTS

FOREWORD

By Professor H. W. SWIFT, M.A., D.Sc., *Professor of Engineering at Sheffield University.*

THE commercial development of pressing and deep drawing has been so rapid and prodigious that it is difficult to realise that they are among the youngest of our industrial arts. The layman is already apt to take their results for granted without pausing to wonder at the metallurgical skill and mechanical technique which have combined to make possible the production at one blow of articles so different as shaving cream tubes and automobile wings. And even the engineering designer is apt to take this skill and technique for granted when he assumes that any shape which he can devise in sheet metal can be produced as a matter of course in the press shop.

Yet the deep-drawing industry is in fact still in its youth, a healthy and vigorous youth and a youth which shows many of the characteristics of precocity ; a disconcerting rate of development, abundant self-confidence, and something of an impatient attitude to rules and principles.

Indeed so precocious has been the development of deep drawing that those whose concern it is to codify rules and enunciate principles —the research worker and theorist in this case—have been fully occupied in the search for a code of rules which will conform to the behaviour of their subject rather than in the enunciation of principles to which their subject must conform. Theory in fact has hitherto been compelled to follow in the wake of practice, collecting and collating data in an endeavour to form a rational picture of the mechanism of the deep-drawing process and seldom, if ever, reaching a position where it could claim to take the initiative.

The failure of scientists hitherto to establish and codify the principles underlying the processes of deep drawing will not be held as evidence of want of ability or endeavour, not at least by those who realise the complexity of the problems or the volume of research work which has already been carried out ; they will rather pay warm tribute to the courage and intuitive skill of those directly engaged in the industry who have surmounted their successive practical difficulties and have largely by their own efforts developed the technique of deep drawing into a successful industrial art.

Yet there can be no doubt in either the practical or academic mind that the phenomena and experiences of deep drawing are capable of rational explanation and are ultimately controlled by scientific principles and that the continued progress of the industry would be more rapid and certain if its methods could be based more consciously on these principles. Any attempt therefore to formulate such principles, whether by deduction from basic theory or by induction from accumulated data and experience should be assured of a sympathetic reception by practical as well as scientific men.

But the responsibilities assumed by the author who undertakes a critical examination of deep-drawing problems are not light. For the subject is deep and wide. Study of the phenomena of plastic flow even under simple impressed conditions is still exercising the minds of eminent physicists and mathematicians and the problems superimposed by the complex conditions of industrial drawing make any theoretical treatment entirely speculative at the present time. The influence of metallurgical conditions, work hardening and other treatment on the plastic characteristics and strength of materials is in itself a problem demanding—and receiving—the full attention of metallurgical research workers. And the design of pressings, press tools and press-shop procedure to take full advantage of plastic properties will provide material for the best brains among mechanical engineers when the true implications of these properties are understood.

The fact that the problems involved are partly metallurgical and partly mechanical and difficult to separate, and the fact that metallurgists and engineers have a joint responsibility in the practical development of the art have naturally made deep drawing a fertile field for controversy in its scientific and more particularly its practical aspects; for in the latter case the commercial interests of the metallurgist and engineer are often divergent and the responsibilities for failure difficult to allocate. This controversial element adds materially of course to the responsibilities of the author of a treatise and make it all the more difficult for the expert, who clearly must be closely concerned with the industrial as well as the scientific aspects of the problem, to refrain from partisan treatment and *ex parte* judgment.

The complete authority would be at once a first-class metallurgist, engineer and physicist, he would have experience in the production of ferrous and non-ferrous sheet metal and an intimate knowledge of the manufacture of pressings and yet be detached in his outlook on both. Since such a combination of qualities is not likely to be found in any individual, the claims of any treatise purporting to deal with deep pressing in a fully comprehensive way would need to be accepted with reserve. Moreover at the present time our knowledge of the mechanism of plastic flow is so limited and in such a fluid state that it is doubtful if any treatment of this important aspect together with its implications in press-tool design and press-shop practice could be of more than ephemeral value.

On the other hand an almost embarrassing volume of metallurgical work is ripe for disentanglement and review and a mass of information and opinion acquired by practical experience needs to be collated, critically examined and disseminated. To undertake this task no one could be in a better position or better qualified than Dr. Jevons.

As chief metallurgist in a group of works producing, among many other things, pressings on an enormous scale, it is his duty to know as much about the production, properties and idiosyncrasies of sheet and strip metal as the manufacturers themselves and at the same time to know as much about the processes of pressing and drawing as the press-shop staffs. It is his business to be critical both of the material supplied and of the processing of that material in his works, and for that reason he occupies a more disinterested position and is able to adopt a more truly perspective viewpoint than any other class of man engaged in the industry.

Apart from the advantages of his position, readers of Dr. Jevons's earlier publications will know that he has just those qualifications, technical and literary, which are required in the author of a work of this character. He is able to write with complete authority on his subject; with an outlook at once scientific and practical, always conscious of the fundamental problems underlying the drawing processes and yet never forgetting the everyday practical problems of industry or the commercial emphasis on cost.

These qualities are admirably suited to serve the needs of a young and vigorous industry in which art and science must be brought to work in double harness, and it is indeed fortunate for those to whom this book is dedicated that a man possessing these qualities should also be endowed with such enthusiasm, industry and patience that he is prepared to devote the spare moments of an unusually busy life to a task whose magnitude would deter many a man whose time is less fully engaged. It is to be hoped that the author will find his reward for this signal service to his industry in the appreciative response of his readers to the stimulus which he provides and in the knowledge that he has brought the practice of deep drawing and pressing measurably nearer to the proper goal of an industrial art, which is applied science.

AUTHOR'S PREFACE

THE fabrication of all kinds of metal articles by the severe plastic deformation of metal sheet is a craft as ancient as that of sheet-making itself. Indeed, as sheet was produced by hammering long before rolls were used for this purpose, the origin of this form of metal-working must be contemporary with that of forging, the father of all metal-working crafts.

Judged by these standards, the more specialised craft of deep drawing and pressing sheet metal in a press by means of a punch and die is young; yet, judged by standards common to our modern industrial age, it is old. It is, therefore, strange that only recently has knowledge of the kind popularly dubbed "scientific" begun to be directed deliberately to the assistance and development of this widely practised craft which, hitherto, has flourished with no other guidance than the peculiar intuitive knowledge which is the birthright of the true craftsman, and, it must be conceded, has flourished exceedingly.

This change is indicated by the appearance of technical publications and researches devoted entirely to certain aspects of deep drawing and pressing. There seems every likelihood that quantitative knowledge will rapidly augment the qualitative and intuitive knowledge of the pure craftsman, enlarging the scope of the craft and rendering possible the more economic production which seems to be an unavoidable, if not wholly desirable, necessity of this century.

Craftsmen and students actively engaged in industry seldom have time to extract from the vast bulk of scientific literature such items as have a special bearing on the particular problems which they encounter. This is particularly so in the deep drawing and pressing industry, because so many branches of metallurgy and applied science are needed to deal with them.

The purpose of this book is to offer in convenient form some portion of metallurgical knowledge bearing directly upon the craft of deep drawing and pressing, and it is my sincere hope that it may prove helpful to those engaged in industry, and may assist in the advancement of the craft by indicating how existing knowledge can be usefully applied.

This volume is intended for both practical workers and scientific students; indeed, one of its main objects is to bring these two categories closer together in their common objective. It has of course been necessary to include a number of metallurgical terms and to assume some metallurgical knowledge on the part of readers. None the less, practical workers to whom such terms are unfamiliar will have little difficulty in following the discussions with the help of the illustrations and diagrams, which I have made as plentiful and as clearly illustrative as possible.

I wish to express my sincere thanks to Messrs. Joseph Lucas Ltd. for permission to reproduce a number of photographs taken in their laboratory, and to Mr. E. S. Lloyd, who has taken many of these photographs and also helped with proof-reading ; to Dr. L. B. Hunt, at whose suggestion the work was begun ; to Mr. R. G. Johnston for his proof-reading and helpful criticism ; to the proprietors of the *Metal Industry*, the *Iron and Steel Industry* and *Sheet Metal Industries* for permission to reproduce certain sections which have appeared in their periodicals ; to all those friends who, by the provision of data and illustrations and by the frank and stimulating discussion of their experiences, have helped me in the compilation of this volume ; and to those who by persuading me that a book of this kind is needed have encouraged me in writing it under somewhat difficult conditions.

Lastly, my indebtedness to Professor Swift, the writer of the Foreword to this book, will be manifest, and I desire to thank him very cordially.

J. DUDLEY JEVONS.

BIRMINGHAM, 1940.

AUTHOR'S PREFACE TO SECOND EDITION

THE demand for a second edition, within six months of publication of the first, of a book of the size and character of this, seems to show that it has gone some part of the way to fill a gap in technical literature. In preparing this second edition the opportunity has been taken to make such additions and modifications as new work published too late to be assessed in the first edition has rendered desirable, and also to enlarge the sections dealing with light alloys and with " soft metal " tools.

It is my hope that this second edition will be of use to those interested in deep drawing and pressing both during the present world crisis, when they are suddenly faced with many new and urgent problems, and also afterwards when, although economic conditions are unpredictable, the need for closer and better-informed technical supervision will certainly be more acute than ever.

J. DUDLEY JEVONS.

BIRMINGHAM, 1941.

NOTE ON THE USE OF TERMS

THROUGHOUT this book the metal offered to the press is described as "sheet." To the producer the terms "sheet" and "strip" often imply a difference in manufacturing procedure; for example, "sheet" may mean that cross-rolling has been used or that several sheets have been rolled together. It has been suggested, on the other hand, that the description "sheet" shall be applied to strip over 24 inches wide, irrespective of the manufacturing procedure used. As the width of what is usually termed "strip" is increasing rapidly, owing to the installation of wider "strip" mills, the significance of the terms "sheet" and "strip" as indications of manufacturing procedure is becoming more and more uncertain, although purists have coined the term "continuous sheet" to describe sheet over 24 inches wide produced in a strip mill.

For the sake of convenience the single term "sheet" is used throughout this book unless special distinction needs to be made. Readers to whom the terms sheet and strip signify important differences with respect to method of manufacture are asked to excuse what to them may seem unwarranted simplification, and to remember that the consumer is concerned more with the physical properties of the blanks fed to his presses than with the exact methods used to produce the metal from which these blanks are cut.

CONTENTS

METALLURGY OF DEEP DRAWING AND PRESSING

CHAPTER I

THE PRODUCTION OF BRASS SHEET

FOR a proper understanding of the true nature of many of the difficulties which they encounter in the press-shop, it is essential for consumers to have at least an elementary knowledge of the methods by which the sheet which they purchase for the purpose of deep drawing and pressing is made. This knowledge is, indeed, absolutely necessary both for a full utilisation of such properties as the metal may possess as well as for intelligent insistence on, and assistance in, the development of desirable improvements in the sheet purchased. Without it, consumers cannot explain to suppliers their exact requirements, nor can they co-operate usefully in the gradual development of the desired special properties and in the elimination of troublesome defects.

For this reason it is hoped that readers who are unfamiliar with this aspect will not skip the first two chapters in which an attempt is made to describe very briefly the methods by which brass and steel, the two metals deep drawn and pressed more than any other, are melted, cast and rolled into the finished product supplied to consumers in the form of sheet, strip or, occasionally, cut blanks. Space precludes any description of the production of non-ferrous metals other than brass, but enough will have been said to enable readers to appreciate the true nature and origin of many of the defects found in them, and to understand how the physical properties in which they are specially interested are influenced by casting, rolling and annealing processes.

For a full description of the production of sheet metal, readers are referred to proper text-books devoted to this subject. A number of modern treatises can be had which deal with steel; for an elementary yet comprehensive manual on the production of steel sheet, the work of Shannon [1] is suggested. For brass the choice of literature is much more limited, and the volume of Genders and Bailey [2] remains the standard and very admirable text-book.

There are three essential stages in the production of brass sheet and strip:

(1) Melting a charge composed of virgin copper and zinc—or, as it

is known industrially, "spelter"—together with a varying proportion of "scrap" brass made up of ingot and mill discards and consumer's scrap.

(2) Casting the molten metal into ingots of various size and shape.

(3) Rolling the cast ingot into sheet or strip.

These processes will be described briefly together with certain others which although minor are yet of considerable importance, such as the scalping of ingots or slabs; annealing; pickling and cleaning; shearing the finish-rolled metal to the dimensions required by individual consumers; inspection and packing.

MELTING

In Great Britain brass destined for the press-shop is melted either in the old type of pit furnace holding a single crucible and usually fired by coke, in oil-fired tilting furnaces, or in low-frequency electric induction furnaces also of tilting type. The fixed-hearth reverberatory type of furnace, which has been used in the United States, has never been popular in Great Britain for the melting of brass, as distinct from copper.

High-frequency induction furnaces, in which a charge placed in either a crucible or a built-in lining is heated by means of high-frequency currents induced in it by a current passed through a surrounding water-cooled coil, are not yet used for the melting of brass on an industrial scale. From the metallurgical aspect this method of melting seems to be the best of any yet devised, and preferable to the usual low-frequency induction furnace method because no priming with molten metal is needed, but the cost of the associated electrical equipment needed to produce electrical energy of the desired kind is very high. The rapid rise to popularity of high-frequency induction melting for steel shows, however, that a high first cost does not present the insuperable barrier which over-conservative executives imagine.

Rocking furnaces employing an indirect arc, that is, an arc struck between electrodes situated above the molten charge and not between an electrode and the charge itself, are being tried for melting brass on an industrial scale, but it seems likely that in Great Britain the tilting induction furnace will remain supreme in the field of electric melting for some time to come.

Pit Furnaces. The pit furnace is a pit, usually about 18 inches square—although sometimes round—and about 4 feet deep, lined with refractory brick and having fire-bars at its bottom and a flue leading from near its top to a stack sufficiently high to ensure brisk combustion of a coke fire held in it. Into this furnace a crucible is lowered, packed round with coke to within a few inches of its top, and the pit itself closed with a refractory brick cover to enable the stack to exert a "pull" upon the fire.

The essential features of a pit furnace are illustrated diagrammatically in Fig. 1, while Fig. 2 shows a view of a typical brass-casting shop having a number of these furnaces ranged at the base of the wall at the right of the picture. At the extreme right can be seen pans containing weighed quantities of copper, spelter and brass scrap—in the form of perforated strip from the press-shop—ready to be charged immediately the crucibles now in the furnaces have been poured. The purpose of the rotating chamber and flue in the centre of the picture is to remove zinc fumes while the crucible, gripped in the special tongs seen beyond the line of moulds, is having its contents poured into successive moulds.

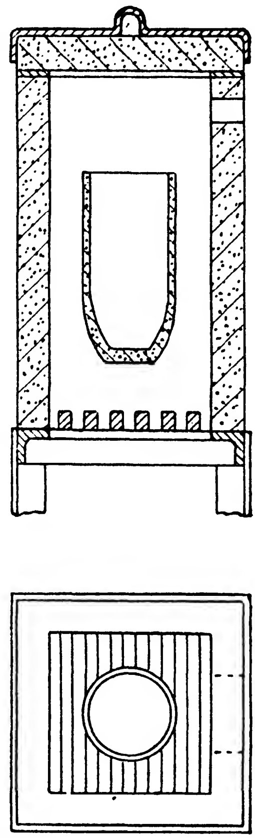


Fig. 1. Diagram depicting sectional side elevation and plan of a coke-fired pit furnace with crucible in position.

Pit furnaces are very inefficient, but the use of special fire-bars, proper dampers and recuperative systems which allow the exhaust gases to heat the air supplied to the bottom of the furnace for combustion can increase their efficiency considerably. Other disadvantages are that it is difficult to control the temperature of the molten metal at all closely; that the charge may become contaminated with fuel, products of combustion or floor sweepings; that the time taken to melt and heat a charge to pouring temperature is relatively long, thus allowing plenty of time for zinc loss, oxidation and contamination; and that accidents due to crucibles breaking in the furnace or while being lifted from it occur sometimes. In spite of this the very low initial cost and low maintenance costs of this type of furnace often weigh strongly in its favour and, although it is sometimes said that the pit furnace is doomed, it is likely that small producers will continue to use it for some time to come.

Crucibles usually hold from 100 to 150 lbs. of metal, but it is interesting to record that brass of exceptionally good quality is being produced in large crucibles holding about 250 lbs. of metal heated in pit furnaces of usual type. The almost universal replacement of fireclay by plumbago as a crucible material nearly halved melting times, thus reducing melting costs and also improving the quality of the brass because less time is allowed during which oxidation and contamination can take place. The advent of laminated plumbago crucibles has reduced melting times still more and has also nearly doubled the useful life of crucibles under normal conditions.

In spite of this, the quality of the brass made in pit furnaces is still influenced by the quality of the fuel used to generate heat. Sulphur and iron are the two most harmful impurities found in fuel; sulphur is a recognised danger, but it is not always appreciated that a harmful percentage of iron can enter molten brass from the ash of coke which contains an unusually high proportion of this impurity.

To assist mixing it is usual for the caster to stir the molten charge in the crucible with a rod. Until recently these stirring rods were invariably iron bars, and too energetic or prolonged stirring by an over-zealous but misguided operator often resulted in the molten brass dissolving an appreciable percentage of iron from the rod. Plumbago rods are now available but, on account of their fragility, are not always popular with casters of the old school.

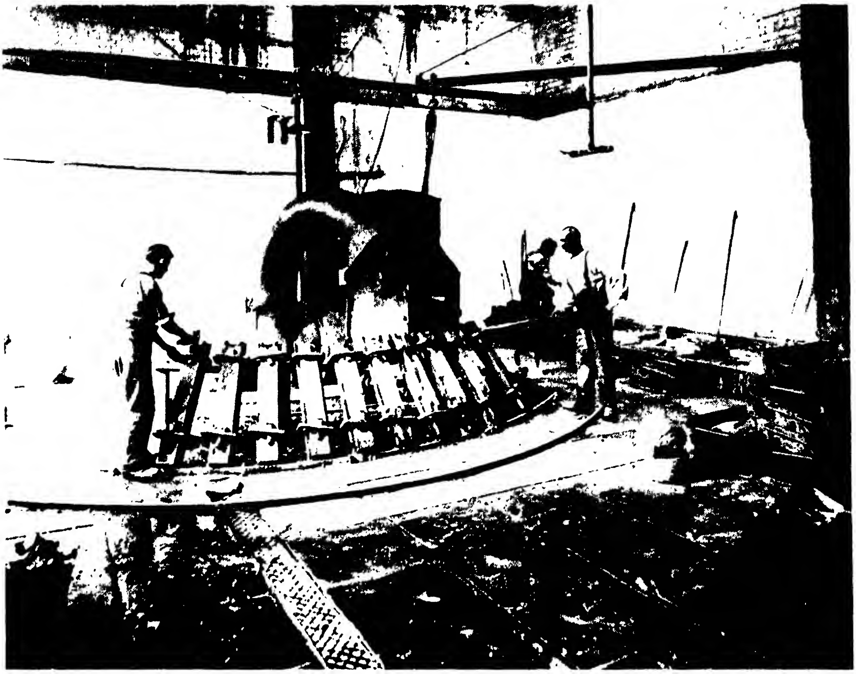
Oil-fired Furnaces. Although oil, and even gas, has occasionally been used to heat crucibles in pit furnaces, this method of heating is usually applied to above-the-floor furnaces which can be poured by tilting the whole furnace by suitable mechanical means; for example, by worm gearing operated by hand or by a small electric motor.

Two types are used. In one a crucible is mounted in a suitable refractory-lined chamber leaving a space in which play flames issuing tangentially from burners in the outer casing; in the other no crucible is used, and the metal is melted in a horizontally-disposed cylindrical drum, having a refractory lining which makes contact with the molten metal, and revolving about its axis to enable the metal to be poured from a spout located in the circular casing. In this type of furnace the metal is exposed to the direct action of flames proceeding from burners located at the ends of the chamber, and it is difficult to avoid serious loss of zinc.

A typical furnace of the first, and more widely used, kind is shown in Fig. 3.

Electric Induction Furnaces. This type of furnace, illustrated diagrammatically in Fig. 4, differs essentially from those already described in that no external source of heat is applied to the metal.

The charge is placed in a tilting furnace lined with suitable refractory material and having a suitably disposed coil (B in Fig. 4) through which is passed a single-phase electric current. This primary current induces a secondary current in the loop of molten metal lying between the core and the sides of the base of the furnace; the secondary current heats the metal in the loop and at the same time causes it to flow in the manner indicated by the dotted arrows, thus ensuring rapid and uniform heating and close temperature control as well as thorough mixing of the charge in the main hearth of the furnace (A in Fig. 4). It will be appreciated that when the charge is poured, enough molten metal must be retained to fill the loop, and that when a furnace is



By courtesy of I.C.I. Metals Ltd.

FIG. 2. General view of brass casting shop equipped with coke-fired pit furnaces and rotating fume-extractor serving strip moulds.

[*By courtesy of J. F. Ratcliffe (Metals) Ltd.*

FIG. 3. Casting brass strip ingots from an oil-fired tilting furnace.

[*To face p.* 4.

[By courtesy of I.C.I. Metals Ltd.

FIG. 5. General view of brass casting shop equipped with electric induction furnaces serving vertical strip moulds supported on turn-tables beneath fume-extractors.

[By courtesy of J. F. Ratcliffe (Metals) Ltd.

FIG. 6. Casting brass strip ingot from crucible heated in coke-fired pit furnace.

[To face p. 5.

started up the loop must be filled with previously-melted metal unless special methods are adopted.

Fig. 5 shows a casting shop containing a battery of electric induction furnaces which tilt to fill relatively small, upright moulds supported on turn-tables beneath fume-extractors. As explained later, the modern tendency is to use larger moulds which are usually water-cooled. Stacks of cast slabs can be seen on the right of this illustration.

Advantages of the electric induction furnace are a very high thermal efficiency due to the fact that the heat is generated actually *in* the metal, and does not have to pass through the wall of a refractory crucible or to heat entirely dead refractory lining; a relatively short melting time; the ease with which the furnace can be closed, thus reducing oxidation and zinc volatilisation; an entire freedom from contamination by fuel or products of combustion and, as indicated already, the ease with which the temperature can be controlled very closely and uniform heating and thorough mixing of the charge can be guaranteed without the useful though uncertain aid of a caster's stirring rod.

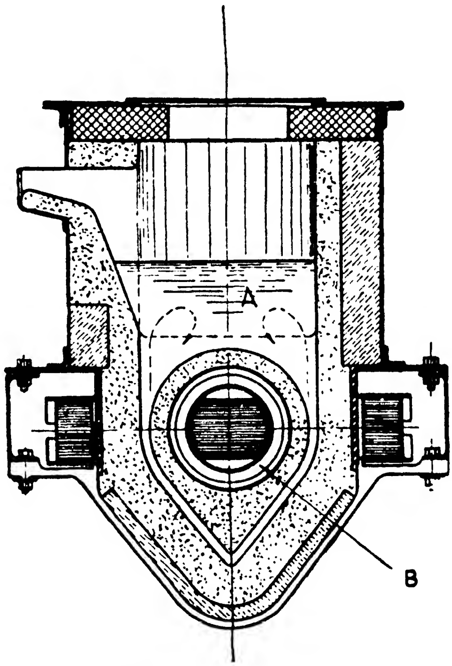


FIG. 4. Diagram depicting cross-sectiona side elevation of Ajax-Wyatt low-frequency cored electric induction furnace.

Its main disadvantages are a first cost which is very high indeed when compared with that of a pit furnace, and the need for priming with molten metal. A minor disadvantage, which does not arise when brass of one grade is being produced continuously, is that a small portion of an old charge left in the furnace for priming will alter the composition of a new charge of different chemical composition.

A word of explanation concerning the difference between low-frequency and high-frequency induction furnaces seems necessary because confusion between the two types is often made. In a low-frequency furnace a low-voltage alternating primary current, usually of standard 50-cycle frequency, is passed through a suitably disposed coil to generate a secondary current in the molten metal as shown in Fig. 4; it is this secondary current which heats the metal. In a high-frequency or "coreless" induction furnace a relatively high-voltage current having a frequency of from 3,000 to 20,000 cycles per second is passed through a water-cooled helical external coil which surrounds the crucible. The charge, whether solid or molten, is heated entirely by eddy currents and, as the metal being melted does not form part of a secondary circuit, as in the low-frequency arrangement, the crucible can be emptied when each charge is poured. Because the strength of the eddy currents depends upon the electrical properties of the metal being heated, high-frequency furnaces are much more efficient with metals which have good magnetic properties—such as iron, nickel and nickel alloys—than with brass, copper or aluminium. Owing to the cost of the necessary electrical machinery, the cost of high-frequency furnaces is very high.

Purity of the Metal melted. In brass-melting most of the impurities present in the metal charged into the furnace remain and are not removed by purification processes as in steel-making. Because of this it is of the utmost importance that both the virgin metals and the scrap used are as pure as possible.

In these days virgin copper and spelter of at least 99·90 per cent. purity are available, and are used by all reputable brass-makers for the production of sheet and strip destined for deep drawing and pressing. Unfortunately the same cannot always be said of the scrap charged, even though the brass-maker takes what in his opinion are careful precautions to prevent impure or contaminated brass scrap or concealed foreign bodies, particularly ones of iron, being charged into his furnaces. More care in the selection of scrap is undoubtedly being exercised by most firms, and better inspection, coupled with the improvement and more general use of electro-magnetic separating devices, has assisted in the lowering of the iron content.

That the exercise of still more care in the preparation, as distinct from the selection, of scrap could bring about an unexpectedly large improvement in the ductility and other properties of the metal to which it is added has been demonstrated by Hutton,[3] who has described the striking results which can be obtained by passing scrap metal through a "laundry" equipped with washing, tumbling barrels and centrifuging apparatus.

With existing standards of purity for deep-drawing quality brass, purity of scrap has become a very serious matter; real trouble is occasioned to metal melters by the unsuspected contamination of scrap purchased in good faith from consumers whose negligence is inexcusable and, in actual fact, prejudicial to their own interests. It is worthy of mention that the practice of the compression-baling of scrap by hydraulic devices, welcomed by hauliers, warehousemen and melters, is responsible for the inclusion in furnace charges of many unwanted additions. The increasing use of large-sized electric furnaces for melting has tended somewhat to reduce the admitted convenience of this undesirable practice in so far as ease of manipulation in the actual casting shop is concerned.

Fluxes. A " flux " or " cover " is usually applied to brass melted in either a crucible or a furnace. Many substances have been used for this purpose, and in the past much secrecy has been maintained concerning the nature of quite ordinary materials of very doubtful value.

Confusion is often made between a " cover " and a " flux." A cover is a substance which merely shields the surface of the molten metal from the direct action of the atmosphere and furnace gases, thus minimising oxidation and volatilisation. A true flux, on the other hand, is a substance whose primary function is to dissolve or to combine with impurities or oxides so that they may be removed with the scum or slag from the surface of the metal before casting. In brass-melting these functions are usually combined in one addition, which is often a mixture of a number of substances. Common salt is often used, but this substance appears to function only as a cover. Powdered green glass acts as an efficient cover and also dissolves certain oxides, for example those of zinc and aluminium, as also does sodium carbonate. Borax possesses useful properties, but is unpopular industrially because it attacks crucibles and furnace linings. Besides these simple substances numerous proprietary mixtures are available, and text-books and papers give many recommended compositions.

Most authorities agree that if pure constituent metals are used it is preferable to melt brass without a flux, perhaps using charcoal as a cover. When scrap is added, as is almost invariably the practice in industry, a flux is usually beneficial ; but, unhappily, not all so-called fluxes combine with or dissolve the impurities it is desired to remove and produce a slag which rises readily to the surface of the melt.

Casting

When the molten charge is thoroughly mixed and has reached the correct temperature for pouring, the " heat," as it is termed, has to be poured. This is done by lifting the crucible from a pit furnace, gripping it in suitably shaped tongs, and pouring the metal from the lip of the crucible into the mould in an unbroken stream while retaining the dross in the crucible, an operation which needs much skill if casting defects are to be avoided in the ingot. The pouring temperature will depend partly upon the chemical composition of the brass, partly upon the size and the number of the moulds which have to be filled and, because pyrometric control is seldom used, partly upon the immediate feelings of the caster. " Cartridge metal," which contains 70 per cent. of copper, is usually poured at a temperature of about 1,050° to

1,100° C.; "basis quality" brass, containing about 63 per cent. copper, is usually poured about 50° C. lower.

Fig. 6 shows a crucible of molten brass removed from a pit furnace being poured into a strip ingot. The method of handling is typical for crucibles of moderate size; smaller crucibles are handled by one man who grips the pot in tongs so designed that he stands in front of the crucible lip to pour, and larger sizes are handled with the help of mechanical hoists and overhead runways, pouring being done as shown in Fig. 6, although the dead weight of the crucible is taken by the chain of the hoist. Fume-extractors, of the kind seen in Fig. 2 (p. 4), are often used to prevent zinc fumes filling the casting shop.

Oil-fired container-furnaces and electric induction furnaces are invariably tilted by mechanical means, and the molten stream directed into the mould which is often placed in a pit in front of the furnace, as shown in Fig. 3 (p. 4) and Fig. 5 (p. 5). The metal is usually poured into a kind of perforated tun-dish or funnel, such as that shown in Fig. 8 (p. 12), which traps dross, distributes the molten stream over the width of the mould, and helps to give more uniform conditions of pouring.

After the mould has been filled it is necessary to continue pouring, though at a greatly reduced rate, in order to fill the cavity or "pipe" which forms at the top of the ingot owing to the metal near to the sides of the mould solidifying while the centre is still molten and the whole ingot is shrinking rapidly. By reason of the lower casting temperature of brass, this "feeding" process is not so lengthy and does not demand the special precautions—such as "hot tops" to retard solidification in the top of the ingot—which are often used with steel.

The moulds into which the metal is poured are heated in order to dry them very thoroughly and are coated with some dressing, usually heavy oil or soot, to prevent the metal sticking to the mould surface and to lengthen the life of the mould. The presence of moisture in a mould is likely to cause a serious explosion, for the instantaneous generation of steam throws molten metal all over the casting shop and has been the cause of serious accidents. Those unfamiliar with molten metal have little idea of its danger; an explosion in a mould is an unpleasant episode, while the breaking or upsetting of a full crucible is likely to lead to serious injury to any who are unfortunate enough to be unable to jump clear. Due to the lower temperature of the metal and the much smaller quantities handled, the danger is less with brass than with steel; a serious explosion in a steel works or the collapse of a really large ladle or furnace is an experience which survivors do not forget.

After the cast ingot has solidified it is "stripped," that is, the mould is opened and the ingot extracted, while it is still at a relatively high temperature in order to lessen the danger of it cracking as it cools and shrinks, owing to parts of it " hanging " on small irregularities on the surfaces of the mould.

Moulds. The soundness of the ingot is determined to a large extent by the nature and arrangement of the mould. A brief description of this important adjunct to the casting process cannot, therefore, be omitted.

Not many years ago brass casting shops stocked a large assortment of moulds for casting thin, strip-form ingots up to 24 inches wide, selection being made according to the width of the sheet or strip it was desired to roll. Of late years there has been a tendency to use narrower and thicker ingots cast in moulds capable of being filled from one crucible. In this way the troubles commonly arising out of trapped films and included dross when several crucibles had to be employed to fill a large mould have been eliminated. The required width of strip can in most instances be obtained by cross-rolling the narrower but thicker ingots now produced. It is stated sometimes that this change is responsible for an increase in the number of surface defects found on sheet, but the general opinion seems to be that, if the thicker ingots are cast with care, the sheet produced from them is decidedly more free from " spills," " laminations " and other familiar surface defects than sheet produced by the old methods.

A marked change in the angle of the mould has taken place. Some years ago an angle of 60 degrees with the horizontal was common and 45 degrees not unknown; to-day moulds are usually placed in a vertical, or nearly vertical, position for filling. It is maintained that this alteration in position has resulted in increased soundness in, and a better surface on, the resulting ingots, and an increased life of the moulds themselves. The change in the size, shape and angle of mould is illustrated in Figs. 7A and 7B. Small ingots are often cast in a back-to-back mould, which is merely a clamped assembly consisting of two moulds, each having its open face closed by opposite sides of a common back-plate, as shown in Fig. 7C. By means of a suitable pouring device, often incorporated in a perforated tun-dish, two or four moulds can be filled at one pouring by this arrangement, thus saving time and avoiding the necessity for an undesirably high pouring temperature for the first of a number of successively-poured ingots.

With both electric and fuel-fired tilting furnaces, forms of turntable- or conveyor-moulds have been developed and used to facilitate the rapid filling of a number of small moulds when the available rolling plant cannot accommodate an ingot equal to the capacity of the furnace used for melting. Persistent defects in ingots cast into such moulds have been traced, not without considerable investigation in the first instance, to effects produced by vibration of the moving mould before the metal within it has completely solidified. Stationary moulds fed

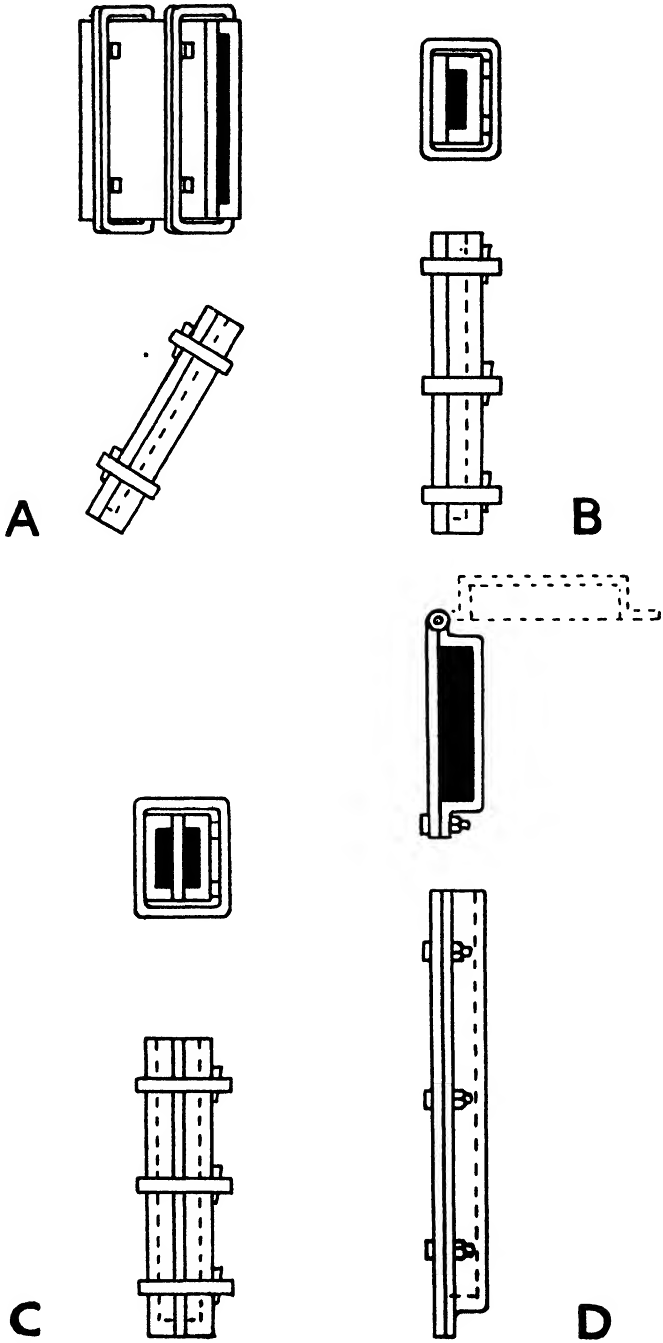


Fig. 7. Diagrams illustrating various forms of moulds for the casting of brass ingots for rolling.

A. Old type of strip mould inclined at an angle.
B. Modern vertical strip mould giving a thicker and narrower ingot.
C. Backed strip moulds filled at one pouring.
D. Modern 1,000 lb. ingot mould hinged and usually water-cooled.

by a movable furnace appear to be the surest way of overcoming this troublesome and often obscure defect.

As the size of electric furnaces continues to increase, a tendency to return to large, wide moulds is discernible. In contrast to the old, thin, wide strip moulds these new moulds are, however, relatively thick, and are completely filled from one crucible or furnace. A typical modern ingot destined for hot rolling may weigh over 1,000 lbs. and have a section 3 to 4 inches thick and 14 to 18 inches wide.

Both large and small moulds are nearly always split longitudinally and are not made solid as are moulds for steel. The two halves of small moulds are usually separate, and are held together during casting by means of rings and wedges driven in with a hammer, as seen in Fig. 2 (p. 4) and illustrated diagrammatically in Fig. 7; hence the term "to knock up" a mould. Larger moulds are usually hinged at one side to open like a book as shown in Fig. 7D, being secured by nuts and bolts at the opposite side and, in large moulds, sometimes at the top and bottom as well.

At one time grey cast iron was used almost exclusively for the construction of moulds, but during recent years copper has been used more and more, particularly for moulds of large size. The special forms of heat-resisting cast iron which have recently become available do not appear to have supplanted the older variety; whether this is due to lack of adequate trial, or to fair trial having shown them to be no less susceptible to "blowing" and surface cracking than the more common varieties, appears uncertain. The percentage of cracked ingots due to "hanging" has in some instances been reduced by the substitution of flat machined faces for the stepped locating faces previously employed where the two halves of a mould abut, and by a more general appreciation of the shortcomings of the old "ring and wedge" method of assembly, including the necessity for "knocking up" from the lowermost ring progressively upwards.

The use of copper as a mould material has increased most of all in the thin water-cooled plates in the large-sized moulds which are now coming into use. The principal advantage offered by copper appears to be a marked reduction in "blowing," a colloquial term which implies the expulsion of gas entrapped in surface cracks, in graphite cavities, or caused by the general porosity common to ordinary cast iron leading to the formation of gas bubbles and discontinuities in the surface of ingots. This is owing partly to the natural freedom of copper from pores, and partly to the very much lower temperature which copper attains by virtue of its greater heat conductivity and of the fact that relatively thin walls, cooled by water, can be used. Another advantage is that with copper moulds of this type it is not found necessary to use heavy carbonaceous mould dressings which are themselves prone to give rise to surface defects in the ingot.

The construction of these copper-faced water-jacketed moulds, of which the hinged Junker variety is well known, usually embodies thin copper plates, of from one-quarter to three-quarters of an inch thickness depending on the size of the mould, supported in a strong cast iron outer casing between which and the copper water flows around suitably disposed baffles. Fig. 8 shows a typical arrangement for the production of a thousand-pound ingot from an electric furnace.

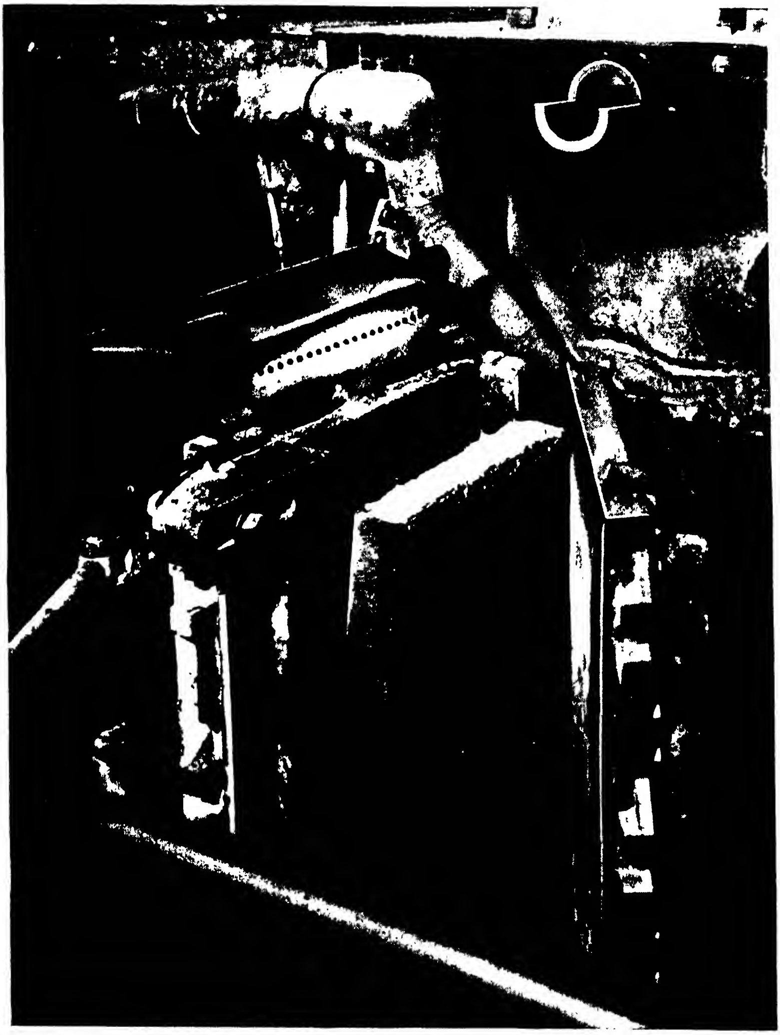
To obtain the full benefit of water-cooling it is essential that the copper used for the inner walls of moulds be as pure as possible, owing to the very marked influence of impurities upon the conductivity of this metal. Discussing this aspect, Genders and Bailey [2] state that at 20° C. the conductivity of copper is decreased approximately 50 per cent. by the presence of 0·4 per cent. arsenic, 0·1 per cent. phosphorus or 1·5 per cent. tin. This fact is not known as widely as is the otherwise beneficial effect of arsenic upon the physical properties of copper intended for exposure to high temperatures.

Little published information is available on the influence of various forms of mould dressing upon the surface of ingots. In some shops the methods adopted have remained practically unchanged for many years, each shop and individual seeming to have their favourite dressings; no real advance can be claimed either in general knowledge or in practice except, perhaps, in the substitution of more modern methods of soot application than are afforded by burning oil-soaked rag, and in a more sparing application of liquid or viscous dressings.

Rolling

Having obtained a sound, satisfactory ingot, the next task of the producer is to roll it into sheet or strip having a thickness which lies within the agreed tolerances of the nominal thickness specified by the consumer and, which is of importance, having an excellent surface finish. Before this is done it is usual to cut off the top of the ingot, but the proportion thus discarded is small and defects in finished brass sheet attributable to inadequate "cropping" are rare.

The reduction of brass ingots to sheet or strip is usually carried out in three stages. The first of these is known as "*breaking-down*" the cast ingot—sometimes termed a "slab" if it is thin—or the slabs obtained from sectioning longitudinally a thick ingot; the intermediate stage, in which the sheet or strip is reduced to nearly the finished thickness, is commonly termed "*getting-down*"; while the final stage, in which the essential object is the production of the best possible surface finish and the closest possible conformity to the desired nominal thickness, is known as "*finish-rolling*." Unless hot-rolling is used for breaking-down, the only essential difference between these three stages lies in the excellence of the surface-finish of the rolls used and the accuracy with which the thickness of the product is



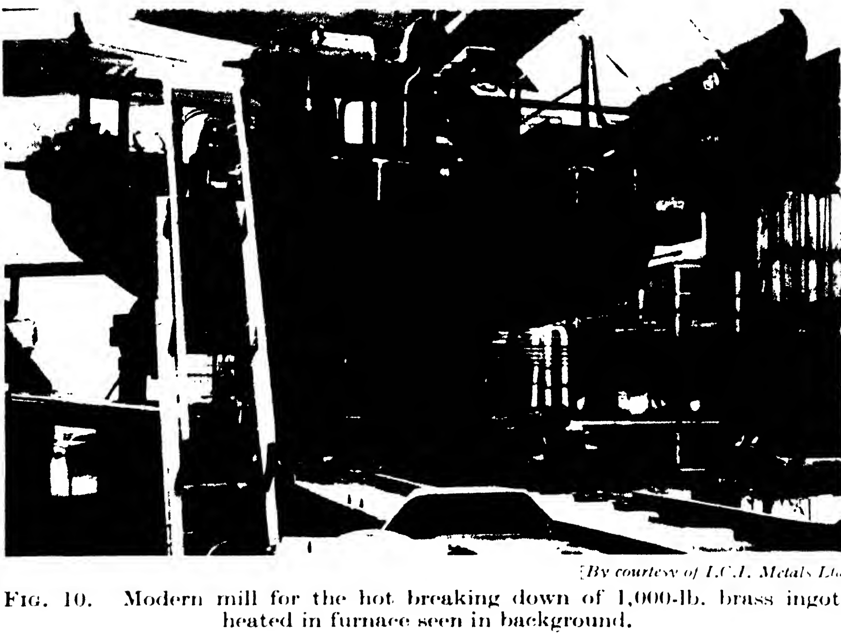
[*By courtesy of the Copper Development Ass.*

FIG. 8. Water-cooled Junker mould shown opened ready for removal of 1,000-lb. brass strip ingot. Observe tun-dish, which narrows to a row of small holes, into which the metal is poured from the tilting electric induction furnace seen in the background.

[*To face p.* 12.

[*By courtesy of I.C.I. Metals Ltd.*

FIG. 9. Breaking-down mill for brass strip ingots.



[*By courtesy of I.C.I. Metals Ltd.*

FIG. 10. Modern mill for the hot breaking down of 1,000-lb. brass ingots heated in furnace seen in background.

[*To face p.* 13.

controlled. The end of each stage is marked by the transference of the metal from one roll stand to another, not by the attainment of any definite thickness or percentage of total reduction; a custom which sometimes puzzles laymen.

Electric motors have now almost entirely superseded the familiar steam engine which formed the heart of old mills, and in modern plant it is common for each stand to have its own separate motor. Apart from other advantages, such as increased cleanliness of the whole mill, electricity offers a more convenient and a more easily controlled source of power, particularly when separate motors are used.

Breaking-down. As a rule brass ingots are broken-down by repeated cold-rolling helped by annealing whenever the metal becomes too hard to withstand further reduction without cracking. Fig. 9 shows a typical breaking-down mill.

Sometimes brass ingots, more particularly those of low copper content, are broken down by hot-rolling, a procedure which enables thick ingots to be rolled down to relatively thin strip at one heating if the lay-out of the mill allows. When this method is used, the ingots are heated to rolling temperature in muffle furnaces, which are usually fired by oil or gas, and work on the continuous principle using a pusher or walking-beam mechanism to carry the ingots through the chamber to the discharge end. Fig. 10 shows a modern reversing mill designed for hot-rolling 1000-lb. brass ingots approximately 4 inches thick into strip less than a quarter of an inch thick at one heating.

Both processes have their advantages and disadvantages, but choice is usually influenced more by economic considerations and by the nature of existing plant than by the quality of the product. It seems fairly certain that in brass of low copper content hot-rolling favours the retention of "*beta*", an undesirable hard constituent which will be studied in a later chapter, and some mills have given up the practice of hot breaking-down for this reason. Some authorities are of the opinion that it is more difficult to obtain a regular crystal structure when hot breaking-down is used, but it is difficult to substantiate such a statement unless it can be shown that the accuracy of control in both processes is comparable; for it is, unfortunately, only too easy to produce an irregular crystal structure by cold-rolling and bad annealing.

Whether breaking-down is done hot or cold, the very important fact remains that the degree of regularity—as distinct from absolute size—of the crystals produced during this process *tends to persist afterwards*. If the crystal structure is spoilt by incorrect thermal treatment at an early stage in the history of the ingot or strip, the most carefully-controlled annealing during subsequent stages will not repair, nor even neutralise, the damage done. Industrial experience and laboratory investigations invariably confirm the statement just made, yet many suppliers who control their finishing processes with care still use unnecessarily high annealing temperatures and leave much to chance during the really vital process of breaking-down and the following getting-down stages.

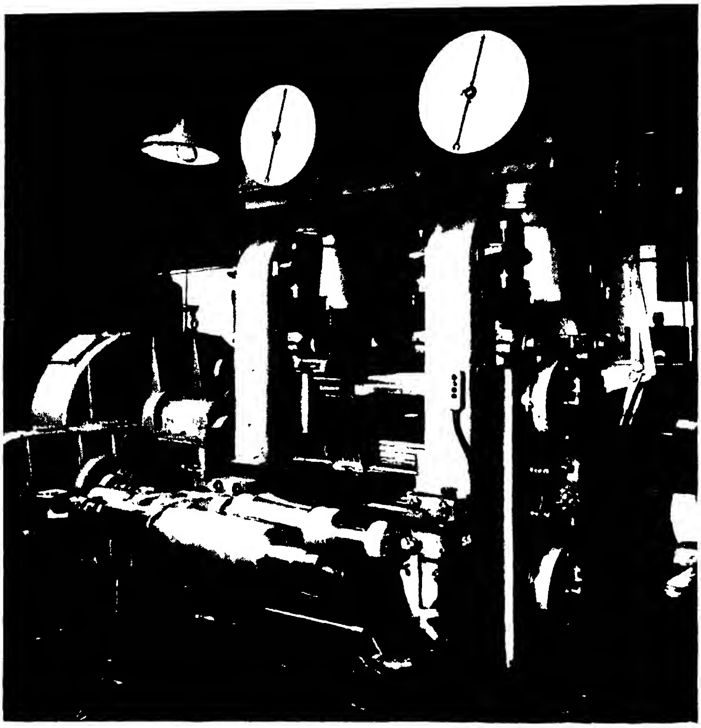
Scalping. It is a common practice to machine off the entire surface of brass ingots either before, during or at the end of the breaking-down stage, thus removing casting defects which would spoil the surface of the finish-rolled sheet. Formerly this was done by the slow method of planing, but high-speed milling cutters, often mounted in gangs, now carry out this " scalping " operation in a very much shorter time and give a better finish to the machined surface.

The most scalping can do is to remove shallow surface blemishes ; the absence of visible defects on the surface of finish-rolled sheet is no guarantee that sub-surface defects due to poor casting will not open up when the sheet is severely worked under the press. Because of this, not all mills carry out scalping. Some producers believe that it is better to exercise great care in casting than to machine away defects attributable to less careful casting, and it must be admitted that in some instances their claim is substantiated by the excellence of their product. The value of what may be termed true craftsmanship is demonstrated by the fact that some of the best brass strip the author has seen has been rolled from unscalped ingots cast from brass melted in crucibles heated in coke-fired pit furnaces—the old, original procedure. This does not mean that the product of a modern mill could not be proportionately better, particularly if the brass is melted electrically and cast in copper-faced moulds ; the inference is that care and craftsmanship are still necessary even though modern appliances and " scientific control " have made it easier to obtain the desired conditions.

Getting-down. In this intermediate stage in the rolling of brass sheet or strip, reduction is continued by further cold-rolling and annealing, the only difference being that the surface of the rolls is better than that of those used in the breaking-down stage and that the thickness of the sheet is brought fairly close to that of the final product. This stage is of little interest to consumers, although of considerable importance to mill-managers concerned with output schedules and production costs.

It should perhaps be mentioned that the infliction of serious surface markings during this stage needs to be avoided, because they may not be obliterated during finish-rolling.

Finish-rolling. This final stage is one which, for the reasons stated already, is of considerable importance. Its principal claim to distinction from the preceding stages is that the surface-finish on the rolls is—or should be—the best which producers can afford to use, and that serious attempts have to be made to keep the rolls, tables and associated equipment clean and free from injurious particles of foreign matter and to avoid damaging the surface of the sheet or strip during handling.



[By courtesy of J. F. Ratcliffe (Metals) Ltd.

FIG. 11. Backed mill for cold rolling brass strip up to 24 inches wide and down to 0·004 inch thick.

[By courtesy of I.C.I. Metals Ltd.

FIG. 12. Modern 3-stand finishing mill for the continuous cold-rolling of brass strip up to 26 inches wide. Observe four-high backed rolls, electric drive to rolls and pinch adjustment, coiling arrangement, overhead runway and hoist for transporting heavy coils. The whole mill is operated from one panel giving independent control of the speed and pinch of each mill.

[To face p. 15.

Methods of finish-rolling, which is always done cold, and sometimes at a relatively high speed, vary in different mills according to the nature of the plant installed. In small mills the necessary reduction is usually accomplished by passing the sheet or strip through one or more separate stands with the "pinch" reduced after each pass. Fig. 11 shows a modern British mill, designed for this purpose, which will roll strip up to 24 inches in width and down to a thickness as small as 0·004 inch. Items of interest seen in this photograph are the totally enclosed reduction gearing which transmits power from an electric motor to the rolls; electrically-operated pinch adjustment with finely-divided large-diameter indicating dials; push-button control to rolls and pinch adjustment; electrically-driven integral coiling device, and the arrangement of the four-high "backed" rolls, the purpose of which will be explained later. In large mills, and in some mills of moderate size, the strip may be passed continuously through a number of stands in "tandem," the speed of each stand usually being so controlled that a definite tension is maintained upon the strip between each stand. A typical modern mill for cold-finishing brass strip, comprised of three stands, is shown in Fig. 12; as many as five stands are sometimes placed in tandem in large mills in the United States and on the Continent.

This outlines the stages commonly used in Great Britain to roll brass ingots into finished sheet or strip. It is beyond the province of this book to discuss rolling technique, but three items which affect the quality of the rolled strip may be mentioned briefly; these are the number of rolls grouped in a stand, the material of which the rolls are made, and the methods used for coiling and handling strip as it emerges from the rolls.

During recent years there has been a tendency to replace the ordinary pair of rolls—or, as is used sometimes, three rolls having their axes in one plane to make a "three high" instead of a "two high" stand—by what are known as "backed" rolls. In stands of this kind the thrust of the driven rolls, which make contact with the metal being rolled, is carried not by bearings at the ends of these rolls but by backing rolls, usually of large diameter, supported in the orthodox manner. By this method the load on the bearings can be reduced and heavier reductions given to the strip at each pass, because in most rolling operations the severity of the reduction is usually limited by the load-carrying capacity of the bearings and the diameter of the working rolls. Other advantages are that the small size of the working rolls makes it easier to change them, lessens the cost of replacement or grinding, and, which is of importance to consumers, makes it easier to obtain strip in which the thickness does not vary unduly from the edge to the middle due to the rolls springing into a bow shape under the high pressures applied. It should be mentioned that the effect of this spring is usually counteracted by making rolls slightly cambered from ends to middle, as indicated in Fig. 13, particularly when they are wide. The effect of this is, of course, to give a smaller clearance between the mid-points

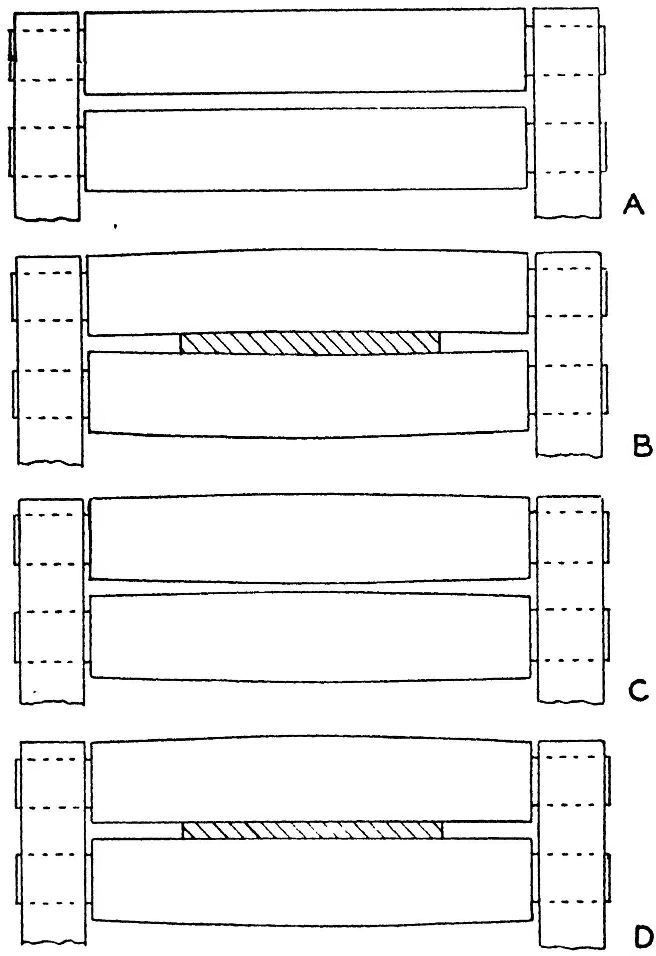


FIG. 13. Diagrams illustrating how roll-spring is counteracted by camber.

A. Parallel rolls unloaded.
B. Elastic deflexion of loaded parallel rolls produces a sheet thicker in the middle than at the edges.
C. Cambered rolls unloaded.
D. Elastic deflexion of loaded cambered rolls produces a sheet of more uniform thickness.

than between the ends of a pair of rolls when they are not under pressure.

Sometimes two working rolls each backed by a single large roll, all rolls having their axes in one plane, are used. A different and popular arrangement known as a " cluster " mill employs at least two backing rolls to each driven roll, thus relieving the bearings of the working rolls of side as well as vertical thrust. The disposition of rolls in backed and cluster mills of simple type is indicated in Fig. 14.

Apart from economies in production, it is usually claimed that strip

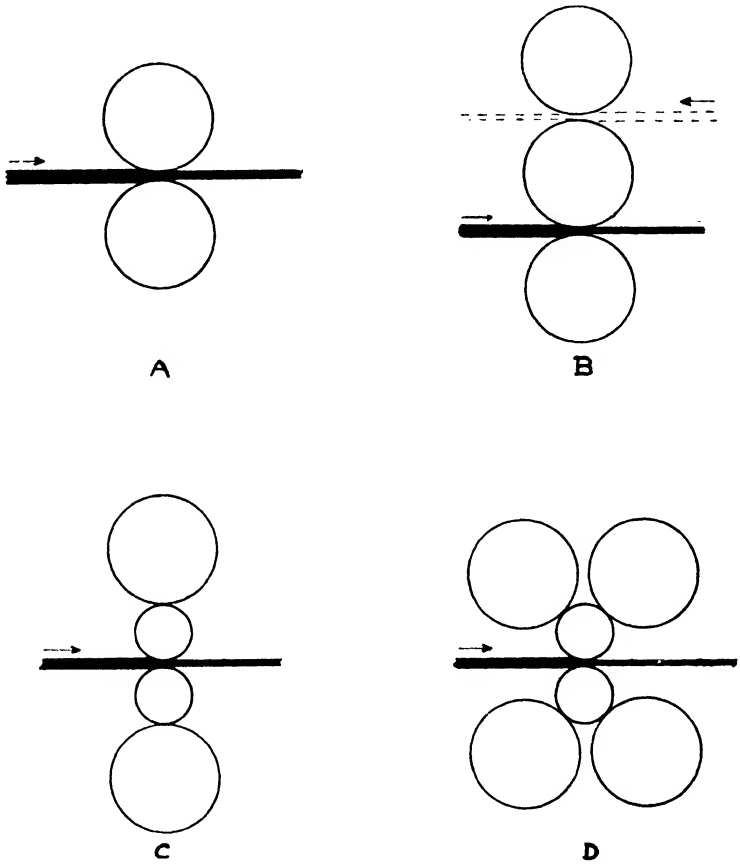


FIG. 14. Diagram illustrating arrangement of rolls.

A. Ordinary two-high mill. Reversing optional.
B. Three-high mill. Reversing unnecessary.
C. Four-high backed mill. The small working rolls are driven and are carried in bearings which take only side thrust, vertical thrust being taken by the backing rolls.
D. Simple form of cluster mill. The small working rolls are driven and the backing rolls take both vertical and side thrust.

rolled in cluster or backed rolls is of more constant and accurate thickness and has a better surface than strip rolled in unbacked rolls. The last, although not the first, claim is often disputed; for it is argued that the presence of the hard backing rolls tends to force particles of foreign matter into either the working or the backing rolls or at least to damage their surfaces, whereas if the working rolls are unbacked any particles are merely embedded in the soft sheet and do not damage the rolls themselves. For this reason there is probably some truth in the counter-claim that sheet having the very best surface comes from unbacked rolls having a specially good surface finish.

Ground and polished steel rolls have mostly superseded the chilled iron rolls which were in general use not many years ago. This change has been largely responsible for a noticeable improvement in the surface finish of rolled brass strip, and recent improvements in roll grinding and polishing technique will help to increase still further the present high standard.

The better the surface on rolled sheet or strip, the more likely it is to be damaged by careless handling. An important improvement is, therefore, the replacement of crude manual or mechanically-assisted methods of coiling and handling by well-designed, wholly-mechanical devices, although these are seldom as " fool-proof " as modern disinterested labour often renders desirable. Apart from the question of accidental damage, the greater weight of the coils now commonly rolled renders wholly-mechanical handling essential.

The surface of some cold-rolled brass is so excellent that it has the appearance of being polished. Indeed in some instances the surface finish is better than users can take full advantage of with present methods of handling and pressing, and complaints regarding surface finish are usually confined to localised defects and blemishes not attributable to the treatment given to the metal in the rolling mill.

Before leaving the important subject of rolling it must be said that the speed of strip-rolling has increased very greatly during recent years. This has been made possible by improvements in the design of roll bearings, coiling devices and frame rigidity, while the introduction of electro-mechanical devices—often termed " flying micrometers "—which automatically indicate the thickness of rapidly-moving strip has removed one of the serious disadvantages of high-speed rolling.

Annealing. From time to time during the rather lengthy process of reduction by cold-rolling it becomes necessary to restore the ductility of severely cold-worked metal by annealing, that is, by heating the slabs, sheet or coils to a certain temperature for a predetermined period. Exactly the same conditions arise, of course, during the subsequent working of sheet in the presses of consumers.

In the past the deep drawing and pressing properties of much brass have been spoilt by incorrect annealing in the mills of suppliers ; even now, in spite of the facilities offered by modern annealing plant and the supposed application of much-advertised " scientific control," annealing conditions are not always controlled sufficiently closely to ensure a crystal structure of desirable uniformity in finished sheet destined for the press-shop.

In brass rolling-mills annealing furnaces are usually of muffle or semi-muffle type heated by coal, producer-gas, town's gas or electricity. Only the oldest types of furnaces are coal-fired owing to the uncertainty of temperature control and the difficulty of ensuring the reasonably uniform or constant heating of a large chamber with a coal fire as a source of heat. Producer-gas possesses the advantage that, although it is very cheap, much more uniform heating can be obtained with it than with coal because heat is generated at a number of burners instead of at one place. A serious disadvantage is that in small plants the producer seldom receives sufficient attention, and the calorific value of the gas, and hence the temperature of the furnace, is liable to vary rather widely throughout a day's run. Oil fuel and town's gas can give tolerably uniform heating in well-designed furnaces; oil is the cheaper, but gas the cleaner and more convenient source of heat. Electrically-heated furnaces are the cleanest, the most easily controlled and, if designed well, give the most uniform heating of any, but their operating cost is high compared with that of other methods just described. Because of this it is likely that the newly-developed "radiant tube" method of heating by town's gas, in which the products of combustion do not touch the work being annealed, will prove popular.

Automatic methods for controlling and often for recording temperature are installed in most modern annealing furnaces, but unfortunately the indication of a certain temperature by pyrometers placed, for example, in the roof—or even the roof *and* sides—of a muffle is no guarantee that all parts of a charge placed on the floor have reached a certain temperature for a certain time: hence the very real difficulty of accurate temperature control during the annealing of bulky charges.

Annealing furnaces for brass may be divided into two groups: batch furnaces into which a charge is placed, allowed to reach furnace temperature, and then withdrawn; and continuous furnaces through which sheet, strip or coils are passed at some predetermined speed.

Batch-type Furnaces. Batch-type furnaces suffer from the inherent disadvantage that it is difficult to heat the whole of a large chamber uniformly by means of a number of isolated hot-spots such as are provided by gas or oil burners. Owing to the larger area covered by the heating elements, electric furnaces are rather better in this respect, but, in a chamber measuring several feet from side to side, there must always be a tendency toward uneven heating of a charge packed into it and heated from the sides.

Useful refinements in batch-type furnaces are the provision of fans, which are usually mounted in the roof, to give what may be termed "disturbed" air circulation, and the incorporation of heating elements on the doors of large furnaces. Both these additions are valuable, but even with their help it is almost impossible to heat the whole of a charge uniformly particularly when, as is usual, the metal is in the form of coils because the outer layers of these heat up more rapidly than the inner layers.

The importance of the part played by convection in the heating of a furnace charge to temperatures up to 700° C. is not appreciated sufficiently. In a so-called "still-atmosphere" furnace the greater part of the heat transference is actually accomplished by convection currents, and appreciation of this knowledge has led to the development of forced circulation produced artificially by means of interior fans driven by exterior electric motors. An electrically-heated disturbed-air circulation furnace annealing coiled brass strip is shown in Fig. 15; the same principle can, of course, be applied to gas-heated furnaces.

The use of *rapid* forced-circulation air furnaces seems to be the best method yet devised for annealing coiled brass strip in a really uniform and closely controlled manner; but even with this method it is essential that the coils be thoroughly unloosened before being placed end-on to the stream of heated air. The principle of forced-circulation, which is described more fully later, consists essentially of causing a current of air or other gas to circulate at high velocity alternately over heating elements and then over and through the charge, and is not to be confused with "disturbed" circulation produced by roof fans in a muffle furnace of ordinary type. It is to be regretted that this very excellent method of heating, which gives such outstandingly good results with pressings, is not adopted more often by the producers of brass strip.

Continuous Furnaces. Continuous furnaces are of two kinds: the old kind in which coils are conveyed through the furnace by a belt or pusher device, and a newer version in which the ends of coils are welded or punched together to form a continuous strip which is then wound through the furnace and again cut up into convenient lengths as it emerges. The old kind of continuous furnace suffers from many of the defects associated with the batch-type of furnace; for example, all parts of a coil are not heated at the same rate and the temperature reached by similar parts of different coils often varies in wide furnaces according to the position of the coil on the belt or hearth. The new type, in which the metal is annealed in the form of a single, continuous strip, seems nearly ideal in theory, but it has not proved as successful in Great Britain as it has in other countries. This is explained by the fact that, for obvious reasons, the process is most suited for the continuous annealing of strip of *one width and thickness.* When, as in small mills, a large number of different thicknesses and widths of strip have to be annealed in one furnace, it is manifestly difficult by continually altering the temperature of the furnace or the speed of travel of the strip to obtain at once exactly the proper conditions for each successive variety of strip passed through it. When production conditions do allow the various heating and cooling zones of a modern automatically-controlled continuous strip annealing furnace to be properly adjusted for the

By courtesy of J. F. Ratcliffe (Metals) Ltd.

FIG. 15. Mechanical charger loading coiled brass strip into electrically-heated batch annealing furnaces. Observe heating elements on door and fans mounted on roof of furnace.

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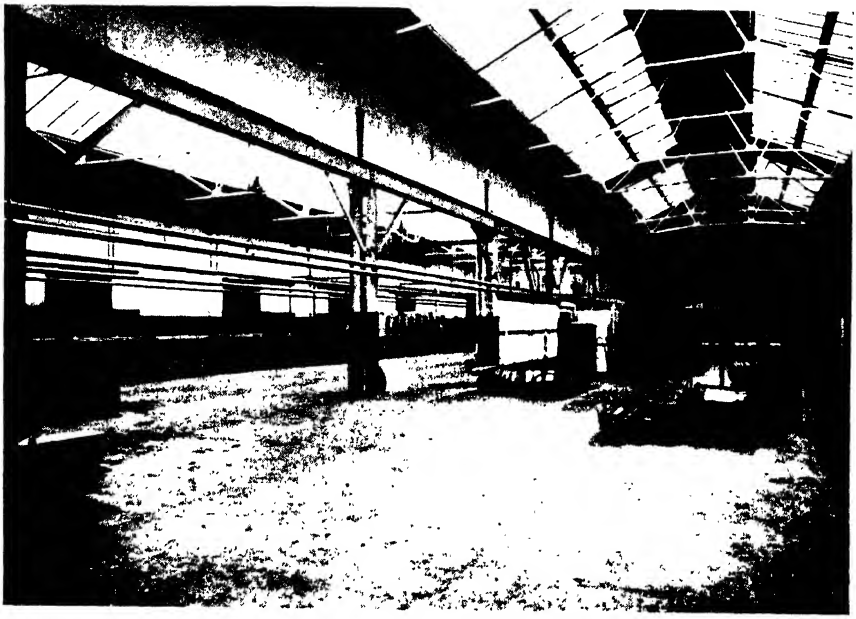


[*By courtesy of Birmingham Electric Furnaces Ltd.*

FIG. 16. Two types of clean-annealing furnaces both electrically heated and utilising a protective atmosphere.

Left : Tunnel furnace with water-jacketed cooling chamber for the continuous annealing of strip.

Right : Batch type plant comprising movable furnace and three sealed containers in which coiled strip is heated and cooled.

[*To face p.* 21.

uninterrupted passage of a large quantity of strip of uniform section, the resulting uniform heating and cooling of every foot of strip can be of great benefit. A continuous annealing furnace for strip is shown in Fig. 16.

Bright Annealing. No review of the annealing of brass strip would be complete without some mention of " bright annealing," an ideal which proves strangely elusive under industrial conditions. Manufacturers of brass strip have attempted for many years to obtain a genuinely bright-annealed product, but the degree of success achieved by most processes and plants seems to have been determined by the interpretation placed upon the adjective " bright " by individual judges.

Three methods are in use. The oldest is the provision of water seals through which work must pass at the entrance and exit of continuous belt or pusher-type furnaces. Although free from scale, few would venture to describe the product of such furnaces as bright; indeed, sometimes the surface is badly stained by the action of the water.

Another method is that of heating and cooling coils of strip in sealed bell-type furnaces or containers of the kind shown in Fig. 16, either with or without the introduction of a special protective atmosphere, but this process is used more for steel and certain non-ferrous metals, for example copper, than for brass. The reason for this neglect is perhaps due to the fact that brass annealed in this way, although clean, is not always sufficiently bright to justify the expense of the necessary plant and the number of containers required to handle a comparatively small output, for it must be borne in mind that the charge has to be cooled as well as heated in the sealed container.

The third and most successful method is the modern one of annealing in continuous furnaces employing a specially-generated " controlled atmosphere " to prevent oxidation. At one time furnaces of this kind were always heated by electricity, but the development of the " radiant tube " method of heating is likely to prove a serious rival owing to its lower running costs. In this method the products of combustion of town's gas are not allowed to reach the work, and a controlled atmosphere of any kind—for example cracked or burnt ammonia, but more often partially-burnt town's gas—can be used in a sealed chamber in exactly the same way as in electrically-heated furnaces. The usual form of controlled-atmosphere continuous furnaces is a long tunnel surrounded by separately-controlled heating zones near the entrance end and by a cold water jacket extending from the furnace portion to the exit. A typical furnace of this type is illustrated in Fig. 16; the tunnel may be made large to accommodate coils or—which is much more satisfactory from the aspect of uniform annealing and, incidentally, conservation of the special atmosphere—small to accommodate flat strip.

It is well recognised that even this type of furnace, which has achieved deserved popularity for the annealing of other metals, does not always give truly "bright" annealing with brass because those atmospheres which are quite satisfactory with many other metals are not always adequate for brass. For example, brass annealed in burnt town's gas or cracked ammonia should have a perfectly clean surface, but it will not usually have that genuine "brightness" which is so desired. Developments in the use of burnt ammonia, whereby under suitable conditions 80 or 90 per cent. of the gas circulating in the system is conserved and "regenerated" by chemical processes, have now brought the cost of this very efficient protective atmosphere to a reasonable level, and it may be that its industrial application to the annealing of brass will satisfy at least some of the critics of bright-annealing as attempted hitherto.

At present clean-annealing is attempted only toward the end of the mill sequence. More general use of clean-annealing throughout the whole sequence would, however, seem desirable from all aspects except perhaps that of economy, because if it were used pickling and cleaning operations could be reduced. It is important to bear in mind that, to secure the full benefits which protective-atmosphere annealing can give, it is essential that all traces of rolling lubricant be removed before the work is placed in the furnace. This is often overlooked.

Returning from this special consideration of clean-annealing to annealing in general, it must be emphasised at the end of this section that, whether a protective atmosphere is used or not, more uniform annealing with respect to temperature is needed badly. Only by the installation and intelligent use of carefully designed modern furnaces and processes can the whole of a charge of metal be given the exact thermal treatment which is so necessary if its best deep drawing and pressing properties are to be produced regularly. No excuse is offered for mentioning again the fact that, at best, no better than mediocre results can be obtained when only the annealing of finished, or nearly finished, brass strip is conducted with proper care; *proper thermal treatment must be given at each annealing throughout the whole mill sequence if the desired crystal structure is to be attained in the finished strip*, a proved fact which many producers of brass strip seem curiously loath to recognise.

Miscellaneous Finishing Processes. After the sheet or strip has been reduced to the desired thickness, a number of minor operations have to be carried out before the metal is ready for despatch to the consumer. Of these operations, pickling, cleaning, shearing and inspection are perhaps the most important. When flat sheet or strip is specified, flattening has to be done.

Pickling and Cleaning. Pickling is the name given to the process wherein metal is cleaned by immersion in a bath, usually of acid. For pickling brass, producers invariably use a warm solution of sulphuric acid. It is agreed that a strength of about 15 to 20 per cent. (by weight) is best, but this percentage is not always adhered to, and sometimes a little nitric acid is added to increase the vigour of the action and improve the colour of the pickled metal.

Pickling may have two objects: the removal of scale produced during annealing, or merely the removal of stains on scale-free sheet and the giving of a pleasing, lustrous appearance calculated to enhance the value of the product in the eyes of consumers. It is a particularly messy and unpleasant operation and, in bygone days when less care was taken to keep pickling vats in proper condition and the percentage of iron found in industrial brass sheet was higher, one which was liable to produce objectionable defects, such as the well-known "red stain."

Two methods of pickling are in common use. In the older method sheets or loosened coils, either loose or supported in racks, are lowered into vats of pickling solution and allowed to stand. In the modern version of this method the metal is continuously raised and lowered in the solution by means of overhead pneumatic devices which, in addition to providing this very beneficial agitation, often act as hoists.

The other and newer method is a continuous one, and is applicable only to strip. In the simplest forms of continuous pickling plant the strip is wound through one, or more often several, vats; in more complicated plants it may pass through a number of pickling and washing vats and then continue through drying devices employing hot rolls, hot air or hot sawdust. Sometimes rotating brushes are included to help to clean the wet strip or to polish the dried strip. In this way a lot of very unpleasant manual tasks are eliminated, and in many instances a uniformly good product is obtained; but it must not be forgotten that, as with most automatic processes, no selective treatment is possible and the speed of operation has—or ought—to be adjusted to deal with the *worst* areas on strip of varying quality.

Fig. 17 shows a typical plant for the continuous electric-annealing, pickling, washing and drying of brass strip. On the extreme left can be seen a coil which, unwinding from a cradle, is being wound through the furnace. The furnace, which is heated electrically by several separate zones controlled by automatic temperature-regulating devices, ends in a cooling chamber through which cold air is blown. From the cooling chamber the strip passes over large drums into pickling and washing vats, then between revolving brushes housed in the casing seen in the very middle of the photograph, then through a drying chamber in which warm exhaust air from the cooling chamber is utilised to dry the washed and scrubbed strip, and finally to the coiling device seen on the right of the photograph.

Even with the help of modern plants, which reduce manual handling to a minimum, pickling is an unpleasant process, and it is likely that the introduction of controlled-atmosphere annealing furnaces giving clean, if not unquestionably "bright," annealing will lead eventually to its elimination, or at least to its simplification.

In order to impart a particularly lustrous, golden appearance to brass, a "dichromate" dip is sometimes given as a final pickling operation. The solutions used usually consist of a sulphuric acid solution to which has been added either chromic acid or a dichromate—for example, that of potassium. Although undoubtedly pleasing to the eye, the finish imparted in this way should be regarded with suspicion in the press-shop because it is likely to cause unduly rapid wear on the tools used for deep drawing and even for pressing. It is well known that brass wire which has been pickled in dichromate solution wears drawing dies unusually rapidly. This behaviour is attributed to the abrasive action of the extremely thin film of chromate which a dichromate dip forms on the surface of brass, and it is certain that a similar action takes place with sheet; the effect is more noticeable with wire because an amount of wear which would spoil a die used for wire-drawing may not be seriously harmful on press-tools.

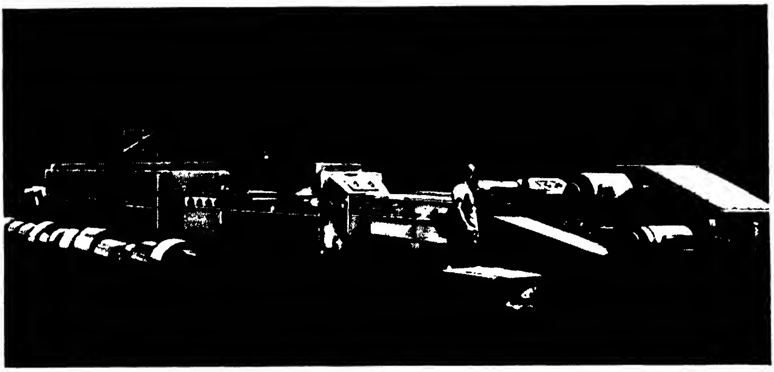
Cleaning and Polishing. When the continuous plants just described are not used, the pickled and washed metal is usually dried with the help of heated sawdust. This is often done in trays heated by gas jets and, although crude, the method possesses the advantage that operators can give extra rubbing to localised unsatisfactory areas. Sometimes the pickled metal is given a final polish with rotating brushes or buffs, but the excellence of the cold-rolled surface is usually such that this treatment is unnecessary except with metal destined for some special purpose.

Shearing, Coiling and Packing. The last operation through which the finish-rolled and cleaned metal must pass is the relatively simple one of cutting to the exact size specified by consumers.

Strip is cut to width by being passed through shearing rolls, as shown in Fig. 18. Sheet may be cut either in this way on wide rolls, or by means of suitable mechanical shears or guillotines fitted with guides to ensure that the sides of the cut sheet are square and parallel. Special machines, such as the one illustrated in Fig. 19, are made which will flatten, measure and shear coiled strip into short pieces of any desired length, thus saving time and lessening the danger of scratching the finish-rolled surface. This danger is greater than consumers may imagine, and considerable care has to be taken during the handling, transport and storage of finish-rolled metal as well as during the finishing processes just described.

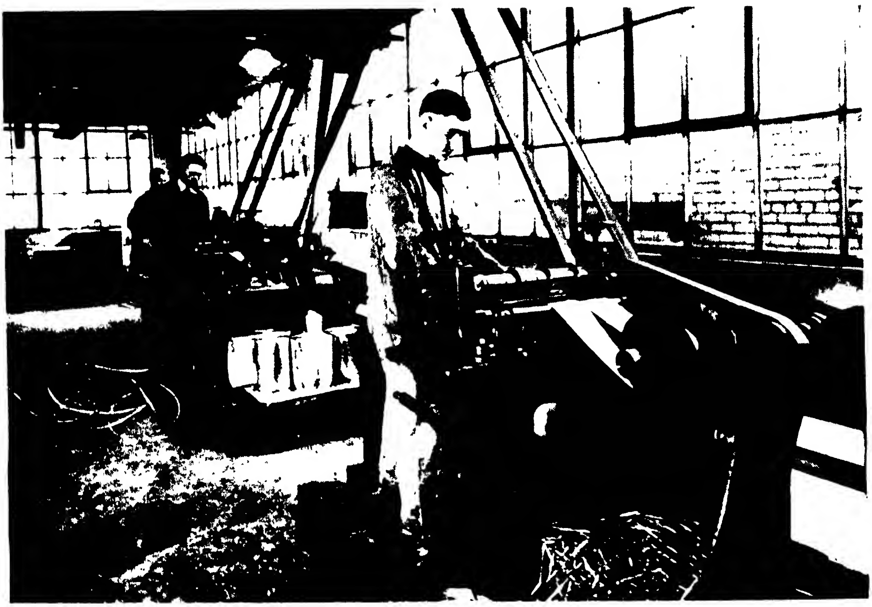
After final inspection sheared strip is coiled tightly, fastened with wire or tape, and identification marks are painted or tied on. Roller-levelled strip or sheet is packed in wooden cases. A protective coat or lubricant is not usually applied to brass.

The methods of packing now used are not always entirely satis-



[By courtesy of I.C.I. Metals Ltd.

FIG. 17. Continuous electric-annealing, pickling, scrubbing, drying and coiling plant for brass strip.



[By courtesy of J. F. Ratcliffe (Metals) Ltd.

FIG. 18. Shearing brass strip to narrow widths and trimming edges.

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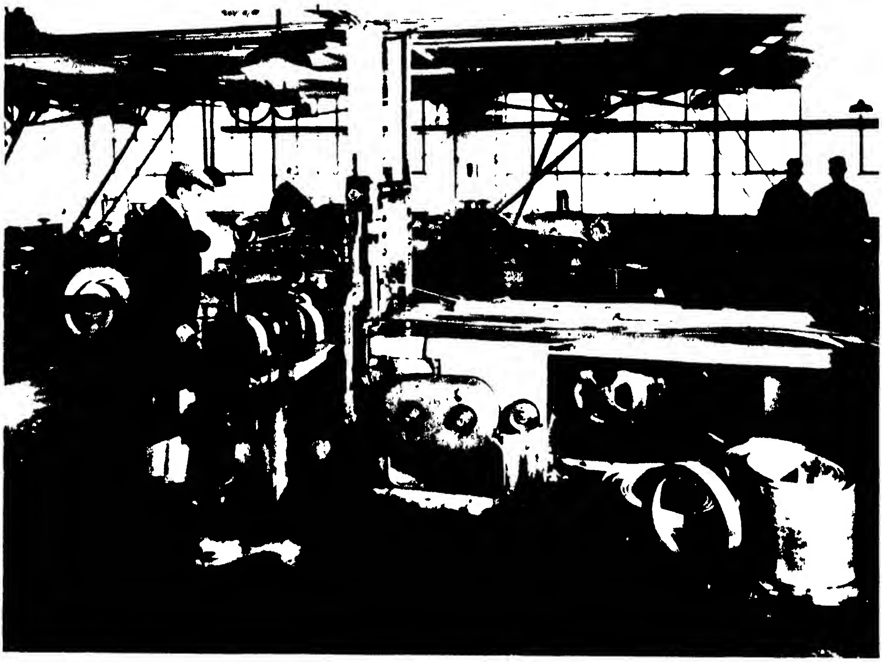


By courtesy of J. F. Ratcliffe (Metals) Ltd.

FIG. 19. Machine for flattening, straightening, measuring and cutting strip to exact length.

[*To face p.* 25.

factory. As the surface finish of cold-rolled brass continues to improve, it becomes increasingly necessary to preserve its surface-excellence during handling and transport to consumers. With softer metals—for example, aluminium—the necessity is even greater. The surface of tightly-coiled strip is self-protected, but the edges can easily be injured if the coil is handled roughly, dragged along hard, uneven floors or thrown about. Sheet or flat strip packed in boxes is often free to chafe, and the more general use of sheets of paper to separate each sheet would often be welcomed by those consumers who attach special importance to surface finish.

Inspection. The nature and thoroughness of the final inspection given by suppliers to their product is a matter upon which much controversy occurs between suppliers and consumers. It must be conceded that in these days visual inspection for visible surface defects is reasonably critical ; it is the physical properties of the metal which, consumers contend, are not always checked sufficiently.

This aspect, which is closely linked with those of purchase specifications and physical testing, is discussed at some length in a subsequent chapter, but it may be said here that adequate inspection for " average grain size " is not always carried out by suppliers, who rely sometimes upon Erichsen cupping tests, a useful but incomplete indication of deep-drawing properties. Some suppliers go so far as to make Erichsen tests on every coil of brass strip sent out ; but, helpful as this practice may be, it is far less reliable than that of examining the microstructure of as many samples as is rendered desirable by the annealing methods used.

Grades of Brass Sheet

Having followed the passage of brass sheet from the melting furnace to the despatch counter of the supplier, it will be useful to end this chapter—devoted, as it is, to a study of the sheet before it reaches the consumer—with a brief description of the grades of sheet which are commonly used in the press-shop and a few observations on their chemical composition.

Although special brasses are used occasionally, the bulk of the sheet used for deep drawing and pressing in Great Britain can be placed in one of three grades which differ mainly in the percentage of copper which they contain. These grades, which are covered by British Standard Specifications, are as follows :—

" Basis quality " brass covered by B.S.S. No. 265/1936, which may contain not less than 61·5 and not more than 64 per cent. of copper and not more than a stipulated maximum of total impurities, only lead being assigned a maximum of its own. This is the lowest grade of brass sheet. If free from defects and having a uniform and suitable crystal size it will withstand quite severe deep drawing and pressing operations if, and only if, the percentage of impurities, particularly of iron and lead, is very much less than the specified maximum and the microstructure is free from certain defects described later, such as free *beta* constituent and zones of very small crystals.

"65/35" brass covered by B.S.S. No. 266/1936, which may contain not less than 64 and not more than 67 per cent. of copper and not more than a stipulated maximum of total impurities, lead and iron being each assigned a separate maximum. This grade is distinctly better than "basis" quality, and is used extensively for pressing and also for quite severe deep-drawing operations. For many true pressing operations it is even preferable to cartridge metal, the next higher and more ductile grade.

"70/30" or "cartridge metal" covered by B.S.S. No. 267/1936, which may contain not less than 68 and not more than 72 per cent. of copper and not more than a stipulated maximum of each of a number of separately-mentioned impurities. This has been the accepted standard grade for severe deep drawing for a long while, but during recent years improvements in the quality of the "65/35" grade have made the cheaper grade a keen competitor in many fields previously held exclusively by "70/30." For the production of articles which can be made only by a long sequence of press operations, particularly when "ironing" has to be accomplished or when it is desired to reduce the number of inter-stage annealings to a minimum, "70/30" is likely to remain the best available grade.

In addition to these three popular grades, there is "French cartridge metal," containing 68 per cent. of copper, which is chosen by some consumers because it possesses deep-drawing properties nearly equal to those of "70/30," yet is slightly cheaper. For specially severe operations—for example, when it is desired to roll a lip on the periphery of a severely-drawn wall without annealing—a grade of brass containing a nominal percentage of 72 or even 75 of copper is used occasionally.

Hardness. Each of the three standard grades of brass sheet, that is "basis," 65/35 and 70/30, can be obtained fully-annealed or annealed and cold-rolled to give a hardness value which falls within one of a number of ranges included in the B.S.I. Specifications already mentioned. Sometimes the hardness of finished sheet supplied in any of these grades for press-work is purposely controlled to meet the requirements of individual articles. As a rule, however, brass sheet which has been ordered specially for deep drawing and pressing is delivered to consumers in a virtually fully-annealed condition. Any small variation in hardness and other properties is caused not by variation in the amount of final cold-rolling given, but by differences in the "average grain size" of the microstructure, a somewhat vexed property which is discussed in some detail in a later chapter.

In each of the three grades of sheet mentioned, the appropriate

B.S.I. Specifications call for a maximum hardness of 80 V.P.N. (Vickers Pyramid Numeral) for sheet in the fully-annealed condition.

Tensile Properties. Values for ultimate tensile strength and percentage elongation are sometimes included in specifications; for example, the three B.S.I. Specifications mentioned above—265/1936, 266/1936 and 267/1936—call for an ultimate tensile strength of 18 tons

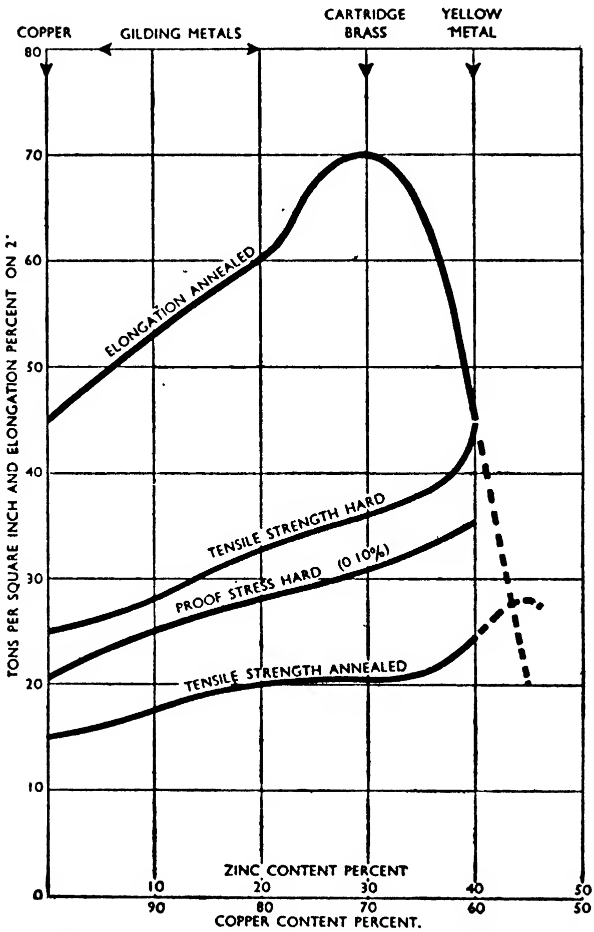


FIG. 20. Curves illustrating the general influence of the copper-zinc ratio upon the mechanical properties of rolled *alpha* brass sheet.

per square inch and a minimum value for percentage elongation on a 2-inch gauge length of 40, 45 and 50 for the "basis," 65/35 and 70/30 grades respectively. However, those having practical press-shop experience know full well that in brass of reasonably normal quality these values give little indication of small, yet important, differences in the behaviour of different consignments of metal under the press. A graph showing how tensile properties and hardness vary according to the relative proportions of copper and zinc present in alpha brasses having a normal crystal structure is reproduced in Fig. 20, but this should be regarded as an indication of general tendencies and not as a chart of reference applicable in all instances, because the values shown are influenced by other factors besides the copper/zinc ratio; for example, crystal size, the presence of unabsorbed *beta* phase and the percentage of impurities present.

Surface Finish. No recognised standards exist for surface finish, which is usually governed by the condition of the suppliers' finishing rolls. The product of modern mills is usually sufficiently good for all except special purposes, when some agreement has to be reached between individual suppliers and consumers for the supply of sheet having a specially good surface finish.

Dimensional Tolerance. The B.S.I. Specifications give tables of dimensional tolerances allowable on sheet and strip of stated width and thickness. For press operations in which tool clearances are critical these tolerances are often too wide, and consumers have to insist upon closer limits than, for example, the plus or minus 0·003 inch, making a total possible variation of 0·006 inch, which is allowed by B.S.I. Specifications on strip between 12 and 24 inches wide and between 0·040 and 0·080 inch nominal thickness. Reputable suppliers usually work to much closer tolerances as a matter of ordinary routine, and on strip, say, 14 inches wide a variation in thickness of no more than plus or minus 0·001 inch from the edge to the middle of all strip and from one coil to another is frequently obtainable from modern mills.

Chemical Composition. In addition to the proportion of the major elements, zinc and copper, which determine the grade of brass as already explained and, other conditions being equal, its behaviour under the press, there remains to be considered the important subject of impurities.

The marked influence which small percentages of unwanted elements exert is well illustrated by the improvement in the deep drawing and pressing properties of industrial brass sheet which even the least generous of consumers will agree has taken place during the last fifteen years. Were a batch of sheet of old quality introduced into a modern press-shop, wholesale failure would certainly occur. This welcome increase in purity has been caused mainly by an increase in the purity of the metal melted, particularly of the scrap; but better melting conditions and closer control by means of chemical analysis have also helped.

Epidemics caused by a high proportion of some one impurity—for example, cadmium or iron introduced with scrap—still occur occasionally, but the following chemical composition is fairly typical of much good quality industrial brass sheet now produced. It should be observed that these percentages are well below the maxima laid down in B.S.I. Specifications, and that serious departures from them occur occasionally.

Copper	Within 1 per cent. of the nominal value for the grade of brass specified.
Lead . . .	Less than 0·02 per cent.
Iron	0·02 to 0·05 per cent.
Tin	Less than 0·01 per cent.
Nickel	Less than 0·01 per cent.
Arsenic	Less than 0·01 per cent.
Bismuth	Less than 0·001 per cent.

The influence of these impurities will be studied in a later chapter which deals with defects in brass sheet, but it can be said here that each reduces the ductility, and hence the deep-drawing properties, of the brass. No value has been included for phosphorus, an element which normally is absent unless added purposely. Sometimes about 0·004 per cent. is added to restrict the rate of crystal growth during annealing, but occasionally, and particularly in France, much higher percentages are added in order to reduce the likelihood of the brass "season-cracking" when it is left in a condition of internal strain.

Deep Drawing and Pressing Properties. It is well recognised by those actively engaged in industry that sheet which conforms to the requirements of the appropriate B.S.I. Specification in every detail may fail to accommodate even moderately severe press operations, and it is a fact that true deep drawing and pressing properties are never specified. This unfortunate state of affairs, which is discussed in a later chapter, seems likely to continue until really essential deep drawing and pressing properties can be both defined and measured in a manner sufficiently precise to enable them to be set out in the form of a useful specification. At present consumers who seek at least to approach this ideal by drawing up more rigorous specifications, which generally include clauses relating to "average grain size," often find that suppliers are unwilling to accept them as actual purchase specifications by which the acceptance or rejection of sheet sold at a normal price must be decided.

Excluding the hardness and tensile tests included in B.S.I. Specifications, which are of little use as an indication of the probable behaviour of sheet under the press, the only test which many suppliers will agree to make the basis for rejection is the familiar Erichsen cupping test, the significance and serious limitations of which are discussed in a later chapter. No general limits representative of sheet of average quality can be given because the Erichsen value varies with the thickness of the sheet tested, and because the depth of the impression must always be considered in conjunction with the smoothness or roughness of the dome. It is, for example, no indication of deep-drawing properties to say that sheet has an Erichsen value of 13·0 mm. A statement that 65/35 brass sheet 0·030 inch thick has an Erichsen value of 13·0 mm. with a smooth dome would on the other hand suggest that, subject to the recognised limitations of the Erichsen test, the sheet is likely to possess good deep drawing and pressing properties.

The way in which brass is melted, cast and rolled into sheet or strip in Great Britain has now been described somewhat briefly yet, it is hoped, in sufficient detail to enable consumers of the finished product to obtain a general idea of the processes by which the metal they purchase is made, to appreciate some of the difficulties which producers have to face and to understand how some of the defects described later arise. Mention has been made of the grades of brass strip now in common use in Great Britain, and also of the serious limitations of the few specifications by which these grades are covered.

Readers who have found this chapter tedious are reminded that many consumers are not familiar with even the essentials of the processes which have been described. Without at least an elementary knowledge of these processes consumers are not in a position to understand the nature of the defects they find in the metal they use, or to co-operate intelligently with their suppliers in attempts to obtain the kind of sheet most suitable for their own particular needs and, it is to be hoped, to improve the general quality of the metal used in the deep drawing and pressing industry.

CHAPTER II

THE PRODUCTION OF STEEL SHEET

It is much more difficult to give a brief yet comprehensive outline of the manufacture of steel sheet and strip from the raw materials to the finish-rolled product than with brass, because the processes—particularly those which have to be undertaken prior to casting—are much more complicated and because different methods are used by different producers. The indulgence of metallurgical readers is therefore asked if what may seem to them serious omissions are made; they are reminded that the purpose of these introductory chapters is to give to consumers unfamiliar with these matters a broad idea of how the sheet which they use is made.

Following the scheme adopted for brass in the preceding chapter, it is proposed to study the manufacture of steel sheet and strip in three stages: melting, casting, and rolling, with some mention of subsidiary operations such as annealing, normalising, pickling and temper-rolling.

Melting

The melting of steel is a far more lengthy and complicated procedure than the melting of brass. To make brass, copper and zinc, already extracted from their respective ores and purified, are simply melted in a crucible or small furnace, usually with a proportion of relatively pure brass scrap, and poured into ingots as soon as the metal is molten and thoroughly well mixed. To make steel, a start is not made with pure constituent metals, although a certain proportion of "made" steel in the form of scrap is added during the second, or refining, stage of the steel-making process. The primary origin of steel is iron ore, and this ore has to go through a number of processes before steel having the desired chemical composition and physical properties can be produced: hence the term "steel-making." The steel-maker has to conduct most of his difficult craft *before* the steel solidifies into ingots which can be despatched to the rolling mill, and the influence of the first two stages, that is melting and casting, upon the physical properties of the sheet finally produced is very much greater with steel than with brass. Another important difference between brass and steel is that in steel-making very much larger quantities are melted, treated and manipulated at one time. This statement is intended to apply only to mild steel as used for the manufacture of sheet; special high-class steels are often melted in small crucibles or electric furnaces of sizes similar to those used for brass.

Production of Pig Iron by Reduction of Iron Ore. Repeated attempts have been made to devise a satisfactory method whereby steel can be produced in one process from iron ore, but so far none of the methods tried experimentally are used industrially and the first stage in the manufacture of mild steel still remains the production of pig iron. This is done in a blast furnace, which is a tall cylindrical steel shell, usually about 80 to 100 feet high, lined with refractory brick, and tapering from the top to a maximum diameter near its lower end before it decreases sharply to the "hearth," as shown in Fig. 21. Near the bottom the furnace walls are pierced by a ring of water-cooled air jets, known technically as "tuyeres," through which pre-heated air, termed the "blast," is forced by large pumps. The blast is pre-heated in huge stoves, often as large as the furnace itself, to a temperature which usually lies in the neighbourhood of 500 to 550° C. These stoves are filled with refractory bricks and operate on a principle of heat-exchange, being heated for a period by the combustion in them of a portion of the waste

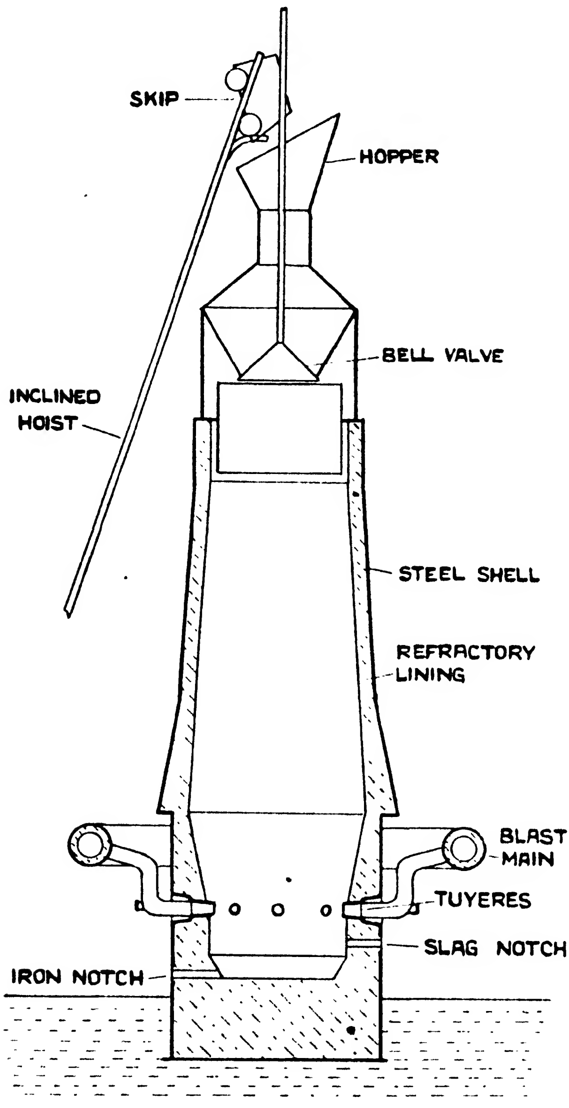
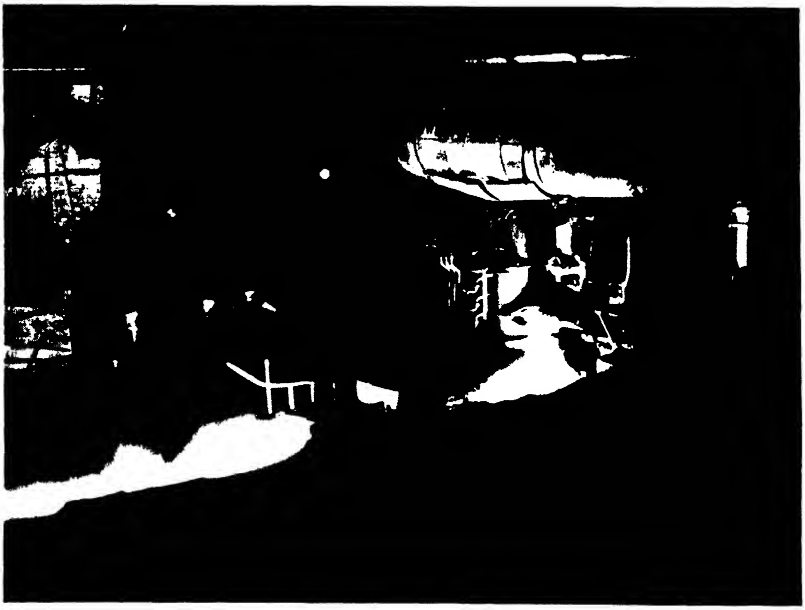


FIG. 21. Sectional elevation of blast furnace illustrating essential features.

[*By courtesy of Ashmore, Benson, Pease & Co. Ltd.*

FIG. 22. Typical blast furnace plant showing (left) three stoves for heating the blast, (centre) furnace with inclined hoist for raising charges to top of furnace, (right) enclosed cast house, (middle foreground) storage bins beneath railway track on which run tip cars and (foreground) ore dumps and overhead travelling crane.



[*By courtesy of Ashmore, Benson, Pease & Co. Ltd.*

FIG. 23. Interior of cast shop, shown in Fig. 22, at casting time. This picture shows the blast main, two of the tuyeres (with spy-holes), and, in background, swinging mechanical clay-gun for stopping the hole from which the molten iron flows to the pig-casting machine.

[*To face p.* 33.

gases from the blast furnace, then allowed to give up some of their heat to the blast for a period, then re-heated, and so on.

A typical British blast furnace plant is shown in Fig. 22. This view shows the stoves for heating the blast; the furnace itself, with an inclined hoist up which the charges are hauled from the row of storage bins seen in the middle foreground beneath a railway track on which tip-cars run; the flues through which the gaseous products of the reactions are led from the top of the furnace to cleaners which remove suspended solids, and the cast-house which, in modern plant, surrounds the base of the furnace.

The temperature of the furnace charge increases gradually from a mere 200° C. just below the bell-door through which the charge is introduced at the top of the shell to a maximum of between 1450 and 1950° C. just below the level of the tuyeres, the exact temperature depending largely upon the quality of the coke and the temperature of the blast. Below the tuyeres is situated the hearth, sometimes termed the crucible, to which the molten iron falls by gravity and remains at a temperature of between 1300 and 1600° C. till the furnace is "tapped" periodically by opening a small outlet, known as the "notch" or "tapping hole," situated in the wall of the furnace at the bottom of the hearth.

When tapped the iron is run into sand beds moulded to give the familiar grids of "pigs," into permanent iron moulds, often arranged on a conveyor belt, or into ladles in which it is conveyed to a "mixer," which is a large heated reservoir lined with refractory material wherein it is kept molten until an open-hearth furnace or Bessemer converter, where the true steel-making processes are carried out, is ready to receive a fresh charge. This last method avoids the delay and expense of re-melting cold pigs, gives a lower sulphur content and enables the composition of the steel to be kept more uniform over a long period of working.

Fig. 23 shows the interior of the cast-house seen in Fig. 22 when the furnace is being tapped. In this view there can be seen the large blast main or horseshoe pipe which surrounds the furnace; several of the tuyeres, in which the relatively low temperature enables glass-sealed spy-holes to be incorporated so that an observer can actually look into the hottest part of the furnace; and the mechanical gun which can be swung into position to ram a clay stopper into the tapping hole when it is desired to stop the flow of molten iron. This particular furnace is being tapped into iron pig moulds carried on an endless belt not seen in the photograph.

A little distance above the tapping hole for the iron (see Fig. 21) is another outlet or "notch" through which the slag, which being lighter than iron floats on the surface of the molten bath, can be run off whenever necessary without disturbing the iron unless its level is allowed to rise to that of the slag outlet. The slag is run into ladle-cars and transported to dumps.

Blast furnaces are operated continuously. If, owing to accidents or to shortage of raw materials, a furnace has to be shut down, the cost of starting up is very great; indeed, often the furnace lining and even the shell have to be entirely rebuilt.

No attempt will be made to study the many and complicated chemical reactions which take place as the charge slowly falls by gravity from the top to the bottom of a blast furnace, but it can be said that these are mainly reducing and carburising processes as a result of which the oxygen in the ore combines with the carbon in the fuel and passes off as gas, while the iron itself dissolves a certain amount of carbon.

Although iron ores consist essentially of oxides of iron together with a small but important percentage of certain impurities, there is also present a proportion of earthy matter, termed "gangue," consisting principally of complex chemical combinations of aluminium, silicon and oxygen. These have to be got rid of in the blast furnace, and in order to do this a flux, in the form of limestone, is added to the mixture of iron ore and coke fuel which is charged into the top of the furnace. This flux combines with the ganguous portion of the ore to form a molten slag which falls with the molten iron to the hearth of the furnace, where it separates and is tapped off from the slag notch as already described. Ores which contain a relatively low percentage of iron are often treated to remove some of the gangue before the resulting "concentrate" is charged into the blast furnace, and by using a mixture of several varieties of ore it is often possible to reduce the proportion of limestone which has to be added separately. Most ores are dried, because it is cheaper to get rid of moisture outside than inside the blast furnace.

The most important impurities in the iron ore are phosphorus, sulphur, silicon and manganese. The proportion in which these elements exist in the original ore will determine the kind of pig iron which is produced, because the phosphorus is almost entirely, and the other named elements partially, absorbed by the molten iron. The proportion of phosphorus is specially important, because this may determine which process is to be used for making the cast iron into steel. In Great Britain the use of high-phosphorus iron ore predominates; countries which have a plentiful supply of low-phosphorus ores are in a more fortunate position.

The chemical composition of the pig iron which comes direct from blast furnaces varies rather widely according to the ore used. The proportion of carbon usually approaches 4 per cent.; in molten pig iron this is all in solution but, in solid pig iron, the proportion of this total which exists as graphite and that which exists in the combined form, that is as iron carbide (cementite, Fe_3C), varies considerably. Phosphorus may vary from 0·02 to 2·0 per cent., and sulphur from 0·02 to 0·5 per cent. or even more. In order to turn cast iron into steel the percentage of these and other impurities has to be reduced to a very low value, and the percentage of carbon, which is also reduced during the purification process, brought back to the desired figure unless, as is nearly always the case with steel destined for the press-shop, a very low carbon content is desired.

Steel-making. The processes by which pig iron is transformed into steel have as their main object the reduction of the percentage of injurious impurities, notably sulphur and phosphorus, to a low value, and the reduction and subsequent adjustment of the percentage of carbon, silicon and manganese to the desired values. In steel destined for rolling into sheet for deep drawing and pressing, the carbon is left at a very low value and not brought back, as is done with most other varieties.

Although electric furnaces are being used to an increasing extent for steel-making, the really large-scale production of the cheaper grades of steel is still carried out by one of two well-established methods, namely, the Siemens-Martin open-hearth process and the Bessemer process.

In the open-hearth process a shallow bath of metal, kept hot by gas flames playing on it from above, is purified by means of additions of iron oxide and slag-forming substances which vary in their nature according to the process used ; in the Bessemer process air is blown through molten pig iron held in a suitable container until the impurities have been burnt up, the process of oxidation supplying sufficient heat to keep the charge molten. In both processes the chemical composition is adjusted by additions made at the end of the purification stage, either in the purification vessel itself or in the ladle into which the purified charge is tapped prior to casting.

Both the open-hearth and the Bessemer processes must be subdivided into *acid* and *basic* according to the kind of refractory lining used and the kind of slag formed. It should be explained that the terms " acid steel " and " basic steel " are derived from the name used to distinguish the process by which any steel has been made, and do not signify any known difference in the " acidity " of the finished product. Characteristic differences in the chemical composition and physical properties of the two types of steel often exist, but these are due to the peculiarities of the respective steel-making processes, not to any fundamental chemical differences in the nature of the steel made by them, although it usually happens that acid steel is the higher in phosphorus.

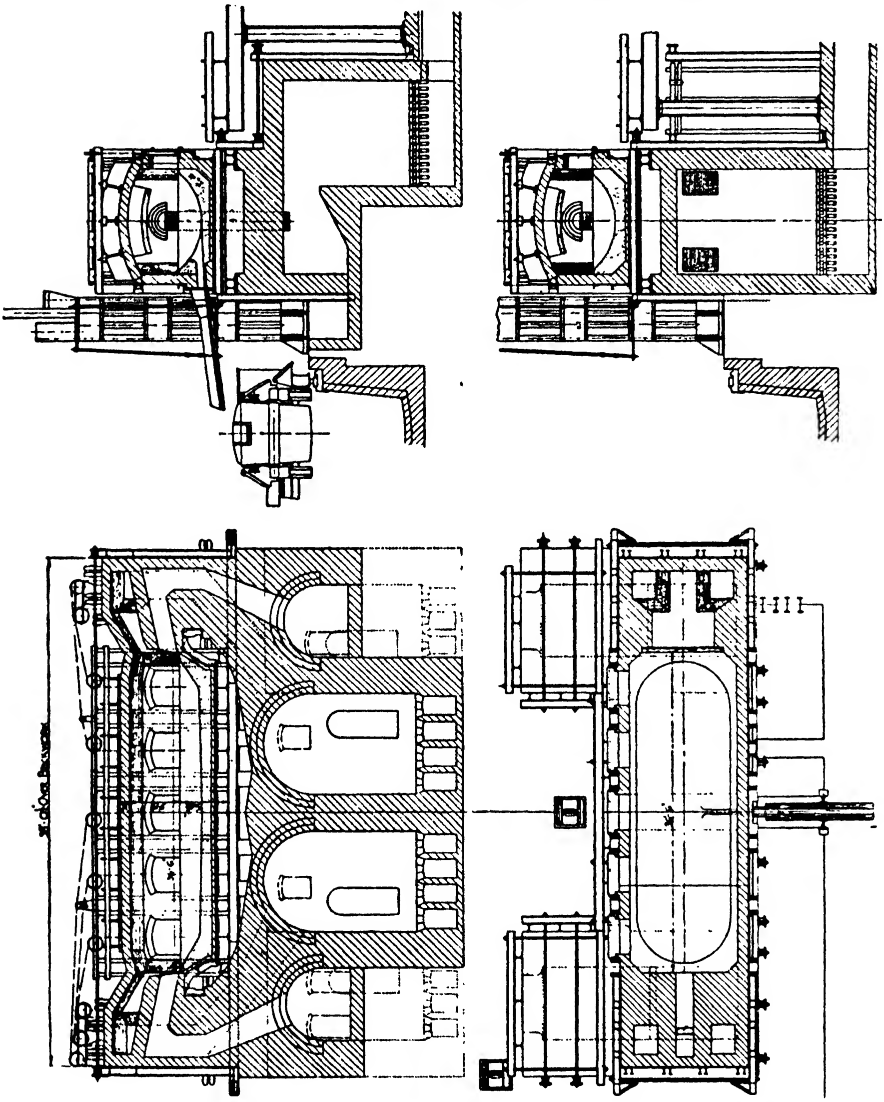
In the acid process of steel-making the proportion of sulphur and phosphorus present in the original charge is *not* reduced, and the process can, therefore, be applied only to pig iron—and steel scrap—which contain a very low percentage of these elements. Both the furnace lining and the slag formed are of a siliceous nature, and the process owes its name to the fact that the linings used consist essentially of silica (SiO_2) which is anhydrous silicic *acid*. Silica bricks, white sand fritted in position, or ganister—a natural form of siliceous rock in which the impurities act as a bond between silica (quartz) crystals—are used for the linings of furnaces or converters in which the acid steel-making process is carried out.

It is held by many authorities that the best steel is produced by the acid process; but, because basic steel is cheaper to make than acid steel, the bulk of the steel produced for rolling into sheet destined for the press-shop is made by the basic process. It is fortunate that in at least one respect basic steel is actually better for this purpose because the percentage of phosphorus, an element which tends to impair ductility and stiffen the sheet, is usually lower than in acid steel unless this is of the very best quality. Only the basic steel-making processes will, therefore, be described.

The Basic Open-hearth Process. An open-hearth furnace consists of a shallow hearth or basin made of refractory material, roughly oblong in shape with rounded corners, supported on a steel framework usually raised some way off ground level and covered with a roof of refractory bricks held by steel frames and tie-bars. The essential details of a typical furnace are shown in Fig. 24. The size varies considerably; in Great Britain the largest furnaces, one of which is shown in Fig. 25 (p. 38), usually hold up to 300 tons of molten steel. Modern furnaces, such as the one illustrated, are made to tilt so that their contents can be poured at a controlled rate from an outlet on the side of the hearth opposite to the charging doors. The source of heat is usually the combustion, in the furnace above the charge, of a mixture of blast-furnace and coke-oven gas, or sometimes producer gas, both gas and the air needed for combustion being pre-heated separately in "regenerative" fire-brick chambers heated by the waste gases of the furnace. These chambers, which are usually located below the hearth of the furnace itself, are grouped in pairs, one pair being heated by the waste products of combustion while the other gives up to the unburnt gas the heat acquired during the preceding cycle, the flow being reversed periodically, usually every twenty or thirty minutes.

In the basic open-hearth process the lining of the furnace is usually made of dolomite. This substance is a natural earth composed essentially of the carbonates of lime and magnesia which, before being used as a lining, is "dead-burnt" to transform it into a mixture of lime (CaO) and magnesia (MgO). Both these oxides are strong "bases," a base being defined in chemical terminology as a substance which will combine with an "acid" to form a "salt"; this is the derivation of the name "*basic*," by which this particular steel-making process is known.

Magnesite is sometimes used as a basic lining instead of dolomite



[*By courtesy of Edgar Allen Co. Ltd. and "Edgar Allen News."*

FIG. 24. Sectional elevations and plan of 75-ton open-hearth furnace showing lay-out of furnace, two recuperative chambers, charging platform and ladle car.

because, although it is more expensive, it is less liable to perish or disintegrate on standing, and therefore may justify its cost in furnaces which cannot be worked continuously. Magnesite occurs as a natural earth consisting essentially of magnesium carbonate and, like dolomite, has to be dead-burnt before it is used as a lining. Both dolomite and magnesite are generally mixed with hot, anhydrous tar before being applied as a furnace lining, and are put on in successive layers, each layer being rammed and heated.

The furnace is fed through doors, usually water-cooled, situated at the level of the charging platform which runs along one side of the furnace. Molten pig iron, drawn from a mixer, is poured from a ladle in the manner shown in Fig. 25. Solid additions of steel or pig are charged by means of a mechanical charger, seen in the middle foreground of this picture, which consists essentially of a car capable of movement parallel to and at right angles to the furnace and carrying a long arm which, when rotated, empties the contents of a pan into the furnace. Fig. 26 shows a mechanical charger charging steel scrap into a somewhat smaller furnace.

The charge consists of steel scrap, lime or limestone, and pig iron, these ingredients being charged in the order given. The pig iron, as explained already, is of the high-phosphorus variety, but sometimes a proportion of high-sulphur pig is added as well. The first slag may be thinned by additions of fluospar, and periodical additions of lime (CaO) and iron oxide in the form of mill-scale (Fe_3O_4) or hematite ore (Fe_2O_3) are made as the slagging process proceeds. These additions oxidise both the carbon and the phosphorus, and it is the aim of the steel-maker to reduce the phosphorus, and at the same time the sulphur, to the desired low percentage before the carbon falls below the specified value. When the charge is molten, rising bubbles of carbon monoxide act as a very efficient mechanical stirrer, bringing all parts of the charge into intimate contact with the slag and added iron oxide and making the bath appear as if it were boiling, the "boil" being the term commonly used to describe this stage of the steel-making process. As the percentage of carbon in the bath falls, the violence of this action diminishes. Rapid check analyses of the contents of the bath are taken on samples removed at intervals in small long-handled ladles as the completion of the purification process is approached. In the past, analysis has always been made by chemical methods, but magnetic methods are now used sometimes, particularly on steels of relatively high carbon content.

If, in steels not of dead-mild kind, the percentage of carbon has fallen below the desired value by the time the phosphorus and sulphur have been reduced to a sufficiently low percentage, the carbon is brought back to the specified percentage by additions of low-silicon pig iron to the furnace, or anthracite to the ladle, at the end of the purification process.

Sulphur is removed mainly by the action of manganese, most of the necessary chemical reactions and separation taking place in the mixer. An adequate percentage of manganese must be present in the

[*By courtesy of Baldwins Ltd*

FIG. 25. The charging platform of a modern 200-ton open-hearth furnace, showing molten pig iron brought from a mixer in a 50-ton ladle being poured through one of the water-cooled charging doors. In the middle foreground is a mechanical charger for solid additions.

[*By courtesy of Steel, Peech and Tozer Ltd.*

FIG. 26. Mechanical charger about to discharge a pan of steel scrap into an open-hearth furnace.

[*To face p.* 38.

[*By courtesy of Steel, Peech & Tozer Ltd.*

FIG. 27. Open-hearth furnace being tapped into ladle.

[*To face p.* 39.

charge in order that this and other important reactions may proceed, and it is often stated that if steel of good quality is to be produced by the basic process it is essential that the percentage of manganese in the bath shall not fall below 0·2 per cent. at any time during the steel-making process.

This outlines very briefly the basic open-hearth process of steel-making. When the steel is judged to be ready for tapping, the charge is poured into a ladle supported by an overhead crane or on a trolley car running on rails and transported to the casting pits. In the older, fixed-hearth types of furnace the charge is tapped, as in a blast furnace, by the breaking of a clay plug; but modern furnaces are usually designed so that they can be tilted by hydraulic or electric power, a refinement which greatly facilitates the manipulation and pouring of the charge. Fig. 27 shows a "heat" being poured from an open-hearth furnace into a ladle.

The Basic Bessemer Process. This process has not proved popular in Great Britain, but a brief description can hardly be omitted because it is used very extensively on the Continent, and to some extent in the United States. Furthermore, British steel-makers have recently shown increasing interest in the basic Bessemer process, and it is possible that in the near future at least a proportion of the steel sheet used in the press-shop may be made by the basic process in Great Britain.

The Bessemer process, named after Sir Henry Bessemer who first introduced it in 1856, differs essentially from the open-hearth process. The principle of the process is that if air is blown through molten pig iron, the impurities—that is carbon, silicon, manganese, sulphur and phosphorus—are oxidised *before the iron itself begins to unite with oxygen,* and that the heat produced by this oxidation is sufficient to keep the iron and slag molten without the help of externally applied heat; hence the low cost of the Bessemer process, especially when, as is done whenever possible, the molten charge is drawn direct from the blast furnace or its attendant "mixer" reservoir, thus saving the cost of remelting solid pig iron.

The "converter" in which the Bessemer process, either acid or basic, is carried out is a steel shell of rather peculiar shape which may be likened to that of a crooked pear, lined with refractory material and supported on trunnions about which it can be rotated on a horizontal axis, as shown in Fig. 28. Compressed air can pass through the hollow trunnions to a shallow chamber in the bottom of the converter. The upper side of this chamber is the refractory bottom of the vessel proper which is perforated by a number of small holes through which the air passes to escape through the molten charge, thus oxidising the impurities in the manner described and also mixing and agitating the charge mechanically. Owing to the shape of the converter, it is possible by turning the vessel on to its side, mouth pointing upwards, to hold a charge of metal in the belly of the converter clear of the perforated bottom. When it is desired to " blow," the blast is first turned on and the converter then swung into the vertical position, the pressure of the air being kept sufficiently high to prevent the molten metal falling through the air passages in the perforated bottom. When it is desired to stop blowing, the converter is again swung on to its side, thus bringing the perforated bottom clear of the charge before the blast is cut off. Flame and particles of slag proceed from the mouth of the converter during blowing, and the state of the purification process is

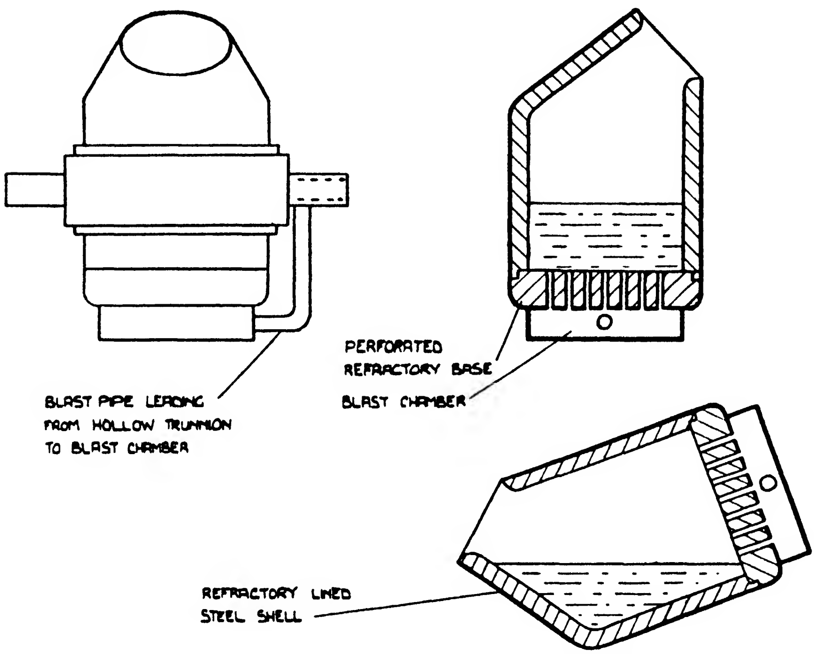


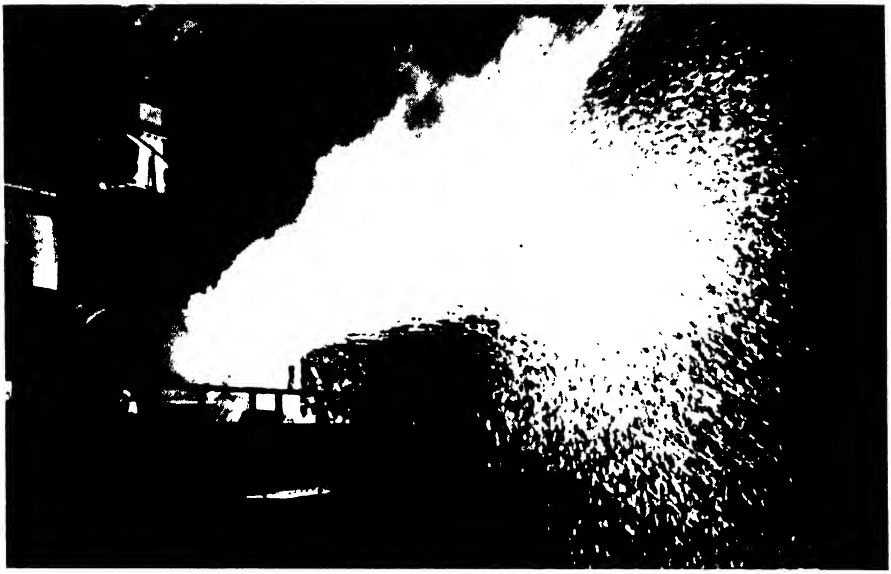
FIG. 28. Diagram illustrating essential features of Bessemer converter.

Top left—front elevation, " blast on " position.
Top right—sectional side elevation, same position.
Below—sectional side elevation, " blast off " position.

judged largely by the size and colour of the issuing flame. Fig. 29 shows a converter in action.

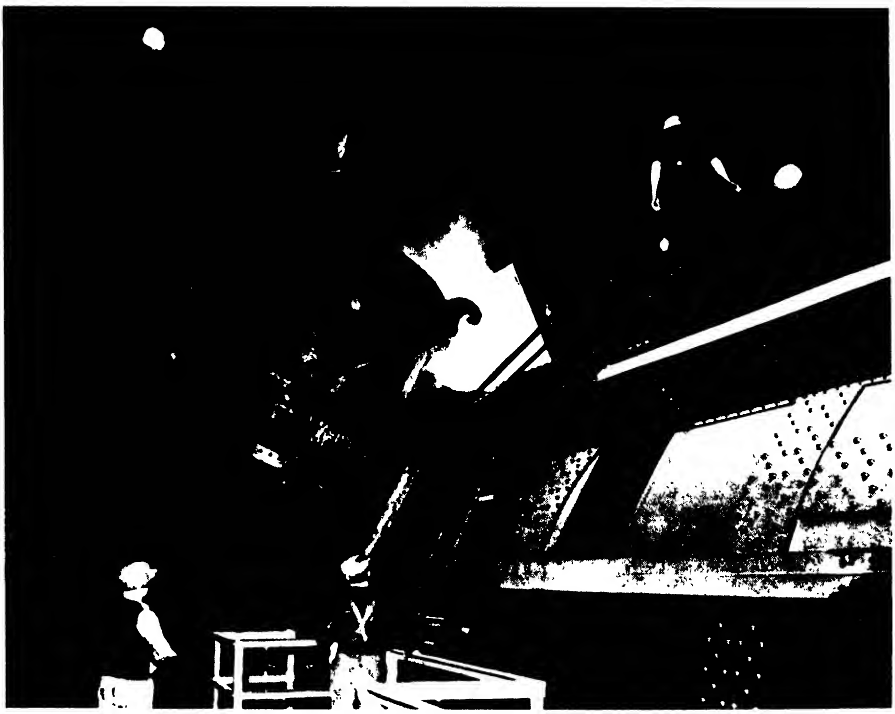
The lining of the Bessemer converter is similar to that of the open-hearth furnace ; in the acid process a siliceous refractory, for example ganister, must be chosen and the slag kept " acid," while in the basic process a rammed lining of dolomite mixed with anhydrous tar is usually employed in conjunction with a lime slag to remove phosphorus from the charge.

The most suitable pig irons for refining by the basic Bessemer process are, obviously, those which are high in phosphorus and which are also high in manganese but low in silicon, so that the slag does not



[By courtesy of Richard Thomas Ltd.

FIG. 29. Bessemer converter in action showing flame and particles of slag issuing from mouth during " blow."



[By courtesy of Richard Thomas Ltd.

FIG. 30. Sixty tons of molten metal from blast furnace being poured into 1,400-ton mixer.

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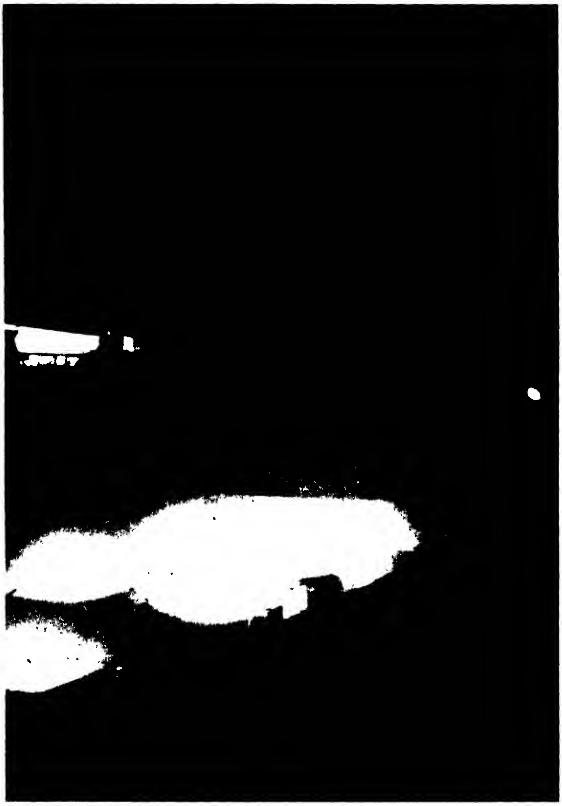


[By courtesy of Baldwins Ltd.

FIG. 31. Steel ingots being teemed from a ladle two at a time.

[To face p. 41.

become "acid." No large additions of steel scrap are used as in the open-hearth process.

The charge of pig iron is sometimes melted in a cupola, but in large plants pig iron is tapped from the blast furnace into ladles which convey it to a mixer, which is often of very large size as is the one shown in Fig. 30, in which it is kept molten and the percentage of sulphur lowered if the manganese content is sufficiently high. This mixer, which has a basic refractory lining when the basic steel-making process is being used, is usually heated by the combustion of a mixture of blast-furnace and coke-oven gas, and is often used as a reservoir for several blast furnaces.

A suitable charge drawn from the mixer into a ladle is poured into the Bessemer converter, lime having been charged previously to neutralise any ("acid") silicon which may be formed. The air blast is then turned on, the converter swung into the blowing position, and what is known technically as the "blow" started. In the basic process the blow proceeds in two distinct stages. During the first of these, carbon, silicon and manganese are oxidised, but only a small proportion of phosphorus is removed. At the end of this stage the flame at the converter mouth drops but—and here the basic process differs from the acid—blowing is continued in what is known as the "after-blow" which oxidises nearly all the phosphorus and removes it to the lime-rich slag.

The production of really good steel by the basic Bessemer process is dependent very largely upon the skill and judgment with which the critical after-blow is carried out. Under-blowing will produce a steel undesirably high in phosphorus, while over-blowing will produce an oxidised or "wild" steel. As the oxidation of phosphorus is a strongly exothermic reaction, the temperature of the charge is often lowered by the addition of lime just before the start of the after-blow.

When the precise instant is reached at which it is desirable to stop the after-blow, the converter is swung on to its side, the blast cut off, and the converter swung right over to empty its contents into a ladle, which is then transported to the casting pits. The necessary additions of silicon, manganese and—unless a dead-mild steel is being made—carbon to bring the steel to the desired chemical composition are added either in the converter at the end of the after-blow or in the ladle itself.

In the opinion of some authorities good basic Bessemer steel is better than good acid Bessemer steel; but, owing to the more complicated nature of the basic process, the opportunities for error are more numerous and mediocre success is more frequent. This probably accounts for the rather poor reputation which basic Bessemer steels have acquired in some quarters. On the other hand, there is a considerable amount of evidence to show that, for the particular requirements of the deep drawing and pressing industry, Bessemer steels are inferior to open-hearth steels. One reason for this is that Bessemer steels absorb a relatively high percentage of nitrogen during the "blow," which tends to reduce the ductility of the finished sheet and to intensify troubles due to "stretcher-strains," "strain-ageing" and "blue brittleness" in the manner described in a later chapter.

The Addition Stage. When the reactions which take place in the open-hearth furnace or Bessemer converter are adjudged complete, the molten charge is poured into a ladle, and the last stage of the steel-making process is to add to the ladle such additions as are necessary first to bring the steel to the desired chemical composition and, second, to complete the deoxidation of the steel to the desired degree before it is cast into ingots. Some of these additions may be made in the furnace or converter before the steel is poured into the ladle.

It will be appreciated that the steel-making or purification process is essentially one of oxidation, and the completeness with which the steel is deoxidised at the end of this process influences the properties of the cast ingot in a profound manner. If deoxidation is thorough, the steel is said to be fully "killed"; if partly deoxidised, "semi-killed" and, if full deoxidation is not carried out, "effervescent." This last variety is used to make "rimming" steel ingots which are used for the bulk of the steel used in the press-shop; the precise meaning of this term will be explained later.

Casting

When the steel has been "made" it is ready for the casting operation which, important with nearly all metals, is specially so with mild steel on account of the large size of the ingots cast and of the profound influence upon the properties of the finished steel product which casting conditions exert.

Mild steel produced in bulk is invariably transferred from open-hearth furnaces or Bessemer converters into large refractory-lined ladles in which, as has been explained, the steel-making process is usually completed by the addition of certain constituents. These ladles are generally suspended from a travelling crane or else mounted on a car which conveys them to casting pits containing the necessary ingot moulds. A number of ingots are usually filled in succession from one ladle which is emptied through an outlet in its bottom, not by being tilted so that the metal is poured over the lip: an essential difference from most non-ferrous casting practice. Large ladles often have two outlets, as shown in Fig. 31, so that two rows of moulds can be filled simultaneously.

The advantage of this metallurgically is that the speed of pouring, or as it is known in steel-works parlance "teeming," is constant and relatively slow and that only clean steel is allowed to flow into the mould, whereas if lip-pouring were used the contents of the ladle would be tipped into the mould at an uncontrolled speed and an appreciable amount of the slag with which the surface of the molten steel is covered would become entangled in the stream. A minor disadvantage of this method is that the rapid flow of metal through the small orifice in the bottom of the ladle and the mechanical action between the valve and its seat tend to detach particles of refractory which are carried into the ingot and become entrapped in the solidifying metal.

The outlet in the ladle is closed by a refractory valve the stem of which projects upwards through the molten charge and is operated through links and rods by a lever projecting away from the ladle, as seen in Fig. 31. By this means the flow of metal can be stopped when a mould is filled so that the ladle can be moved on to an unfilled mould.

Mild steel of "rimming" quality is usually teemed into moulds from the top without the aid of any device to reduce the head of liquid metal and hence the splashing which occurs. Bottom-pouring, which is held by most authorities to give better ingots, is, however, used sometimes for the bulk production of the cheaper grades of mild steel. Advantages of bottom-pouring are that the mould is filled at a slower rate; that no metal is splashed on to the sides of the mould where it solidifies, oxidises and, not being completely dissolved in the rising metal, gives rise to "shells" and similar defects; that the metal rises quietly and is not violently agitated by the downcoming stream which leads to the entanglement of slag and also tends to produce a bad surface on the cast ingot, and that the "sinking" and "rising" actions described later are not so violent.

The kind of steel ingots under consideration are not "fed," as brass ingots are, because this would delay the transference of the ladle from one mould to another and thus allow its contents to cool too much. "Rimming" steel ingots are simply filled, left to "work" and covered with a heavy plate after an adjudged suitable lapse of time; but a self-feeding device, known as a "hot-top" or "feeder-head," is often arranged on top of the mould to feed "killed" steel ingots. A hot-top is a short, refractory-lined extension, smaller in bore than the mould itself, which keeps the steel in it molten for a sufficiently long time to feed the contraction cavity which forms in the shrinking ingot beneath it (see Fig. 51, p. 65). In addition to feeding the ingot, a hot-top helps to restrict the major pipe to the part of the ingot within the hot-top and, due to this and to its relatively small bore, also helps to reduce the weight of the unsound, top portion of the ingot which has to be "cropped" off and discarded. It is thus doubly useful.

Sometimes solid pieces of aluminium are added to the molten steel in the mould, as well as in the ladle, to quieten it and produce a calculated degree of deoxidation. This practice, although effective, is deprecated by some authorities because of the danger of particles of alumina becoming entrapped as the steel solidifies, and there are some purchasers of sheet who will not have steel which has been deoxidised with aluminium in this way.

When the ingots have solidified completely the mould is stripped, often by means of "bumping," and the ingot is either allowed to cool and taken to the stock-yard or else transferred while still hot to the "soaking pits," in which it is heated to rolling temperature. At a later stage ingots are always "cropped," that is, a portion from the top and usually a smaller portion from the bottom is cut off, discarded and remelted because these portions contain—or should contain—the bulk of the unsoundness and major masses of slag. As much as a quarter of the length of a killed steel ingot cast without a hot-top may have to be cropped to remove the deep "pipe" or contraction cavity which forms at its top, but a smaller discard normally suffices to remove the bulk of the slag and general sponginess which are found at the top of a rimming ingot.

The Solidification Process. Viewed metallurgically, the solidification of a large steel ingot is a most complicated process, and it is impossible to give here even a brief comprehensive description of the many actions which occur. An immense amount of work has been done in all countries, particularly in Great Britain, by sectioning whole ingots longitudinally, examining the macrostructure of the polished section, recording the position of cavities, and analysing drillings taken in a large number of recorded positions. In this way the influence exerted by various casting conditions and different shapes of mould and types of feeder-head has been examined, the soundness improved and—though in less degree—the variation in chemical composition from place to place in steel ingots reduced.

Cavities are produced either by contraction of the cooling ingot leaving holes which have no connection with still-liquid metal, or by the evolution of gas which cannot escape. Differences in chemical composition are produced mainly by a process known as "segregation" which in steel ingots is a most important phenomenon. The layman is apt to forget that steel is not a pure metal but a solution of a number of elements in iron. During cooling the metal which solidifies first will be purer than that which solidifies later, as illustrated by the familiar example of a solution of salt in water, and the tendency is therefore for the centre and top of an ingot to be richer in impurities than the skin and lower middle portion. Unfortunately this seemingly simple action is modified profoundly by many factors such as the rate of cooling, the evolution of gas in the cooling metal, and the disposition of planes of dendritic crystallisation produced by the shape of the mould.

Further attention to this important matter will be given when the nature of "rimming" steel is explained, but two facts may be stated here. One is that, as both the soundness and the chemical composition of a large steel ingot vary from place to place, sheet rolled from certain portions of an ingot will be better than that rolled from others; for this reason the very best quality of sheet needs—in theory—to be rolled only from selected portions of an ingot: an observation which is strongly confirmed by practical experience. The other is that in general the surface of a rimming ingot, and therefore of the sheet rolled from it, tends to be purer and sounder than the inner portion; a fortunate fact which makes it easier to produce sheet having a good surface free from defects likely to open up when the sheet is subsequently worked in the press-shop.

The importance of casting temperature, and indeed of the temperature at all stages of the steel-making process, is becoming better appreciated. Hitherto only optical pyrometers have been employed for estimating temperatures in steel works, and it is well known that these instruments are likely to give misleading indications owing to the fact that the slag and oxide which usually cover the observed surface have an emissivity different from that of clean steel, and that the true "black body" conditions which are necessary for the accurate estimation of temperature by optical methods do not obtain around, for example, a molten stream of steel flowing into a ladle. The introduction of thermocouples of new design, for example ones having silicon-carbide and graphite elements, promises more accurate control of temperature in the future. The provision of improved temperature-indicating instruments will not, however, remove one of the main causes of temperature variation which is the time, and consequent cooling of the molten metal, which elapses between the pouring of the first and last of a number of ingots filled from one ladle.

Moulds. The moulds into which mild steel of the type under consideration is cast differ essentially from those used for brass. In addition to the obvious difference in size, moulds for steel are solid, not split as for brass; are usually open at both top and bottom, being rested on a flat, thick cast-iron base-plate when ready to be filled, and taper slightly from top to bottom to facilitate the stripping of the one-piece mould from the solid ingot after casting.

Controversy has arisen in the past as to whether the bore of the mould should increase from the top to the bottom as shown in Diagram A, Fig. 32, thus enabling the mould to be lifted straight off, or whether it should decrease as shown in Diagram C, Fig. 32, thus making it necessary for the mould and ingot to be picked up and reversed before the mould can be stripped. This difficulty is sometimes overcome by casting a hook into the top of a "big-end-up" ingot and bumping the bottom of the ingot. It is certain that the last-named shape tends to reduce the size of the "pipe" in killed steel ingots; to draw it nearer the top of the ingot, thus reducing the proportion which has to be cropped; and to reduce the tendency for a secondary pipe to form in the position indicated in Diagram B, Fig. 51 (p. 65). Diagram C in the same

Figure shows the theoretically ideal result of the combined use of an inverse-taper mould, a hot-top and bottom-pouring. The ingots depicted in these diagrams are " killed " or deoxidised ; the peculiarities of " rimming " ingots, which contain no major pipe, will be explained later.

Moulds for steel are invariably made of grey cast iron of low sulphur and phosphorus content, and are given a dressing which often contains a derivative of pitch, bitumen or asphalt. This is usually ignited prior

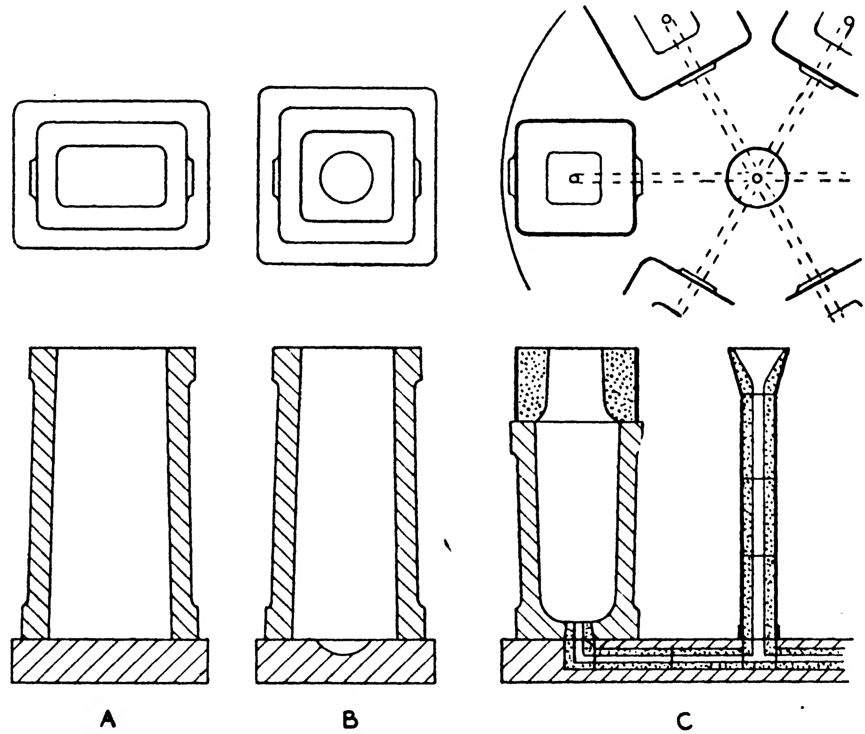


FIG. 32. Plan and sectional elevation illustrating ingot moulds for steel.
A " Little end up " top-pouring rectangular mould.
B " Little end up " top-pouring square mould.
C Central runner feeding six " big end up " bottom-pouring square moulds, with hot-tops, mounted on base-plate.

to casting in order to disperse the dressing, but at one time it was common practice merely to pour a quantity of pitch diluted with naphtha on to the bottom of the mould and to rely on the first addition of molten steel to vaporise this and thus " smoke " the walls of the mould. Needless to say this crude method is likely to lead to the formation of serious surface defects on the cast ingot.

To those accustomed to the casting of brass, the condition of the large moulds used for steel and the care bestowed upon them seems deplorable having regard to the fact that the whole surface of the cast ingot is not machined off as is often done with brass. It must be remembered, however, that steel ingots are always rolled hot, a practice which tends to reduce the severity of some—though not all—ingot-surface defects ; that the large size of the moulds and the low price at which the finished product has to be sold render the maintenance of a good surface virtually impracticable, and that the high temperature of liquid steel would quickly spoil a carefully dressed surface. The best answer to this implied challenge is, perhaps, that the percentage of finished sheet and strip which consumers have to reject purely on account of blemishes attributable to defects of the ingot surface is small.

Rolling

This, the last of the three major processes in the manufacture of steel sheet and strip, cannot always be divided into three definite stages corresponding to the " breaking down," " getting down " and " finish rolling " stages of brass rolling, because the processes used vary somewhat in different mills, with the grade of sheet or strip produced and also according to whether sheet or strip is being rolled.

In general, however, ingots destined for strip are heated and rolled or " cogged " to " blooms " in a cogging mill, cropped, and the blooms are rolled to " slabs " or " billets " either with or without re-heating, depending upon their size and the nature of the plant available. The billets are then cooled, inspected, dressed, re-heated and rolled to strip either of finished gauge or of a gauge suitable for finishing by cold-rolling. For sheet, as distinct from strip, ingots are heated, cogged to blooms, cropped, and rolled to " sheet bars " with or without re-heating. The sheet bars, having in many instances a length approximately equal to that of the width of the sheets it is desired to produce, are then re-heated and rolled at right angles to the direction of the previous passes to the desired gauge, which may be the final one or, more often, one which can be reduced to the final gauge by cold-rolling. Right-angle rolling is not always used ; sometimes diagonal rolling is given to spread and lengthen the slab at one pass.

Hot-rolling is necessary because owing to the much greater hardness and higher limit of proportionality of steel as compared with brass, cold steel could not be given the necessary severe reductions in any rolls yet devised. For example, the cold-cogging of a square steel ingot perhaps one to two feet thick would be impossible. From at least one aspect this is fortunate, because hot-rolling tends to weld up cavities in the ingot which would otherwise be formed into planes of discontinuity in the finished sheet. Unhappily, the presence of oxide and slag sometimes prevents all the cavities being welded up ; a fact which upon occasion becomes painfully apparent in the press-shop.

Cogging. For this first stage in the sequence of rolling operations the ingot is heated to a temperature of about 1200 to 1250° C. in special furnaces termed "soaking pits," such as those shown in Fig. 33, which are usually heated by a mixture of blast-furnace and coke-oven gas or, if the mill is not near a blast-furnace plant, by producer gas. In order to reduce the cost of re-heating, whenever possible ingots are transferred from the moulds to the soaking pits while still hot. If this cannot be arranged, heating needs to be gradual and, in either case, the ingots need to be thoroughly soaked to ensure that the whole section attains the full temperature without the surface layers becoming over-heated and "burnt." Over-heating or bad adjustment of the furnace atmosphere may produce irremediable defects in the surface layers of the ingot, and therefore of the finished sheet. When the ingot has attained the proper temperature throughout the whole of its section it is lifted from the pit and conveyed by a crane to the mill.

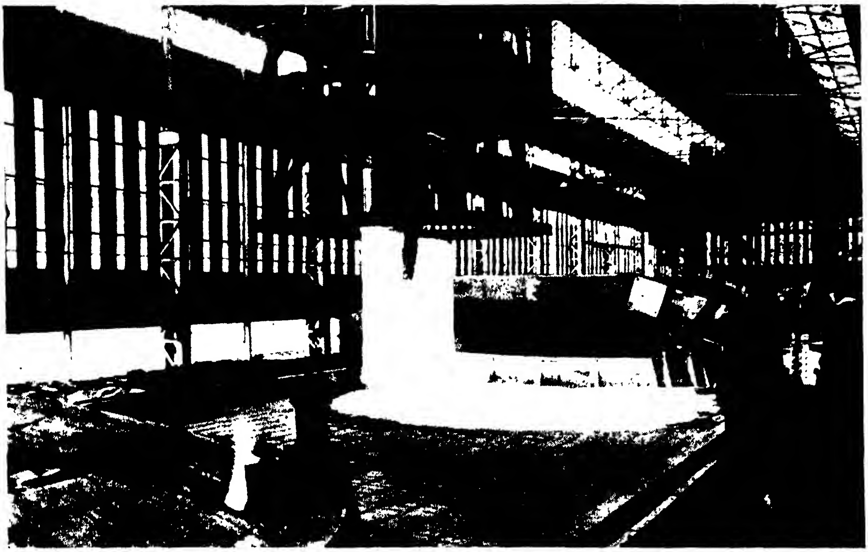
Owing to the size, weight and high temperature of the kind of steel ingots under consideration, all manipulation during the cogging process is done by mechanical devices such as roller tables, guides, manipulators which move the ingot sideways or turn it over through 90 degrees, and, in some mills, tilting or lifting tables which raise it from the lower to the upper pair of rolls in a three-high mill. Fig. 34 shows a "close-up" view of an ingot being turned over by the manipulators of a two-high reversing cogging mill. Two of the series of rollers which feed the ingot backwards and forwards can be seen in the left-hand bottom corner of the picture, and adhering scale shows as a dull patch on one face of the ingot.

Blooming. The product of the cogging mill, known in mill parlance as "blooms," passes to another mill in which it is reduced to billets or slabs for strip or to sheet-bars for sheet. The speed and layout of modern mills is such that this can be done without re-heating.

Various devices are used to remove the scale which always forms on the surface of the heated steel. Small rolls placed in front of the main rolls, known as "scale breakers," are often used, and in some modern plants a series of these rolls gives the bloom a bend-and-straighten operation during which the loosened scale is removed by the impingement of high-pressure water jets.

At the end of this intermediate stage of reduction the blooms are in the form of either billets or slabs, often about an inch thick, destined for strip rolling, or of sheet bars, often about $\frac{5}{16}$ inch thick, destined for sheet rolling. They are then allowed to cool, after which they are either stacked in stock-yards or at once passed forward to be dressed.

Discussion of this stage is of little interest to consumers, but it may be pointed out that, provided the use of an excessively high temperature does not permanently damage the surface of the steel, accurate temperature control of the heating furnaces is not necessary in these early stages of rolling. The crystal structure of the final product is controlled by the temperature of annealing and the amount of cold-reduction given in the final stages of rolling, or by normalising, if this



[*By courtesy of Richard Thomas Ltd.*

Fig. 33. Steel ingot being lifted from soaking pit for conveying to blooming mill. (Note observer using optical pyrometer.)

[*By courtesy of Baldwins Ltd.*

Fig. 34. Ingot being turned over by the manipulators of a two-high reversing cogging mill.

[*To face p.* 48.

[By courtesy of Baldwins Ltd.

FIG. 35. Three-high cold reduction sheet mill.

[By courtesy of The Whitehead Iron and Steel Co. Ltd.

FIG. 36. Reversing strip mill with automatic tensioning, flying micrometers and remote control from desk panels.

[To face p. 49.

process is used instead of annealing: the influence of an incorrect temperature in all but the final heating stages does not persist, as it does with brass, to give an irregular crystal structure in the finished sheet.

Dressing. It will be noticed that in ferrous as distinct from non-ferrous practice, dressing is always undertaken after the ingots have been rolled into billets or slabs. Both ends of a billet are usually cropped, the proportions discarded being determined by the kind of ingot and also by the quality of the finished sheet or strip it is desired to produce. The surface is inspected and visible major blemishes are marked with chalk and either cut out with pneumatic chisels or "burnt" out with an oxy-acetylene cutting torch; if not deep-seated, they are sometimes removed by portable electric grinding wheels. Proper ingot turning, in which the whole of the surface of the ingot is turned off in a special lathe, is not carried out with the relatively low-priced varieties of steel used in the deep drawing and pressing industry.

The standards which govern the dressing of brass and steel slabs are very different, and defects which would be regarded as serious in brass are considered of no consequence in steel; indeed, the gashes left by the dresser's chisel would ruin any brass slab. One reason for this is that the drastic hot-rolling which dressed steel slabs still have to suffer obliterates apparently serious pits or troughs and also some—but not all—kinds of minor blemishes to an adjudged negligible standard. Were only cold rolling to follow dressing, much more care would have to be taken.

Sheet and Strip Rolling. These terms, which are the ones whereby the finishing stages which follow cogging and blooming are known, imply different operations to steel-makers. To consumers of both sheet and strip they merely signify final, and very important, stages in the production of the product they buy: for this reason they will be considered together. The only essential difference is that whereas strip is rolled in one direction in one thickness in lengths determined by the size of the billet, sheet is rolled from sheet-bars placed in the rolls at 90 degrees, or sometimes diagonally, to that of previous passes, the width of the sheet approximating to the length of the sheet-bar and the length being determined by its width and thickness, and that for reasons explained elsewhere several sheets are often rolled together.

Three distinct methods are used for finishing both sheet and strip of deep drawing and pressing quality, namely, hot-finishing, cold-finishing and cold-reduction. These will be considered separately.

Hot-finishing. In this method, hot-rolling is continued to include the final pass, the only difference in the finishing process being a better surface on the rolls themselves and the exercise of more care to obtain as uniform a thickness as possible across the width of the finished sheet or strip.

After the thickness of the sheet has reached about 0·060 inch, several sheets are usually rolled together, or a single sheet is " doubled " over on itself. The main object of this practice is to enable the rolls to get a better " bite " and to obtain sheets having a more uniform thickness across their width, because variation in thickness caused by the " spring " of wide rolls (see Fig. 13, p. 16) is distributed among several sheets and not manifested entirely in one sheet as it would be if only a single sheet were rolled at a time. Incidental advantages are a saving in time and conservation of heat.

In order to reduce the natural tendency of sheets to stick together during hot-rolling it has been the practice, particularly in the tin-plate industry, to use steel containing a relatively high percentage of phosphorus. Because phosphorus lowers the ductility of steel sheet, this practice must be avoided with sheet destined for deep drawing.

Cold-finishing. This term generally implies that sheet or strip, previously hot-rolled to very nearly its final thickness, is pickled and then reduced to its finished thickness by cold-rolling between rolls having a good surface. The principal benefits given by the final light cold-rolling are closer conformity to the specified nominal thickness and an improved surface-finish. Obviously, the surfaces of hot-rolls cannot be kept polished, and the impressions of particles of scale are bound to give the sheet a relatively rough surface. The surfaces of cold-finishing rolls can, on the other hand, be maintained at a very high standard, and the modern tendency is to use elaborate roll grinding and polishing machinery for this purpose. This method of finishing is more popular for sheet than for strip.

Cold-reduction. This process implies that the final thickness of the sheet or strip is attained by a considerable amount of cold-rolling, not by the light cold-rolling of sheet already hot-rolled to very nearly its final thickness. It is a process which has gained in popularity during recent years, but the very high pressures which have to be imposed have only been made possible by marked improvements in the power and rigidity of cold-rolling plant, particularly by the adoption of the " backed-up " mill (see Diagrams C and D in Fig. 14, p. 17). Fig. 35 shows a typical mill designed to give the heavy bites at relatively high speeds which are a feature of the modern cold-reduction process.

Advantages claimed for cold-reduced as opposed to cold-finished sheet and strip are a better surface finish, because the sheet is rolled a number of times between polished rolls ; greater uniformity of thickness ; a reduction in annealing temperatures, and, lastly, better deep drawing and pressing properties due to the production of a more uniform crystal structure. This last claim does not hold if normalising is used instead of annealing because, if it is, an excellent crystal structure can be obtained without the aid of severe cold-reduction, and the industrial advent of clean-normalising in controlled-atmosphere furnaces has greatly enhanced the value of this method of removing the effects of cold-work from steel.

Starting with sheet or strip which has been hot-rolled to a thickness approaching one-eighth of an inch, the usual procedure in a cold-reduction mill is to pickle, cold-roll to a reduction as severe as 50 or even 60 per cent., anneal and, very often, finish the sequence by a light " skin-pass." A considerable proportion of the sheet and strip used for deep drawing and pressing is finished by this method, and the surface finish—and as a rule the crystal structure—obtained usually leaves little cause for serious complaint.

Reversing Mills. Although mills of the kind shown in Fig. 35 are usually made to reverse, it is usual to pass a number of coils or sheets through in one direction without altering the " pinch " of the rolls. Fig. 36 shows a type of true reversing mill which is gaining in popularity for the cold-rolling of strip when long lengths are available. The essential features are a high-speed backed-up stand of great rigidity and, on each side, coiling drums by means of which the strip is wound backwards and forwards through the rolls under tension, the unreduced ends of the strip being ultimately severed and discarded. This tension is comparatively small, and mills of this kind must not be confused with Steckel mills in which the strip is pulled through *undriven* rolls entirely by the action of tension imparted by a coiling drum.

The mill illustrated shows many interesting features typical of modern practice, such as entirely remote control operated electrically from the two desk panels seen on the extreme right and left of the photograph, one for each direction of rolling ; flying micrometers for indicating continuously the thickness of the moving strip ; large-diameter roller bearings for the backing rolls, and flood-lubrication of the strip by the pump seen on the top platform. In the left background can be seen stacks of annealed and pickled strip awaiting rolling and, on the left of the mill, the large-diameter loose drum on which coils are placed for the first pass before each end of the strip is secured to the small-diameter automatically-controlled coiling drums of the mill itself. The most important feature of a mill of this kind is the automatic system which maintains a constant tension on the strip as it emerges from the working rolls, and the 8 feet high electrical control panel for this and for the normal working and controlling of the unit illustrated occupies the whole length of the white wall seen in the background.

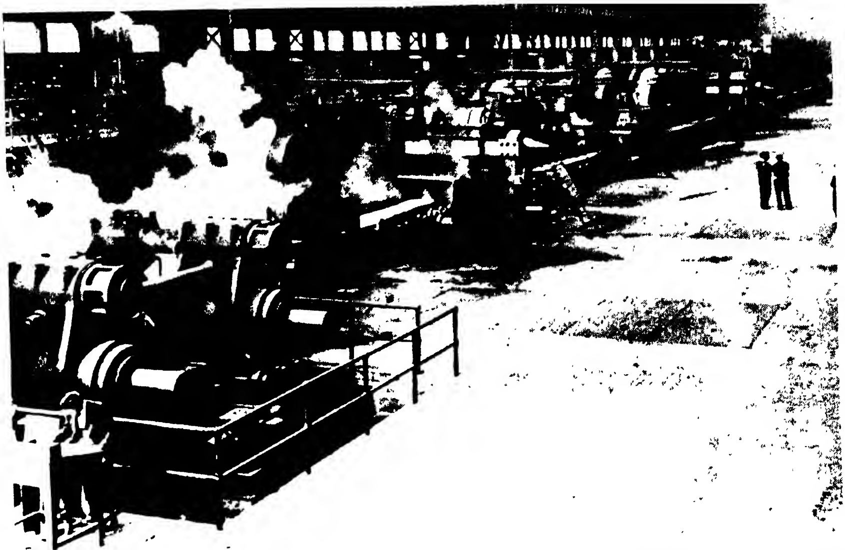
Continuous Mills. The description of rolling procedure so far given applies to reductions carried out one pass at a time, the clearance between the rolls being altered after each pass. As there is an increasing tendency to use continuous mills whenever the output will justify the high cost of the necessary plant, a brief description of this type of mill cannot be omitted even though the underlying principles of the reduction process are the same as in those already described.

Continuous mills are of two kinds, hot and cold ; terms which need no explanation. Continuous cold-mills are already well-established in Great Britain, yet it is only comparatively recently that, following American practice, continuous hot-mills have been laid down for strip of substantial width. The reason for this is due not to lack of initiative but to the fact that a continuous hot-mill is capable of producing what, judged by demands in Great Britain, is a very big output. To allow a very costly mill to stand idle for part of each week is, obviously, uneconomic.

Continuous Hot-mills. In a continuous hot-mill, billets are reduced to strip approaching an eighth of an inch thickness at one heating. The speed at which this reduction is carried out will be appreciated when it is remembered that the ingot starts its travel at a temperature of about 1200 to 1250° C., and that strip of the best quality is always finished at a temperature just above the critical point, which—for steel containing a little less than 0·1 per cent. carbon—is near 875° C. during cooling. To obtain this speed, the manipulation of the ingot and strip has to be almost entirely mechanised.

Billets or slabs are usually heated in a horizontal position in reverberatory furnaces through which they are pushed, usually down a sloping hearth, to fall as required on to rollers which convey them to the first mill. Roughing mills are often three-high to avoid the delay of reversing after each pass, but this type cannot be used for the finishing stands because the thin strip would cool too much during repeated travels backwards and forwards, and several stands are therefore arranged in tandem. Fig. 37 shows a general view of a continuous hot-mill operating in Great Britain. It must be pointed out that this is not a continuous mill in the full meaning of the word because, although the strip—which at the stage shown is fairly thick and therefore in relatively short lengths—passes through a number of stands without stopping, each piece leaves one stand before entering the next. In truly continuous mills, one length of strip is passing through closely-spaced stands at the same instant, as seen in the mill illustrated in Fig. 12 (p. 15).

As many as six stands are sometimes arranged in tandem, and some mills can roll strip up to 100 inches wide. Scale-loosening and removing devices are usually incorporated before the first mill, near the end of the train, and sometimes at intermediate stages. These take the form of rolls which flex billets, scraper bars which both flex and scrape the surface of relatively thin sheet or strip, and water jets operating at a pressure of 1000 lbs. per square inch or more. The action of water jets is threefold : their cooling action causes the scale to contract suddenly, thus loosening its adherence to the surface of the hot metal ; the water, penetrating into interstices in and under the scale, immediately turns to steam, thus exercising a powerful disruptive action and,



[*By courtesy of Richard Thomas Ltd.*

FIG. 37. Hot-roughing mill for wide strip.

[*By courtesy of Richard Thomas Ltd.*

FIG. 38. Entrance end of five-stand continuous mill for cold-rolling steel strip.

[*To face p.* 52.

lastly, the flushing action of the high-velocity streams washes away loosened flakes and particles.

After the final pass the strip is either cut to lengths by flying shears or else coiled hot. Remembering the high temperature, the size, the length and the speed of the strip, it needs little imagination to visualise the danger and chaos which results if anything goes wrong during the final stages of the rolling of a large billet in a continuous hot-mill, and every precaution is taken to ensure that the hot metal shall pass rapidly through all the stages without a hitch.

Continuous Cold-mills. These consist of a train of heavy stands, usually having backed-up rolls, placed in tandem as shown in Fig. 38. The foreshortened view in this photograph gives but a poor impression of the size of the whole mill. It need hardly be added that strip produced in mills of this kind is of the " cold-reduced " variety, a term already explained.

In the older mills the strip was allowed to sag between each stand, but the modern tendency is to control the speed of the rolls so that a definite tension is maintained on the strip between each stand, and ingenious automatic tensioning devices, as well as flying micrometers which indicate the thickness of rapidly-moving strip continuously and with great accuracy, are becoming increasingly popular. Fig. 39 shows one form of electro-mechanical indicating flying micrometer applied to strip.

Annealing

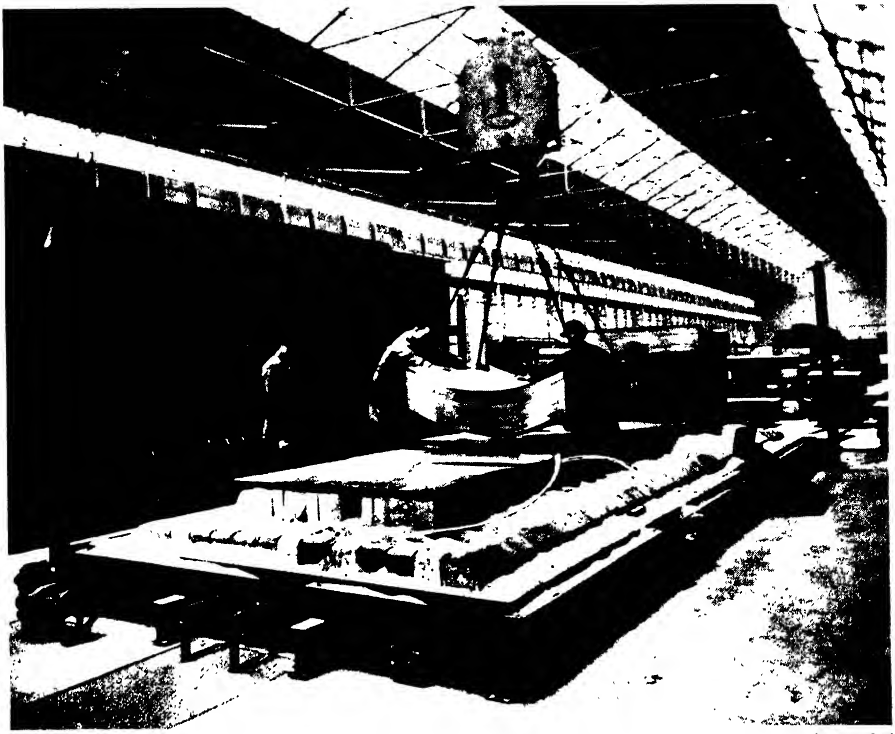
Three principal methods are in use for annealing steel sheet and strip after rolling : box annealing, annealing by the Grünewald or a similar process, and continuous normalising which is usually in a protective atmosphere. In addition to the primary object of heating the steel to a predetermined temperature in order to remove the effects of cold-work, each of these processes has as a special object the minimisation of the surface oxidation which always occurs if steel is heated to a red heat in air.

Box Annealing. This, the oldest method of annealing, consists of packing coils of strip or stacks of sheet into large boxes or " coffins " which often hold several tons of metal, heating in suitable furnaces, and allowing the whole mass to cool slowly. The temperature attained usually lies between 650 and 720° C. The lids or covers of these containers are sealed with sand or luted with clay to make them as airtight as possible, and the containers usually have pipes through which reducing gas is passed into them during the cooling stage in order to prevent air being sucked in and to reduce any oxide which may have been formed during the heating stage by the air originally sealed up in the container. Sometimes coils, and even flat lengths of cut strip, are packed in cast-iron swarf in order to reduce the bulk of the air sealed up and to induce preferential oxidation of the swarf rather than of the sheet. Owing to the large mass of these containers the annealing cycle is a lengthy one : heating may take one to two days and cooling from three to five days.

Annealing boxes are either pushed on bogies very slowly through huge, brick-lined tunnel furnaces or are placed one at a time in separate furnaces as shown in Fig. 40 ; both types of furnace are usually heated by gas. The batch method has the advantage that the time and temperature can be adjusted to the needs of each charge ; whereas in the continuous method, which is more satisfactory if all charges are of the same size and weight, individual treatment of the boxes passing through the tunnel is impossible. In the most modern version of the box-annealing process containers are kept stationary, and portable furnaces are lowered over them by means of a travelling crane which serves the whole of a spacious floor on which are disposed many units in the process of loading, heating, cooling or unloading. Fig. 41 shows a base being stacked with sheets ; in the background can be seen a furnace in position over a base. When this form of annealing was introduced first, furnaces were often heated by means of electric resistance elements ; but gas heating by means of " radiant " tubes, in which gas is burnt without the products of combustion reaching the interior of the furnace, is rapidly gaining in popularity. The furnace shown in Fig. 41 is of this type.

In the past the difficulty of heating uniformly a pile of sheets weighing several tons often produced a considerable difference between the crystal structure of metal situated near the surfaces and that of metal situated at the centre of the pile. Owing to improved methods of heating giving better control and to the use of several thermocouples inserted at various positions in the pile it is, however, now possible to obtain a temperature difference of not more than 15 or 20° C. between the hottest and coolest parts of a large pile ; although unfortunately the period of heating is not the same for all parts, because heat must take time to penetrate to the centre of a large mass of metal.

The Grünewald Process. This process, which is used more for the annealing of coiled strip—and still more for wire—than sheet, consists of placing the coils into a strong steel container, usually of cylindrical shape, having an airtight lid in which is situated a non-return escape valve. As a rule these lids are screwed to the shell by clamps and have a water-seal to prevent the ingress of air. The furnaces, into which the containers are lowered by a crane, are usually sunk in the floor and are heated electrically with the help of automatic temperature control. Fig. 42 shows a typical installation in which the furnaces are grouped in the middle flanked by cooling chambers. The automatic temperature-control panels can be seen in the background ; from the cranes are suspended frames, and tops carrying charges of coils ready to be lowered

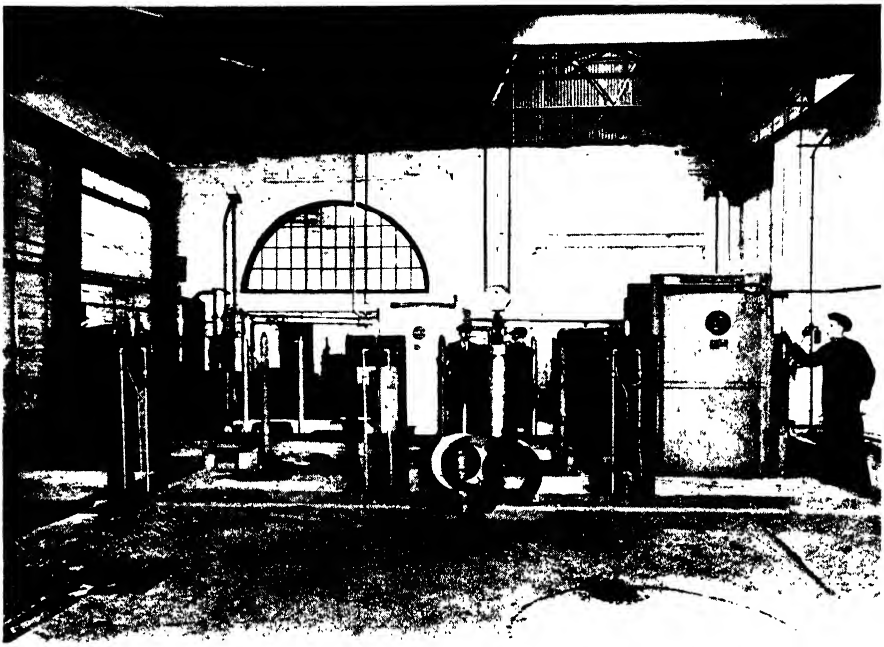


[*By courtesy of Richard Thomas Ltd.*

FIG. 41. Steel sheets being stacked on base of movable radiant-tube gas furnace seen on left. Observe flexible thermo-couples for insertion at different positions in charge.

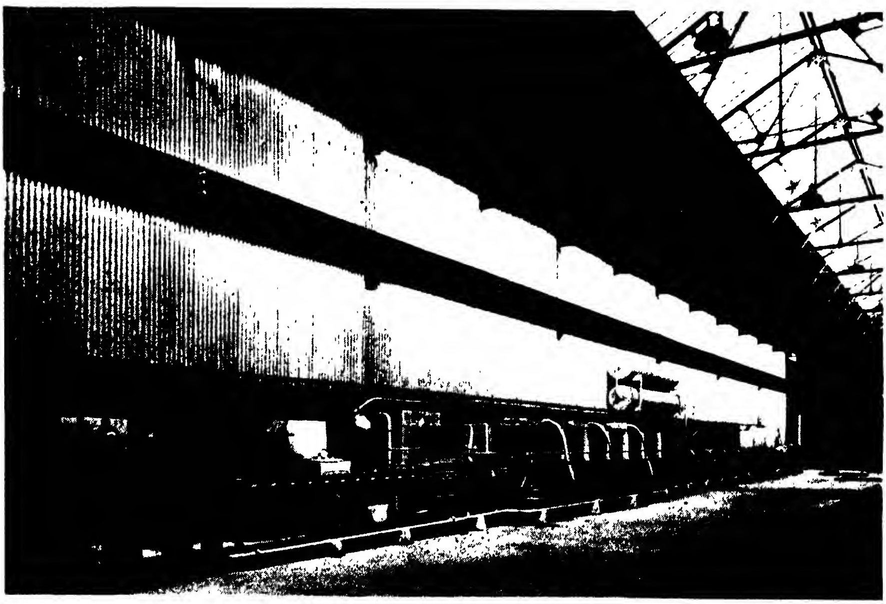
[*By courtesy of The Whitehead Iron and Steel Co. Ltd.*

FIG. 42. Modified Grünewald installation for annealing coiled steel strip.



[By courtesy of Birmingham Electric Furnaces Ltd.

FIG. 43. Loading coiled strip on to one of the bases of a batch-type annealing plant utilising electric heating, forced circulation and a protective atmosphere generated in the plant seen in the background.



[By courtesy of Arthur Lee & Sons Ltd. and G.E.C. Ltd.

FIG. 44. Continuous electrically-heated clean-normalising furnace for steel strip utilising a protective atmosphere of burnt ammonia.

[To face p. 55.

into containers ; and, in the angle of the guard rails between the two suspended frames, there can be seen the control panels for controlling the protective atmosphere of burnt town's gas used in the whole system.

It must be explained that in the original Grünewald method no external protective atmosphere is used because the theory of the process is that the bulk of the air is expelled from the container through the escape valve by expansion during heating, that oil present on the strip acts as a deoxidiser, and that the non-return valve prevents the ingress of air during cooling because a partial vacuum is formed. In practice quite good results are obtained ; but, because the product cannot always be described as truly "bright-annealed," the help of an externally-generated protective atmosphere is often utilised, as in the installation illustrated.

Bell Furnaces. Bell furnaces, in which category the purist will probably wish to class the modified version of the Grünewald furnace just illustrated, generally take the form of sealed containers in which coils of strip are heated and cooled, usually in a protective atmosphere derived from town's gas although for some non-ferrous metals cracked or burnt ammonia is used. Either electric resistance elements or gas-heated "radiant tubes" are the usual source of heat, and modern furnaces often have "forced circulation" produced within the container by a fan located in the base on which containers are lowered for heating, a most valuable refinement which enables the charge to be heated more uniformly as well as more quickly. A typical installation for annealing steel strip is shown in Fig. 43.

Continuous Normalising Furnaces. Most modern continuous normalising furnaces are of the clean or, as it is sometimes termed, "bright" normalising type. The principle of this process, which is generally held to be the most satisfactory of any yet applied industrially on a large scale, is that the sheet or strip is heated to above its critical temperature—which, on heating, approaches 920° C. for steel of very low carbon content—for a few minutes only and is then cooled relatively quickly. The principle of annealing, it will be recalled, is that the cold-worked steel is heated to some temperature below the critical point, soaked for a relatively long period, and then cooled slowly.

The method adopted is to pass sheets or strips on rollers through a long tunnel in which an efficient protective atmosphere is maintained. The apparatus takes the form shown in Fig. 44, and consists essentially of the tunnel surrounded near the entrance end by a furnace and for the rest of its length by a cooling water-jacket. Automatically-regulated electric heating has been popular, but it seems probable that gas heating by means of "radiant tubes" may be used in the future ; with either method it is preferable for the heating arrangements to be divided into separate zones each of which can be regulated independently of the others.

The outstanding advantage of this type of furnace is that the strip or sheets can be passed at a controlled rate through the heating and cooling zones in a single—or perhaps a double—thickness, instead of being heated and cooled in bulky stacks or coils. Another advantage is that the charge is at a fixed distance from, and relatively close to, the heating elements. The result is that all the sheet and strip passed through such a furnace ought—in theory—to receive exactly the same thermal treatment, and that this treatment can be controlled very closely by regulating the temperature of the furnace and the speed at which the charge passes through the cooling chamber. In practice the uniformity of the product is usually of a very high order, a statement which cannot always be made concerning annealed steel.

Partially-burnt town's gas is often used as a protective atmosphere in furnaces of this type, and its adoption is likely to increase with the anticipated increase in popularity of the gas-heated radiant-tube type of furnace. Regenerated burnt ammonia, as used in the furnace illustrated (Fig. 44), gives a cleaner surface to the normalised product, but both the first cost of the plant and the running costs are rather higher than with town's gas. Atmospheres of this kind possess the special advantage that by suitable adjustment of their composition it is possible actually to reduce the surface scale on hot-rolled sheet or strip, thus obtaining a pleasing, silvery finish. Indeed, the steel is so "chemically" clean when it emerges from the furnace tunnel that a protective coat of oil or lanoline needs to be applied at once to prevent rusting.

It might be thought that genuinely clean-normalised sheet or strip would not need to be pickled. A considerable tonnage of steel is actually used in the clean-normalised condition, but experience shows that, if further cold-rolling has to be done, a better surface is obtained on the cold-rolled product when a light pickle is given after clean-normalising. This is explained by the nature of the clean-normalised surface which, owing to the reduction of the oxide by the active reducing atmosphere of the furnace, bears a thin layer of "spongy" iron which does not roll well and, sometimes, has beneath it traces of unreduced oxide. In the opinion of some producers this seeming drawback does not detract seriously from the advantages of clean-normalising, because the necessary pickling operation is very different from that needed to remove heavy scale on hot-rolled sheet or strip; but other producers are still of the opinion that, as it is so often desirable to pickle after clean-normalising, there is little to be gained by changing from the old methods.

Not all continuous-normalising furnaces are of the type just described. In some of the older plants continuous normalising is carried out by passing sheets through gas-fired furnaces of ordinary type having roller or "walking-beam" hearths, but no special protective atmosphere. During this treatment the sheets become scaled and have to be cleaned by pickling; but, as with clean-normalised steel, the advantages of uniformity of product and refined "equi-ax" microstructure are obtained, although the accuracy of control is usually less.

Pickling. Any oxide scale which has been formed on the surface of the steel during annealing or hot-rolling has to be removed by pickling before the cold-rolling—or, in the case of hot-rolled sheets, the finishing—processes can be proceeded with. Mild steel is generally pickled in a warm solution of sulphuric acid to which there is usually added a small percentage of what is known as an "inhibitor" or a "restrainer." These additions—which, as a rule, are complex organic substances such as pyridine, quinoline or glue—retard the solution of the steel itself in the acid without seriously impairing the scale-loosening action unless too much inhibitor is present. They therefore reduce the "pickle-loss" on the steel treated, save acid, minimise spray and reduce the amount of hydrogen absorbed by the steel during the pickling process.

The usual method of pickling is to load sheet or loosened coils into suitable racks of inert metal, and oscillate the loaded rack in a steam-heated vat of acid by means of an overhead crank or pneumatic cylinder until all scale has been removed from the surface of the work. Various methods are adopted to separate sheets, or the turns of coils, so that the acid has free access to the whole surface; for example, sheets are often separated by a grid arrangement of bars in a rack or by loose "hairpin" clips. The turns of loosened coils are sometimes kept apart by "hairpins," but a more satisfactory method is one in which the vertical oscillating motion of the automatic hoist imparts a telescopic movement to the turns of the coils. This is accomplished with the help of conically-disposed base members to the supporting frame which pass between corresponding, but inverse-taper, members fixed to the bottom of the pickling vat. Fig. 45 shows a pickling plant for strip in which this telescopic movement is used. Coils are loosened on the turn-tables seen in the left background; placed on the conically-disposed bottom members of the racks; wheeled on the overhead runway to the vats seen in the right background; transferred to hoists centred over the corresponding cone members in the vats; oscillated for the necessary time in pickling solution, washing swills and, lastly, a soluble-oil swill; wheeled out of the fume-laden atmosphere of the pickling shed, and unloaded on to the racks seen in the foreground.

Before being pickled, strip is sometimes subjected to mechanical flexing between a train of staggered rolls in order to loosen adhering scale ; but, unless an efficient inhibitor is used in the pickling solution, this procedure has been known to produce over-pickled zones where the oxide has been dislodged.

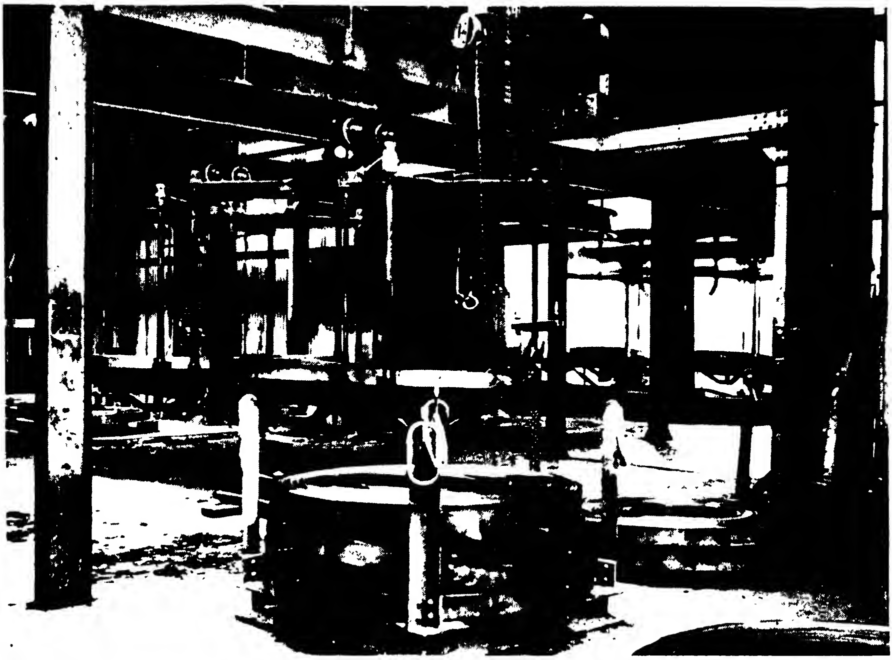
After pickling, sheet or coiled strip is washed in water, sometimes given an alkali dip to neutralise any trace of residual acid, washed again, and is then heated in boiling water or hot-air ovens to make it dry quickly, to prevent rusting and to drive off absorbed hydrogen which tends to make steel brittle. It is then ready for cutting to size and oiling.

In Great Britain continuous pickling plants are not yet as common in steel mills as in brass mills. Fig. 46 shows a typical plant, and it will be seen that its size is much larger than that of the continuous pickling plant for brass strip already illustrated in Fig. 17 (p. 24). The difference in the length of the plant is due mainly to the greater difficulty which is experienced in removing scale from steel ; the width is, obviously, determined by the width of the widest strip with which the plant has to deal. One great practical advantage of modern pickling plant of this kind is that the acid vats are covered, a matter of importance owing to the considerable volume of spray given off by the action of the hot acid on the steel.

The removal of scale from a steel surface is not a simple process involving merely the chemical solution of the scale by the acid. Mill-scale consists principally of black oxide of iron (Fe_3O_4) which is not readily soluble in the pickling solutions used. Its removal is believed to be due mainly to the mechanical action of hydrogen evolved at the surface of the underlying steel by acid which penetrates through cracks or pores in the coat of oxide scale, and partly to true solution of a layer of ferrous oxide (FeO) which exists beneath the main coat of Fe_3O_4 in a proportion dependent upon the atmosphere in which the scale formed.

Temper-rolling, Roller-levelling and Stretching. Annealed or normalised steel sheet or strip is often given a special treatment designed to minimise the severity of the particular surface defect known as " stretcher-strain " markings, which cause so much trouble to the consumer when dead-soft low-carbon steel sheet is subjected to small extensions under the press. This defect, which is examined in a later chapter, can be prevented if fully-softened sheet is cold-worked a certain amount before it is pressed, and it is fortunate that this amount is so small that serious reduction in ductility—and hence impairment of the deep drawing and pressing properties of the cold-worked sheet—can be avoided.

Two methods are used to impose the desired amount of cold work—temper-rolling and roller-levelling. Each of these is given as a final operation in the sequence of mill operations when used for the definite purpose of preventing stretcher-strain markings, but roller-levelling



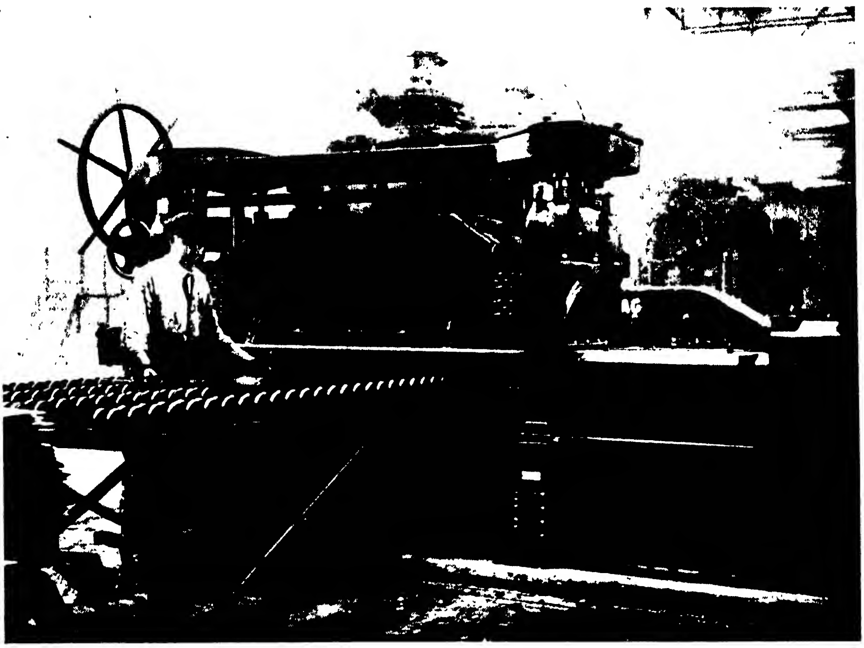
[By courtesy of The Whitehead Iron and Steel Co. Ltd.

FIG. 45. Pickling plant for coiled steel strip. Observe conical base members of frames which impart a telescopic movement to the loosened coils.

[By courtesy of The Wellman Smith Owen Engineering Co. Ltd. and Richard Thomas Ltd.

FIG. 46. Continuous pickling and drying plant for steel strip.

[To face p. 58.



[By courtesy of Baldwins Ltd.

FIG. 48. Roller-leveller for flattening sheet.

[To face p. 59.

is used to flatten sheet rather than to prevent stretcher-strain markings because its effect in this respect passes off relatively quickly.

Temper-rolling. This operation, which owes its name to the old and somewhat confusing practice of describing the hardness of cold-rolled metal as "temper," is purely one of ordinary cold-rolling. It is, in fact, sometimes alluded to as a "skin-pass" or "pinch-pass." The rolls used are generally of the two-high type and have a very smooth surface, while the percentage reduction given to the sheet or strip is very small, usually of the order of 0·5 to 1 per cent., although this amount may be varied to meet special needs when the sheet is earmarked for some particular consumer and purpose. The development of the art of temper-rolling to its present standard has been a real boon to many consumers.

Roller-levelling. The principle of this very simple operation, illustrated diagrammatically in Fig. 47, is that sheet or strip is given a number of flexures by being passed between an upper and lower train of rolls which are staggered and meshed slightly so that the sheet cannot proceed without flexing first one way and then the other. By

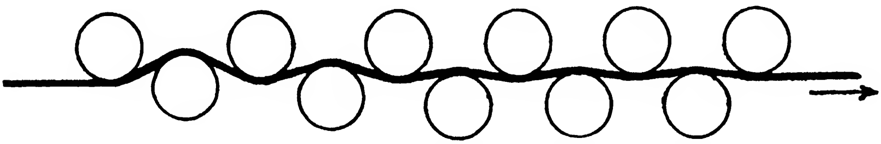


FIG. 47. Diagram illustrating passage of sheet through leveller rolls.

means of this device the sheet is cold-worked, but not reduced in thickness as it is during temper-rolling. The method possesses the advantage that wide sheet is cold-worked uniformly across its entire width, whereas this is not so with temper-rolling owing to the spring of the rolls; but it has the serious disadvantage that, for reasons explained later, its effect passes off much more quickly than that of temper-rolling. Because of this, its real purpose when given by producers is, as its name implies, to flatten sheet; not, as when given by consumers, to prevent the formation of stretcher-strain markings during pressing. Fig. 48 shows a typical roller-leveller.

Stretching. Like roller-levelling, the stretching process is used primarily to flatten sheet. The whole lengths of two opposite sides of a sheet are gripped in long jaws, one pair of which is fixed and the other connected to a hydraulic ram, and the sheet is stretched—as in a tensile testing machine—to some predetermined permanent extension. Stretching cannot be relied upon to prevent stretcher-strain markings; indeed, the stretching operation itself sometimes produces them on the flattened sheet.

Miscellaneous Finishing Processes. Besides levelling and straightening by the methods just indicated, a number of miscellaneous operations, such as shearing, oiling, coiling and packing, and also the important items of inspection and testing, remain to be carried out before the finished sheet is ready for despatch to the consumer. These operations have already been outlined in the previous chapter which dealt with brass; the only important difference in the case of steel is that this metal has to be coated carefully with some light oil, lanoline or other substance to prevent it rusting during transport and storage. This is usually done by passing the sheet or strip between absorbent cloth rolls or, sometimes, by immersing sheets or loosened coils in a vat and then draining.

In large mills some of the mechanical finishing operations are done in automatic plant. Fig. 49 shows a typical installation for roller-levelling, side-shearing and cutting to length bright strip, and it is interesting to compare the size of this plant with that of the machine shown in Fig. 19 (p. 25).

Routine tensile and hardness tests are usually made by producers before the sheet or strip is passed out. Erichsen and hardness tests are used to a limited extent, and sometimes microscopical examination is made on selected samples; yet many consumers feel that more critical examination and more thorough testing of steel sheet and strip is needed. One important advantage possessed by steel over brass, as purchased for deep drawing and pressing, is that with modern methods of production its crystal structure is usually reasonably satisfactory. On the other hand internal discontinuities are frequent, but in fairness to suppliers it must be admitted that the detection of this defect is difficult unless really extensive routine examination is made; the only certain remedy lies in the regular production of sound ingots.

Grades of Steel Used for Deep Drawing and Pressing

Unlike brass, low-carbon steel sheet and strip is not as a rule divided into grades according to its chemical composition. Little useful purpose would be served by such a scheme of classification because in the bulk of industrial sheet and strip the carbon content is very low, usually between 0·05 and 0·11 per cent., and because it is unwise to regard an *average* figure for the percentage of certain impurities as an indication of behaviour under the press. Usually it is the severity of segregation—that is *localised concentration*—of impurities which is the important factor, and an *average* analysis gives no clue to unevenness of distribution of the elements estimated.

At present no standard specifications having any value for deep drawing and pressing quality steel sheet and strip exist in Great Britain. The only classification having general industrial application is one in which the sheet or strip is described and identified by the nature of the processes by which it has been finished in the mills of the supplier *after*

[*By courtesy of Richard Thomas Ltd.*

Fig. 49. Continuous sheet automatic cut-up plant, operating at 350 feet per minute, for side trimming, end-shearing and roller-levelling.

[*To face p.* 60.

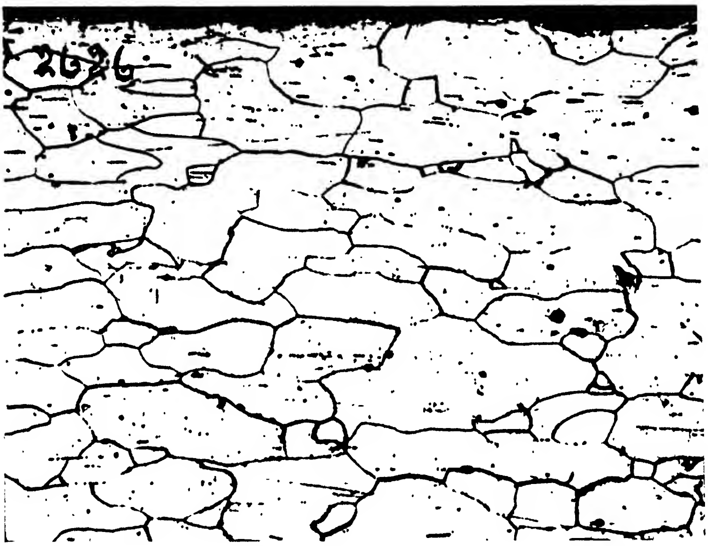


FIG. 50. Microstructure of hot-rolled close-annealed 0·04 per cent. carbon rimming steel.

Microspecimen cut normal to surface of sheet parallel to direction of rolling. × 100.

[*To face p.* 61.

hot-rolling, such as cold-rolling, normalising or annealing, pickling and temper-rolling. As the possible combinations of these various processes are many, it follows that the number of virtually " standard " grades is also large, and choice is governed partly by the available plant and methods of the supplier and partly by the nature of the processes which the sheet has to withstand in the press-shop of the consumer and upon the kind of surface finish which he needs.

This method of classification is illustrated by the following popular grades of sheet and strip. Readers will be able to understand the significance of others, and the meaning of the letters by which they are often described, after studying the examples given.

P.CA (Pickled, Close-annealed). With the possible exception of unpickled " black-plate," which is sometimes used for heavy pressings such as brake drums and commercial-vehicle hubs, P.CA is the cheapest grade used for genuine deep drawing and pressing operations. Its surface finish, which is that imparted by the final hot-rolling process, is relatively rough because the surfaces of hot-rolls are not comparable to those of cold-rolls and because the surface of the sheet is pitted by the oxide which is rolled into it and afterwards pickled out. Because no refining treatment is given, the crystal size of this grade of sheet tends to vary widely and owing to the influence of " critical strain crystal growth "—a phenomenon described later—an abnormally large crystal size is sometimes developed. As a large crystal size produces a rough surface on deep drawn or pressed shapes and also gives low tenacity, trouble is likely to be encountered if P.CA sheet is used for the majority of press-shop operations. Fig. 50 shows a microstructure typical of that found in much P.CA sheet of good quality.

There is a growing tendency to substitute normalising for annealing in many sequences of finishing operations. If this change is made in the case of P.CA, which should then read N.P, a much more uniform crystal structure will be produced and the usefulness of this inexpensive grade of sheet will be greatly increased. With the advent of " clean-normalising " furnaces which actually de-scale oxide-coated sheet, the preliminary pickling may be omitted. It is to be hoped that the letters " CN " will be adopted as soon as possible to signify " clean-normalising."

P.CR.CA (Pickled, Cold-rolled, Close-annealed). In this grade the hot-rolled sheet or strip is finished by light cold-rolling and then given a final close-anneal to restore its ductility. The main object of the cold-rolling treatment is two-fold. First, the rough, scale-pitted surface of the hot-rolled sheet is ironed out into a smooth, bright finish which is more attractive for many purposes. Secondly, the conformity of the sheet or strip to the specified nominal thickness is increased and, with modern cold-rolling plant, the variation in thickness across the width of sheet is reduced. Because the amount of cold-reduction given is usually very small, no appreciable refining of the crystal structure takes place during the subsequent annealing.

P.CR.CA is popular for many deep drawing and pressing operations in which the sheet is not deformed very severely and when the formation of stretcher-strain markings is not objectionable. Sometimes a final "skin-pass" is given to prevent this defect occurring. When this is done the grade ought to be identified by the letters P.CR.CA.CR, but this is not always done and "P.CR.CA" may or may not have received a skin-pass. The final light cold-rolling might usefully be distinguished by the letters TR (temper-rolled); temper-rolled P.CR.CA would then be designated as P.CR.CA.TR, and no confusion would arise.

The remarks already made concerning the possible substitution of normalising for annealing apply in relation to P.CR.CA, which then ought to read P.CR.N. As the microstructure of the hot-rolled sheet will be refined by normalising irrespective of the amount of cold reduction given, it is likely that severe cold-reduction—which necessitates expensive modern rolling plant—may not be given: relatively light cold-reduction will impart a reasonably good surface to the hot-rolled sheet.

N.P.CR.CA.CR (Normalised, Pickled, Cold-rolled, Close-annealed, Cold-rolled). This grade, which represents a good class of steel suitable for automobile press-work and general deep drawing and pressing, is sometimes known as "full-finished." The addition of the preliminary normalising refines the crystal structure and helps to reduce "directional" effects, that is variation in the physical properties of the sheet in different directions relative to that of rolling. The first, and principal, cold-rolling gives the sheet a good surface, and the main purpose of the final skin-pass is to prevent stretcher-strain markings.

Due to the consequent refinement of the crystal structure, the more complicated sequences of processes improve the deep drawing and pressing properties of the steel. This is indicated by the following typical Erichsen cupping test values obtained on the same batch of sheet finished to the same thickness, namely 0·040 inch, in the ways indicated :—

P.CA	10·6 mm.
N.P.CR	10·9 mm.
N.P.CR.CA.CR	11·1 mm.

It will be observed that the reduction in ductility which results from the final skin-pass is more than outweighed by the increase produced by the refinement of the crystal structure due to normalising and by the softening due to the final annealing.

For reasons already explained, a better nomenclature for this grade would be N.P.CR.CA.TR.

Extra Deep-Drawing Quality. Some suppliers produce a special grade of steel to meet the demands of very deep-drawing operations. In addition to being "full-finished"—although temper-rolling may not be given if the sheet is to be used for genuine deep drawing as distinct from pressing—this grade is rolled from selected portions of special ingots and is usually specially low in carbon, manganese, sulphur and phosphorus. The so-called "Extra" grades of steel sheet and strip are the best yet available for true deep-drawing operations when maximum ductility is needed to enable some difficult shape to be produced at all, when it is desired to eliminate inter-stage annealing or, when this is impossible, to reduce the number of inter-stage annealings given. Although the most expensive of all grades, its use is often an economy when inter-stage annealing can be eliminated or reduced. It is usually described by some proprietary mark, not by a series of abbreviations.

These few examples will serve to indicate the kind of grades and finishes which are available in both sheet and strip form, but it must be pointed out that it is common practice for suppliers to finish each so-called grade of sheet somewhat differently to meet the needs of individual consumers and, sometimes, their own convenience. This form of grading applies to sheet and strip produced in Great Britain; in other countries other schemes of grading are used.

Bessemer *v*. Open-hearth Steels. The essential difference between the two steel-making processes known respectively as "Bessemer" and "open-hearth" have already been explained, but mention must be made of certain differences between the actual deep drawing and pressing properties of sheets, perhaps similar in other respects, rolled from these two kinds of steel. These differences are well recognised by steel-makers, but consumers are not always aware that they exist and are sometimes at a loss to explain observed differences in behaviour.

The principal difference is that owing to differences in chemical composition, particularly with respect to nitrogen, Bessemer steels work-harden more for a given amount of plastic deformation than open-hearth steels, although the influence, already described, between acid and basic varieties exists for steel made by either the Bessemer or the open-hearth process. Other things being equal, deeper draws can, therefore, be accomplished with open-hearth steels. On the other hand if the amount of deformation inflicted is relatively small, Bessemer steel is sometimes preferable to open-hearth steel because it gives a stiffer product which is often an advantage in, for example, panels and other shallow pressings.

Other important differences between Bessemer and open-hearth steels are the magnitude of the changes which take place as a result of "strain-age-hardening," and also the severity of "stretcher-strain" markings developed when sheet is strained to small extensions; two subjects which are discussed fully in subsequent chapters.

"Killed" *v.* "Rimming" Steels. Besides classification into the various grades of steel sheet in the manner just described, another and very important distinction has to be made according to whether the steel used for any of these grades is "killed," "semi-killed" or "rimming." The deep drawing and pressing properties of the sheet are influenced in a marked manner by the kind of steel used, and it is to be regretted that this important item is not stated as a matter of course in all descriptions of steel sheet and strip.

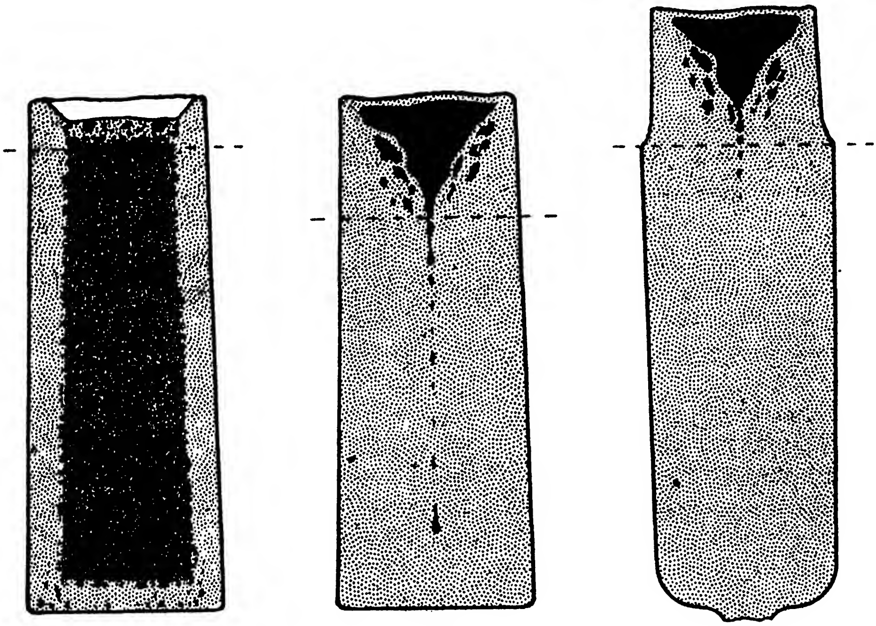
It has been explained that the steel-making process is essentially one of oxidation of impurities; therefore, when this purification process is stopped, the steel will contain dissolved oxygen and iron oxide. If the molten metal is cast into ingots without being fully "deoxidised," the iron oxide will react with the remaining carbon while the molten steel is cooling in the mould. This chemical reaction generates carbon monoxide which, escaping to the surface of the ingot, violently agitates the cooling steel causing it to rise in the mould until, as the metal gradually solidifies from the faces of the mould inwards and from the bottom upwards, the remaining pool of bubbling metal sinks, leaving an upstanding "rim" round the top of the solid ingot. This is the true origin of the term "rimming" steel, which is synonymous with the terms "effervescent," "fiery" or "unkilled" steel. The term does not owe its being to the existence of a "rim" of pure ferrite round a "core" high in impurities, a derivation sometimes imagined by consumers unfamiliar with steel-works practice.

The effect of this internal generation of gas and resulting mechanical agitation is to make rimming steel solidify relatively slowly from the faces of the mould inwards, thus enabling the impurities to segregate in the still-liquid central zone; to allow large bubbles of gas to become entrapped by the ever-advancing dendrites or tree crystals; and to eliminate the central "pipe" or shrinkage cavity which forms in the top portion of the ingot, as depicted in Fig. 51A, thus enabling a larger proportion of each ingot to be used.

If before being cast the liquid steel is "deoxidised" so that it contains very little iron oxide, it will solidify quietly in the mould without effervescing, because no gas is generated in it by chemical action. Steel of this kind is said to be "killed" and, due to the quiet way in which the molten metal cools, a relatively large "pipe" or shrinkage cavity tends to form at the top of the ingot, and sometimes at other positions, as indicated in Fig. 51B. A larger proportion of the ingot has therefore to be cropped off and, due to the fact that the metal solidifies at a relatively uniform rate throughout the cross-section of the mould because there is no continual mechanical agitation, the impurities do not tend to segregate in the central zone of the ingot.

Also, because large quantities of gas are not generated actually in the liquid steel—although some dissolved gas may be expelled from solution—there is far less tendency for gas pockets to be formed as the metal solidifies.

Deoxidation of mild steel is usually accomplished by the addition of silicon or aluminium. On account of their cost the very excellent deoxidising agents titanium, zirconium and vanadium are rarely



A. B. C.

FIG. 51. Diagrammatic sectional elevations of three types of low carbon steel ingot illustrating disposition of pipe, gas cavities and inclusions.

The portion of the ingot above the dotted line is cropped off and discarded when the ingot is rolled.

A. Top-poured "rimming" ingot.
B. Top-poured "killed" ingot without hot-top.
C. Bottom-poured "killed" ingot in inverse-taper mould with hot-top.

added to the relatively low-priced low-carbon steels used in the deep drawing and pressing industry. When aluminium is used there is a danger that small particles of alumina (Al_2O_3) may become entrapped instead of rising to the surface while the steel is molten, and if these particles are numerous or relatively large they may cause trouble when sheet rolled from killed steel is worked under the press. For this reason the better qualities of steels destined for the press-shop are deoxidised with silicon, not with aluminium.

"Semi-killed" steels are those which are partly deoxidised and, depending upon the degree of deoxidation effected, resemble more or less closely one or the other of the two extreme kinds just described. By carefully regulating the deoxidation process some authorities claim that it is possible to obtain at least a partial combination of the principal virtues of each kind, that is, the skin of pure ferrite coupled with the absence of pipe usually associated with rimming steel, and the relatively uniform distribution of impurities in the core and freedom from gas cavities associated with killed steel. Other authorities disagree with this opinion, and maintain that true semi-killed steel is rarely satisfactory.

From the viewpoint of steel-makers, the principal difference between rimming steel (or semi-killed steel approximating to the full rimming variety) and killed steel is that they can roll a greater proportion of a rimming steel ingot into sheet. In other words, a much shorter discard has to be cropped off unless it is desired to produce sheet of the very best quality suitable for the most severe press operations.

From the viewpoint of consumers, the principal differences between the two varieties are four in number :—

(1) In theory, if not always in practice, the cost of rimming steel sheet is lower than that of sheet rolled from fully-killed steel or semi-killed steel approaching the fully-killed condition.

(2) Rimming steel has an outer skin of nearly pure iron, known metallurgically as "ferrite," which contains a very low percentage of impurities and slag inclusions; this surrounds a core containing a much higher percentage of carbon and impurities, a difference well illustrated by the sulphur prints reproduced in Fig. 52 and by the microsections shown in Fig. 53. The result of this is that the surface-finish of sheet rolled from rimming steel tends to be better than that of sheet rolled from killed steel, and that the extreme surface layers are less likely to contain hidden defects which will open up into visible surface blemishes when the sheet is deformed under the press. On the other hand if the average percentage of impurities is high, their concentration into a core of reduced sectional area tends to reduce the ductility of the sheet as a whole. In other words, for a given average percentage, the more *even* the distribution of impurities the higher will be the ductility of the sheet tested as a complete section.

From what has been said it will be clear that, in theory, the thickness of the pure ferrite surface zone will depend upon the degree of deoxidation of the steel, a condition often determined industrially by the percentage of iron oxide in the slag. The thickness of the ferrite skin can, however, be controlled to some extent irrespective of the degree of deoxidation by varying the length of the period between the time of pouring and the time when the cover plate is placed on the top of the effervescing ingot, a short period giving a thin skin. An attempt is usually made to produce a skin of approximately one-fifth

[*By courtesy of Arthur Lee & Co. Ltd.*

FIG. 52. Sulphur prints of cross sections through slabs rolled from ingots of (left) "rimming" steel and (right) "killed" steel. × ¼.

[*To face p.* **66.**

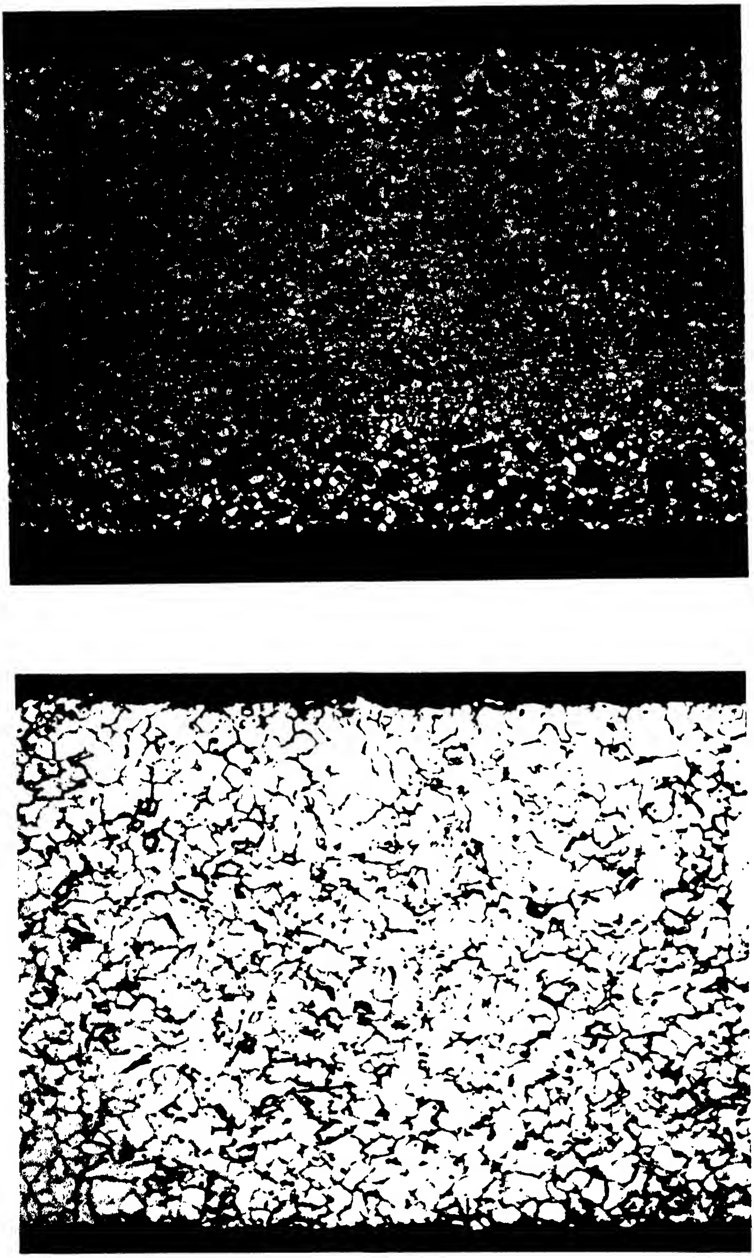


Fig. 53. Microstructure of (top) " rimming " and (below) " killed " steel sheet.

Microsections cut normal to surface of sheet. × 75.

[*To face p.* 67.

the thickness of the finish-rolled sheet or strip, but considerable departures from this occur sometimes.

(3) Rimming steel may contain more internal discontinuities and segregations of slag than killed steel. In killed steel the slag tends to segregate to the main pipe which, of necessity, must be cropped off and discarded; in rimming steel masses of slag, and also isolated gas cavities, tend to occur throughout the whole "core" of the ingot but, as already explained, not in the pure ferrite skin. This tendency is particularly marked at the junction of the skin and the core, and major discontinuities in rolled sheet are usually found in this position. Fig. 51A (p. 65) attempts to depict diagrammatically the disposition of the skin, core, cavities, inclusions, spongy top and "rim" in a fairly typical rimming ingot.

In theory gas cavities are welded up during hot-rolling, but in practice this assumed welding is not always complete; while trapped slag inclusions cannot, of course, be eliminated by rolling, although they can be elongated or broken up. Hence the origin of the minor "laminations" or internal planes of discontinuity illustrated in a later chapter which deals with defects in steel sheet.

(4) If rimming steel and killed steel are rolled into sheet of similar thickness by exactly the same sequence of processes, the rimming steel sheet will tend to have the coarser crystal structure or, as it is usually termed, the larger "average grain size." This difference, which is believed to be due to the higher oxygen content of the rimming steel and is perhaps helped by its lower carbon content, is naturally allowed for in the manufacture of sheet from each kind of steel. It is particularly noticeable in normalised sheet.

Normalised *v*. Annealed Sheet. When the merits of normalised and annealed sheet are being compared, it should be borne in mind that, in any sequence of finishing processes, the substitution of normalising for annealing tends to give the steel a more regular, a more "equi-axed" and often a finer crystal structure. Moreover, the pearlite particles are small and compact instead of being elongated into streaks or discontinuous strings as they are in annealed steel sheet. This difference is illustrated by photomicrographs A and B reproduced in Fig. 54 on the next page.

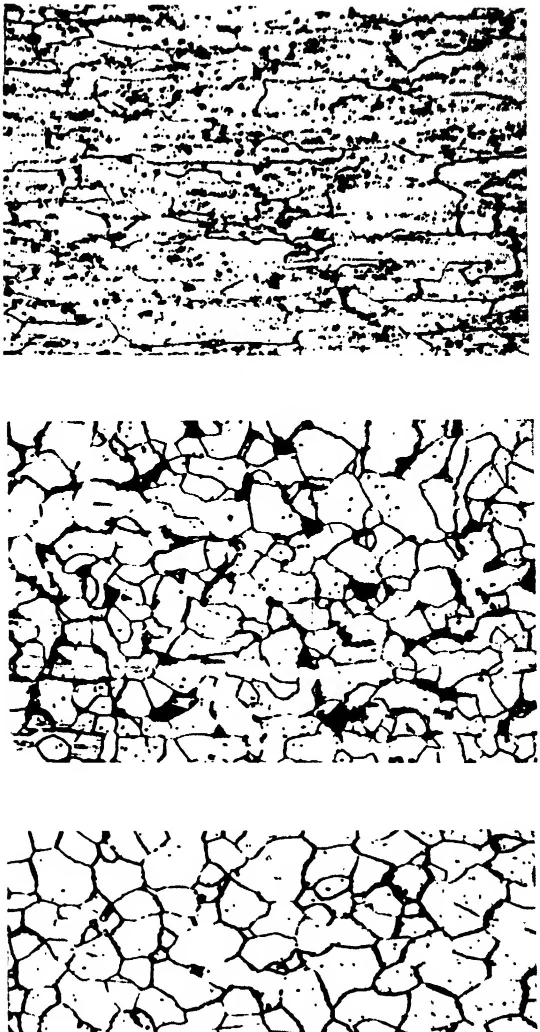
The general tendency of these changes is to improve the deep drawing and pressing properties of the steel if the carbon content is low; but if it is relatively high, some authorities maintain that sheet has greater ductility when the carbide exists as discontinuous stringers of small globules or, still better, as small globules dispersed uniformly. However, it is usually found that the refinement of the crystal structure produced by normalising outweighs the influence of a slightly less favourable condition of the carbide. It must be added that micro-structure A (Fig. 54) is not typical of all close-annealed sheet for, if conditions are just right, an excellent microstructure can be produced by annealing heavily cold-worked sheet ; such a structure is illustrated at C, in the same figure, which shows an excellent close-annealed sheet of rather lower carbon content than that shown at A.

Some producers maintain that, when conditions are controlled sufficiently closely, severe cold-reduction followed by close-annealing at a temperature between 650° and 720° C. can produce sheet having deep drawing and pressing properties better than those of the best normalised sheet. These claims have been investigated by Edwards, Gullick and Pipe[4] who determined the tensile properties and Erichsen values of sheet rolled from the same ingot, part being close-annealed and part normalised after different amounts of cold-reduction. Both basic and acid steels were included in the investigation, which deserves close study by readers interested in the relative merits of close-annealed and normalised sheet and strip. The results obtained do not show that one process necessarily gives sheet of better quality than the other. On the other hand they do show that, if a really good crystal structure is to be produced by close-annealing cold-reduced sheet, very close control and matching of percentage reduction and annealing temperature is necessary. For this reason there is a tendency under industrial conditions for normalised sheet to be more uniform and to have a better crystal structure than close-annealed sheet.

An interesting minor observation recorded in this investigation was that a relatively impure acid steel proved much less susceptible to excessive crystal growth under certain conditions of annealing than did a basic steel of relatively high purity, an observation which, although it only confirmed what might have been expected from theoretical considerations, was specially valuable because it was made under semi-industrial conditions on sheet of industrial quality.

One other matter must be mentioned in this comparison of the merits of normalised and close-annealed sheet. If, as often happens, the rate of cooling from the normalising temperature is rapid, some authorities maintain that certain constituents remain in solution, thus hardening the ferrite crystals and preventing the full measure of ductility being obtained. Annealing at a low temperature, say 650° C., after normalising allows these constituents to precipitate and, in sheet containing a relatively high carbon content of the order of 0·10 per cent., further improves ductility by spheroidising the areas of sorbitic pearlite which are produced by normalising.

If normalising is not carried out in a protective atmosphere the sheet will have to be pickled to remove scale ; subsequent annealing then has the added advantage that it removes all tendency toward hydrogen embrittlement remaining from the pickling operation. It has already been explained that it is advantageous to give even clean-normalised sheet a light pickle if further cold-rolling has to be done.



A.

B.

C.

FIG. 54. Comparison of close-annealed and normalised microstructures.

A.	Close-annealed	0·08	per cent.	carbon	rimming	steel.
B.	Normalised	0·09	,,	,,	,,	,,
C.	Close-annealed	0·04	,,	,,	,,	,,

Microspecimens cut normal to surface of sheet parallel to direction of rolling. × 100.

[*To face p.* 68.

It can therefore be accepted that close-annealing after normalising always improves ductility, but that the improvement is greatest in sheet of relatively high carbon content which has not been clean-normalised. On the other hand, plain normalised sheet possesses deep drawing and pressing properties which are sufficiently good for many industrial press operations, so that a final anneal may be necessary only when these operations are severe.

Returning from this digression to explain the meaning and significance of the terms "Bessemer," "open-hearth," "killed," "rimming," "normalising" and "annealing" to the general discussion of available grades of steel sheet and strip, a few comments must be added regarding certain important properties of the finished sheet which are not, unfortunately, indicated specifically by the grade names already described and explained. For example, "P.CR.CA" implies no limits or condition for surface finish, dimensional tolerance, chemical composition or even actual deep drawing and pressing properties: the onus of supplying sheet having limits and properties suitable for some particular press operation rests entirely on suppliers, hence the present need for the closest possible contact between suppliers and consumers.

Hardness. No range of hardness is implied by any of the nomenclatures already described. The hardness of any sheet of any grade will depend upon the crystal size, upon the rate of cooling if the sheet is normalised and not subsequently annealed, upon the amount of temper-rolling—or equivalent treatment—which has been given after the final normalising or annealing and, to a smaller extent, upon the chemical composition of the steel because the higher the percentage of carbon, silicon, manganese, sulphur and phosphorus the harder the steel will be for any given crystal size or degree of temper-rolling.

For reasons already stated, the hardness of normalised sheet is often slightly higher than that of annealed sheet. An average value for close-annealed sheet having a crystal size in the region of 0·035 mm., a popular compromise, is 75 to 90 V.P.N. (Vickers Pyramid Numeral) and for normalised sheet 85 to 100 V.P.N. Temper-rolling may increase the hardness of either annealed or normalised sheet by from 3 to 15 V.P.N.; but, in the experience of the author, hardness is an unreliable indication of the amount of temper-rolling given, even when the hardness before temper-rolling is known. These values apply only to sheet having a carbon content less than 0·10 per cent.

Surface Finish. As with brass, no recognised standards exist, and the surface finish of steel sheet and strip is governed by the nature of the finishing processes—as already explained—and by the condition of the surface of the finishing rolls. Hitherto the production of as brightly-glazed a surface as possible has usually been aimed at, particularly on cold-rolled strip, but there is a growing tendency to supply finished steel sheet and strip with a fine matte surface produced by shot-blasted roll surfaces or by the reducing action of controlled-atmosphere normalising furnaces.

The inspection of steel sheet for surface blemishes tends to be less critical than with brass. When the article to be made has to have a really good surface—for example, when it has to be polished and plated—consumers often find what in their opinion is an undesirably large number of surface defects on sheet passed as first class by suppliers. As a rule, defects of this kind are inherent in the sheet rolled and are not due to poor methods or lack of care in the actual finishing processes.

Variation in Thickness. At one time variation in thickness across the width of steel sheet or strip was a source of constant trouble to consumers. Owing to the increasing use of cold-reduction and of more robust mills for the finishing passes, this variation has diminished to such an extent that the variation in thickness across cold-rolled strip 15 inches wide is often less than 0·0015 inch, and sometimes less than 0·0010 inch, above or below a nominal thickness lying between 0·030 and 0·060 inch; a notable achievement. In hot-rolled strip the variation is naturally greater. Improvement has also been made with sheet, as distinct from strip, due to the same changes in plant and processes, but the variation across the width of large cold-rolled sheets is not yet as small as consumers would like. In hot-rolled sheets the variation is often considerable.

Chemical Composition. It has already been explained that chemical composition, expressed as an *average* value, is usually of little significance in assessing the excellence or otherwise of steel sheet intended for deep drawing and pressing unless a real abnormality exists. The influence of carbon and of the common impurities silicon, manganese, sulphur and phosphorus, and also the very important influence of segregation, will be examined in a later chapter which deals with defects. As a matter of interest, however, the following typical analyses of killed and rimming steel sheet of average deep drawing and pressing quality are given, but readers are reminded that the values

	Killed Steel.	Rimming Steel.
Carbon . . .	0·08 to 0·12	0·05 to 0·09 per cent.
Silicon . . .	0·03 „ 0·05	Trace [1] „ „
Manganese . .	0·30 „ 0·50	0·30 to 0·40 „ „
Sulphur . . .	0·03 „ 0·04	0·015 „ 0·03 „ „
Phosphorus . .	0·005 „ 0·025	0·02 „ 0·05 „ „
Oxygen . . .	0·005 „ 0·025	0·02 „ 0·05 „ „

[1] This applies to aluminium-killed steel. If silicon is used in place of aluminium, the percentage of residual silicon is usually 0·05 to 0·10.

given are average ones and do not represent the skin zones of rimming steel sheet.

Deep Drawing and Pressing Properties. Attempts to assign definite properties to steel sheet of any particular grade have so far been less common and certainly less successful than with brass. Tensile and Erichsen cupping tests are sometimes made; but, as will be explained later, the value of results given by these tests provide a most inadequate guide to the probable behaviour of sheet steel under the press.

At present the usual practice is for suppliers to find by trial what sequence of finishing processes produces sheet best suited to some particular press operation, and then to adhere as closely as possible to this sequence in future deliveries. Hardness and cupping tests are best regarded by both suppliers and consumers as an indication of the *probability that some particular sequence of mill operations has been carried out*, not as an indication of true deep drawing and pressing properties. This fact is particularly cogent when sheet has been temper-rolled.

It has been impossible in such a brief review of the processes by which brass and steel sheet and strip are produced to give more than a mere outline of the more important operations, but references have been given in the introduction which readers who wish for more information can follow up. The purpose of this and the preceding chapter will have been accomplished if consumers have acquired at least a general idea of how the sheet which they feed to their presses is made and, having this knowledge, become more tolerant concerning unnecessary properties and characteristics; more appreciative of genuine attempts made by producers to overcome what, it will be conceded, are the very real difficulties encountered in the manufacture of sheet on an industrial scale and, withal, on a competitive basis; yet increasingly persistent in their demands for the elimination of defects of which the cause is known and the remedy not unduly difficult.

Increasing knowledge of the physical and special drawing and pressing properties of sheet metal shows very clearly that many defects in sheet or peculiarities in its behaviour under the press must be attributed directly to casting conditions and to the treatment given to ingots, slabs and sheet in the rolling mill. From the viewpoint of consumers this is in a way unfortunate, because they are not in a position to dictate to suppliers nor, indeed, can they do more than offer broad suggestions regarding lengthy and complicated processes with the details—and difficulties—of which they are usually unfamiliar, if not entirely ignorant. Suppliers, being only human, often tend to be more interested in the maintenance of uninterrupted production and sales than in the prosecution of energetic research aimed at giving consumers sheet more free from defects and having the exact combination of special properties necessary to meet the demands of some particular press operation.

Often suppliers—and sometimes consumers themselves—are unaware of the exact nature and significance of these special properties which are, therefore, not likely to be obtained regularly and in the desired measure in sheet of industrial quality until suppliers and consumers work together much more closely. In Great Britain it has been common practice with steel, if not with brass, for rolling mills not to do their own casting, but to purchase billets or even slabs from a number of different sources. This makes it very difficult for the precise history of any sheet to be traced and studied when, ultimately, its behaviour under the press has been ascertained. The very few concerns who cast, roll and press metal are in an exceptional position, and could benefit the deep drawing and pressing industry enormously by recording and studying their experiences and by carrying out planned investigations which, by reason of their unique facilities, they alone can undertake in a complete manner.

Readers are reminded of the note included at the beginning of this book stating that the practices and conditions described are to be regarded as applying only to Great Britain. This is particularly so in these first two chapters because the order of popularity of the methods mentioned differs in other countries, and in a few instances quite different methods may be used in certain localities.

CHAPTER III

DEFECTS AND DIFFICULTIES (GENERAL)

WHEN questioned as to the value of the improvement in the quality of sheet metal which has taken place during recent years, practical men having a lengthy press-shop experience often deny this implied improvement in no uncertain terms. It is a positive fact that the improvement in quality is very substantial but, as a works' metallurgist knows full well, theoretical opinions and expectations often have to give way before irrefutable practical experience until a satisfactory reason can be found which will reconcile theory with fact. In this instance the reason is that, simultaneously with improvements in the sheet metal used, manufacturing conditions have greatly changed. Much more is now demanded of the sheet fed to the press ; increasingly brutal methods of shaping, a greater depth of draw, fewer press operations to form a given article, higher press speeds, less inter-stage annealing, the demand for a smoother surface after pressing, the use of cheaper grades of sheet and the exercise of much greater vigilance on production costs have entirely consumed the ample safety margin which sheet of present quality would certainly possess if deep drawn and pressed under the conditions which obtained not long ago. In short, any improvement in the quality of sheet has instantly been taken full advantage of by consumers in their unending striving continually to reduce their own production costs.

As a result of this race between improved quality and increased demands, it often happens that the sheet purchased for deep drawing and pressing is, by the deliberate choice of consumers, not of a quality calculated to produce a good article with a fair margin of safety. It is, rather, of a quality calculated *just* to produce the article with not more than a certain percentage of scrap when the metal delivered is near the upper limits of its inevitably slightly varying quality which no specification, however carefully drawn up, can ensure remaining virtually constant. Any improvement in the quality of the metal, and consequent raising of the margin of safety, is soon swamped by the imposition of still more severe demands, and so the vicious circle is continued.

There has, for example, been a marked tendency to replace 70/30 cartridge metal with brass containing 65 per cent. of copper, while the use of 62–63 per cent. copper " basis brass " as a recognised deep-drawing quality is now widespread. Were cartridge metal to be substituted in place of the basis-quality brass which the modern press operator has to coax through his tools, his opinion concerning the merits of present-day sheet would assuredly change. Indeed, it would probably be found that modern basis-quality brass is equal to much of the cartridge metal produced a few years ago.

This is no idle fancy. When examining special samples of sheet which have behaved unusually well in the press-shop the author has often found them to be of a better, and therefore more expensive, grade than that normally used. Brass, for example, might be of higher copper content, or steel of a better grade rolled from a selected portion of a good ingot.

The striving to produce a given shape in the least possible number of press operations and with the least possible number of inter-stage annealings is natural; but when, as often happens, it is carried too far, the assumed saving in production costs becomes entirely illusory. It is a curious fact that, in large organisations, costs often seem to be based more on the *calculated* output of presses than on the output of usable articles actually produced; and that the cost of delayed production due to breakages, the need for "coaxing," tool-dressing and suchlike causes seldom finds its way into exhibited figures. Indeed, often the cost of quite a high percentage of scrap seems to be neglected. Assuredly, this natural but dangerous tendency to use the cheapest grade of metal and the least possible number of press operations which can be made *just* to produce a certain article is, at the present time, responsible for a certain proportion of such dissatisfaction as is sometimes expressed by consumers concerning the sheet which they have purchased.

Some small variation in the properties of sheet metal of industrial quality must be expected; the inference that a certain safety margin should be allowed in choice of grade and throughout deep drawing and pressing operations is so obvious that lapses in its general observance are foolish even under economic pressure. When persistent failures occur under the press, yet no serious defect is apparent in the metal, no useful purpose will be served by blaming the sheet manufacturer for the quality of his product; either the tools or the severity of the draw for the grade of sheet being used is probably at fault.

It is a regrettable fact that even those men who have had a scientific training are not always entirely free from bias toward the interests of their own firms. Examination of sheet, tools and operations by an entirely impartial but well-informed individual would in many instances be of real value in determining the true cause of many of the troubles encountered in the press-shop.

When considering surface finish, a quality to which increasing importance is being attached by consumers, two facts must always be borne in mind before hasty comment is passed. One is that the standard of surface smoothness demanded on articles as they come from the press grows higher and higher. The second is that polishing costs are now watched far more carefully than of old, particularly in large factories, and, furthermore, that on the whole the amount of polishing, particularly in the preliminary stages, is considerably less. Automatic polishing has brought problems of its own, not the least of which is the inability of machines to make allowance for variation in surface roughness from one article to another or on different parts of each article.

Having indicated certain general and often unrecognised reasons why, notwithstanding continued improvement in the quality of the sheet metal which finds its way into the press-shop, difficulties and sometimes failures are still plentiful, some of the more specific causes of these troubles will now be examined. It is proposed to divide these troubles into three groups: those attributable to the condition of the purchased metal, those attributable to the treatment accorded to the metal under the press and, lastly, those attributable to its treatment during what may be termed the auxiliary operations of the press-shop, such as annealing, pickling and polishing.

Defects and Difficulties attributable to the Metal used

The first impulse of most industrial users of sheet metal, whether they shape their sheet by deep drawing and pressing or by other methods, is to blame the metal for many—and often for all—the failures or difficulties which they encounter. That this assumption is in many instances entirely unjustifiable will become evident during the review, made later in this chapter, of troubles attributable solely to the treatment—or, as suppliers would often like to call it, maltreatment—given by consumers to the sheet they purchase. Fairly often the cause of the troubles experienced in the press-shop must, however, be attributed directly to defects in, or to an unsuitable condition of, the purchased sheet. It is this category of defects with which the first part of this chapter deals.

The majority of these defects will be described very briefly because in subsequent chapters their nature and significance will be illustrated and described in greater detail with special reference to various individual metals; their inclusion here is, however, essential in order to make this review of general troubles encountered in the deep drawing and pressing of *all* metals reasonably complete.

Chemical Composition. Troubles attributable to chemical composition may be divided conveniently into two categories: those caused by an incorrect percentage of major constituents in an alloy, and those due to the presence of too high a proportion of harmful impurities in either an alloy or an industrially-pure metal.

Major Constituents. Troubles caused by an incorrect proportion of the major constituents of an alloy are uncommon and, in general, arise only when the specified proportions are near to some limiting composition. For example, in " basis quality " brass of nominal 63 per cent. copper content, a drop of only 1 per cent. in the proportion of this element—while not reaching the limit of the ductile *alpha* phase which lies at about 61 per cent. copper—will greatly increase the likelihood of the occurrence in the final sheet of appreciable quantities of *beta* phase. The presence of this relatively non-ductile *beta* constituent, or of a comparable constituent in other alloy systems, can seriously impair the ductility of sheet and may be directly responsible for failures experienced under the press. Figs. 96 and 97 (p. 145), show typical examples of *beta* phase in basis-quality brass sheet which has actually failed during deep drawing.

In alloys in which no such phase change exists—for example in the cupro-nickels and austenitic steels—quite an appreciable variation from the nominal percentage composition often has little effect upon the deep-drawing properties of sheet, but in others a variation of a few per cent. of one element—for example in the zinc content of nickel-silver—may exert an appreciable influence on the behaviour of the metal when cold-worked and also upon its behaviour when annealed.

When, as in the case of aluminium containing small percentages of magnesium, copper or manganese, the hardening effect of the added element varies in a marked manner according to the percentage added, the chemical composition of purchased sheet needs to be watched carefully to ensure that different consignments behave in a similar manner in a given set of tools, and that the arrival of a batch of metal having an unusually high proportion of hardening elements does not lead to failure on a large scale.

Impurities. The effect which small, and in some instances minute, proportions of harmful impurities can exert upon the physical and mechanical properties of the metals containing them is so well known that little need be said here concerning it. When, in later chapters, the deep-drawing properties of a number of metals are examined in detail, the nature and effect of the impurities commonly associated with each will be indicated ; readers specially interested in the effect of certain impurities on any particular metal will find many exhaustive and erudite papers and treatises among available metallurgical literature.

It is of interest to observe that impurities may exist wholly in solid solution, for example phosphorus in steel ; partly in solid solution and partly in separate form, for example iron in brass ; or essentially in separate form, for example lead in brass. When the impurity combines with one of the parent alloying elements, as does copper in aluminium alloys, or with some other substance, as does sulphur in steel, conditions become more complicated. A change in solid solubility with temperature may give rise to precipitation-hardening effects which may be harmful, as with steel, or beneficial, as with beryllium copper and with light-alloy sheet of Duralumin type. If precipitation is confined to the crystal boundaries, its effect may be to cause embrittlement *unaccompanied* by a general increase in hardness; carbide precipitation productive of what is popularly termed "weld decay" in austenitic steels is a familiar example of this condition.

Although generalisations are unwise, it may be accepted that, as a rule, those impurities which go into solid solution are the most harmful from the aspect of deep drawing and pressing; yet precipitated or separated impurities can impair the ductility of sheet to a serious extent by the "keying" action exerted by multitudinous small and hard particles distributed throughout the microstructure. Apart from their influence upon ductility, the influence of impurities upon temperature of recrystallisation (as in the instance of iron in brass) and upon rate of crystal growth during annealing (as in the instance of phosphorus or chromium in brass) must not be overlooked. It will be appreciated that, as in the instances just given, an impurity may be tolerated—or even added purposely—when some beneficial influence outweighs an associated small loss in ductility.

Instances of impurities which exert a peculiar effect, some of which will be examined later in appropriate sections, are not uncommon. The action of carbon in austenitic steels in causing the phenomenon of weld-decay, and of copper oxide in causing embrittlement during the annealing of copper in a reducing atmosphere, constitute familiar examples of special effects of this kind.

The influence of dissolved or occluded gases, which must be regarded as impurities, is only just beginning to be appreciated. It seems likely that the effect of gases is far greater than is now imagined, but present knowledge is insufficient to enable even generalisations to be made on this important matter.

It is often regarded as surprising that the presence of a very small percentage of some impurity, for example 0·01 per cent. bismuth in copper or in many copper alloys, can so alter the physical properties of a metal or alloy that it becomes entirely unfit for normal use. It has already been explained that harmful impurities of this kind often tend to segregate in the crystal boundaries and are usually insoluble, or of limited solubility, in the parent metal. Bearing this in mind it becomes easier to understand the pronounced influence of impurities of this kind when it is realised that, in a crystal aggregate having an "average grain size" of 0·1 mm. (100 grains per square millimetre), 0·01 per cent. (one part in ten thousand) of insoluble impurity would suffice to cover each crystal grain with a layer of about 100 atoms thickness. Between each crystal grain there would therefore be a layer of impurity some 200 atoms thick, and it can readily be imagined that, if brittle or lacking in cohesion, an envelope structure of this kind can reduce the ductility of a normally ductile crystal aggregate to a very low value.

Chemical Segregation. In this consideration of the influence of proportions of major constituents and impurities it has been assumed that both the chemical composition and the distribution of impurities is uniform throughout the length, breadth and thickness of a sheet. Unhappily this desirable condition is seldom attained in sheet metal of industrial quality, and the defect commonly termed " chemical segregation " is one which is often responsible for the failure of sheet under the press.

The segregation of impurities—and, in some instances, of major alloying elements—which tends to take place in ingots cast under ordinary conditions is manifested in the final sheet as planes or stringers of impurities or of metal having a different chemical composition from that of the bulk. This leads to an observation of some importance, namely, that sheet in which the *average* proportion of impurities, as determined by chemical analysis, is satisfactorily low may contain planes in which the proportion of impurities is so high that these planes possess relatively low ductility, and thus impair the ductility of the sheet as a whole. Sometimes these planes will have a much smaller crystal size than the rest of the sheet, a condition which still further lowers their ductility. Typical illustrations of segregation will be given later; steel sheet, in particular, often fails solely on account of pronounced segregation of either dissolved or non-metallic impurities in a number of forms, and brass sheet of low copper content is sometimes rendered unfit for severe press-work operations owing to the segregation of its major constituents.

Non-metallic Inclusions. Non-metallic inclusions are usually one of three kinds: those due to the retention in the molten metal of slag or oxide, those due to the detachment and entrapment of particles of refractory from the lining of the furnace or ladle and, thirdly, foreign particles introduced in a variety of ways during melting and casting. Of these three the first is by far the most common and the most harmful.

The non-metallic inclusions which are found in metal are, almost without exception, hard and brittle at ordinary temperatures. They act as keying particles offering resistance to the plastic deformation of the sheet containing them, and they form starting points for cracks; indeed, very careful microscopical examination will often reveal the presence, even in annealed sheet, of tiny cracks at each end of a non-metallic particle, these cracks having been formed during previous rolling of the sheet. Continuous planes or stringers of closely adjacent particles of non-metallic inclusions can be regarded as virtual discontinuities which will not transmit stress and which will readily open up into actual voids when the sheet is deformed by severe cold-working.

Trouble due to non-metallic inclusions is, fortunately, confined

FIG. 55. Surface defect produced by the opening-up of an elongated sub-surface discontinuity during the pressing of a hemispherical copper shell. × 2.

[*To face p.* 79.

principally to steel sheet, and illustrations of various types of inclusion will be given in the next chapter (see Fig. 123, p. 188 and Fig. 128, p. 191). Occasionally, however, inclusions are the cause of impaired ductility if not—as is common in steel—actual failure in non-ferrous metals ; but, having studied steel, readers will be able to identify the various types of inclusion found in non-ferrous metals and to judge their effect.

Gas Cavities. Gas cavities, which may occur in any metal cast under ordinary conditions, are due to the retention of gas entangled when the molten metal is poured, expelled from solution as the metal cools, or formed in the metal by chemical action. When, as is usual with some non-ferrous metals, ingots are cast thin and cold-rolled into sheet, these gas cavities will be formed into elongated discontinuities which, even though they appear as no more than a fine line on a micro-section, are true fissures in the rolled sheet. When ingots are hot-rolled, elongated gas cavities tend to be welded up, but it is unwise always to expect a complete welding of all cavities because when, as often happens, the surfaces of these cavities are coated with oxide, welding may be incomplete and may not even occur at all.

The harm which gas cavities will cause will vary with their size, their distance from the surface of the sheet, the amount of welding which has taken place, and both the nature and the severity of the deformation imposed upon the sheet during deep drawing and pressing. If the cavities are close to the surface, the thin covering layer of metal may break, exposing the actual cavity or, as it will have become, fissure. A typical example of a surface blemish on a drawn shell caused by a sub-surface cavity in the sheet is shown in Fig. 55. When the covering layer remains intact, an area of rumpling is often produced which will be difficult to polish out and may open up during grinding.

In general, internal discontinuities become manifested on the surface of an article most clearly if, as often happens during deep drawing, the section containing them has been subjected to both tensile and compressive stresses ; their presence tends to be less marked if only pure tension or one-way bending has been imposed.

When a partly-shaped article formed from sheet containing gas cavities is given an inter-stage annealing, blisters are sometimes produced by the expansion of gas within the sub-surface discontinuities. The gas may be residual, but more often it diffuses into the discontinuity through the covering layer from the atmosphere of the annealing furnace. If oxide is present in the discontinuity and if the furnace atmosphere contains hydrogen, steam may be formed which will produce blisters of large size, an occurrence which is common in copper.

It may be observed that internal planes or streaks of non-metallic inclusions can produce local areas of rumpling, and even blisters, similar to those produced by gas cavities.

Surface Blemishes. The degree of excellence of the surface of sheet metal intended for deep drawing and pressing is frequently a matter of considerable importance, and one to which increasing attention is being paid by users in their continual striving to reduce polishing costs or, if polishing is not given, to improve the appearance of the surface of the final product.

Surface blemishes on sheet metal are usually one of three kinds : scratches, indentations or other mechanically-imposed defects produced during rolling, annealing, pickling, drying, storage or transportation ; surface defects attributable to imperfections in the mould, to the action of the mould dressing, or to the actual pouring operation, such as seams, laps, " shells " and " cold shuts," most of which are removed when the surface of the ingot is machined early in its passage through the mill ; and, thirdly, sub-surface defects, such as inclusions and gas cavities, having their origin in the original ingot. Fortunately for consumers, serious surface blemishes, when visible, lead to the rejection of sheet in the inspection departments of reputable suppliers.

A variety of blemish not included in the groups just mentioned is that due to rolled-in mill scale. Sometimes the scale itself is removed during the final pickling of the sheet, leaving cavities which may be barely visible yet which will open up into unpleasant blemishes when the sheet is deep drawn or pressed. An illustration of this type of defect is given in Fig. 130 (p. 192).

Staining and other surface defects due to pickling are largely a thing of the past owing to the greater cleanliness and control of baths and processes which is now exercised, but these troubles are still experienced occasionally.

It needs to be borne in mind that the importance of minor blemishes, such as light scratches and minor " spills," varies with the purpose for which the finish-drawn article is intended. The rejection of otherwise good-quality sheet for slight surface imperfections which will actually be of no detriment causes unnecessary friction between suppliers and consumers, and is to be discouraged. On the other hand it is true that, wisely or unwisely, the production lay-out in some modern plants will not allow the acceptance of sheet having a surface finish even slightly below normal standard.

Variation in Thickness. A sheet may vary slightly in thickness across its width due to the finishing rolls having been adjusted slightly out of parallel, which will produce a uniform variation in thickness across the sheet, or to spring of the rolls themselves, which, for reasons already explained, will make the sheet thinner at its edges than at its middle. Variation in thickness will, for obvious reasons, tend to increase as the width of the sheet increases, and variation caused by roll spring will naturally tend to be greater with relatively hard metal, such as steel, than with relatively soft metal, such as aluminium. Troubles directly attributable to variation in thickness tend, therefore, to be confined to sheets of medium and large size of the harder metals, but this does not mean that these troubles may not be of serious consequence in many press-shops. Instances are on record in which the breakage of very large and expensive cast-iron press-tools used for forming steel sheet into automobile bodies has been attributed solely to the use of sheet of irregular thickness. Such instances must be rare, and even controversial, but it is not uncommon for a high percentage of large sheets or blanks to be made into scrap metal for the same cause.

A shape which is deep drawn or pressed from a blank of irregular thickness may become worthless for two reasons, both of which are directly attributable to excessive gripping of the thicker portions of the blank by certain localised regions of the tools or pressure-plate : actual rupture in the wall of the partly-drawn shape adjacent to the regions of excessive friction in the tools and, secondly, uneven flow of the metal due to some parts of the tools or pressure-plate not having been able to exert the proper amount of control on the thinner parts of the blank.

Tools for large pressings frequently have to be " doctored " by local easing, or the flow of metal assisted locally by selective lubrication. In such instances the introduction into the press of sheet of uneven thickness may upset some carefully established procedure, particularly when the variation in thickness is not the same in all blanks.

In addition to variation in thickness across the width of a sheet, a gradual variation is occasionally found to occur along the length of a long strip due to the rolls having warmed up, and thus expanded, during the passage of each coil through them, a trouble which does not occur in strip rolled in continuous or nearly continuous mills. Even when variation of this kind does occur, its effect on *individual* blanks will, clearly, be negligible ; the practical effect will be the introduction into the press of blanks of a thickness which, although uniform in each blank, varies slightly from blank to blank. This variation in thickness from blank to blank, which can also occur due to variation across the width of sheet if a wide sheet is slit into narrow strips, will not produce irregular flow of metal in the tools ; but it can and does lead to failure in the walls of shapes drawn from those blanks which are unusually thick.

The permissible variation in thickness which can be tolerated in blanks will depend upon the nature of the operation, the severity of the draw, the efficiency of the lubricant, the design of the tools but, principally, upon the clearance given between punch and die relative to the thickness of the sheet for which they have been designed. To take the simplest illustration, if a blank of simple shape is deep-drawn in tools designed with a clearance such that no " ironing " of the walls takes place, the introduction of a blank having a thickness somewhat greater than the normal may cause " ironing " to take place during the latter part of the stroke. The effect of this will be to impose extra tensile stress on the wall of the shape and, if this is already stressed severely, the additional load may cause failure.

Strange though it may seem, the author has come across instances where through temporary shortage of sheet of proper thickness, or through other reasons, sheet of appreciably different thickness from that for which a set of tools has been designed has been used. When, as often happens, such substitution leads to wholesale or partial failure, the unsuspecting metallurgist may be at a loss to account for the failure of apparently satisfactory sheet unless he has taken the precaution of ascertaining whether its thickness is correct.

Unsuitable Crystal Structure. Due to its prevalence, and also to the unwillingness of some suppliers to regard it as a genuine defect, an unsuitable crystal structure is probably responsible for more failures and difficulties in the press-shop than any other cause.

The paramount importance of a satisfactory crystal structure in sheet metal destined for deep drawing and pressing cannot be emphasised too strongly. Even though sheet contains relatively serious defects, it will sometimes withstand the desired amount of deep drawing or pressing if its crystal structure is suitable for some particular combination of metal and press operations; if, on the other hand, sheet possessing an excellent surface, having a uniform thickness and devoid of all the common defects has an unsuitable crystal structure, it is likely that attempts to deep draw or press it by ordinary methods will prove unsuccessful.

This occasions no surprise to those having some metallurgical knowledge, because much of the sheet destined for deep drawing and pressing is annealed and the microstructure completely recrystallised after the final cold-rolling. This means that the physical properties of any metal of given chemical composition, cleanliness and homogeneity are determined entirely by the crystal structure in a single-phase microstructure, and very largely, if not always entirely, in a multi-phase microstructure. If, as happens sometimes, sheet is given a certain amount of cold-rolling after the final anneal, its ultimate physical properties, and also the magnitude of the change in properties produced by a given percentage reduction in the final cold-rolling, will still be determined—with the qualification just mentioned relating to the number of phases present—by the crystal structure.

Defects in crystal structure are usually three in number: an unsuitable "average crystal size," a large variation in the size of individual crystals and, thirdly, pronounced preferred orientation. It will be convenient to examine these three defects or conditions separately; only a brief indication of their practical effect will be given here, because the influence of crystal structure upon deep drawing and pressing properties will be examined at some length in a later chapter.

Unsuitable "Average Grain Size." The term "average grain (or crystal) size " is one concerning the precise meaning of which considerable controversy has, quite rightly, taken place. Deferring discussion of its real meaning till later it can be said that, industrially, the term can be interpreted most usefully as the numerical label attached to that standard photomicrograph or chart whose appearance resembles most nearly that of a representative microspecimen cut from the sheet whose behaviour it is desired to predict. Interpreted in this way which, although difficult to express in words, is in practice quite simple, the property of " average grain size " is one of great importance and having genuine significance from the aspect of deep drawing and pressing. Unfortunately for consumers, it is one which all too often does not fall within the range which they specify or, if they do not actually specify, desire with or without a full and true understanding of their own particular needs. As a result they experience failure under the press or, sometimes, the production of deep-drawn shapes which, though intact, have a surface so rough that normal polishing costs and times are increased several-fold.

Too small an " average grain (or crystal) size " will lead to the production of a deep drawn or pressed article having an unusually smooth surface, but the ductility of the sheet will be relatively low and may be so poor that the wall of a shape will fracture before the full desired depth of draw has been accomplished. Other conditions being similar, too large an " average grain size " will produce an unusually rough surface on the drawn shape; yet although the ductility of the sheet will be unusually good, its tenacity will be low. It may be so low that the walls of the shape take on a localised reduction in thickness—popularly termed " necking," as seen in a tensile test-piece of ductile metal—and break before the shape has been drawn to its full depth. This is illustrated very clearly in Fig. 85 (p. 120), which shows the bottom part of two brass shells deep drawn in the same tools from two blanks which differ only in their " average crystal size." It will be seen that the shell in the upper photograph has drawn satisfactorily and has a smooth surface, whereas the shell in the lower photograph has a very rough surface and the wall has " necked " and fractured before the full depth of draw could be accomplished.

For any sheet of given metal and given thickness destined for a given set of press operations, a compromise—which, though indicated by experience, may have to be found by experiment—must be struck, and the best " average grain size " will usually be the smallest which will allow the desired shape to be produced regularly, under industrial conditions, with a fair margin of safety. If smoothness of surface on the drawn article is of no importance, the safety margin can be increased by using sheet having a rather larger " average grain size " than would otherwise be specified.

Undesirable Variation in Crystal Size. There is reason to believe that sheet metal of ideal quality for deep drawing would be made up of crystals of uniform size. In sheet of industrial quality it is rare for this ideal to be so much as approached and—even in sheet possessing what, most erroneously, is often described as a " uniform " crystal size or structure such as that illustrated in the upper photomicrograph of Fig. 56A—the variation between the size of the smallest and the largest crystals is often considerable. When, however, the variation in size is more than usually pronounced, as in the microstructure illustrated in Fig. 56B, the deep-drawing properties of the sheet become impaired.

It might be imagined that the effects engendered, respectively, by the small and the large crystals in an aggregate would tend to counterbalance each other when the aggregate was stressed and strained as a whole. Unfortunately, this is not so. Comparing two sheets of adjudged similar " average grain size," one having a usual and the other an unusually large variation in the size of its crystals, it will be found that the latter will possess less ductility yet will give a rougher surface than the former when worked in a similar manner under the press. It is certain that this fact explains the indifferent behaviour of much sheet metal having no serious defect other than an undesirably large variation in the size of its crystals ; its wider recognition by both suppliers and consumers is long overdue.

Distinct from a marked variation in the size of the crystals composing a homogeneous sheet, there exists the condition in which, due to chemical segregation or other causes, well-defined stringers or planes of crystals of abnormal—and usually small—size run through the microstructure. These planes may be isolated and distributed at random throughout the section of sheet, as shown in Fig. 57, or a single plane may run through the centre of the section to give a " core " which may be thin or so thick that it occupies a good proportion of the section, as shown in Fig. 117 (p. 186).

The ductility of any sheet tested as a whole will tend to become more nearly that associated with any zones of small crystals as the relative proportion of the section which these zones occupy increases, and if a cross-section of the sheet contains only a few isolated planes of small crystals, its ductility as a whole may not be lowered greatly. There is, however, always a likelihood that internal fractures will occur on such planes when the sheet is worked under the press, and the presence of even a few planes of very small crystals is, therefore, often more harmful than might be imagined. If these planes are numerous or of relatively large size, as in the sheet illustrated in Fig. 57, the ductility of the sheet as a whole will certainly be lowered, while the ductility of sheet having a relatively thick core of small crystals—as occurs sometimes in rimming steel—will tend to be more nearly that

A

B

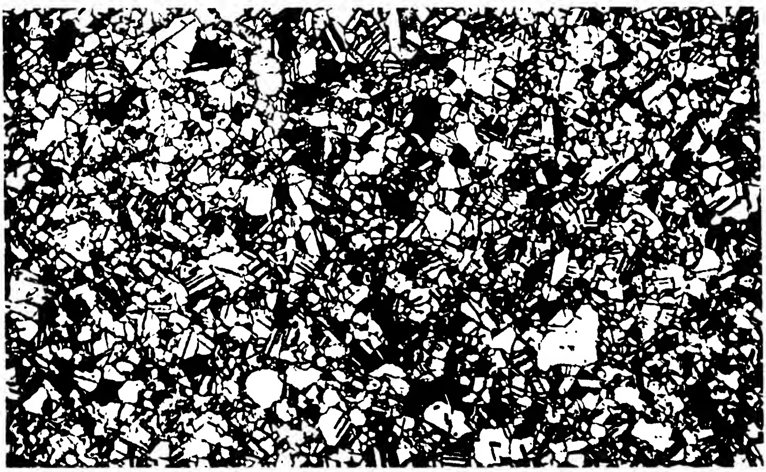


FIG. 56. Typical examples of (A) relatively regular and (B) irregular crystal size in "basis quality" brass sheet. × 75.

[To face p. 84.

FIG. 57. Planes and stringers of tiny crystals running through matrix of normal crystal size in brass containing approximately 63 per cent. of copper.

Microsection cut parallel to surface of sheet. × 75.

[*To face p.* 85.

of the core than of the outer zones, although the smoothness of the surface of pressed articles will be determined by the crystal size of the surface zones, not that of the core.

Pronounced Preferred Orientation. "Preferred orientation" is the term coined by crystallographers to describe the condition in which the principal axes, or some other common characteristic, of the crystals composing an aggregate tend to lie in the same direction. If the crystal structure of a sheet exhibits pronounced preferred orientation, the physical properties of that sheet will vary according to the direction in which they are measured. This effect, which is known as "directionality," may constitute a serious defect, but it will be reviewed separately because, although preferred orientation of crystal structure is often its main cause, other causes can aggravate it and can even be the sole cause of its existence.

It is important to notice that an absence of visible preferred orientation in the appearance of a microstructure must never be taken as an indication that directional properties do not exist. Examination of a crystal structure by means of X-rays may reveal the existence of preferred orientation when the most careful visual examination of the microstructure fails to do so.

Concluding this brief review of the three principal types of defective crystal structure found in sheet metal of deep-drawing quality, namely, an unsuitable "average grain size," a large variation in the size of crystals above and below the adjudged "average," and pronounced preferred orientation, it must be emphasised again that these defects are often serious ones and, although tending to be less acute than of old, are still responsible for much of the trouble which is experienced in the press-shop.

Directionality. Applied to sheet metal of industrial quality, the term directionality means, or implies the existence of, appreciable variation in the physical properties of sheet according to the direction relative to some line of reference, usually the direction of rolling, in which measurement of these properties is made or the behaviour of the sheet observed. It can be said without fear of contradiction that, in many modern deep drawing and pressing operations in which the metal is worked nearly to its limit, the degree of directionality inherent in a sheet will determine whether it will or will not withstand the desired amount of deformation in the desired manner and without breaking; a fact which is not sufficiently well recognised.

As the property termed "directionality" is discussed at some length in a later chapter, it is proposed at this stage merely to indicate some results of its practical and visible influence, and to state that it can be caused by preferred orientation of crystal structure, which may or may not be discernible by visual examination of the microstructure; by planes of chemical segregation, crystals of abnormally small size or elongated non-metallic inclusions; or by the combined effect of several of these factors. It is important to notice that directional effects in sheet or partly-drawn shapes cannot always be entirely removed by annealing even when this treatment produces complete recrystallisation.

Directionality must be regarded as a defect because it may cause actual breakage, uneven flow of metal or, a special form of uneven flow which will be examined separately, the effect known in the terminology of the press-shop as "ears." Fig. 58 shows a typical failure due to the presence of pronounced directionality in cupro-nickel sheet. This particular cup, which is produced in very large quantities, is usually deep-drawn without difficulty to three times the depth illustrated. Sometimes, owing to variations in rolling-mill procedure, a batch of sheet is received which fails, in the manner illustrated, at a comparatively early stage; no alteration to tools, tool-setting, lubricant or other conditions having been made. In this instance the directions of minimum ductility lie at 45 degrees to the direction of rolling in the original sheet, and careful measurement shows that the splits in the cups always conform very closely indeed to these directions.

The cup just illustrated forms an excellent example of failure attributable to really pronounced directionality, yet much less pronounced directionality can also cause failure on a large scale though not at such an early stage in the sequence of deep-drawing operations. When, as happens frequently in modern production methods, very nearly the maximum possible depth of draw is demanded regularly from blanks of given size and metal of an assumed constant quality, it will be obvious that any appreciable lack in ductility in certain directions in these blanks is likely to lead to failure in these directions.

The failure illustrated in Fig. 59 provides a typical example of the effect of only a moderate degree of directionality. This particular cup, which like the one already illustrated is also made in large quantities, is deep-drawn from steel sheet without any inter-stage annealing and in such a way that the sheet is cold-worked and stressed nearly to its limit. If a batch of sheet free from other defects but having rather more than usual directionality is received, the cups invariably split during the final draw in the manner illustrated. In Fig. 59 the direction of rolling in the original sheet is indicated by a continuous line, and directions at 45 degrees to this by dotted lines. It is known that, in steel sheet rolled in a certain way, minimum ductility occurs at 45 degrees to the direction of rolling, and it will be seen that the closeness with which the splits in the walls of the drawn cup conform to these 45-degree directions in the original blank is striking.

Even when the presence of an appreciable degree of directionality in a blank does not produce actual rupture in the walls of an article,

FIG. 58. A typical failure attributable to " directionality " in cupro-nickel sheet. The rim of the cup has assumed a wave-like contour and cracks have spread from the apices of the depressions which occur in directions of minimum ductility.

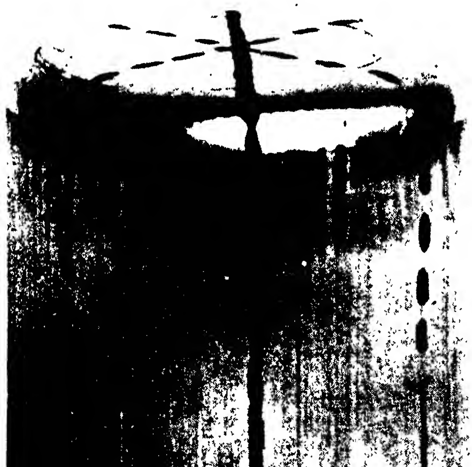


FIG. 59. Steel cup, drawn without inter-stage annealing, showing formation of cracks in directions oriented at 45 degrees (marked by dotted lines) to the direction of rolling (marked by continuous line) in the original sheet.

[*To face p* 86

FIG. 60. Drawn brass shell illustrating influence of directional properties on the flow of the blank.

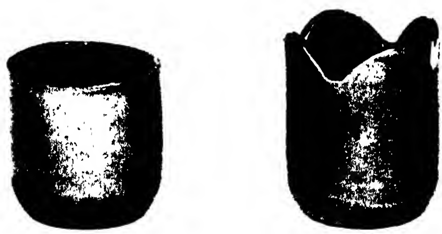


FIG. 61. Proof that "ears" are caused by inherent "directionality" in sheet and not to conditions of drawing. Both cups are drawn in the same tools from 80/20 cupro-nickel sheet reduced to the same thickness by different methods of rolling and annealing.

[*To face p.* 87.

it may yet render it worthless by producing uneven flow of the blank over the radius of the drawing die. This is illustrated in Fig. 60 which, by way of contrast, shows a non-circular article deep-drawn in one operation from a non-circular brass blank in which, as can be seen, the direction of rolling runs from bottom right to top left in the photograph. It will be seen that, owing to the decreased ductility of the sheet in a direction at 90 degrees to that of rolling, as is usual in brass, the flange of the shell has been pulled in almost to danger point in the part situated at the top right of the photograph : a little further, and the edge of the trimmed shell would have shown a depression in this region which would have rendered the article worthless. At the top left, where the pull has been parallel to the direction of rolling, it will be seen that the flange is considerably wider owing to the metal having elongated a greater extent under the same load.

In deep drawn or pressed articles of irregular or rectangular shape it is impossible for the metal in all parts to be strained uniformly in all directions of the original blank ; consequently the harmful influence of inherent directionality becomes of increased importance in determining whether excessive wrinkling, puckering, ear-formation, thinning or actual rupture will take place in regions and directions of maximum deformation. To obviate or at least to minimise each of these five defects, skilful adjustment of clearances between die and pressure-plate and die and punch is usually made in tools used for deep drawing or pressing rectangular-shaped articles and, in addition, blanks of uneven outline are sometimes used in order to facilitate as far as may be possible the flow of metal in the desired manner. If, therefore, blanks possessing markedly directional properties are placed at random orientation in such " doctored " tools, trouble must assuredly arise when, as is not uncommon, the safety margin between a satisfactory draw and failure is small. On the other hand, if the directional properties in a particular variety of metal remain reasonably constant from batch to batch, and if the blanks can be cut and placed in the tools at a chosen orientation relative to the original sheet, directional properties can be allowed for and even utilised beneficially. Unfortunately, directional properties are seldom constant ; in the light of existing theoretical and applied knowledge the property of directionality is, for this reason, best regarded as harmful and desirable of reduction to the minimum possible value.

It is known that the orientation of the directions of minimum ductility—and other properties—of sheet metal relative to the direction of rolling is dependent not only upon the natural properties of any particular metal or alloy, but also upon the treatment given to sheet in the final stages of rolling. A factor of particular importance in determining these directions is the stage at which both the penultimate and the final annealing are given to sheet during its successive stages of reduction in thickness by cold-rolling. For this reason it is not always safe to predict the directions of minimum ductility for rolled sheet of each metal and alloy ; but, in sheet of industrial quality, the directions of minimum ductility relative to that of rolling usually lie at 45 degrees—although occasionally at 0 and 90 degrees—in steel, copper and cupro-nickel alloys, though at 0 and 90 degrees in brass.

Ears. " Ears " is the term commonly used to describe the crests of the wave-like formation which the top edge of a deep-drawn shell assumes if the blank has pronounced directional properties. A typical example of ear-formation is shown in Fig. 61 (p. 87). An example of more marked formation accompanied, as it often is, by the formation of actual splits running from the apices of the troughs has already been illustrated (Fig. 58, p. 86).

Ears themselves may not always be detrimental, because the top of a shell is usually trimmed to give an even periphery ; but, if they are pronounced, the intervening indrawn portions of the wavy edge will be equally pronounced and may extend sufficiently far down the walls of a shell to spoil it. The likelihood of this happening is increased very greatly by the modern tendency to economise by using blanks of only just adequate size. For example, in the deep-drawn shell illustrated in the frontispiece to this book, ears having a maximum height of $\frac{3}{8}$ inch would extend into the wanted portion of the shell, thus spoiling it.

It will be evident that, if pronounced ears are formed, thinning of the walls of a deep-drawn shape must of necessity occur on axes running through the peaks of the ears. Even though the height of the ears—or, more accurately, the depth of the intervening depressions —formed during initial draws may not be sufficient to spoil the actual deep-drawn shape, the associated local thinning may yet be of serious detriment to the strength of the finished article or to the successful completion of subsequent draws.

The fact that in a given article the shape and the size of ears can be controlled to some extent by varying the shape of the blank and by giving increased local clearance on tools has tended to attract attention away from the fundamental cause of their formation. In rectangular-shaped articles uneven flow cannot be avoided, but the formation of quite pronounced ears in circular articles constitutes certain proof that they are produced by some inherent property of the metal. It has been definitely established, for example by the several investigations mentioned in Chapter XIII, that the formation of ears is due to the existence in the original blank of directional properties and that, other things being equal, the height of the ears in any given shell is proportional to the severity of this directionality.

In a circular blank deep-drawn into a circular shell, ears will form in directions lying at right angles to the directions of minimum ductility.

When the blank or the article is not circular, the natural location of ears may be modified owing to the uneven flow of metal which must take place, but the tendency to form in the natural directions will always exist and can often be traced even in an article of complicated and unsymmetrical shape.

It is not unusual for blanks from which even circular shapes are to be deep-drawn to be cut oval, or somewhat square, in order to minimise the size of the ears. It will now be clear that, admirable though the aim of this practice may be, the desired object will not always be attained unless the most suitable orientation of the major axes of a non-circular blank are determined by tests made on carefully grouped batches of rolled sheet and not, as is done frequently, chosen in some fixed relation to the direction of rolling for all batches. Very frequently the direction of the axes of irregularly-shaped blanks is chosen without thought of the directional properties existent in the sheet and with the sole object of conserving metal as, for example, when octagonal or nearly square blanks are cut from strip of width equal to the distance between the flat edges of the blanks.

No matter what may be the shape of the blank, the tendency will be for ears to form in that direction of the original sheet in which occur maximum ductility and minimum tensile strength. For this reason the most satisfactory way of eliminating ears in circular articles, and of minimising them in rectangular articles, lies in reducing the magnitude of the directional properties of the sheet used: a matter entirely beyond the control of consumers.

Special Defects. In addition to the general defects which have now been reviewed, some metals possess peculiar defects or inherent properties which may lead to trouble in the press-shop, but it will be convenient to postpone discussion of these special defects till later when the deep drawing and pressing properties of a number of individual metals are examined separately and in detail. As examples of this kind of special defect there may be instanced stretcher-strain markings in steel ; age-hardening in steel and in light-alloys of Duralumin type ; surface fissures in certain nickel alloys ; embrittlement of copper due to oxygen ; abnormal crystal size in zinc due to continued growth at normal or only slightly raised temperatures ; loss of ductility in austenitic steels caused by carbide precipitation ; critical-strain crystal growth, a phenomenon which is particularly marked in steel and aluminium ; fire-cracking ; season-cracking and other defects peculiar to certain metals with the practical effect—if not always with the cause—of which users of these metals are, unfortunately, only too familiar.

Unsuitable Physical Properties. The inclusion of this heading, implying as it must a distinct and separate type of defect, may seem strange because it is obvious that the success or failure of sheet metal in the press will be determined mainly, if not always entirely, by its physical properties which, in turn, are controlled—or at least influenced profoundly—by the various separate factors already reviewed in this section. Its purpose is, however, to remind readers that sheet of suitable chemical composition and devoid of serious structural defects may yet fail under the press if its physical properties are for some reason unsuited to meet the demands of the particular press operation given.

For example, its hardness may be too great and, in consequence, its ductility too low, owing to the treatment which sheet has received during the final stages of its progress through the mills of suppliers. Consumers are apt to measure the extent of final cold-rolling by indentation-hardness tests; in a later chapter the complete unreliability of this particular test as a measure of deep-drawing properties will be demonstrated, as also will the difficulty of measuring these properties even by much more informative tests. An increase in hardness is usually indicative of an increase in tensile strength accompanied by a decrease in percentage elongation and reduction of area: three changes which result from cold-rolling. With many metals, for example brass, these changes are usually prejudicial to the behaviour of sheet under the press; with others, for example aluminium, they may *improve* the deep-drawing properties to a remarkable degree if the amount of cold-rolling is not too great. With steel, which behaves in a rather peculiar manner, the influence of a small amount of cold-rolling is of special benefit because, although this treatment reduces the ductility, it prevents the formation of the serious surface blemishes known as "stretcher-strains."

Without trespassing upon the province of a subsequent chapter, it may be mentioned that, although useful for other reasons, the Erichsen cupping test—which is so popular in many press-shops—often fails to reveal the suitability of cold-rolled sheet metal for deep drawing and pressing; like the indentation-hardness value, the Erichsen value invariably diminishes as the amount of cold-rolling is increased, even though with some metals the true deep-drawing properties of the sheet increase.

Useful generalisation is virtually impossible, and, in the not very clear light of present knowledge, it must be accepted that even the best quality of sheet metal must be offered to the press with its physical properties modified in a way which *past experience* has shown to be most satisfacotry for any particular metal and press operation.

It is possible to define most defects or defective conditions—such as inclusions or directionality—in a reasonably precise manner, and even to measure their effect; at present it is *not* always possible to do this with "unsuitable physical properties," the particular condition reviewed in this section. That this is so constitutes one of the main difficulties of the inspection department of any press-shop, and impatient readers are asked to defer criticism of the vagueness of these comments until they have perused those chapters in which the nature and measurement of deep drawing and pressing properties are discussed in greater detail.

Defects and Difficulties Attributable to the Treatment accorded to Metal under the Press

Having examined the nature and the causes of most of the defects and difficulties experienced in the press-shop which are attributable to defects in, or to an unsuitable condition of, the *metal*, attention must be given to troubles attributable to the *treatment* accorded to the metal under the press. It is the experience of the author that those in control of press-shops, though not always operators themselves if they be true craftsmen, seldom realise how often the causes of their troubles lie on their own doorsteps and can be remedied only by their own actions. Even when troubles are not actually apparent, a better appreciation of matters usually dismissed as of merely "academic" interest, the exercise of greater care, and intelligent modification of the methods used would in very many instances lead to a reduction in production costs and to an improvement in the quality of the article produced.

Troubles Attributable to the Inherent Design of the Article to be Produced. It happens sometimes under modern production conditions that the shape, the quality of the sheet purchased and even the schedule of forming operations are such that a wholly satisfactory, or even sound, article simply *cannot* be produced with regularity. To those unacquainted with such conditions this statement may appear extravagant, yet it is undoubtedly true. It is beyond the scope of this book to discuss the ethics of the "good enough" type of article which forms, unhappily, a considerable proportion of the output of modern factories engaged on cheap mass-production; attention is drawn elsewhere to the less controversial matter of the trouble which is so often caused by lack of co-operation between drawing-office and press-shop leading to the attempted, and sometimes continued, production of a shape rendered unnecessarily difficult for production by deep drawing or pressing by reason of some really unimportant detail.

A typical example of the "good enough" type of article, tens of thousands of which have been produced without, it must be conceded, a high proportion of service failures, is shown in Fig. 62 (p. 92). The two sides of the triangular piece of steel are sheared in sheet of about 0·080 inch thickness, and the whole triangle is then raised to a depth of nearly ⅝ inch from the curved, unsheared base of the triangle. No radius is provided at the end of the sheared edge and, no matter how good the metal may be, cracks of a severity which vary with the properties of the sheet always occur either in the position shown or else at the corner itself.

As distinct from the faulty yet usable type of article, there is also the one which fails completely at some stage of its formation. Fig. 63 shows such a failure, again attributable primarily to bad design and indicative of a lamentable lack of understanding of the properties of a drawn metal cup by those responsible for its design and production lay-out. This particular cup is deep-drawn from steel sheet 0·060 inch thick, the slots punched, the top trimmed and the recessed groove machined on the inside without any annealing treatment whatever. Sometimes no trouble is experienced ; but, when a batch of steel is received which has a rather small grain size, or which possesses some other attribute detrimental to continued ductility, cracks occur across the narrow band of metal bounding the top of the longer slot, as shown in the photograph. Clearly, this band is of inadequate section to afford any margin of safety in resisting the strong residual stresses which will exist in the rim of the deep-drawn cup, and indicates an entire absence of co-operation between drawing-office and press-shop. It would be possible to avoid cracking by annealing the cups before the slot-piercing operation, but this would introduce another relatively expensive operation (since bright-normalising would be virtually essential) and the completed cup would still be very weak mechanically. The static strength of the bounding rim may seem adequate from a consideration of its sectional area, but it must be borne in mind that incipient cracks will exist on the punched edge and that the presence of these may reduce the useful strength of the rim to a fraction of its calculated strength.

As in the instances mentioned previously, the fact that a proportion of cups do *not* crack renders it strangely difficult to convince those unfamiliar with the nature and properties of metal that epidemics of failure are not necessarily due to genuinely faulty sheet, but rather to the absence of any safety margin by reason of the design of the article and to the methods adopted in its forming.

The weakening influence of actual or incipient cracks on a sheared, blanked or punched edge has just been mentioned. As this cause of failure is not considered separately elsewhere, attention must be drawn here to its dangerous influence ; an influence, let it be observed, which is very often unrecognised. Cracks are particularly dangerous when the wall in which they occur is subjected to alternating stress in service, or when the residual stresses due to deep drawing have not been relieved by annealing.

This matter of cracked edges is more closely related to design than may at first sight be apparent, for the location and subsequent treatment of any blanked edge is determined on the drawing board and the possible, and ndeed probable, existence of dangerous cracks in any

Fig. 62. Sheared and raised flap in 0·080 inch steel plate. Observe crack in vertical edge nearest camera.

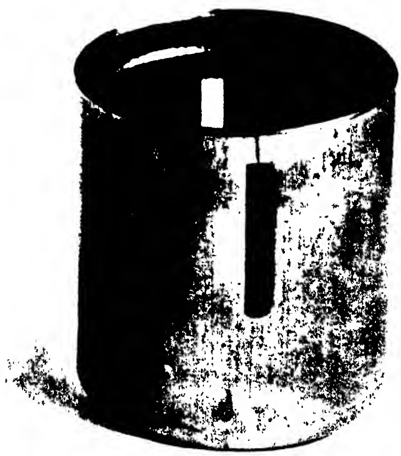


Fig. 63. Crack at top of slot which has been punched in wall of steel cup drawn without inter-stage annealing. The rim has been weakened by the machined recess on the inner surface.

[*To face p.* 92.

FIG. 64. Section through edge of 0·035 inch-thick steel blank showing "burr" or "lip" and general bending of edge produced by unsatisfactory blanking.

[To face p. 93.

blanked or punched edge ought to be kept continually in mind. Blanking and punching tools are seldom kept really sharp due, possibly, to the fact that evidence of bluntness becomes visible in the product only when the tools have reached a very bad condition indeed. Attention is drawn later to the harmful effect of badly-burred edges on blanks intended for deep drawing ; the benefit to be derived from keeping all cutting tools in a properly sharpened condition, in order to minimise both burrs on blanks and cracks in drawn shapes, is well worth the slight extra trouble thereby entailed.

The industrialist is asked to pay special attention to the few preceding and following pages : were he to neglect all else in this book save these, his patience would have been rewarded. Only those who spend their days trying to coax from press-tools articles to which only a slight alteration would remove the major part of the difficulties encountered in their production will appreciate this plea. Often their experiences are rendered all the more exasperating by the knowledge that the particularly difficult feature of some design is of no real significance, and could be altered at a word from those in authority without affecting adversely either the appearance or the usefulness of the finished article. When for some reason there arises a *genuine* need for a design having some awkward feature, the practical man will nearly always be willing —indeed eager—to produce it as best he may ; yet, even here, he is often hindered by stipulations regarding number of draws, gauge of sheet and size of blank imposed by persons having no practical press-shop experience. At the risk of anticipating a subject which will be treated later, it must be stated in no uncertain terms that many of the production difficulties encountered in large press-shops would and could be lessened, and in many instances overcome, if the practical man was called in to offer advice when an article destined to be made by deep-drawing operations was being designed on the drawing board. At this stage modifications can be made by a stroke of a pencil ; when tools costing perhaps hundreds of pounds are made, alteration is such a serious matter that, even if other considerations allow, the cost of alteration may be prohibitive.

Troubles attributable to Unsatisfactory Blanking. It is commonly believed that blanking, which is usually the first operation imposed by the consumers upon the sheet which they purchase, is such a simple and straightforward one that no particular care or supervision is necessary. In many instances this belief is untrue, and badly-sheared blanks are sometimes the unsuspected cause of serious and mysterious breakages under the press.

If the blanking tools are blunt, incorrectly set, or have a clearance unsuited to the particular gauge and also to the particular metal which is being blanked, a severe burr or lip may easily be formed on the edge of the blank sent to the press-shop. This burr is seldom noticed ; when it is, its importance is rarely appreciated. If the operation is a double one of the popular " blank and raise " variety, a burr cannot be seen unless the press is stopped in the middle of a stroke and the blank extracted for examination: a precaution seldom taken after tools have been set at the start of a run.

If the burr on the edge of a badly-sheared blank is pronounced, the pressure-plate may be prevented from exercising the desired degree of control during the first draw. Worse still, should the clearance between punch and die be small and the operation a " draw-through " one, the sudden resistance to flow offered by the burr as it leaves the radius of the die and enters the restricted space may cause the wall of the

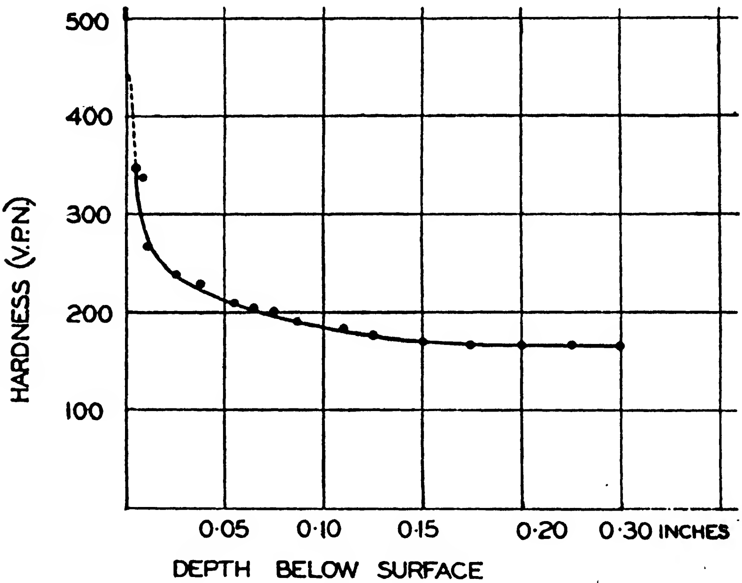


FIG. 65. Graph showing marked increase in hardness near the sheared edge of a mild steel plate.

drawn shape to break. When this happens, the true cause of failure often remains unsuspected. Fig. 64 (p. 93) shows the appearance of a typical burr on the edges of a batch of steel blanks with which a high percentage of failures was experienced for no apparent reason. When cleanly-cut blanks were substituted, no other alteration being made, no breakages were experienced.

The effect of a burred edge may seem unexpectedly large, but it must be borne in mind that this burr is very severely work-hardened, a fact which no doubt accounts in no small part for its harmful influence. Accurate measurement of the true hardness of the sheared edge and burr on a thin blank is extremely difficult, but the degree of work-hardening which is likely to occur is demonstrated by some measurements made by the author on mild steel plate about one quarter of an inch thick. These measurements are shown plotted as a curve in Fig. 65, from which it will be seen that the hardness of the original plate was approximately 170 V.P N., equivalent to about 38 tons per square inch tensile strength. Ten-thousandths of an inch below the surface of the sheared edge this hardness had increased to 280 V.P.N.; five-thousandths of an inch below the surface it had increased to 350 V.P.N., or approximately 75 tons per square inch: values which would hardly be regarded as favourable for mild steel destined for severe plastic deformation by deep drawing. By extrapolation of the curve, the hardness at the extreme edge seems likely to be of the order of 450 V.P.N., or nearly 100 tons per square inch tensile strength. Be this as it may, it is certain that the extreme periphery, and particularly the burred lip, of a sheared blank is so severely work-hardened that it will offer considerable localised resistance to subsequent plastic deformation, and will readily open up into cracks which may spread.

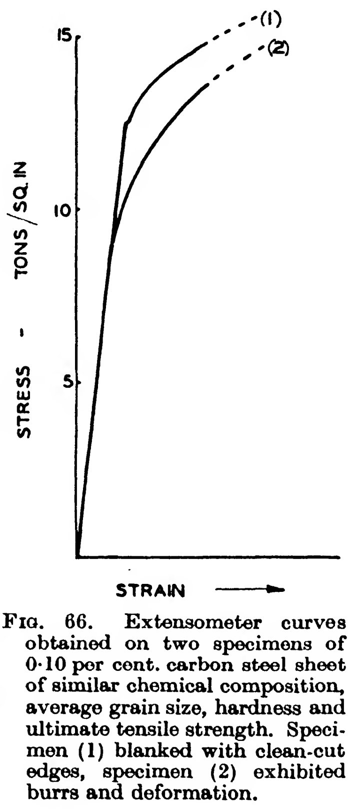


FIG. 66. Extensometer curves obtained on two specimens of 0·10 per cent. carbon steel sheet of similar chemical composition, average grain size, hardness and ultimate tensile strength. Specimen (1) blanked with clean-cut edges, specimen (2) exhibited burrs and deformation.

It must be borne in mind that sheet used for deep drawing is usually in its most plastic, and therefore its most unsuitable, condition for shearing and blanking with clean-cut edges. For this reason even more care ought to be given to the clearances and sharpness of blanking tools than when harder sheet is being sheared. Elsewhere [5] the author has shown that in steel sheets having practically identical chemical composition, "average grain size," ultimate tensile strength and hardness, the sharpness of the sheared edges produced under the same blanking tools varies markedly with the elastic limit of the sheet. An actual example of this, which occasioned considerable trouble and bewilderment until actual stress-strain curves were taken on the satisfactory and unsatisfactory sheets, is illustrated by the two curves shown in Fig. 66. Both sheets had an ultimate tensile strength of 24 tons per square inch: that represented by Curve 1 blanked with cleanly cut edges, whereas that represented by Curve 2 exhibited a marked "burr" accompanied by plastic deformation at the edge of the blank.

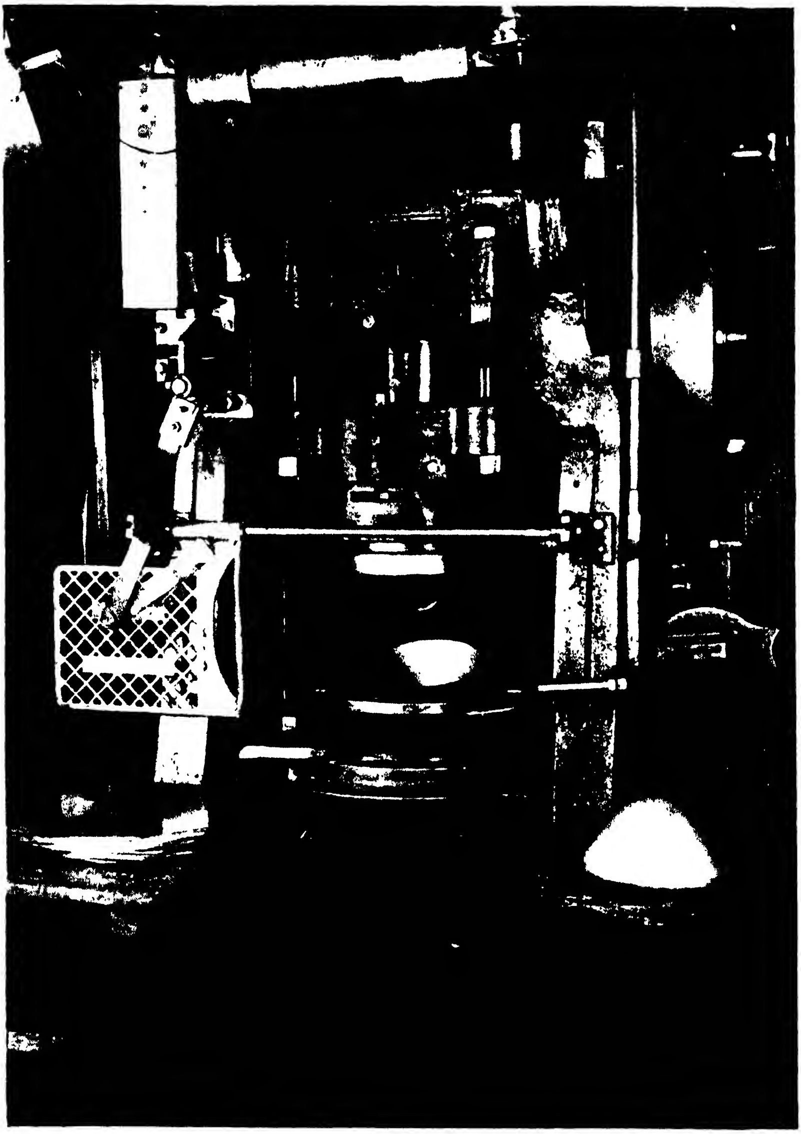
These observations on the effect of the condition of the sheared edge of a blank may seem to some to border on the academic, yet their practical significance can often be seen in the behaviour of the upper part of deep-drawn shells and, as has been pointed out, sometimes in actual failures. A clean-cut edge is particularly desirable on blanks of metal which work-harden in a marked manner, for example austenitic steel.

Troubles attributable to Incorrect Tool Design, Setting or Operation. Tool design, not being a truly metallurgical aspect of deep drawing and pressing, falls outside the scope of this book ; but readers are warned that incorrect tool design and setting can be—and undoubtedly often are—responsible for the persistent failure of metal of perfectly satisfactory quality. In a following section in which the defects known as " wrinkling " and " puckering " are discussed, some of the elementary principles of metal-flow in press-tools have of necessity to be pointed out ; but, for detailed consideration of this important subject, readers are referred to the ever-growing volume of useful papers in which various aspects of the flow of metal in press-tools is studied and numerous mathematical formulæ proposed.

It is certain that in the future the design of tools for deep drawing and pressing will become less and less—as it is now—a matter of guesswork aided by empirical data of doubtful value supplemented by such practical experience as each individual designer has acquired, and that the metallurgist will be called in to say what amount of deformation can be imposed upon any sheet of given metal and thickness and what is the best method for securing the maximum possible amount of deformation consistent with safety. How theoretical studies can help this to be done will be indicated in a later chapter : the point it is wished to emphasise here is that incorrect design of tools, both as regards their shape and also the apportionment of successive draws, often leads either to failure or to the full capacity of the sheet to suffer deformation not being taken advantage of—an omission which, were it recognised, would surely cause consternation to most modern production superintendents.

To give one example, in order to obtain the maximum depth of draw from the austenitic variety of stainless steels it is desirable to give the severest possible first draw followed by ones of less severity, whereas if, with the ferritic variety, a mild first draw is given, it is possible to follow this with more severe ones than would otherwise have been possible. Again, a deeper shell can often be produced in soft aluminium sheet if the first operation is a severe one than if it is fairly mild. Naturally the shape of any particular article influences these generalisations, but experience indicates that they are true in principle.

With some metals it is best to reduce a shell to nearly the finished diameter in the early stages and then to " iron " the walls to give the



[By courtesy of Joseph Lucas Ltd.

FIG. 67. A press operation in which the pressure-plate loading is so great that the blank is scarcely drawn in. Observe almost identical size of blanks (*on left*) and surround of reflector (*on right*).

[*To face p.* 97.

required depth. With others it is preferable to form the shell by means of gradual reductions in diameter accompanied by gradual increases in depth. Again, with some metals—such as aluminium—it may be advantageous to substitute a bevelled face of some width for the usual radius of the punch, while the importance of the dimensions of the radius on both die and punch relative to the thickness of the sheet being drawn is well recognised.

Failure to observe these precautions—which, as has already been indicated, vary in nature with different metals—will lead to breakages under the press, to the use of an unnecessarily large number of press operations, or to the full capabilities of the metal not being taken advantage of.

Turning from these necessarily vague generalisations to more specific details, the metallurgist should always be on the watch for an unsuitable radius on the punch and the die ; for too deep a throat or an insufficiently good polish on the die ; for too little clearance on regions where the shape of the article produces a thickening of the metal, as at the corners of rectangular-shaped cups ; for excessive loading of the pressure-plate ; for inaccurate centering or axial alignment of punch and die, and for any other condition which imposes an excessive strain on the whole or on local regions of the drawn shell.

The possibly serious effects produced by a variation in the thickness of the metal offered to the press, whether this variation be from blank to blank or across the width of each blank, have been pointed out in the first part of this chapter because such variation must be accounted a defect inherent in purchased sheet. The influence of this defect upon tool setting and adjustment, the particular conditions now being reviewed, will be obvious.

For reasons which are not wholly clear, a very small " wobble " on one tool relative to the other can cause persistent failure of deep drawn or pressed work even when other conditions are satisfactory ; periodic vibration or chatter may be a clue to the cause of such failure.

The influence of speed of drawing, a most important factor, will be considered separately later.

It happens sometimes that the method or sequence of drawing operations demands the imposition of a loading upon the pressure-plate of such magnitude that the margin of safety is so small that slight and unavoidable variation in the properties of the metal causes a percentage of failures. Breakages resulting from such conditions, although accompanied by all the visible signs of excessive pressure-plate loading, ought not be attributed to faulty tool-setting when a reduction in this loading produces wrinkling or other defects ; the method of producing the desired shape is, clearly, at fault.

Attention having been drawn to excessive loading of the pressure-plate as a likely cause of rupture, it must be pointed out that with certain articles in which unusually close conformity of the shape of the drawn shell to that of the punch is desired, a pressure which, judged by normal standards, would be excessive is sometimes imposed purposely in tools designed to accommodate this condition. In such circumstances, as in many others, the attainment of the best adjustment to give the desired effect without imposing too high a stress upon the walls of the drawn article calls for much skill on the part of tool-designers and tool-setters. In addition, and of special interest to the metallurgist, such critical drawing demands metal possessing uniform properties from batch to batch; variation on either the plus or the minus side of the desired average is likely to cause trouble.

An extreme example of this practice is seen in Fig. 67 (p. 97), which shows blanks and finish-shaped lamp reflectors produced therefrom in one draw. The bright ring visible on the upper side of the reflector in the tools has been produced by the pressure-plate, and that on the lower face by the radius of the drawing die. The surface of the dome is slightly rough as a result of having been plastically stretched over the die through the restraining grip of the pressure-plate upon the blank. It will be seen from the photograph that the periphery of the blank has scarcely decreased in size, and that almost the whole of the extension has occurred in the free, central area.

In contrast to this, the headlamp outer shell shown in the frontispiece is drawn with far less pressure on the pressure-plate, because it need not conform very closely indeed to the shape of the punch and a deeper-drawn shell with a thicker wall is desired. It will be seen that the parallel portion of the shell has a bright surface where it has been in forceful sliding contact with the die, whereas the surface of the dome is slightly rough. Practically the whole of the blank is used up, a modern tendency which can result in the production of a large proportion of sound yet unusable drawn shells if the degree of directionality existing in the sheet is sufficient to cause the formation of "ears," and thus leave an inadequate margin for trimming.

Deep drawing and pressing remains very much an art and, given sheet of uniform quality free from defects, the determinant of successful drawing is still the skill and practical experience of the tool-designer, of the tool-setter and of the press-shop foreman. Even in the absence of obvious indications of tool imperfections such as localised bright areas on drawn articles, a first-class man can often tell with uncanny precision what alterations to tools or to pressure-plate will be likely to remedy many of the faults which occur in practice.

This intuitive sense, a relic of the true craftsmanship of bygone days, will probably never be supplanted by purely theoretical knowledge and may always render necessary the services of the modern, and all too scarce, descendant of the craftsman whose skill it is now fashionable to underrate on the ground that precise scientific data can show the

[*By courtesy of Vauxhall Motors Ltd.*

FIG. 68. "Spotting-in" a pair of large press-tools to obtain a good mating after assembly in press.

[*To face p.* 98.

FIG. 69. Steel shell burst during first draw owing to incorrect tool setting.

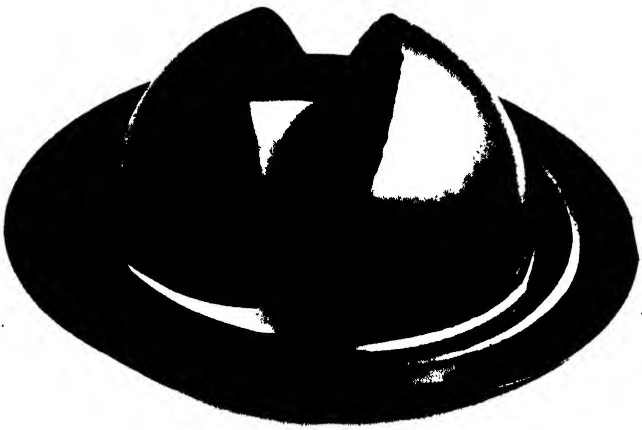


FIG 70. Steel shell burst during first draw owing to presence of severe internal discontinuity in the sheet.

[To face p. 99.

exact way in which any operation ought to be done ; a belief which those familiar with shop practice will rightly question.

Although " doctoring," *i.e.*, local easing of clearances in tools by a process of trial and error, is sometimes necessary in small pressings of irregular shape, this practice is more common with large pressings such as are used in the automobile industry. The final adjustment and local easing of clearances in these large tools, as well as the control of metal flow by the local application or removal of lubricant, is indeed an art in the full meaning of the word. This fact is not always appreciated in these days of tables and formulæ, yet the final finishing of a pair of large press-tools has so stirred the imagination of at least one novelist that a story, well worth reading by all interested either by desire or circumstances in deep drawing and pressing, has been written round this theme alone[6]. Fig. 68 shows a pair of large press tools being " spotted in."

As distinct from surface markings and the appearance of the fractured surfaces, the *disposition* of the fracture on a burst drawing can form a useful indication of the cause of failure when considered in conjunction with other characteristics. For instance, the type of fracture shown in the first-stage draw of the shell illustrated in Fig. 69 does not point to the presence of localised or directional defects, while the fractured edges indicate a reasonable balance between tenacity and ductility. Inadequate tool clearances or excessive grip in the pressure-plate are suggested as likely causes of such a burst. Contrast the appearance of this fracture with that of the one shown in Fig. 70 which, even if an internal discontinuity in the metal were not clearly visible to the eye, would indicate the existence of some marked directional defect. When considered in conjunction with the results of physical tests and, possibly, of " average grain size " estimations, the appearance of the fractured surfaces on a " burst " drawing can be of considerable help in deciding whether tools or metal are the cause of persistent failure.

Lest it be thought that the appearance on the surface of burst pressings of markings which point quite obviously to the existence of tool defects is sufficient to ensure rectification of these defects, it must be stated quite bluntly that, under modern factory conditions, all too frequently this is not so. Absence of the true craftsman—or, if he be present, the over-riding of his opinion by the necessity for immediate and continued " production "—may result in the continued use of inherently unsatisfactory, or possibly badly worn and roughened, tools. Under these circumstances it is not uncommon for that proportion of metal which possesses properties lying near the upper limits of the range common to the particular grade being used to be sufficiently accommodating to pass through the defective tools without failure. When this happens, it is very hard to convince a certain type of individual of the true cause of failure. The argument that, if some metal fails whilst other does not, the tools or process *cannot* be at fault is often extremely difficult to refute ; the notion that some small variation in properties within any one so-called grade is normal and therefore to be allowed for seems, to those ignorant of the nature and structure of metals, to be strangely incomprehensible.

The raised steel cup shown in Fig. 71 aptly illustrates the result of circumstances such as have just been described. The deep scores, which are shown at a somewhat higher magnification in Fig. 72, bear convincing testimony to the condition of the surface of the radius of the die over which the cup has been drawn. Yet many thousands of pressings were produced in this die with a high and varying proportion of failures due to the formation of a tear as shown in the particular specimen photographed. The die in question was of plain carbon steel, properly hardened; yet the severity of the draw, coupled with the presence of annealing scale on the partly-drawn shapes offered to it, had produced rapid wear and bad scoring on its radius. No apology is offered for the inclusion of this example, which may be judged ludicrous by enlightened readers, in a review of common troubles. Those readers to whom the continued use of such tools may seem unbelievable are assured that the example is neither exaggerated nor rare.

When no indication of unsatisfactory tools is given by visible markings on the surface of burst pressings, nor of inherently defective metal by the appearance of the fracture, microscopical examination of sections cut transversely through the fracture can sometimes be of great value in determining whether the tools or the metal are at fault. In the example of a burst steel drawing shown in Fig. 73, it is apparent that the degree of " necking " which has occurred before actual rupture has taken place indicates a normal and satisfactory compromise between tenacity and ductility ; tool-setting is indicated as the probable, and was subsequently found in this instance to be the actual, cause of failure.

Troubles attributable to too High a Speed of Drawing. The influence of the speed at which any deep-drawing operation is carried out is not always appreciated sufficiently. This is strange because it is the experience of nearly every press operator that, if a high percentage of failures is being experienced in some particular deep-drawing operation, reducing the speed of the press will often make the operation entirely successful, other conditions remaining unchanged. Further proof of the importance of speed is hardly necessary, but it may be pointed out that what, to those accustomed to crank-actuated presses, seem amazing draws are accomplished without difficulty on presses actuated by other methods which give a relatively slow and, which is important, *constant* motion to the descending punch. This aspect will be discussed more fully in a later chapter.

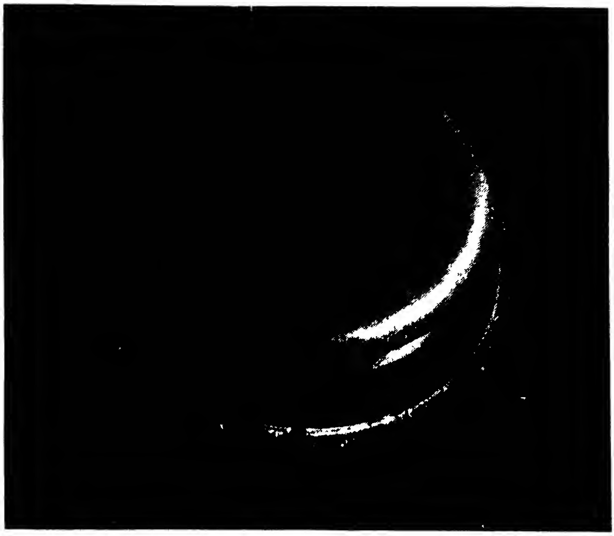


FIG. 71. Fractured cup drawn from oxide-coated steel. Failure is due to excessive friction set up by the scored and roughened radius of the draw-ring.

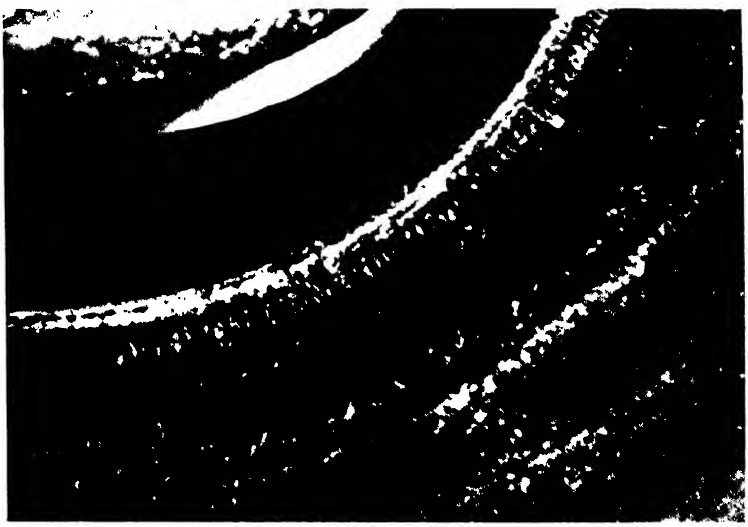


FIG. 72. An enlarged view of a portion of the same cup. The condition of the draw-ring can be visualised.

[*To face p.* 100.

FIG. 73. Transverse section through the edges of the fracture shown in Fig. 69. Observe normal degree of necking, appearance of fractured edge and absence of defects in the sheet. × 40.

[*To face p.* 101.

Extraordinary reluctance is usually shown by production managers to reduce the speed of presses even when it has been demonstrated to them that perhaps only a moderate reduction in speed will eliminate a high percentage of failures. This tendency is rendered all the more curious by the fact that the actual working stroke of a hand-manipulated press usually occupies only a small fraction of the total time of the cycle. In high-speed automatic-feed presses a reduction in speed is a more serious matter because it must entail a considerable reduction in output, and it is fortunate that in presses of this type a rather higher safety margin is usually allowed in order to accommodate slight variations in the quality of the metal and in the efficiency of the lubrication.

Too high a speed of drawing may cause failure, or at least defects, for one of two reasons. The force of the impact of the punch may be sufficient to tear the bottom out of a cup before motion can be imparted to its wall. Secondly, with either a flat blank or a cup which has been set in motion without being broken, the heat generated at the surface of the work and the tools may be so high that the film of lubricant is weakened, or even destroyed, with the result that metal-to-metal contact is established which may lead to scoring, fouling and even breakage of the metal being drawn as well as to "loading" and rapid wear of the tools.

Many students have thought that high temperatures are attained at the surfaces of work and tools during deep-drawing operations. These temperatures have now been measured in a convincing manner [7, 8], and have been found to be even higher than was imagined: for example, temperatures approaching 1000° C. have been shown to be attained at the extreme surfaces of two pieces of steel in sliding contact under conditions of indifferent lubrication and under pressures less than those obtaining in many press operations.

No further elaboration of these several points will be attempted here, because each will be considered from the theoretical aspect later. In this review of practical difficulties met with in the press-shop it will suffice if readers can be persuaded to recognise the vary marked influence which speed of drawing has in most press operations, and to remember that a reduction in this speed will often enable production to be carried on with no other alterations when persistent scoring or breakage is being experienced.

Unsatisfactory Lubrication. Troubles due to unsatisfactory lubrication can be divided into two groups : scoring and fouling of the work and loading of the tools and, secondly, actual breakage due to excessive friction causing the tensile stress in the wall of a partly-drawn shell to rise above the ultimate tensile strength of the metal being drawn.

The influence of the lubricant upon scoring, fouling and loading will be examined later in the section devoted to these special defects ; its influence upon actual breakage, the limiting condition, needs little explanation. Clearly, when metal-to-metal contact occurs, the friction between the work and the tools will increase very greatly, even if actual seizure does not take place. This increase in friction may be sufficient locally to retard the flow of the metal to such an extent that rupture—or possibly only uneven flow—occurs, particularly when sheet of thin gauge is being drawn.

All too often the condition and appearance of deep drawn or pressed shapes is the only aspect considered when inadequate lubrication is obvious or suspected, yet the permanent damage to possibly expensive tools is surely of equal, if not greater, importance ; for the polishing out of scores and roughened areas on large, really hard tools is a lengthy and expensive procedure.

Another effect of poor, if not visibly inadequate, lubrication is that a considerable amount of energy is wasted in overcoming friction between the work and the tools, particularly during the final stages of a deep cupping operation. The replacement of an apparently adequate, yet really indifferent, lubricant by one possessing markedly greater " slipperiness "—to use a term whose meaning will be explained in a subsequent chapter—will often reduce the power needed to carry out a deep-drawing operation to such an extent that the same tools can be set up in a smaller press. The saving in floor-space in the first-cost of presses and in power consumption which can be effected by the general substitution of a truly " slippery " lubricant for others less " slippery " can be unexpectedly large in a press-shop of considerable size. It is regrettable that those who try this experiment often meet an unexpected difficulty because, as already explained, a change to a more slippery lubricant may cause puckers to be produced in the walls of many articles unless the tools are modified to deal with the increased ease of flow of the blank.

The causes of unsatisfactory lubrication are three : an insufficient supply of a suitable lubricant ; unsuitability of the lubricant for the particular metal being drawn and, lastly and perhaps most common, an inadequate film strength.

Insufficient Supply of Lubricant. The usual method of applying a lubricant is to give blanks, and sometimes tools, a casual wipe with a rag. This procedure may leave some parts of a blank dry, in which case it is only the fact that the regions of the tools which make contact with these areas will probably bear a film of lubricant left from previous blanks that will prevent the occurrence of continual trouble. At best the coating of lubricant will be uneven and, unless the particular lubricant used is very mobile and the speed of drawing relatively slow, the blank will tend to flow in an uneven manner due to the varying friction in different regions. This effect is often turned to advantage when large pressings of irregular shape are being made : if the tools are not quite right, judicious dabs of some slippery lubricant applied locally may enable the desired draw to be carried out even when failure is inevitable if the dabs are omitted or located incorrectly. The inference is obvious : irregular application of lubricant must be regarded as a possible cause of uneven flow, and even of breakage in smaller blanks over the surface of which it is assumed, often erroneously, that lubrication is uniform.

Another undesirable effect associated with the application of lubricant by means of a rag is that dirt and particles of grit are often applied as well. This foreign matter accumulates on the surfaces of the tools, scoring the work and quickly spoiling the polished surfaces of the tools themselves.

Methods for applying a uniform coating of lubricant will be examined later ; it is desired here only to draw attention to the fact that irregular, and by inference locally inadequate, application of lubricant constitutes an often unsuspected cause of trouble.

Lubricant Unsuited to the Metal. In complex lubricants it happens sometimes that a constituent of the lubricant reacts chemically with the metal being drawn. This action, by which is meant actual chemical attack and not merely the formation on the surface of the work of a strongly adsorbed film, is usually harmful.

The chemical action of lubricants will be discussed in Chapter XI, but a few typical examples will indicate some of the troubles which can arise from the use of an unsuitable lubricant. Lubricants containing sulphur blacken brass and many other copper alloys ; they have an even more serious action on nickel and most nickel alloys. Lubricants containing an alkali react chemically with zinc and, if this metal is allowed to stand with alkaline lubricant upon it, successful drawing may become impossible owing to increased friction attributable to the roughened surface of the metal and the abrasive action of the solid compounds formed. Some of the new " extreme pressure " lubricants are chemically active toward many metals and even toward hardened steel tools, and caution is necessary unless work can be quickly and adequately cleaned and the rate of attack on the tools themselves is found to be sufficiently slow not to impair seriously their useful working life.

Inadequate Film Strength. Film strength, a term whose true meaning will be examined later, is assumed to mean the ability of a lubricant to prevent actual metal-to-metal contact between work and tools during a deep drawing or pressing operation. Interpreted thus, the breakdown of a lubricant under the particular conditions obtaining in any operation implies that its film strength is inadequate and, assuming that a proper supply of lubricant is present, the fundamental importance of adequate film strength requires no further emphasis. In an earlier section attention has been drawn to the important influence which speed of drawing exercises upon the ability of most lubricants to function satisfactorily during any given press operation ; the practical effect of reducing the speed of drawing, and hence the *temperature* attained locally at the extreme surface of the work and tools, is to produce an apparent increase in film strength when—as is usual—this property decreases with increasing temperature. The use of sheet having a smoother surface, the giving of a better polish to tools, and the special treatment of tool surfaces—as by chromium-plating—or of the metal surface—as by plating steel with lead—all produce an *apparent* improvement in the efficiency of the lubricant, although actually its true film strength is not increased as a result of these changed conditions.

Concerning the selection of a suitable lubricant having a sufficiently high film strength for any particular deep drawing or pressing operation, it must be admitted that at present individual practical experience is often the only criterion. A very large amount of useful practical knowledge is in existence in the industry, yet little attempt at collection and critical review seems to have been made. In Chapter XI a number of different types of lubricant are described and some indication of their relative efficiency given. In this review of defects and difficulties encountered in the press-shop it is sufficient to state that, if the lubricant does not possess a sufficiently high film strength in the widest meaning of the term, metal-to-metal contact will occur between work and tools and that, when this happens, scoring, fouling, loading, uneven flow and perhaps breakage in the walls of shells may result. The importance of adequate lubrication or, when this is beyond reach, the best possible lubrication in all deep drawing and pressing operations cannot be emphasised too strongly. All too often lubrication is treated as a matter of small significance, yet the ability or inability of any chosen lubricant to prevent metal-to-metal contact may be the deciding factor in determining the success or failure of any press operation.

Wrinkling and Puckering. The defects of wrinkling and puckering are ones which can cause a lot of trouble, more particularly when the production of a new article is about to be started and the first set of tools has been designed, made, and then found on trial to cause wrinkling and puckering. It is the practice of those not versed in the art of tool design to lay the blame for these defects, which may seriously delay the start of production perhaps already overdue, on the tool-designers and tool-setters. These sorely-tried individuals, often more as an excuse than in good faith, attribute the delay to "bad metal," with the result that in the past the true cause of wrinkling and puckering, as well as the means for eliminating it, has been shrouded in mystery. The fact that a skilled tool-setter can sometimes overcome wrinkling by adjustments which are "sensed" rather than arrived at by a process of logical reasoning, or puckering by an apparently careless dab of lubricant, has not helped to elucidate the true cause of these troubles.

It can be stated quite definitely that both wrinkling and puckering are dependent upon both the natural properties of the metal and the

FIG. 74. Steel shells drawn with insufficient pressure-plate loading.

Top: wrinkles confined to unwanted rim.

Bottom: wrinkles extending below trimming line into wanted portion of wall.

[*To face p.* 104.

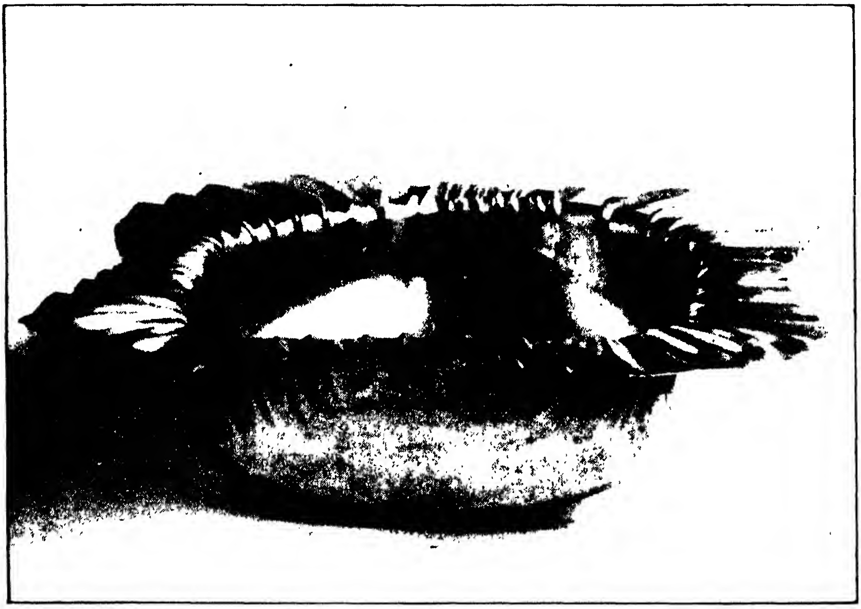


Fig. 75. Severe wrinkling extending beyond the rim which is trimmed off in shell drawn from Duralumin.

[*To face p.* 105.

design and setting of the tools. The skill and intuitive sense of the experienced tool-setter cannot, unfortunately, be committed to paper; but it is possible to give some indication of the mechanical and metallurgical factors which determine whether or not wrinkling and puckering will occur, even though it is not always possible, by considering these factors beforehand, to predict how serious these defects will prove when an entirely new shape is being made for the first time.

Wrinkling. Wrinkling is the name given to the formation of wrinkles or corrugations in that part of a blank which has not passed over the radius of the drawing die. Typical examples of wrinkling are illustrated in Fig. 74, which shows relatively slight wrinkling in a circular steel shell, and in Fig. 75, which shows severe wrinkling in a non-circular aluminium-alloy article.

The practical effects of wrinkling are mainly three: the "drag" exercised by the pressure-plate on the blank may be upset sufficiently to cause the metal to flow in a manner other than that desired; the resistance offered by the wrinkles when they enter the narrow space between the punch and the inner wall of the die may be sufficient to cause the metal to break and, thirdly, the presence of wrinkles in the wall of the finished article may render it worthless and will always be objectionable. In articles in which the rim is trimmed off, wrinkles—like ears—may not be harmful if they extend no further than the unwanted rim, as in the upper shell shown in Fig. 74. When on the other hand the wrinkles are so severe that they extend into the wanted part of the wall, as in the lower shell illustrated in the same figure, they may render the shell worthless. The very pronounced wrinkles shown in the light-alloy article illustrated in Fig. 75, besides extending into the wanted part of the wall, have actually caused localised fracture, although the break is not very distinct in the photograph.

Wrinkling is caused by the action of compressive forces which act on that part of the blank which has not yet passed over the radius of the die. How these compressive stresses arise will be made clear by an examination of the diagrams reproduced in Fig. 76 which show how, owing to the gradual reduction in perimeter which a blank suffers during the progress of a draw, the outer portions of a blank must either thicken in a uniform manner, as shown in the middle diagram, or else wrinkle, as shown in the bottom diagram. For the sake of simplicity a circular blank and a circular cup are shown, but it will be readily appreciated that comparable conditions will arise in a blank or article of non-circular shape.

If in the original blank there be visualised a segment bounded by two radii, this segment will, during drawing, take on one or both of the forms shown in the lower diagrams. It is clear that the portion (A) of the segment lying in the flat bottom of the cup will remain nearly unchanged in shape and thickness except near the side; the top or undrawn portion (C) must either thicken or else wrinkle by reason of its contracting effective perimeter in the plane of the original blank; the side wall (B) will assume a thickness which will depend upon (*a*) the relative diameter of the blank and the cup, (*b*) the depth of draw, (*c*) the physical properties of the metal and (*d*) the degree of " ironing " exerted by the tools. Ironing is the term used to denote the process by which, owing to the clearance between punch and die being less than the thickness of the thickened blank passing over the

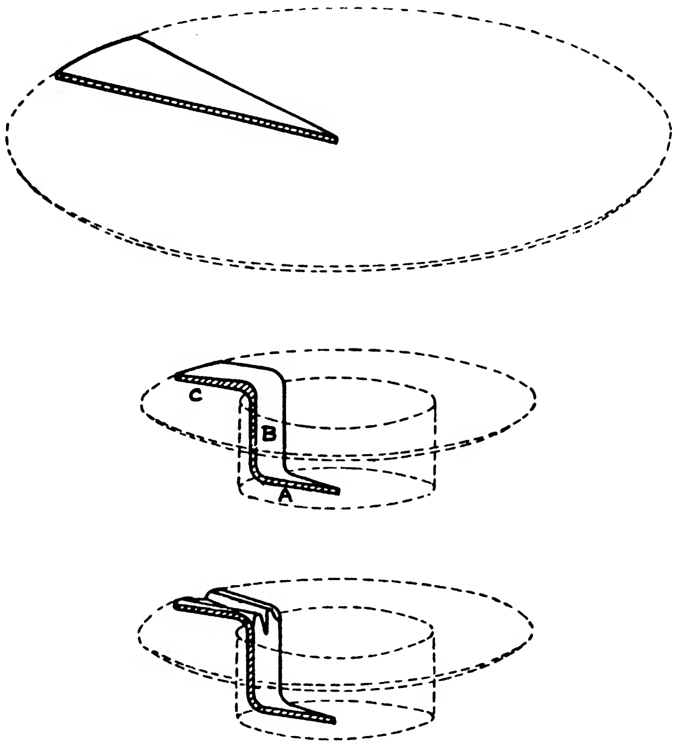


FIG. 76. Diagrams illustrating how wrinkles are formed near the periphery of a blank during a cupping operation.

radius of the die, the thickness of the wall of a drawn cup is reduced to some value less than that of the blank as it passes the radius of the die or draw-ring.

Considering the portion (C), it will be seen that, if no pressure-plate is used, and if the sheet is thin, the compressive forces acting upon this portion will be most easily relieved by the sheet corrugating or wrinkling, as shown in the bottom diagram. The purpose of a pressure-plate, the form and action of which is indicated in Fig. 77, is forcibly to prevent such wrinkling and thereby to cause the compressive forces to be dissipated in producing a more or less uniform increase in the thickness of the blank, as shown in the middle diagram of Fig. 76. The tendency to wrinkle lessens as the thickness of the blank increases ; with thick gauges it is possible to draw, without the use of a pressure-plate, shapes which require the very forcible use of this adjunct when thin-gauge sheet having similar physical properties is used.

Sachs [9] has illustrated in a very pretty manner the influence which variation in the loading upon the pressure-plate, other conditions remaining constant, exerts upon wrinkling. Fig. 78 shows a series of cups drawn by this investigator.

It will be evident that the imposition of excessive force upon the pressure-plate may, by increasing the resistance to the passage of sheet between it and the top surface of the die, quite easily stress the wall of

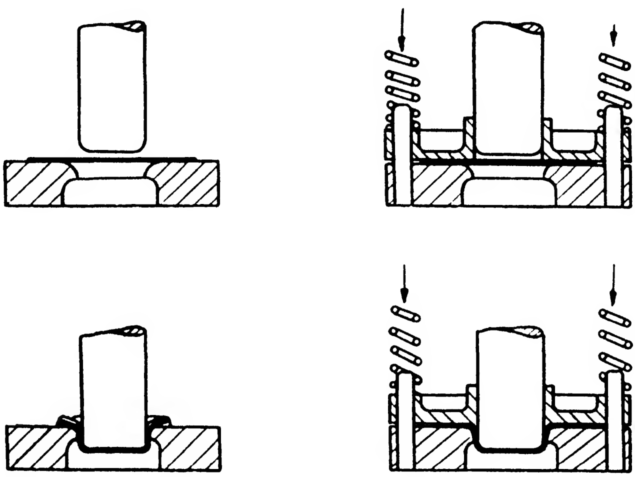


FIG. 77. Diagram illustrating form and action of pressure-plate used to prevent the formation of wrinkles during the drawing of a cup from a thin blank.
Left. Without pressure-plate.
Right. With spring-loaded pressure-plate.

the deepening cup sufficiently severely to exceed the tensile strength of the metal and thus to produce rupture. On the other hand it is desirable to use, if other conditions allow, a pressure sufficient to prevent the formation of even small wrinkles because, once formed, they will often grow in size by forcing the pressure-plate upwards. In a later chapter there is described a scheme—which as far as the author is aware is novel—for preventing wrinkling by means of a pressure-plate, *not* controlled by spring pressure, which maintains a predetermined clearance-space in which the blank moves. Such an arrangement would eliminate the possibility of failure due to excessive pressure-plate loading.

When non-circular shapes have to be drawn, the problem of wrinkling becomes far more acute. In rectangular articles wrinkling near the corners is frequently unavoidable ; but, if it can be restricted to a stage and size such that it remains confined to that part of the blank which is finally sheared off, it may not be seriously detrimental. Judicious adjustment of the clearance between certain areas of the surfaces of die and punch, and also die and pressure-plate, can assist in the control of wrinkling, and other difficulties, at the corners of rectangular-shaped articles. Even on articles of simple and symmetrical shape it may be desirable slightly to taper the top surface of the die to allow for the thickening of the blank as it approaches the drawing radius.

Although the formation of wrinkles must be attributed to mechanical action, experience shows that, in a given set of tools, blanks of the same size and thickness, but of different metals, will exhibit a different susceptibility to wrinkle. The reason for this is not yet established clearly, but it is likely that—as with puckering, the next defect to be examined—the natural rate of work-hardening, the hardness and perhaps the crystal size of any metal blank are factors of importance. In general those metals, for example aluminium, which exhibit a proneness to pucker are also unusually liable to wrinkle badly.

The degree of " directionality " manifested by any blank of given metal is another factor which affects wrinkling. If, in any given operation which does not normally lead to the formation of serious wrinkling in blanks of a certain metal, there are introduced blanks of the same metal, thickness and hardness but having unusually pronounced directional properties, local wrinkling may occur in certain areas. A rather interesting example of how the presence of an unusual —although by no means pronounced—degree of directionality can influence the flow of such a blank in an operation in which trouble is not usually experienced is illustrated in Fig. 79, which shows a circular cup drawn from a circular brass blank. When in an earlier section the formation of " ears " was being considered, it was pointed out that in brass sheet the directions of minimum ductility nearly always lie at 45 degrees to that of rolling. In the cup shown in Fig. 79 directionality has manifested itself in the formation of ears in one of these 45-degree directions and in areas of local wrinkling in the other ; an interesting though unusual effect. In this circular cup the stresses act in a uniform manner, but it will be readily appreciated that in blanks and shells of unsymmetrical shape the effect of localised wrinkling or ear formation due to the inherent directional properties of the sheet may be accentuated by non-uniform stressing. How this accentuation is brought about can be visualised if the wrinkles depicted in Fig. 76 are examined. Wrinkling attributable to directionality in the original sheet can prove a very troublesome defect because ordinary remedies, for example increasing the loading on the pressure-plate, cannot always be used to overcome it.

The properties of the lubricant used have a distinct influence upon

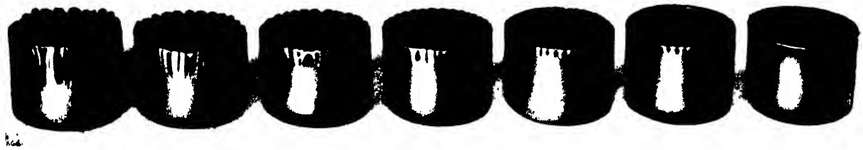


FIG. 78. Influence of blank-holder pressure on wrinkle formation. The number represents the load in pounds applied to the blank-holder during the drawing of the respective cups. [*Sachs.*

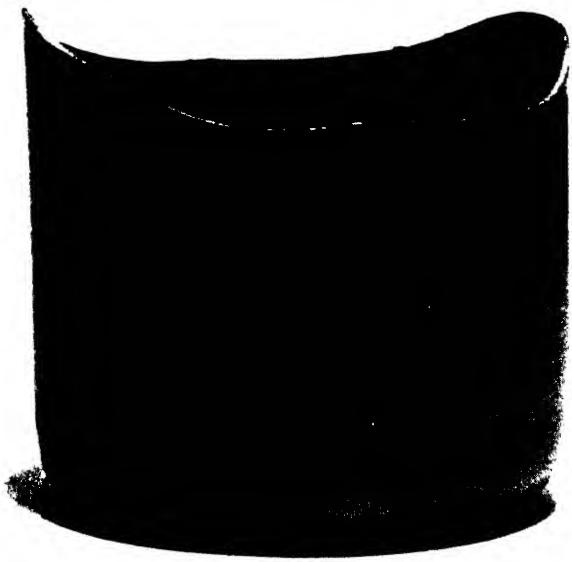


FIG. 79. Uneven flow in drawn cup due to inherent directional properties in brass sheet. Ears have formed on one, and wrinkles on the other, 45-degree plane relative to the direction of rolling, which is indicated by the black line.

[*To face p.* 108.

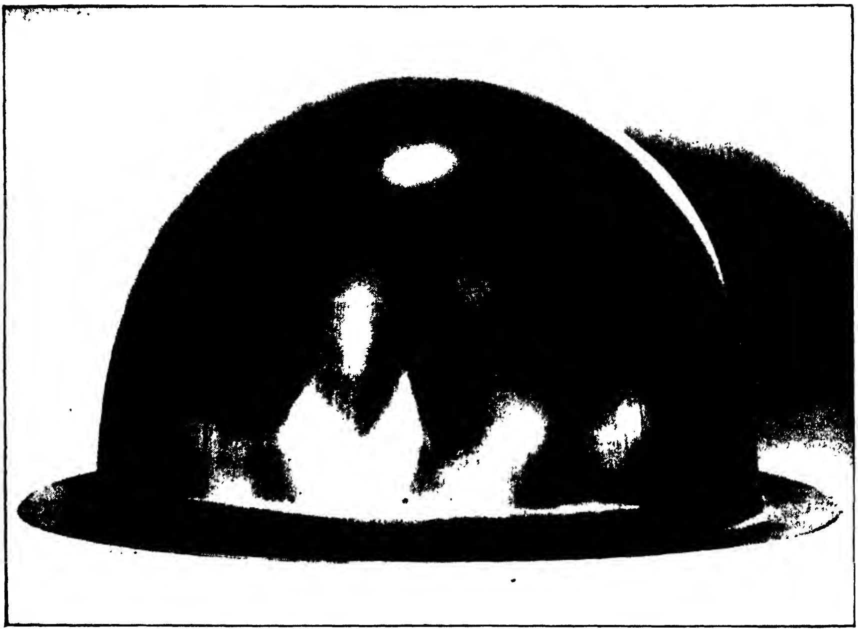


Fig. 80. Puckers in steel shell.

[*To face p.* 109.

wrinkling in an indirect way. It has been pointed out that, in general, the more heavily loaded is the pressure-plate the less is the likelihood of wrinkles being formed. Clearly, the loading which can be imposed without causing the wall of a shape to break will be determined in some degree by the efficiency of the lubricant, because a poor lubricant will increase the " drag " on that part of the blank which is gripped under the pressure-plate. When, therefore, conditions are such that the heaviest possible loading of the pressure-plate is desired, it is advisable to reduce friction as much as possible by using a " slippery " lubricant so long as, for reasons explained later, this does not lead to the production of puckers.

It is of interest to mention that although wrinkling usually has to be classed as a defect, it can sometimes be utilised to advantage because of its surprising regularity in blanks which do not possess pronounced directional tendencies. The most familiar example of the utilisation of wrinkling is perhaps to be found in the " Crown " metal-backed cork seals with which many kinds of bottles are now sealed. Another is provided by cheap ash-trays in which the natural tendency shown by the metal blank to wrinkle is allowed full play to give to the periphery of the tray a " crinkled " effect which is deemed more pleasing than a flat, even edge.

Puckering. Puckering is the name given to a corrugated or wave-like formation in that part of the wall of a drawn shape which has passed over the radius of the die ; wrinkling, as has just been explained, being the term restricted to the formation of corrugations in that part of the blank which has *not* yet passed over this radius. A typical example of puckers in the wall of a nearly hemispherical steel shell is shown in Fig. 80. It can be seen that this effect, which is attributable to the action of compressive stresses (portion B in Fig. 76, p. 106) can easily render an article worthless if, as often happens, its walls are required to be smooth and of regular contour.

Puckering is influenced by a number of factors, the most important being certain obscure natural properties of the metal being drawn, as well as its hardness and its crystal size ; the " slipperiness " of the lubricant used ; the radius of the drawing die ; the size and thickness of the blank and, of course, the shape of the article itself.

Having regard to the conditions which produce puckering, it might be imagined that the severity of this defect would be determined by the shape of the article and tools rather than by any inherent property of the sheet being drawn. This assumption is far from true. In practice it is found that, other conditions being equal, the proneness to pucker which is exhibited by different metals varies considerably ; for example, aluminium and zinc will pucker badly under conditions which do not produce this defect in brass and steel. The precise physical properties of metal which determine its natural tendency to pucker do not as yet seem to have been established, but the increasing attention which is being given to the study of deep-drawing properties by special tests and by examination of various forms of stress-strain curves may yield some clue to their nature. It is likely that rate of work-hardening will prove to be the factor of greatest importance.

Apart from what has been termed the natural tendency of a metal to pucker, the hardness and crystal size of any particular sheet of given metal will have some bearing upon its behaviour in a given set of tools. An illustration of this is provided by the brass shell shown in Fig. 81, which was produced regularly in sheet of normal quality without the formation of puckers. When, due to over-annealing, a batch of shells was produced which had an unusually large crystal size, the puckers shown in the photograph were formed, even though no alteration to tools or lubricant had been made.

The " slipperiness " of the lubricant used has a marked influence upon the tendency of a blank to pucker. If, in a regular production draw in which no trouble due to puckering is experienced normally, a change is made to a lubricant which reduces the friction of the blank as it passes over the radius of the die, quite often serious puckering will occur. This is doubly unfortunate because it often leads to the abandonment, after brief trial, of a lubricant which, considered from other aspects, is markedly better than the one used normally.

The influence of the radius of the die is complicated by the fact that two opposing factors are at work. The larger the radius the less the friction but, on the other hand, the less the work-hardening—due to bending—which the metal receives. As a rule the first-mentioned factor is the more important and, therefore, the larger the radius of the die the greater the likelihood of puckering ; but this statement may not be true in all instances.

The influence of the shape of the article will be readily appreciated : when, in articles of irregular shape, the flow of the metal tends to cause severe compressive stresses in certain regions of the walls, there will, clearly, be an added inducement to pucker in these regions. If a circular article, in which the flow of metal is uniform, is of such a shape that the compressive stresses in any zone are greater than the tensile stresses, there will exist a tendency to pucker ; whether or not this tendency manifests itself will depend upon other contributory factors, particularly the thickness of the blank and the natural properties of the metal. Often only a slight change in the shape of an article will exert a marked influence on its tendency to pucker. For example, a circular flat-bottomed cup or tray of diameter large in relation to its depth can be drawn even in aluminium without any sign of a pucker ; yet, if the bottom be made slightly domed, a region of puckering will often occur. In shells of roughly hemispherical or parabolic contour slight changes in shape may either cause or eliminate puckers, apart

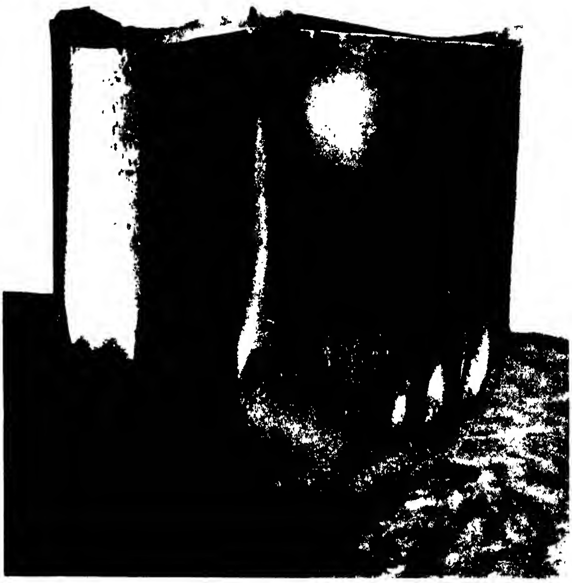


FIG. 81. Puckers in shell drawn from over-annealed brass.

[To face p. 110.

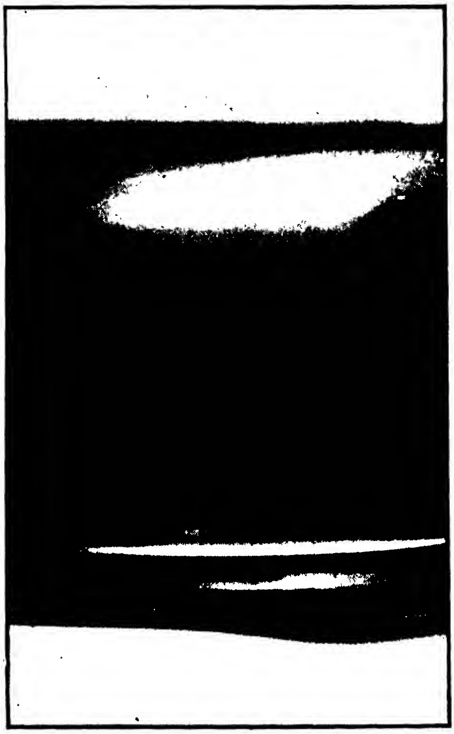


FIG. 82. Mild scoring on wall of steel cup caused by action of abrasive particles.

[*To face p.* 111.

from any influence exerted by changes in the radius of the die or in the pressure-plate loading.

Lastly, there has to be considered the influence of directionality. If the physical properties of a blank vary in different directions, so also will the tendency of that blank to pucker. In this sense puckering below the radius of the die corresponds to the formation of ears above this radius, a matter which has been discussed earlier.

With certain soft metals which are unusually prone to wrinkle and to pucker—for example aluminium—it is sometimes possible to remove puckers and residual wrinkles from the wanted part of an article by a drop-stamping operation between suitably shaped dies, a procedure which will be described in greater detail in a subsequent chapter.

To summarise, the defects of wrinkling and puckering, although controllable by tool design, are to some extent dependent upon certain natural and as yet incompletely understood properties of any particular metal, and also upon its hardness, crystal size and the severity of its "directionality." Puckering, like wrinkling, can only be avoided by careful tool design arrived at through long practical experience assisted by what little help present metallurgical knowledge can give. It can sometimes be minimised by increasing the load on the pressure-plate, because this has the effect of restricting the flow of metal over the radius of the die and thus producing tensile stresses in the wall of the shell to counteract the existing compressive stresses which cause puckering.

In general, other conditions remaining the same, an *increase* in the radius of the die will lessen the tendency to *wrinkle*, and a *decrease* in this radius will lessen the tendency to *pucker;* so that a compromise usually has to be made. A practical difficulty associated with the use of an unusually small radius is that "draw-marks," scoring and fouling tend to be accentuated.

Scoring. Scoring, which must be distinguished from fouling, implies the formation upon the surface of drawn work of grooves or score-marks during its passage over and through the drawing die. The seriousness of this defect is dependent upon the depth of the scores and upon the nature of the article being drawn ; scores which would be too deep to polish out prior to plating may be of small consequence on constructional parts on which a smooth surface of good appearance is sometimes of relatively small importance. Fig. 82 shows a portion of the wall of a deep-drawn cup bearing scores which, although of small detriment on this particular article, would be difficult and expensive to polish out had a plated finish been called for.

Scoring in the true meaning of the term is usually due to one of three causes : surface irregularities on the surfaces of the tools ; foreign particles embedded in the surface of the tools or the work and, thirdly, casual particles borne by work, lubricant, operators' hands or atmosphere.

Surface irregularities on the tool surfaces may have their origin in previous scoring or loading, the effects of which have been neglected or incompletely effaced. Sometimes marks are caused by careless handling during the transport and setting of the tools ; they can also be caused by maltreatment during normal production use by the insertion of two blanks at a time or of a blank having some piece of metal, swarf or other substance adhering to it. Having regard to the great importance of preserving the best possible surface on the working areas of drawing tools, the entire lack of enthusiasm usually shown by both operators and superintendents in attempting to ensure the desired end is a continual source of surprise to the detached observer.

Foreign particles embedded in hard steel tools are usually of a non-metallic abrasive nature ; if relatively soft tools are used, particles of swarf may be forced into the tool surfaces and, being severely work-hardened, will readily score the softer sheet being drawn. The action of an abrasive particle will be to produce a clean-cut score of uniform size, whereas that of a particle of embedded swarf will be to produce a less uniform, roughened score more like those attributable to fouling and galling, defects which will be considered in the next section.

Foreign particles embedded in the surface of the *metal* to be drawn are, perhaps, a more common source of trouble than ones embedded in the surfaces of the *tools*. They are doubly dangerous because they may be transferred to the tools either to remain on them for a short time or else to become embedded permanently in them. Particles of non-metallic abrasives in all metals, and of steel in brass and aluminium, are common examples ; yet the author has come across such unexpected examples as particles of chilled-iron shot. Naturally, the softer the metal the more readily and deeply it will score. A far higher standard of shop cleanliness is necessary when soft metals, such as aluminium, are being drawn than when steel is the only sheet used.

A cause of scoring which merits separate mention is a coating of oxide on the surface of purchased sheet or produced during the inter-stage annealing of shapes drawn from what originally was clean sheet. Surface oxide on steel can produce extensive scoring of work by direct action ; also, which is much more serious, in time it may produce very severe scoring and general attrition of the tools with the result illustrated in Figs. 71 and 72 (p. 100).

A somewhat different form of scoring, characterised more by actual " picking up " of the metal than by isolated cleanly-cut grooves—although distinct grooves are often associated with it—arises from metal-to-metal contact between sheet and tools, not, as in the form illustrated in Fig. 82, from pure attrition by foreign particles or from surface defects on the tools. Fig. 84 (p. 114) shows an example of such scoring, which must be classed as a form of fouling, the next defect to be considered.

The opinion of practical workers is not wholly in agreement as to whether relatively soft or very hard tools are more prone to score; because, strange as it may seem, it is a fact that instances are met with where a soft die does prove less liable to develop scores than does a very hard one. A point of practical importance is that the ease with which scores can be polished out decreases as the hardness of the tool surface increases. The influence of die hardness and nature upon the fouling variety of scoring needs separate consideration; this matter will be discussed briefly in the section on fouling and, more fully, in Chapter X which deals with tool materials.

Speed of drawing exercises a pronounced influence upon the fouling variety of scoring; when, under a given set of conditions, this defect causes trouble, an appreciable reduction in the speed of drawing may prove a partial, or even completely effective, remedy.

To summarise, the avoidance of genuine scoring can best be attempted by the maintenance of a high standard of cleanliness of work, tools and lubricant; the fouling type of scoring can be minimised by the use of the most suitable of available lubricants, by the avoidance of localised areas of very high pressure such as often occur at the corners of rectangular-shaped articles and, to an appreciable degree, by chromium-plating steel tools, although even this remedy may prove inadequate on local areas of very high contact pressure.

Fouling and Loading. "Fouling," or as it is sometimes termed "galling," can be a most troublesome defect which, as its name implies, arises from the intimate union of work and tools.

Fouling is usually accompanied by "loading" of the tools, the term used to indicate the actual welding to the surface of the tools of particles of the metal being drawn. Fig. 83 shows a typical example of loading on the surface of a drawing die used both to draw and to "iron" steel sheet. The actual tool illustrated is of plain carbon tool steel hardened to approximately C64 Rockwell. It will be seen that loading has been confined to the lower part of the walls of the die, where lubrication tends to be poorest.

When a tool becomes loaded it is necessary to interrupt production to repolish the affected areas, a matter of considerable expense. For this reason alone every possible precaution should be taken to avoid the occurrence of loading, yet there exists the added danger that permanent damage may be inflicted on the tool if the loaded areas are completely polished out. If they are not removed completely, the tendency to load will be heightened because traces of the soft, loaded metal will remain and will readily unite with the drawn sheet when operations are resumed.

It should be borne in mind that, once the tools have become loaded or scored, fouling tends to become cumulative for two reasons: the metal will be far more likely to adhere to the loaded areas—which are, of course, nothing less than detached particles of the metal itself which have become welded to the surface of the tool—than to the far harder surface of the tool proper ; secondly, irregularities on the tool surface, whether these be scores or loaded zones, will help to break the film of lubricant which should separate the work from the tool, and thus increase the tendency to score, foul and load. For this reason, once a tool has become loaded it is best to rectify the damage as soon as possible and not to attempt to continue production with the ever-present danger of scoring and fouling.

Turning from the effect on the tools of the defect known as fouling to its effect on the metal being drawn, the alternative term " galling " describes most graphically the appearance of the surface of damaged work. Sometimes this defect resembles in appearance very bad scoring ; indeed it is difficult to say where scoring ends and fouling starts, for the two are closely allied in both cause and effect. A typical example of this border-land condition, produced in this instance through the entire inability of the particular lubricant used to prevent almost general metal-to-metal contact, is shown in Fig. 84. When more pronounced, fouling will be manifested as deep scores often of considerable depth and width and terminating in characteristic scabs.

The defects of fouling and loading are influenced by many factors of which the most important are the severity of the contact pressure with which the metal bears upon the surface of the tools ; the efficiency of the lubricant ; the hardness and smoothness of the tools ; the size and nature of any abrasive particles which cause localised rupture of the lubricating film ; the speed of drawing and, of considerable importance, that indefinable property sometimes termed the " nature " of the metal being drawn and the metal used for the tools. This imposing list explains in part why fouling is often regarded as a mysterious defect which may or may not occur and about which little can be done by way of remedy. Much practical and valuable information undoubtedly exists in industry but, as little sifted and collected knowledge is available, it will be useful to examine in order the influence of the seven separate factors just enumerated.

The severity of the contact pressure between work and tools is, clearly, the primary condition which will determine whether fouling will or will not occur in any given operation. Under practical conditions an unlubricated sheet will not foul even soft and indifferently-polished tools if it is not pressed against them with sufficient force. Whatever special or contributory causes may exist, the primary factor will, therefore, be the magnitude of the loading. This deduction is confirmed by practical experience which shows that, with any given combination of metals for sheet and tool, the tendency to foul will increase with the severity of the draw, particularly when pressures are severely localised. It is well to bear this possibly obvious fact in mind because, notwith-

FIG. 83. A typical example of "loading" on a hardened steel die used for drawing and "ironing" a steel cup. The "loaded" areas are confined to the lower part of the throat where lubrication tends to be worst.

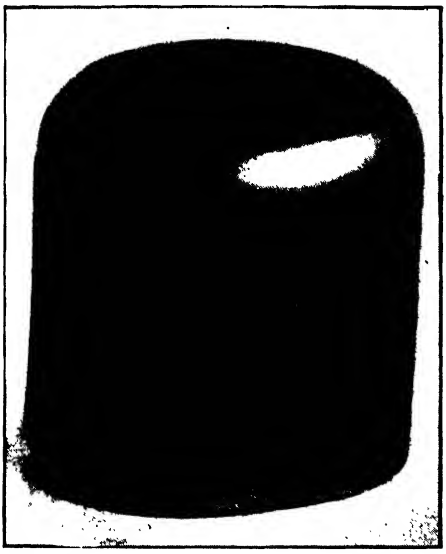


FIG. 84. Severe scoring, bordering on "galling," on walls of steel cup caused by inadequate lubrication.

[*To face p.* 114.

standing the importance of other factors, the surest way to avoid fouling is to avoid the occurrence of regions of high contact pressure. When, owing to the design of the tools and the severity of the attempted deformation, high contact pressures cannot be avoided, greater attention must be paid to minimising the other conditions which tend to aggravate the defects of fouling and loading.

Fouling cannot take place while a continuous film of lubricant separates work and tools. The replacement of any lubricant by one having a higher film strength, whether this be a true film strength or one produced artificially by means of a solid "filler," will often overcome fouling if conditions are not too severe. As the subject of lubricants is discussed fully in Chapter XI, elaboration is unnecessary here.

The condition of the tool surfaces is a factor of great importance. The better the polish the less will be the likelihood of the lubricating film being ruptured locally—even momentarily—through highly concentrated pressure or heat at the summits of the ridges or pimples which form any ordinary metal surface. Quite often the giving—and careful maintenance—of a better polish to tools which tend to foul in a certain operation will overcome this defect without further alterations; proof of this statement will be offered later.

The hardness, as distinct from the smoothness, of the tool surfaces is also of importance. In general the harder the tools the less likely they will be to foul. This can be demonstrated with plain carbon steels of different hardness, but caution is necessary if this generalisation be extended to nitrided steel—still more to chromium-plated steel—because, although the apparent effect most certainly holds good, the explanation may not be attributable solely to hardness: the chemical nature of the surface of the tools may play an important part.

The action of foreign particles has already been examined in relation to scoring. Clearly, any particle which ruptures the film of lubricant even locally and momentarily will, by this action, greatly increase the likelihood of fouling.

Speed of drawing is a most important factor. Its influence is caused not by an increase in contact pressure but by an increase in the *temperature* attained momentarily by the peaks of the surface irregularities of work and tools. If the speed of drawing is slow the heat generated at these peaks has a chance to become dissipated; whereas if the speed is high the temperatures at the extreme surface of metals sliding one upon another may rise momentarily to a temperature as high as 1,000° C., or to the melting point of the metal if this be lower: a striking and very important fact which has been demonstrated very prettily by Bowden and Ridler [7]. This marked increase in temperature, although highly localised, increases the likelihood of fouling for two reasons: the film strength of the lubricant in the immediate vicinity of these areas of extreme temperature is reduced very greatly, if not destroyed entirely, and, secondly, the activity of the molecules of the metal is greatly increased, thus heightening the likelihood of welding or of chemical union between the surfaces in contact.

Another effect of a high speed of drawing is that, with lubricants of normal viscosity, a film of lubricant may not be able to spread with sufficient rapidity to heal local ruptures or even to follow the metal as it moves. From all aspects, therefore, a high speed of drawing appears to increase the danger of fouling and loading.

The last of the factors to be considered in relation to fouling is the inherent " nature " of the contacting metals. Expressed more precisely, this influence can be divided into two : first, the natural activity of the surface molecules of any metal and, secondly, the natural affinity of the molecules of any two metals one for another. It is envisaged that the activity of a metal surface is determined at least in part by the condition of the unsatisfied atomic linkages of the outermost layer of molecules. A chromium surface, whose peculiar " slippery " nature and very low tendency to foul is of such value in industry, is believed to possess this virtue because its unsatisfied atomic linkages curve over and unite with adjacent ones instead of remaining upstanding, free and ready to unite with those of an adjacent surface. It is possible that some comparable but less marked effect explains the decreasing tendency to foul exhibited by steel as its hardness increases, but present knowledge concerning the nature of metal surfaces is still far from complete.

The different degree of chemical affinity which different metals have one for another is seemingly capable of explanation on the grounds of ordinary chemistry. Brownsdon[10] has studied the apparent practical affinity of various metals under certain controlled though somewhat empirical conditions, and has published records of an interesting series of experiments to measure, among other things, the relative tendency of a revolving disc of hardened, plain carbon steel to foul, or rather to load, when test pieces of various metals, lubricated with a very large number of different lubricants, were pressed against it under known conditions.

It is particularly interesting to observe that Brownsdon's experiments show that the tendency of the hardened steel disc to " load " decreases as its surface is smoothed with emery of increasing fineness and finally polished ; also, that the wear on the test pieces decreases markedly if the surface of the wheel is continually dressed to remove any trace of loading long before this becomes visible to the eye. These laboratory observations afford striking proof of the importance of two of the factors already isolated through practical shop experience, namely, the benefit of the smoothest possible tool surface and of removing any trace of loading as soon as this becomes visible—or, as it now seems, even before it becomes visible—to the eye.

As a result of these experiments and of his observations in the press-shop Brownsdon [11] arranges metals in the following order with respect to their proneness to foul steel tools, the first being the worst: cupro-nickel, aluminium-bronze, copper, nickel-silver, brass. Adding to this list, the author would place aluminium near to aluminium-bronze, and steel and austenitic steel between nickel-silver and brass.

The order just suggested often needs to be modified under industrial press-shop conditions because, as was stated at the beginning of this section, the primary factor in determining whether or not fouling will take place is the severity of the contact pressure. Some metals need greater force than others to deform them a given amount; the contact pressure with these will be higher than with metals which are softer or have a lower rate of work-hardening. Aluminium, although soft, readily fouls steel tools and, under industrial conditions, must be accounted one of the most troublesome metals as regards its liability to foul.

Leaving the established fact of the natural chemical affinity of certain metals one for another, mention must be made of an interesting hypothesis advanced [12] to explain on more mechanical grounds the varying tendencies which different metals exhibit with respect to fouling. Careful microscopical examination of the surface layers of nickel-silver alloys severely cold-worked by rolling and also by deep-drawing reveals the existence of minute fissures. It is suggested that the formation of these fissures while deformation is actually taking place exposes tiny areas of chemically-clean metal which will be unusually ready to unite with the surface of the tool against which they are forced so quickly that a film of lubricant has not time to penetrate and hinder intimate union. How far this explanation suffices to account for the known proneness of nickel-silver alloys to foul, and whether corresponding minute surface fissures are formed during the cold-working of other metals, remains to be established; but the hypothesis is of undoubted interest.

Still another factor contributory to fouling needs to be considered. It has been observed that the tendency of some metals to foul and to load the surface of tools is considerably heightened if drawing is carried out immediately after pickling. This is, of course, perfectly logical, for the formation of a thin and often invisible film of oxide on a chemically-clean metal surface provides a useful hindrance to the attainment of the actual molecular contact between work and tools which, under suitable conditions of temperature and pressure, is necessary for, and productive of, fouling.

A similar increased tendency to foul is sometimes observed with metal which has been bright-annealed in a controlled-atmosphere furnace, and this has been held to be a serious drawback to the use of such furnaces, notwithstanding their advantages, for the inter-stage annealing of deep-drawn or pressed articles. The explanation is the same as for recently-pickled metal : its surface is free from—or, more often, bears an unusually thin film of—oxide. In a later chapter it will be explained how by careful control of the furnace atmosphere it is sometimes possible to avoid this condition, often without serious practical detriment to the appearance of the surface of the annealed work.

No apology is offered for having devoted so much space to a consideration of the factors which influence fouling and loading, because these two associated defects can at times be very troublesome ; and this makes it all the more regrettable that a certain amount of mystery has become attached to their cause and remedy. It must be conceded that the all-important matters of the actual mechanism of lubricant breakdown and the slippery " nature " of various metals are extremely complicated and not wholly understood ; yet, fundamentally, fouling is nothing more than the " seizing " or welding together of the tool and the work at local areas of high pressure. To avoid seizing it is necessary, therefore, to prevent such intimate contact by reducing the pressure at the affected areas, by substituting a lubricant of higher film strength, or by reducing the temperature attained locally at the surface of the work by reducing the speed of drawing. Certain metals are, admittedly, more prone to seize together than others ; but, with any combination, the remedies are those just enumerated and are free from mystery, if not always conveniently and quickly applied in shop practice. The production and maintenance of as smooth a polish as possible on the die will, given proper lubrication, always reduce the tendency to foul. The chromium-plating of steel tools is frequently a most valuable remedy.

Miscellaneous Defects and Difficulties

Of the numerous causes of defects and difficulties encountered in the press-shop there have now been considered those inherent in the purchased metal and those which rightly should be, but are not always, attributed to the demands made upon it by users either by reason of the design of the article or the treatment accorded to the metal under the press. There remains still another group, namely, causes which do not come under these headings, such as inter-stage annealing ; pickling ; stains, spots and specks ; and polishing.

Troubles attributable to Unsatisfactory Inter-stage Annealing. When metal is cold-worked it work-hardens at a rate and to a degree determined by its nature. During the deep drawing of many articles a stage is arrived at when the metal has work-hardened to such an extent that its ductility becomes inadequate and must be restored by the familiar process of annealing before further press operations can be carried out.

Annealing, the name given to the operation in which cold-worked metal is heated to a temperature such that all or most of the effects of previous cold-working are eliminated—a condition which usually implies recrystallisation—is, in theory, simple. Unfortunately, the conditions needed to restore ductility without impairing the quality of the metal—for example by increasing the size of its crystals—are often relatively critical, and it can be said without exaggeration that, as in the past so occasionally at the present time, unsatisfactory inter-stage annealing is responsible for more trouble in the press-shop than any other cause.

It is indeed strange that after spending perhaps hundreds of pounds on a set of tools and installing these in the most modern press available, users of sheet steel have continued persistently to spoil their work by failing to grasp the fact—so obvious to those having any metallurgical knowledge—that " annealing " means something more than packing articles for an indefinite period into a furnace heated to an uncertain temperature and often having an atmosphere calculated to cause quite unnecessary damage to the surface of the work.

Using furnaces of what must now be regarded as of obsolete design, the user was, it must be admitted, usually unable to obtain a reasonable degree of temperature control, even if he recognised its desirability. Pyrometers, although available and fitted as a matter of course to new furnaces, were seldom added to old furnaces and, if they were, one stem was deemed sufficient, even though this was high up in the roof and in actual fact gave little indication of the true temperature of articles in all, if indeed in any, parts of the furnace. It was a popular practice to connect these lone pyrometers to an instrument placed in some high official's office where, when its novelty had paled, attractive calendars soon concealed the less appealing dial or recording chart. Actually this was of less consequence than might be imagined, for the high official was often ignorant both of the correct temperature to be maintained and also of the difference existing between the indicated temperature and that of the work itself.

Many readers, while admitting that these allegations were correct a few years ago, will protest that they are now untrue. The author ventures to describe the following two recent experiences to show that, even in this age of advertised " scientific control," persons responsible for the control of annealing of deep-drawn work on a large scale are not always familiar with even the first principles of such operations. In one instance a responsible works manager, engaged in rearranging the lay-out of certain press-shops, planned to use an existing and quite excellent furnace for inter-stage annealing. It was pointed out to him that this particular furnace would not operate at the necessary temperature, whereupon he conceived the idea of halving the temperature and doubling the time for the proposed annealing schedule, and needed considerable persuasion to deter him from putting this ingenious notion into execution ! In the other instance, an operator having no experience whatever of annealing was placed in charge of several furnaces engaged in the continuous annealing of drawn work. Becoming imbued with the spirit of modern production, on his third day he attempted to increase the output of his plant by the simple expedient of increasing the annealing temperature by some 300° C., with results which are best left to the imagination. The operator could not be blamed for his ignorance: the fault lay with those who allotted him his task.

Turning to the actual effects produced by unsatisfactory inter-stage annealing, these are five in number, namely, inadequate restoration of ductility due to annealing at too low a temperature or for too short a time; excessive crystal growth due to annealing at too high a temperature or for too long a time, a condition which includes too slow cooling after otherwise satisfactory treatment; cracking due to too rapid heating; the production of oxide scale on the surface of the work and, lastly, injury to the metal by the action of reducing gases which may produce blisters or inter-crystalline embrittlement. The defect of abnormal crystal growth arising from the existence of regions of "critical strain" in the articles to be annealed must be attributed to a natural property of the metal rather than to unsatisfactory annealing, and it will be discussed separately, although the method of annealing will influence the severity of this defect.

Under-annealing. Under-annealing hardly calls for comment. Obviously, if the combination of time and temperature is insufficient, the full measure of ductility will not be restored to a cold-worked article, which will break under the press before the usual number of subsequent draws have been accomplished. By comparison with over-annealing, under-annealing is a comparatively rare happening, but the increasing modern tendency to use relatively short-time annealing treatments in continuous furnaces has tended to heighten the probability of its occurrence unless close control of annealing conditions is maintained.

Over-annealing. Over-annealing, which implies the use of too high a temperature or holding work at a normally satisfactory temperature for too long a time, is, as has already been said, a common defect of the past and one which is by no means unknown at the present time. The principal effect of over-annealing is to cause the crystals of a metal to grow to an undesirably large size. This may cause two things to happen: the metal may fail under the press owing to its unusually low tenacity or, should the desired draws be accomplished without actual failure, the surface of the drawn article may be so rough that its appearance is spoilt and, when the surface has to be plated, the normal cost of polishing will be increased several times. Fig. 85 shows the same area on two pressings made in the same tools from blanks cut from the same piece of brass. During the necessary inter-stage annealing operation

FIG. 85. Illustrating the influence of crystal size on the appearance of the surface of a drawn brass shell.

Top : Shell re-drawn after proper annealing has produced a normal crystal size.

Bottom : A similar shell re-drawn in the same tools after over-annealing has produced an unusually large crystal size.

[*To face p.* 120.

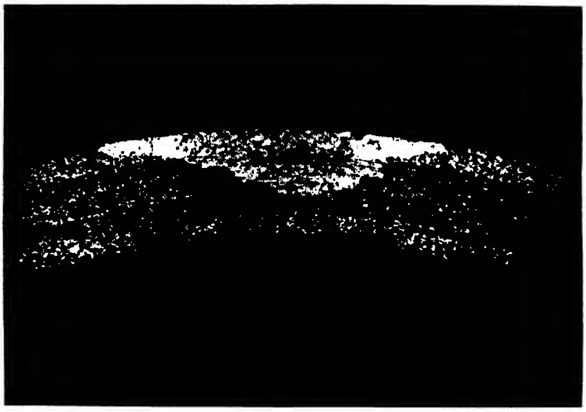


FIG. 86. Section through wall of annealed steel pressing showing sharply defined zone of critical-strain crystal growth on tension side of bend. × 8.

FIG. 87. Typical examples of abnormal crystal growth in aluminium bronze containing 8 per cent. aluminium.

Microsections cut normal to surface of sheet. × 100.

[*To face p.* 121.

one has been annealed satisfactorily and the other has been purposely over-annealed. The difference in the condition of the surface is evident even in the photograph, which gives little idea of the difference in the time needed to polish these two articles.

The cause, as distinct from the effect, of both under-annealing and over-annealing is explained by the very names given to these conditions. As in many other operations which have to be carried out in the press-shop, their remedy is often difficult if modern furnaces and methods of temperature control are unavailable. When, as is still done in older plants, a large muffle or pan is filled with work, it is quite possible for a proportion of the charge to be under-annealed and a portion to be over-annealed. This condition can be brought about by two causes : variation in the prevailing temperature of the muffle from place to place, and the longer time taken by the centre of a bulky charge to reach the maximum temperature.

It cannot be emphasised too strongly that a pyrometer which indicates the correct annealing temperature for certain work is seldom a guarantee that all, if indeed any, of a furnace charge is reaching the desired temperature. This misapprehension may explain in part the distrust which experienced annealers of the old school show for pyrometers ; unfortunately the new school tends to rely wholly on pyrometers and does not acquire the ability to " sense " the temperature, and uniformity of temperature, of a furnace charge.

A pyrometer shows the temperature attained by the end of its sheath. In still-atmosphere furnaces the sheath is often placed well away from the charge to lessen the likelihood of mechanical damage and, depending upon its position in the furnace, it may indicate a temperature considerably above or below that of the charge. Moreover, it will usually return to the working temperature of a furnace cooled by the introduction of a fresh charge some time before the charge reaches that temperature. Clearly, except in furnaces of special design having relatively small sectional areas and containing several thermocouples, pyrometric readings should be regarded as nothing more than a guide to the repeated, regular attainment of certain *unindicated* conditions which experience has shown to be suitable for certain metals and articles. Used thus, pyrometers are of inestimable value, but the warning needs to be added that they must be checked at reasonably frequent intervals, a precaution which in the experience of the author is often omitted by reason either of ignorance or, not infrequently, sheer laziness.

Fire-cracking. Cracking due to too rapid heating of severely stressed articles—or, as it is commonly termed, " fire-cracking "—is a defect to which some metals are far more prone than others. Nickel-silver, for example, is well known for its proneness to fire-crack and, when iron contents were higher, drawn brass articles would often crack if they were thrust unwarmed into a muffle at full annealing temperature.

It is fortunate that most of the common metals used in the press-shop can be heated without the need for caution and delay. With those metals which *are* liable to fire-cracking, a simple and sometimes entirely adequate precaution is to warm work on top of the old types of annealing muffle ; with modern well-lagged electric furnaces this practice cannot be carried out, and preliminary warming in ovens may have to be resorted to unless annealing can be carried out in continuous furnaces in which the work enters the hot zone at a relatively slow rate.

Scaling. The formation of oxide and scale on the surface of work during annealing is always objectionable, and sometimes seriously harmful. If heavy scale is left on, it may score the tools used for subsequent drawing operations ; if, as is desirable, it is removed by pickling, the expense and inconvenience of this objectionable operation have to be tolerated. An example of the damage caused to tools used for drawing scaled steel sheet has already been given (Fig. 72, p. 100).

With furnaces which carry no refinements whatever to enable "clean-annealing" to be carried out in them, the degree of surface oxidation which occurs on their charges can sometimes be influenced to a considerable extent by combustion-control in gas, oil or coal-heated semi-muffle furnaces and, in true muffle furnaces, by reducing air leaks to a minimum.

The only way effectively to prevent surface oxidation is to anneal work in muffles having a controlled atmosphere or, using ordinary furnaces, to pack it in sealed boxes which may be purged with some suitable gas, as is done with steel, or packed with some substance such as charcoal, as is done with cupro-nickel alloys.

Injury by Special Action. Permanent damage may be done to some metals by the presence of reducing gases, such as hydrogen, or impurities, such as sulphur, in the furnace atmosphere. By diffusing into the metal, hydrogen may react with oxides to form steam and produce inter-crystalline fissures or, should discontinuities exist in the sheet, blisters of considerable size. Sulphur may cause staining or, which is more serious, it may actually attack the surface of the metal. Oxygen, in addition to producing a coating of oxide scale, may penetrate along the crystal boundaries and when an attempt is made to draw the annealed shell the embrittled surface layer will open up into cracks which usually lead to failure. Nickel and cupro-nickel are liable to an attack of this nature, which with these two metals was for some time believed to be caused by the action of sulphur.

The principal defects which arise from unsatisfactory inter-stage annealing have now been indicated and, again, it must be said that even to-day these particular ones are sometimes the cause of a considerable proportion of the troubles experienced in the press-shop. The methods adopted in modern annealing plant to avoid these defects as far as is possible, and also the means employed to secure " clean " if not always genuinely " bright " annealing, will be considered in a later chapter.

Abnormal Crystal Growth. With some metals it is possible for abnormal crystal growth to occur under what must be regarded as wholly satisfactory industrial annealing conditions. As a rule this occurrence is due to the phenomenon known as " critical-strain crystal growth," which means that if the crystals of some metals are strained a certain " critical "—and usually small—amount and then heated to a suitable temperature the crystals will grow, often with surprising rapidity, to an entirely abnormal size.

If, therefore, a shell is drawn from a metal which is prone to critical-strain crystal growth and given an inter-stage annealing, there is every likelihood of an abnormal crystal size being developed in those regions of the shell which have been strained within the critical range. As a result these regions will possess unusually low tenacity and fracture may take place in them when further press operations are attempted. If actual failure does not occur, the surface of the drawn or pressed article will be very rough indeed in the affected regions. Fig. 86 shows crystals of entirely abnormal size produced on the tension side of a slight bend in the wall of an annealed steel pressing.

Of the industrial metals manipulated in the press-shop, steel and aluminium are by far the most susceptible to critical-strain crystal growth, although trouble is experienced sometimes with nickel-silver and aluminium bronze. How this difficulty can be overcome—for example, by normalising instead of annealing steel and by starting with aluminium or nickel-silver sheet which has been cold-rolled to beyond the " critical " range of elongation—will be considered more fully in subsequent chapters.

Distinct from genuine critical-strain crystal growth there exists another form of abnormal growth whose cause, and hence whose remedy, is understood less clearly. Although apparently influenced by strain, this special form seems to be caused more by inherent crystal habits ; it can certainly take place in metal in which the degree of strain is far below the range usually associated with true critical-strain growth.

Aluminium bronze, copper and occasionally brass exhibit this peculiar form of crystal growth, a good example of which is given in Fig. 87. The pecularity of this second form of abnormal growth is that, unlike the first, it does not seem to be confined to regions which have suffered some critical degree of strain, and that isolated crystals of enormous size often occur instead of zones of relatively large ones.

It has been suggested that this particular form of crystal growth takes place in regions which are of unusually high chemical purity or in which, due to the existence in the sheet of distinct " directionality "—meaning preferred orientation of the crystals—certain crystallographic planes have been disposed in some particular way relative to the direction of applied stress. However, pending further investigation, the precise cause of this special kind of abnormal crystal growth is best regarded as unestablished.

Troubles due to Non-removal of Lubricant. Notwithstanding the vital necessity for adequate lubrication during actual deep drawing and pressing operations, once passage through the tools has been accomplished satisfactorily the lubricant which remains on the surface of the shaped article usually becomes annoying, and often injurious. As the important matter of lubricant removal will be discussed at some length in a subsequent chapter, it is here desired merely to call attention to several distinct troubles which may arise if lubricant is not removed from the surface of drawn work.

Adherent lubricant may cause trouble during enamelling, plating or other finishing processes if these are preceded by nothing better than ordinary cleaning operations such as swills or dips not specifically devised to remove the particular drawing lubricant used. For example, some of the " fillers " commonly embodied in drawing lubricants cannot be completely removed by merely swilling work in ordinary cleaning solutions ; trichlorethylene, particularly in vapour form, will not remove solid fillers or the soap constituents of greases, and the so-called " soluble " oils are not removed completely by swilling work in water.

Possibly the most easily understood and most widely recognised defect caused by non-removal of lubricant is the staining which is produced when certain lubricants are left in contact with work for considerable periods, or when work is annealed with lubricant adhering to it. Articles pickled, drawn and low-temperature annealed seem particularly prone to develop staining when cleaning prior to annealing is omitted. A possible explanation of this established fact is that the lubricant tends to be absorbed by the etched surface and mechanically entrapped in the pores of the metal during subsequent drawing. Fig. 88 shows a typical example of staining on brass caused by the non-removal of a complex proprietary lubricant before the shell was passed through a water-sealed muffle.

Although staining can be a serious defect, the still more serious ones of severe scoring—and occasionally actual failure—during subsequent draws must sometimes be attributed to the non-removal of lubricant. If lubricant containing a solid filler is allowed to dry on work, and in even greater degree if it is baked on as a result of annealing, the resulting dry powder may not be quickly taken into suspension by the fresh lubricant placed on the work for the next press operation. As a result, greatly increased friction is set up in the tools, which may themselves wear and roughen rapidly. This effect is increased by the tendency evinced by some fillers, originally in a very fine state of division, to coagulate into gritty particles of appreciable and injurious size.

Although not strictly within the province of the press-shop, mention must be made of troubles experienced during the spot or seam welding of pressed or deep-drawn shapes from which drawing lubricant has not been entirely removed. Difficulty is more likely to occur with lubricants containing a solid filler, such as chalk, than with un-thickened oils and emulsions, because these are squeezed out and burnt away far more readily than solids, which remain to form an insulating film. As the residual film of lubricant—whether wet, dried or baked on—will vary in thickness, it is impossible to adjust welding machines to deal with it, and proper cleaning of work prior to welding is, therefore, the only certain remedy.

Without trespassing on the more detailed study of problems associated with the removal of lubricants which is attempted in Chapter XI, it will be useful to include in this present discussion of defects a brief summary of the behaviour of the more common constituents of lubricants when left on work and passed through an annealing furnace.

Oils and greases will carbonise, but their behaviour will vary with the maximum temperature attained and the rapidity with which this temperature is reached. If the work is heated quickly to a high temperature, a thin coating of oil or grease may burn off, leaving little or no deposit; but the products of combustion may upset the balance of the atmosphere in a controlled-atmosphere furnace. At moderate temperatures, such as are used for the annealing of brass, a black deposit of carbon is usually left on the surface of the work.

Soaps leave an alkaline residue, that left by lime-base soaps tending to be white and adherent in contrast with that left by sodium-base soaps which is often more in the nature of a glazed film giving a tarnished appearance to the annealed work.

Sulphur produces severe stains on most metals, particularly on brass and copper; sometimes it impairs their physical properties, and it is always likely to injure the heating elements and conveyor belts of electrically-heated continuous furnaces.

Water evaporates, often leaving some slight stain. It will be readily appreciated that, as considerable pains often have to be taken to remove all traces of water vapour from a controlled atmosphere, the evaporation of water from the work itself may prevent this emerging in the desired bright condition.

In addition to these four substances which find their way on to the work *viâ* drawing lubricant, two others, for which the lubricant cannot be blamed, deserve mention because they can cause serious staining.

Rust on steel is usually reduced to masses of spongy, chemically clean iron. Patches of this reduced iron often lead to trouble during subsequent pickling and plating operations, due partly to electrochemical effects and partly to the difficulty of removing corrosive pickling or plating solutions from them by ordinary methods of rinsing and drying.

Corrosion products on brass, such as the green verdigris deposit which is often formed if this metal is allowed to stand for some time with lubricant on it, or even without lubricant in a moist, contaminated atmosphere, are usually baked to a deposit of copper oxide which in turn is reduced to copper, causing red stains. In addition to this, the oxygen which is given off during this change may upset the controlled atmosphere and prevent the remainder of the work from coming out bright.

Troubles attributable to Pickling. Pickling operations are seldom in themselves directly productive of trouble; yet, because they often show up more clearly an unsatisfactory surface produced by previous incorrect treatment, undeserved blame is not infrequently attached to them. For example, roughness of surface attributable to the deep drawing or pressing of metal possessed of an abnormally large crystal size is made more clearly visible, while scores, pits and other blemishes are brought more clearly into relief.

Although, in instances of extremely severe deep-drawing, previously invisible actual or incipient cracks may open up, pronounced preferential local attack on severely worked areas does not usually cause trouble unless the time of immersion in the pickling bath is prolonged unduly through forgetfulness or through attempts to remove unusually tenacious scale produced by improper annealing of sheet or partly formed pressings. Plunging articles which are in a high state of internal stress into strong acid has been known to cause them to crack; when this happens, the appearance of the cracks usually resembles that associated with "fire-cracking." The precise action of the acid in causing failure of this kind does not seem to be known; it is by no means certain that, as is imagined sometimes, its action is comparable to that of ammonia in producing season-cracking, although it has been suggested that traces of ammonia may be formed on the surface of the metal.

One serious practical difficulty encountered with some metals, particularly with austenitic steels, is the formation of a deposit of sludge on the surface of the pickled work. It is not always possible to remove this sludge by ordinary swilling and, unless high-pressure sprays are available, wiping by hand—a procedure which tends to be unreliable and demands close supervision—has to be resorted to. Should this sludge be allowed to dry and remain on the surface of inter-stage annealed and pickled articles, it will be likely to cause increased friction and even scoring of work and undue wear on the tools.

Pickling is always an objectionable operation and, unless special methods and plant are used for it, the elimination of this Cinderella of the press-shop by the installation of modern controlled-atmosphere clean-annealing furnaces is a change which can be recommended with every confidence.

Staining. Staining can generally be traced to improper maintenance of pickling solutions, to lack of cleanliness in the bath or during handling or slinging prior to or after immersion, or to inadequate drying or subsequent protection of pickled surfaces. The remedy is usually obvious although, unhappily, not always easily applied under some factory conditions and procedure. A new source of trouble has, however, arisen with the introduction of controlled-atmosphere annealing furnaces from which metal may emerge in such a chemically-clean condition that staining produced by fumes, or rusting of steel in ordinary air, may take place unless some protective covering is applied immediately.

Staining attributable to a definite chemical action, for example the " red staining " of brass, can usually be traced to contaminated or otherwise unsatisfactory pickling solutions. When the same pickling bath is used for more than one kind of metal, it sometimes happens that one of these metals becomes coated with a thin film of some other. For example, if nickel is pickled in certain baths used previously for pickling Monel metal or cupro-nickel, a coating of copper may be formed upon it. This effect can hardly be classed as genuine staining, although the practical man usually calls it such.

The most common form of staining is probably that caused by inadequate removal of drawing lubricants, a matter which has already been discussed separately. When water-sealed annealing furnaces are used, slight staining is unavoidable with many metals and will naturally be most noticeable if the annealing has been of the so-called " bright " kind. The actual film of oxide with which the surface of pseudo-" bright " annealed metal which has not passed through a water seal may be covered, perhaps in an irregular manner, is often regarded as " staining " : this appearance, which cannot be classed as true staining, has already been considered.

Staining produced by the action of lubricant or of pickling or cleaning solutions allowed to stand on work for long periods may seem too obvious a defect to justify mention, yet surprise and annoyance is often expressed when, after a period of perhaps weeks, a stack or pile of partly-drawn shapes is found to be stained if not badly corroded. Even when work is cleaned, the action of moisture and the usually contaminated atmosphere of a factory may soon cause staining and corrosion. Whenever it is necessary to store partly-drawn articles for any length of time it is, clearly, most desirable that these articles should be cleaned, in some instances—as with steel—coated at once with some protective substance, and covered up to prevent the settlement on them of particles likely to cause spots, the next defect to be considered.

Spots and Specks. In press-shop terminology "spots" and "specks" are localised surface blemishes which become visible on the surface of an article, usually during the finishing stages of its production. Any defect which renders an article worthless is, obviously, serious, but spots and specks are unusually so because, not becoming visible until the article is nearly finished, all the expense of the various operations through which it has passed have to be added to the cost of the actual metal used, while, if the articles are needed urgently, rejection in the final stages of production may cause serious complications.

Spots may be divided into three classes : those due to the presence of cavities, inclusions or discontinuities on or just below the surface of the original sheet ; those due to the presence of foreign particles which have become embedded in the surface of the metal during or after drawing and, lastly, those due to the corrosive action of particles of solid or liquid which have settled upon the surface of the article.

Cavities, inclusions, discontinuities and surface blemishes, being defects inherent in purchased metal, have already been considered. They may cause spots or specks either by reason of their unaggravated manifestation on the surface of the finish-drawn article or by reason of their ability to entrap and exude lubricant, pickling solution or moisture to produce localised areas of staining or corrosion. Defects too small to be noticed by casual inspection may become very evident in this way. In either instance their seriousness will be dependent upon the degree of excellence of surface finish demanded on the finished article. Being attributable to a defect present in the purchased metal, they cannot be guarded against in the press-shop except by subjecting the original sheet to as careful and thorough an inspection as possible before it is blanked and started on its hazardous travels through the shop.

The second cause of spots and specks, namely, foreign particles, is one which must be attributed solely to carelessness on the part of the user of sheet metal unless, as happens very occasionally, the purchased sheet contains embedded particles. Particles picked up in the press-shop are usually one of two kinds : particles of metal or particles of non-metallic abrasive. The first is picked up during the actual shaping of the metal, during storage in bins, or during transport and handling ; the second is usually picked up during rough-grinding and polishing operations but, occasionally, abrasive particles find their way on to the surface of work during annealing, storage, transport or handling. The remedy for particles picked up by the metal during grinding lies in the use of a more suitable grade of wheel or grit, or of more secure

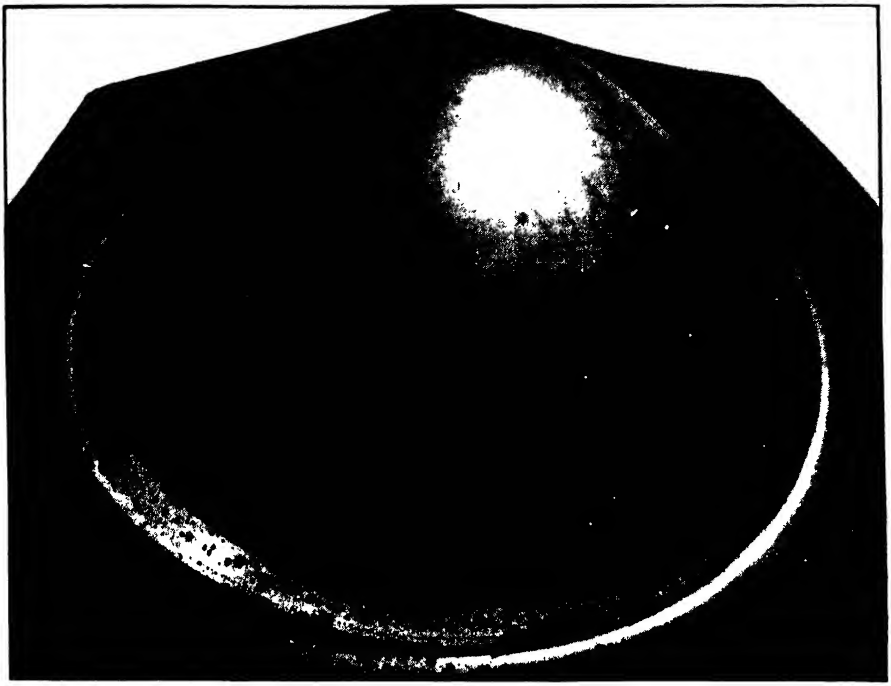


FIG. 88. Staining on brass shell due to non-removal of lubricant prior to inter-stage annealing.

FIG. 89. Characteristic markings produced by polishing a surface in which are embedded particles of abrasive. × 3.

[*To face p.* 128.

FIG. 90. Particle of steel embedded in surface of brass pressing. × 15.

FIG. 91. Hard particles embedded in surface of brass pressing. (Actual size.)

[*To face p.* 129.

bonding of home-covered bobs ; the only remedy for each and all of the other enumerated methods of acquisition is the maintenance of a higher standard of cleanliness in shops, furnaces and bins, and the better protection of work from stray particles.

Fig. 89 shows the appearance of a polished surface in which particles of abrasive detached from the wheel used for rough grinding have become embedded. The shape of the defects in this photograph is typical and explains the origin of " comet tails " and other familiar terms to describe them. The " tail " always lies in the direction of polishing, thus distinguishing this type of defect from inherent directional defects in the metal. The fact that the particle may have become dislodged when the polished surface is submitted for examination does not alter the diagnosis by experienced observers taken to task by those who, responsible for polishing, demand to be shown *carborundum* if not *concrete* proof of allegations made against them !

Turning from the special class of embedded particles formed by abrasives picked up during rough grinding to the general one, it is surprising how readily metal articles will pick up particles of grit or metal during their travel through the press-shop. Naturally this readiness is influenced to some extent by the hardness of the metal ; for this reason special care needs to be taken with aluminium articles into the surface of which all kinds of particles readily become securely embedded. Usually the embedded particle is harder than the matrix, but sometimes particles of the *same* metal become embedded, particularly when, as is the case of fragments off sheared edges, they are severely work-hardened. Steel is, perhaps, more prone to this trouble than the other common metals.

Steel particles often become embedded in the surface of non-ferrous metals. Fig. 90 shows a particle of steel which has been forced into the surface of a brass pressing. Being relatively large, this particle is clearly visible in the unpolished surface, but smaller particles often escape notice until during or after polishing. Fig. 91 shows a number of particles embedded near the lip of a drawn brass shell. The particles illustrated are of chilled iron from, it is presumed, a metallic substitute for sand used for sand-blasting, but the appearance is typical of many kinds of foreign particles.

Non-metallic particles may have their origin in the refractory linings of furnaces, in grit blown in from outside the shop or from sand-blasting plants. Occasionally the products of a baked-on drawing lubricant may behave as abrasive particles ; the author recollects one instance in which a proprietary brand of " filled " lubricant actually contained an appreciable proportion of silica, a surprising fact established quite definitely by chemical analysis.

The microscope can be of great help in determining both the nature of embedded particles and the stage at which these became embedded. Microscopical examination of a spotted surface, sometimes assisted by micro-chemical methods of analysis, will usually reveal the nature of embedded particles. When evidence is needed to show at what stage in the history of an article a particle has become embedded, a micro-section is useful. Fig. 92 shows such a section : the unmistakable evidence of work-hardening in the crystals surrounding the particle proves that it was pressed forcibly into the surface *after* the last inter-stage annealing operation. In the example illustrated, the article is of brass and the particle is chilled-iron shot as used to replace sand for sand-blasting.

The last of the three causes of spots and specks to be considered is non-embedded particles which by chemical action produce either areas of staining or corrosion cavities on the surface of the drawn article. These particles may be soot, or merely dust, which act as collectors of moisture to cause chemical attack by absorption of the impurities which are present in most works' atmospheres, for example, sulphur. The effect of actual drops of lubricant, pickling or cleaning solutions, and even water hardly calls for explanation. The only way to avoid the possible occurrence of spots and specks attributable to these causes is to clean and dry work thoroughly, and to keep it covered and in as dry a place as possible.

Readers who have found these observations tedious are reminded that, in those branches of the deep drawing and pressing industry in which a fine finish has to be imparted to work prior to plating, spots and specks may cause a serious percentage of rejections in almost the final stages of a long and costly series of production operations. Those engaged in the production of articles which need a less perfect finish have cause to congratulate themselves.

Defects attributable to Period or Conditions of Storage. In those press-shops in which that truly continuous flow of work which is the popular aim of modern production methods does not always occur, the storage of partly-drawn shapes becomes unavoidable. More often than not little attention is paid to the period, still less to the conditions, of storage; and, as a result, a number of inevitable but sometimes unforeseen troubles may arise.

Staining, Corrosion and adhering Lubricant. Attention has already been given to defects such as staining and spotting attributable to the storage of uncleaned work, and even of cleaned work should this be left unprotected from direct ingress of works' atmosphere and the particles suspended in it. A point not yet mentioned which is often lost sight of is that, if uncleaned work is allowed to stand for considerable periods, the difficulty of cleaning it is often greatly increased owing to the oxidation and " gumming " of oily residues. Even, therefore, when a visible defect such as staining does not occur, cleaning may become a needlessly

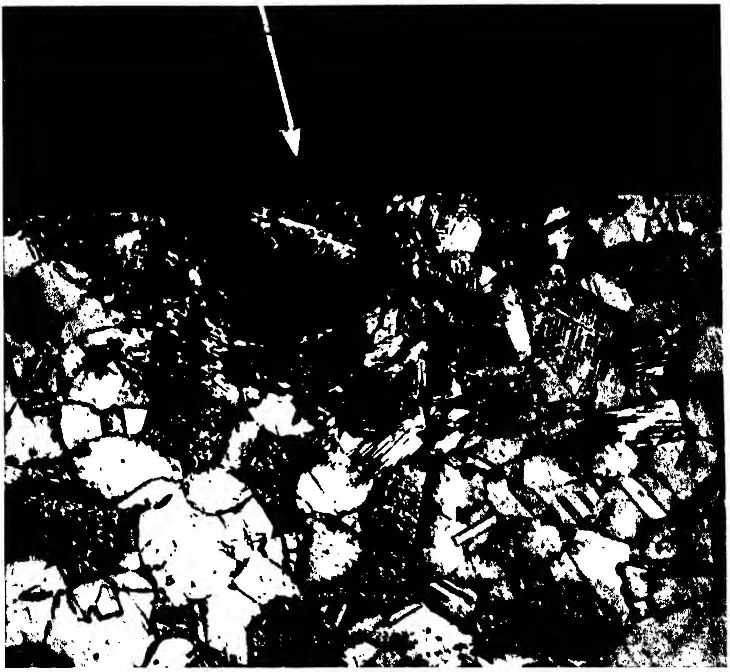


FIG. 92. Microsection cut through particle of chilled iron embedded in surface of drawn brass shell. Observe evidence of cold-work in crystals surrounding particle. × 250.

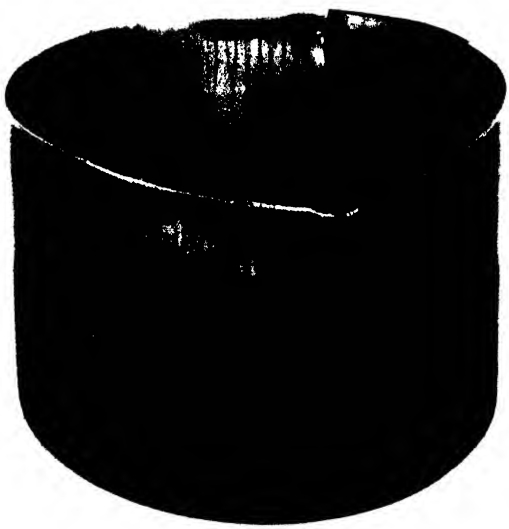


FIG. 93. Shell 8 inches diameter drawn in one operation from 18/8 austenitic steel 0·036 inch thick. The cracks appeared within half an hour of drawing.

[*To face p.* 130.

troublesome and expensive operation if uncleaned work is allowed to stand for long periods.

Stress-cracking. Should severely-drawn metal be allowed to stand before it is given a proper inter-stage anneal, or at least a low-temperature stress-relieving anneal, it will often crack. This tendency varies markedly with different metals. Austenitic steels are perhaps the most dangerous, and in some shops trouble can be prevented only by strict adherence to a rule that drawn work in this metal must be annealed within half an hour of the actual press operation. Fig. 93 shows one of a number of shells in " 18/8 " austenitic steel which, having been deep-drawn in one operation to the depth illustrated, cracked in less than an hour.

Brass, although not nearly as liable to stress-cracking as austenitic steel, is another metal which is liable to crack when left to stand in a highly-stressed condition; but it seems uncertain how far this tendency is caused by the peculiar phenomenon of season-cracking and how far it is caused by true stress-cracking.

Temperature has a marked influence upon the tendency shown by severely cold-worked brass, and by other metals, to crack during storage. During cold spells in this country it is common for whole bins of stored, cold-worked articles to crack when, under normal conditions, no such trouble is experienced. The remedy, although obvious, seldom seems to be applied; even when the need for immediate annealing is appreciated, it often happens that furnaces are not available in small plants worked to their full capacity.

Age-hardening. Another possible change to be considered is that of age-hardening. By this is meant the loss of ductility which some metals suffer if allowed to stand in a work-hardened condition. Steel is perhaps the worst offender in this respect, although the tendency varies considerably according to the variety of the steel, its chemical composition and the treatment which has been given to it. It is generally recognised that if temper-rolled steel sheet is not used within a reasonably short time of the giving of the temper-rolling operation its ductility may be found to have become seriously impaired. It is *not* recognised so widely that a similar ageing effect can occur between stages of deep drawing or pressing; and, should mysterious failures occur with originally satisfactory metal during a sequence of normally successful press operations, inquiry should always be made to find out whether the work has stood for an unusually long period between any two operations.

When metals have to be drawn in a " solution-treated " condition, the damage of too long a period of storage—which in the case of some light alloys must not exceed one hour—is soon learnt by hard experience, yet it often happens that, owing to inadequate precautions rather than to unforeseen delays, the period during which maximum ductility obtains is exceeded.

The fact needs to be borne in mind that loss of ductility due to age-hardening is *not always reflected in indentation hardness tests* which, therefore, are in themselves an entirely unreliable guide as to whether serious age-hardening has taken place.

Spontaneous Recrystallisation. Some metals are self-annealing at or near room temperature. To take an extreme example, zinc, emerging warm from the drawing tools, may in a very short time attain a crystal size so large that further drawing becomes impossible, and it becomes necessary to follow on through a sequence of press operations with a lapse of not more than a few minutes between each. This trouble is, fortunately, rare because the majority of the common metals do not recrystallise at ordinary temperatures.

Mechanical Damage. Actual mechanical damage is a trouble which is seldom given sufficient attention. This defect, which for obvious reasons is most marked with soft metals such as zinc and aluminium, can arise in two ways: the lower articles packed in a bin with reasonable care may become deformed owing to the weight of the articles above them, or, secondly, the contents of a bin may be deliberately pressed down in an attempt to secure closer packing. When the utmost is demanded of a metal, the use of deformed shells or the presence of dents in their walls may be quite sufficient to cause an increase in resistance to the smooth flow of the metal sufficiently great to produce failure. Mechanical deformation of shells may seem a trivial matter, yet upon occasion it does constitute a primary cause of failure which often escapes notice.

The infliction of scratches upon the surface of articles destined to be polished is a defect which, unlike general deformation or dents which if they do not cause failure will be obliterated during the next press operation, is usually held to be serious because it increases the time taken to polish the articles. Digressing somewhat, this illustrates a tendency in modern production which cannot fail to strike an observer as curious, namely, that any item or condition which increases the time occupied by any single operation viewed separately seems to be regarded as of much more consequence than the production of actual scrap. Attention seems to be focussed on the specious goal of so many operations per hour; the cost of a considerable percentage of scrap seldom seems to be taken into account when the efficiency of that particular operation is judged.

Troubles encountered during Polishing. Neglecting the natural behaviour of each particular metal and alloy when polished, and also the obviously detrimental influence of scores, any special difficulty in polishing is usually attributable to the existence of an undesirably coarse crystal structure in the metal. As the crystal structure of sheet metal of industrial quality has improved considerably during recent years, some explanation must be found to account for the seemingly contradictory fact that complaints from those responsible for polishing have increased in spite of continued improvement in the quality of the metal to be polished.

Several of the reasons which have already been given to explain a similar increase in other complaints apply equally well here. To mention only two, a general tendency to lower the grade of metal used for any given depth of draw and the ever-increasing severity of the draws attempted are hardly conducive to an improvement in the condition of the surface of the drawn product when it leaves the tools: it will tend to be more "open" in texture and will be more likely to exhibit scores and regions of fouling and galling.

There exists, however, another very definite cause of prevalent complaints, namely, a growing tendency to cut down polishing operations to the very minimum and certainly to a fraction of the scale used normally a few years ago. It is not uncommon for deep-drawn or pressed articles to be enamelled without any, or with only a very light, surface smoothing, or to be plated after a relatively light polishing not preceded by grinding or rough emery bobbing. In many such instances, therefore, complaints should be directed not to the quality of the sheet, but rather to the insatiable attitude of some consumers. In actual fact the surface of some high-class cold-rolled brass sheet is at the present time so good that, unless users have very carefully polished tools and excellent lubrication they are, without doubt, unable to take full advantage of its potentialities.

Mechanical polishing, which is being used more and more, brings problems of its own which are not always recognised. Although very little precise information has been published, it is becoming increasingly evident that a different crystal size is often desirable when mechanical as distinct from hand polishing is used to finish any given article, this difference being particularly noticeable with austenitic steels. Again, it has been found that to secure the best results with a given metal, a larger crystal size is advantageous when flat sheets as distinct from drawn, domed surfaces have to be polished. What proportion of this difference is due solely to the work-hardening produced by drawing is uncertain. It is always unwise to suggest that unconfirmed individual experiences are typical, but the two generalisations just instanced will serve to draw attention to the reality of the problems which are arising with the rapidly increasing use of mechanical polishing, and to the urgent need which exists for properly conducted research to elucidate them.

It is necessary to emphasise a fact which often remains unappreciated notwithstanding its apparent obviousness. During hand-polishing operators can dwell as long as they deem advisable on special areas where isolated surface defects, or unusual roughness produced by localised severe drawing, exist; with machine polishing such selective treatment is not possible. For this reason metal which, when drawn into a given article, may be perfectly satisfactory when polished by hand may be deemed unsatisfactory when the same article is polished mechanically.

Clearly, many factors ought to be taken into consideration before a decision is made to replace hand polishing by mechanical methods. Mechanical polishing followed by hand polishing can sometimes effect an economy when fully mechanical polishing is not possible or necessitates complicated machines and numerous operations.

The modern tendency to cut down polishing times and to use mechanical methods whenever possible renders it increasingly desirable to select the most suitable grade of abrasive and polishing compound for each individual operation. The study of abrasives is one which is being pursued much more seriously than of old, and readers are referred to the already considerable amount of published literature upon this subject. In spite of the genuinely altruistic insistence of makers of abrasives on the importance of using the correct grade of abrasive for any particular set of conditions, it often happens that insufficient care is still given to the selection of the best available grade and to ensure that, once chosen, the correct grades are used for each particular metal and operation where several are in use in one shop.

The object of this chapter has been to classify, discuss and when possible to illustrate many of the defects and difficulties encountered in the average press-shop. These defects and difficulties have purposely been dealt with in a general way so that, with a few unavoidable exceptions, both text and illustrations apply to most of the common industrial metals. In the next five chapters special defects and difficulties peculiar to certain metals will be studied, but readers are reminded that in these chapters the general defects and difficulties which have just been reviewed may be passed over or given but scant mention with special reference to the various metals about to be discussed. This omission does not imply that these common troubles are unimportant or not experienced with any particular metal; but, having once considered them, it would be tedious to repeat the whole classification for each metal studied separately.

CHAPTER IV

DEFECTS AND DIFFICULTIES (BRASS)

THE preceding chapter has dealt in a general way with some of the defects and difficulties which are encountered during the deep drawing and pressing of *all* kinds of sheet metal. Because the bulk of the sheet used for this purpose industrially consists of brass and steel, it is proposed to devote two chapters to a study of those defects and difficulties which are peculiar to these two metals, and to indicate in what form and to what extent some of the common defects already considered in a general way are manifested in these common industrial metals. This, the first of these two chapters, deals with brass.

CHEMICAL COMPOSITION

The influence of chemical composition on brass sheet may be conveniently studied under two headings: that due to major constituents, and that due to minor constituents, which may be divided again into intended additions and unwanted impurities.

Major Constituents. It is rare for the copper content of the higher grades of deep-drawing quality brass sheet to vary sufficiently from the specified value to cause trouble unless by accident the wrong grade is used: for example, " basis quality " when " cartridge metal " is intended.

The precise influence of the exact copper content in " basis quality " brass of nominal 62 to 63 per cent. copper content seems unestablished. In the opinion of the author the true influence of an increase or decrease of 1 per cent. of copper above or below 63 per cent. is usually masked by that of other factors, such as crystal structure or the presence of *beta* phase; the rejection of sheet purely because of low copper content, although possibly a wise precaution, may not always be genuinely necessary. Brass sheet containing 62 per cent. of copper having a good crystal structure and containing little *beta* phase will draw better than sheet containing 64 per cent. of copper having an indifferent crystal structure or containing a considerable proportion of unabsorbed *beta* phase. It follows, therefore, that careful control throughout the whole sequence of mill operations is of even greater importance with basis-quality brass sheet than with the higher grades.

Segregation of copper in brass of 70/30 or higher grades is usually of little industrial significance, but in basis-quality brass it may be directly responsible for zones of *beta* separation and hence for the failure of sheet under the press. Unfortunately ordinary microscopical examination of sheet does not reveal segregation of copper: the existence of zones of unabsorbed *beta* has not yet been proved to be due entirely to these zones being deficient in copper, and it is unsafe to assume that this is a natural consequence.

It is worth recording that consumers who use large quantities of basis-quality brass sheet sometimes object to the regular delivery of brass containing approximately 64 per cent. of copper instead of 62 to 63 per cent. on the grounds that, being purchased by weight, less metal is supplied for a given sum of money. Needless to say, this objection does not emanate from the press-shop.

It is unnecessary to comment upon the influence of the percentage of zinc because, brass being a binary alloy, the foregoing study of the influence of varying percentages of copper deals also with that of zinc.

Minor Constituents. *Tin.* The proportion of tin found in brass of present-day quality is usually less than 0·01 per cent. Some years ago 0·05 per cent. was common and 0·1 per cent. not unknown and, in these proportions, tin certainly reduces the ductility of brass to a small yet noticeable extent.

However, the influence of a small percentage of tin is not as harmful as that of certain other impurities, and 1 per cent. of this element is sometimes added to brass of approximately " 70/30 " composition in order to enhance its corrosion-resisting properties. The resulting alloy, which is known industrially as " 70–29–1," possesses sufficient ductility to enable it to be rolled or drawn into thin-walled tubes, but its behaviour under the press cannot be compared with that of ordinary cartridge metal containing about 0·01 per cent. of tin.

The precise condition of tin in *alpha* brass seems uncertain. Bauer and Hansen [13] state that although at 400° C. *alpha* brass will dissolve 1·4 per cent. of tin, its solubility at room, or ordinary, temperatures is only 0·4 per cent.; yet the brittle *gamma* phase postulated by these investigators for concentrations exceeding 0·4 per cent. of tin at ordinary temperatures is not usually apparent in the industrial 70–29–1 alloy. The explanation may be that in this alloy, as annealed industrially, true equilibrium is not attained.

Besides lowering the ductility of brass sheet, tin also causes fire-cracking. Relatively small percentages are not usually harmful alone, but if the percentages of both tin and iron happen to be decidedly above normal the likelihood of fire-cracking will be much greater than might be anticipated from the separate influences of these two impurities. A high percentage of tin causes fire-cracking even in the absence of iron, and brasses of the 70–29–1 type mentioned previously are often very prone to this defect.

Lead. Lead is virtually insoluble in brass at ordinary temperatures and, naturally within limits, its harmful effect upon ductility is deter-

FIG. 94. Microstructure of an *alpha* brass containing about 2 per cent. of lead. Instead of being dispersed throughout the crystal structure uniformly in small particles, a few of which can be seen, nearly all the lead has segregated to the crystal boundaries, giving poor ductility. × 250.

[*To face p.* 137.

mined more by the size of particles and their position in the crystal structure than by the actual percentage of the element present. If the particles exist in the crystal boundaries, particularly if the percentage of lead present is sufficient to give a semi-envelope structure, the ductility of brass will be affected so seriously that deep drawing and pressing will be impossible. When, on the other hand, the particles are fine and dispersed uniformly throughout the crystal structure, the behaviour of sheet under the press may be prejudiced to an unexpectedly small extent. The reduction in ductility produced seems to be proportional to the size of the lead particles ; the thinner the sheet the more important it is for the particles to be very fine and uniformly distributed. Fig. 94 shows the microstructure of brass containing approximately 2 per cent. of lead in which the particles are of relatively large size and partial migration to the crystal boundaries has taken place, giving poor ductility.

If special means are adopted to secure a very fine dispersion of lead when the brass is molten, cartridge metal containing up to 2 per cent. of this supposedly injurious impurity can be deep drawn and pressed quite severely and, moreover, unusually heavy reductions can be given when the cast ingot is being cold-rolled into sheet.

However, because in ordinary industrial practice a very fine and uniform dispersion of lead and freedom from crystal boundary segregation cannot always be guaranteed, it is an advantage to reduce the percentage of this element to as low a value as possible. Good quality brass sheet usually contains from 0·01 to 0·05 per cent. of lead and, although in view of what has been said it will be clear that 0·05 per cent. of lead segregated entirely in the crystal boundaries might exert a noticeable influence, the presence of lead alone is rarely responsible for the failure of non-leaded brass sheet under the press. Microscopical examination of *alpha* brass rarely reveals the presence of lead unless the percentage of this element exceeds 0·1.

It should be noticed that in the opinion of many authorities the presence of lead in appreciable quantities accentuates very markedly the normal influence of iron and phosphorus upon both the mechanical and thermal properties of brass, and that it may cause " fire-cracking," a defect described later, which is sometimes believed to be caused only by iron.

Iron. The condition of iron in annealed *alpha* brass is at present a subject of controversy. Some investigators, for example, Bauer and Hansen,[13] claim that iron is practically insoluble in *alpha* brass at room temperature, although at 1,000° C. the solubility is about 3 per cent. and at 650° C.—that is, at annealing temperature—about 0·3 per cent. Other authorities believe that, although this statement may apply to the *true* equilibrium condition, brass of industrial quality may contain an appreciable proportion of iron in solid solution. This belief is strengthened by the fact that if brass which contains iron is "aged" for some time at a raised temperature, which may be as low as 100° C. if the time be prolonged, a distinct increase in hardness occurs which can only be attributed to the precipitation of iron from solution.

Turning from theoretical considerations to established industrial knowledge, it is recognised that a small proportion of iron assists in the attainment of a fine crystal size in annealed brass, this influence being attributed by some, but not all, authorities to a supposed capacity of very finely dispersed precipitated iron particles to act as nuclei for recrystallisation of *alpha* crystal grains. It is also recognised that iron exercises a marked influence upon the temperature at which complete recrystallisation is produced by annealing after cold-working, for which reason incomplete annealing of some particular batch of metal may occur should the proportion of iron in it exceed a normal, and hence assumed, value.

If present in relatively large amounts, iron certainly impairs the deep-drawing properties of brass by reason of appreciable hardening and consequent loss of ductility. Its reduction to the usual present-day proportion of between 0·02 and 0·05 per cent. has, therefore, been of considerable benefit even when really fine and uniform dispersion can be depended upon; the desirability of the total elimination of the relatively large-sized particles which were not uncommon in bygone days hardly calls for emphasis.

The influence of small additions of iron upon the properties of brass has been studied by several investigators besides those already mentioned.[13] The work of Cook and Miller [14] and of Gibson and Doss [15] is perhaps specially worthy of study by those interested in deep drawing. Although more work is required to establish clearly the effect of iron, particularly in small proportions below 0·05 per cent., upon the deep drawing and pressing properties of brass, it seems certain that the effect exerted by any small proportion of this element is influenced to a marked degree by the proportion of lead and phosphorus which exist with it. For example, the influence which a given proportion of iron exerts upon annealing temperatures is increased if lead is present in appreciable quantity; phosphorus behaves in a similar manner and also increases the hardening influence of the iron present. When the proportions of lead and phosphorus are very small indeed, present knowledge indicates that no really marked influence upon normal annealing ranges occurs unless the iron content exceeds 0·09 per cent., between which value and 0·118 per cent. a marked discontinuity in behaviour during annealing seems to take place. Should appreciable proportions of these two other impurities be present, a maximum iron content of 0·05 per cent. may have to be adhered to if special annealing procedure is to be avoided.

Besides increasing the hardness, lowering the ductility, raising the temperature of recrystallisation and inducing possible precipitation-hardening, iron is a potent cause of "fire-cracking" when cold-worked brass is heated suddenly. Indeed, before the effect of tin and lead became recognised, iron was believed to be the sole cause of this happening.

Phosphorus. The benefits derivable from small additions of phosphorus have aroused considerable discussion.

Genders and Bailey [2] state that no appreciable hardening, as indicated by indentation hardness tests, occurs in 70/30 brass if the phosphorus content does not exceed 0·045 per cent., at which value, they state, the whole of the phosphide is taken into solution after an hour's annealing at 650° C. It is interesting to observe that according to Cook and Miller [14] this percentage—0·045—is the optimum with respect to retardation of crystal growth. Notwithstanding these findings, practical experience has shown that brass containing percentages of this order does not always possess a desirable degree of ductility, but this may be due to an unsuspected need for a raised annealing temperature or to an increased hardening effect in brasses containing less than 70 per cent. of copper.

Present knowledge suggests that if added in the proportion of approximately 0·004 to 0·006 per cent., a proportion which has often been greatly exceeded in unsuccessful trials by interested producers, phosphorus exerts an entirely beneficial action. Although additions of this order may not have such a marked influence upon ingot structure as that recorded by Genders and Bailey [2] for appreciably higher percentages, they do retard the rate of crystal growth and thus tend to counteract the harmful effect of over-annealing and to increase the uniformity of crystal size—two very valuable aids.

Another benefit claimed for the addition of phosphorus to brass is that it prevents—or at least hinders—season-cracking; but, as far as the author is aware, no quantitative work has been done on the effect of various percentages of phosphorus as a preventative of season-cracking. Although the value of phosphorus in this particular respect has been questioned, the bulk of opinion suggests that the claims are substantially true, and on the Continent it is not uncommon for as much as 0·15 instead of the more usual 0·006 per cent. of phosphorus to be added to cartridge metal for the special purpose of preventing season-cracking. With this very high percentage of phosphorus an appreciable reduction in ductility has to be allowed for, and the percentage of iron has to be kept very low indeed or it becomes practically impossible to anneal the metal even when the annealing temperature is raised considerably.

Owing to the heavy loss which occurs when additions of phosphorus are made to brass in the furnace, the percentage of this element found in the finished product tends to depart rather widely from the percentage aimed at. This fact may explain some of the conflicting opinions which have been expressed regarding the influence of phosphorus, first, because the actual percentage may differ from the assumed one, and, secondly, because the annealing temperature—which varies considerably with quite small differences in phosphorus content—may in consequence not always have been suitable. Indeed, many manufacturers who have tried adding very small percentages of phosphorus have found that when, for example, 0·004 per cent. is aimed at, the amount actually present in the cast brass may vary from 0·002 to 0·006 per cent. in different ingots. They have therefore discarded the practice because, if brass containing 0·006 per cent. of phosphorus is annealed under conditions suitable for brass containing 0·003 per cent. of this element, an unsatisfactory crystal structure will probably be produced, particularly when the percentage of iron happens to be somewhat high.

Chromium. Chromium, which finds its way into brass *vià* chromium-plated scrap, is normally present in percentages less than 0·001. In this proportion its influence is believed to be negligible; but Gonser and Heath [16] have shown that in higher percentages, of the order of 0·1, chromium retards the crystal growth of brass to an even greater degree than phosphorus without lowering the ductility appreciably. Due to the difficulty of adding chromium to molten brass and of securing proper and uniform solution of the desired percentage, trials of this new alloying element have not always proved successful. The development of special methods for introducing exactly the desired percentage into the molten brass might make chromium a very valuable industrial addition, because it would tend to make annealing conditions less critical and would therefore tend to give a more satisfactory crystal structure.

Summarising the results of their investigations, Gonser and Heath state that an addition of 0·05 to 0·06 per cent. of chromium limits the "average grain size" of 70/30 brass annealed at 550° C. to 0·02 mm.; 0·1 per cent. limits it to 0·04 mm. up to 750° C., and 0·17 per cent. restricts grain growth up to annealing temperatures as high as 850° C.

Aluminium. Small percentages of aluminium go into solid solution in *alpha* brass. As a rule only a trace of this element occurs as an impurity in brass sheet of good quality, but no injury to deep-drawing properties occurs with relatively high percentages. If, as is sometimes done, the proportion of aluminium is increased purposely to as high a value as about 1 per cent., some reduction in ductility may be noticed; yet the alloy can still be drawn into thin-walled tubes. A 1 per cent. addition of aluminium increases the corrosion-resisting properties of brass very considerably, and is popular for condenser tubes.

In contrast to its slight effect upon the behaviour of brass sheet under the press, even a small percentage of aluminium can cause serious surface imperfections on cast ingots, and hence on rolled sheet, due to the very high tenacity of the film of alumina which forms on the surface of the molten metal even though only a trace of the element be present in solution. The influence of this film, which causes laps and folds on a cast surface, is purely mechanical.

Bismuth. Many years ago bismuth introduced into brass *viâ* the copper used in making the alloy gave serious trouble to producers, if not to consumers, because contaminated metal seldom got further than the rolling mill. Bismuth is virtually insoluble in brass at ordinary temperatures, and a very small percentage of this element forms a hard, brittle envelope structure surrounding the crystal grains which reduces the ductility of the metal to such an extent that working by ordinary methods becomes impossible.

The percentage of bismuth found in modern brass is negligible, and rarely more than 0·001 per cent. In bygone days, when metal of less purity was the accepted standard, it was customary to regard 0·005 per cent. of bismuth as the most which could be present without causing serious trouble.

Arsenic. Arsenic is another element which in brass sheet of modern quality has been reduced to a negligible percentage, usually less than 0·01 per cent., due to the increased purity of the copper used. Arsenic goes into solid solution and, if present in relatively high percentages, increases the hardness and lowers the ductility of brass without causing any sudden or unexpected change in mechanical properties. In this respect its behaviour may be likened to that of tin, but it differs from this element in that it tends to raise the temperature at which cold-worked brass starts to soften.

Cadmium. Cadmium is an element which, normally absent, finds its way into brass *viâ* cadmium-plated scrap. Opinions differ concerning the maximum percentage of this element which can be tolerated. Guillet [17] states that the mechanical properties of 70/30 brass are not sensibly affected by the presence of cadmium in proportions up to 1 per cent., but that above this value cadmium tends to separate out of solution in the crystal boundaries, seriously affecting ductility. On the other hand, industrialists know to their sorrow that as little as 0·05 per cent. of cadmium may render brass sheet quite unsuitable for normal deep drawing and pressing operations.

It is difficult to reconcile these definite, considered, yet conflicting opinions of laboratory and industrial workers. A possible explanation is that cadmium alone is relatively inert, as found by Guillet, but that a trace of sulphur leads to the formation of cadmium sulphide, a compound which, even in minute proportions, forms brittle envelopes round the crystal grains and thus destroys ductility.

Antimony. Like cadmium, antimony is an impurity which, normally absent, occasionally finds its way into brass from the scrap used. Ammunition fuses seem to be the principal origin of this impurity, which caused considerable trouble during and for some time after the Great War. It was then established that as little as 0·004 per cent. of antimony was sufficient to make brass split either during rolling or, if it survived this stage, during deep drawing or pressing. It does not seem to be known whether this very small percentage applies to antimony alone or whether, as with cadmium, a considerably higher percentage can be tolerated in the absence of sulphur. Needless to say, elements of such potential harm as bismuth, cadmium and antimony should always be regarded with suspicion, and every effort should be made to avoid the inclusion of even traces of them in brass destined for the press-shop.

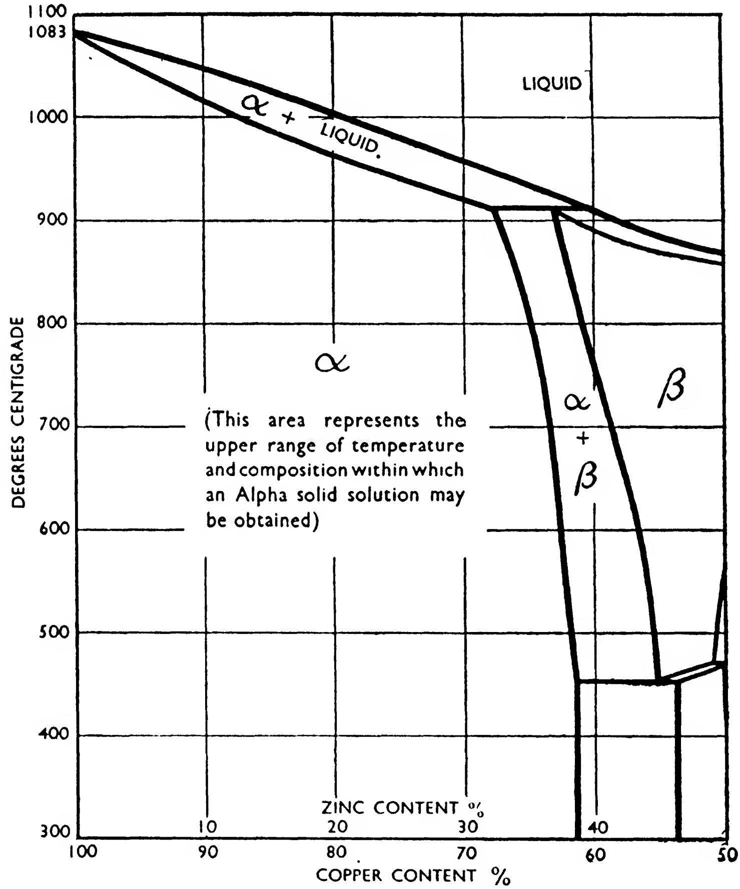
The influence of the more common impurities found in brass has now been studied separately and, whenever possible, an indication given as to the maximum percentage which can be tolerated before the behaviour of sheet under the press becomes seriously affected. It must be borne in mind, however, that quite often it is the cumulative effect of a *number* of impurities present in slightly high percentages, rather than of one impurity present in an *abnormally* high percentage, which spoils the behaviour of sheet just enough to cause an unusually high incidence of failure under the press. It must also be remembered that the influence of several impurities is not always the sum of their separate influences; often two or more combine to produce a disproportionately large change, as do the elements iron, lead and phosphorus.

No mention has been made of gases. Metallurgists are becoming more and more alive to the important, and till recently unsuspected, part which gases play in determining the physical properties of metals, but so far very little investigation has been made of the influence of gases on brass sheet of industrial quality. Although it seems unlikely that this influence will be as great in brass as in steel because, unless *beta* is present, fully annealed brass is in a relatively stable condition, it is possible that future investigations will show that gases do influence the behaviour of brass under the press to a certain extent.

The influence of gases upon the surface condition as distinct from the mechanical properties of rolled brass sheet is already beginning to be appreciated, for experiments have shown that brass which, while molten, has been "degassed" by treatment with some inert gas is relatively immune from the common surface defects caused by gas bubbles.

Unabsorbed *Beta* Constituent. In "basis quality" brass sheet containing approximately 63 per cent. of copper, and occasionally in sheet containing a higher percentage, the presence of free *beta* phase is a defect which causes a considerable amount of trouble in the press-shop.

Cause. The presence of *beta* is usually attributed to the proximity of the copper content of this grade of brass to the phase boundary which, as shown in Fig. 95, is believed to lie at approximately 62 per cent. of copper at ordinary temperature, but this explanation needs



[*By courtesy of The Copper Development Association.*

FIG. 95. Portion of copper-zinc equilibrium diagram simplified.

elaboration adequately to account for the presence of *beta* in brass sheet of industrial quality.

As far as the author is aware no proper investigation has been made to determine why the exact percentage of copper—up to, say, 64 per cent.—in brass sheet is no certain determinant of the apparent liability of the sheet to contain free *beta* phase. On the basis of the common assumption just mentioned, sheet containing 62 per cent. of copper should be markedly more prone to contain free *beta* than sheet containing 64 per cent., yet extended observation shows that this is not always so. One explanation is that the copper content of brass sheet as determined by the usual methods of chemical analysis is an *average* value, and that the actual copper content of zones which contain free *beta* is lower than this average. This explanation seems to be disproved by practical experience which shows that although zones of stringers or *beta* suggestive of chemical segregation are often visible, at other times an almost uniform dispersion of *beta* is found throughout the entire section of a sheet of relatively high average copper content, for example, 64 to 65 per cent. Furthermore, free *beta* is sometimes observable in sheet of still higher copper content in which it seems reasonable to assume that no zones containing less than 62 per cent. of copper exist. It seems, therefore, that a low average copper content is by itself an inadequate explanation of the existence of free *beta* phase.

Another explanation is that the presence of certain impurities, either solid or gaseous, tends to produce free *beta*. Pending proper investigation this explanation must be regarded as possible even though not wholly confirmed by observed facts unless the impurity is one which may occur, with equal facility, either segregated into well-defined zones or else distributed uniformly through the section of a sheet and, in addition, one which is so active that its influence eclipses entirely that of the percentage of copper present. It is important to notice that recent investigations by means of X-rays have shown that the boundary of the *beta* phase does not lie where it was thought, and that the presence of traces of impurities in the alloy moves the boundary toward the zinc end of the diagram. It is, therefore, unsafe to assume that at ordinary temperatures 61 per cent. of copper, the value shown in old constitutional diagrams, or even the new value of approximately 62 per cent. represents the limit above which *beta* should not exist in brass of industrial quality even when the alloy is in perfect equilibrium, a condition which may not always be attained.

A third explanation, which in the opinion of the author accounts for the apparently chance proportions of *beta* phase which may occur in a number of samples having approximately the same copper content, is conditions of mill procedure. Records show that in sheet of similar chemical analysis—at least with respect to copper and the commonly-estimated impurities—the likelihood of free *beta* being present varies markedly with different suppliers, and, furthermore, that it increases if slabs are hot-rolled. Precisely what the conditions conducive to the production or retention of free *beta* are is as yet unestablished. A careful investigation having as its objective the determination of these conditions would be of particular benefit to industry in this country, because here basis quality brass is deep-drawn more extensively than

FIG. 96. Elongated masses of *beta* in brass containing approximately 63 per cent. of copper.

Microsection cut parallel to surface of sheet. × 75

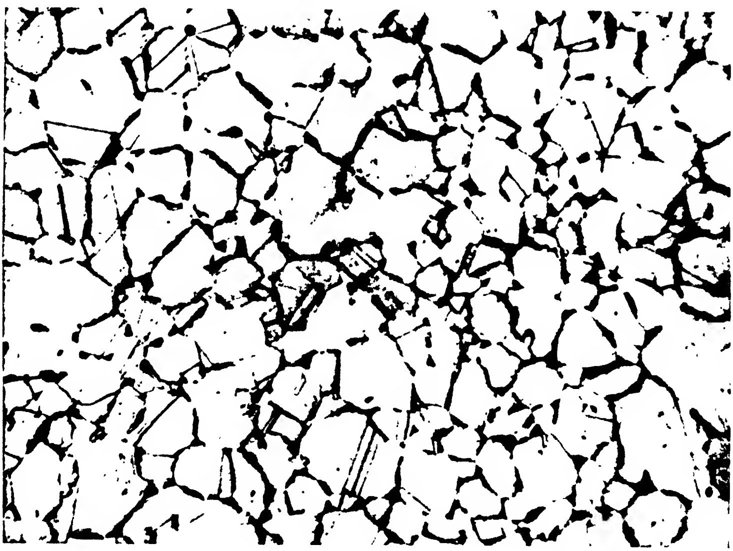


FIG. 97. Typical arrangement of *beta* in crystal boundaries in brass containing approximately 63 per cent. of copper.

Microsection cut parallel to surface of sheet. × 300.

[*To face p.* 145.

abroad, where 65 per cent. of copper is often the lowest grade with which severe draws are made.

In connection with these tentative explanations for the existence of unabsorbed *beta* phase, it is of interest to notice that Wurstemberger[18] is of the opinion that *beta* behaves as a mother liquor to *alpha* crystals, and that he ascribes to this the location of free *beta* in the crystal boundaries of an *alpha* structure and its existence in brass containing as much as 70 per cent. of copper. It is common knowledge among industrial workers that routine microscopical examination, if conducted with more care than is customarily given when no more information is needed than "average grain size," will often reveal finely dispersed *beta* in the crystal boundaries of a good proportion of 70/30 brass.

If, as Wurstemberger says, *beta* behaves as a mother liquor to alpha crystals, then rapid cooling—as helped by the use of thin, slab ingots and water-cooled moulds—should increase the amount of *beta* trapped. Some authorities agree that this is indeed a fact, and others have observed that the vibration of moulds on a revolving turn-table, as is often used, appears to favour the retention of *beta*. Others disagree with both these opinions; so, until more precise knowledge is obtained, it seems best to regard them as interesting hypotheses worthy of close attention.

Once separated, *beta* phase is difficult to reabsorb. A pronounced separation can often be completely absorbed by means of an annealing treatment extending over many hours, but it is almost impossible to give this treatment without seriously impairing the regularity of the crystal structure of the final product.

Forms of Occurrence. Free *beta* occurs in brass sheet in two distinct forms: large, and usually elongated, masses such as those shown in Fig. 96, and very small masses, usually existing at crystal boundaries but sometimes apparent as isolated particles within the crystal. A typical example of boundary separation is shown in Fig. 97. In either of these two forms free *beta* may be confined to well-defined planes or stringers small in relation to the thickness of the sheet, as illustrated in Figs. 98 and 99, or else it may be distributed more or less uniformly throughout the section. When the separation is confined to definite zones, the crystal size of these zones is usually markedly smaller than that of the rest of the section.

Influence. Compared with *alpha*, *beta* phase is hard and non-ductile. The effect of free *beta* is, therefore, to impair the normal ductility of sheet in which it exists. How serious this effect will be will depend upon both the amount of *beta* separated and the nature of its form and distribution. In general, the finer the dispersion the greater will be the reduction in ductility: for example, the microstructure illustrated in Fig. 97 will be more harmful than that illustrated in Fig. 96.

In addition to what may be termed the primary effect of free *beta*, there exists at least one important secondary effect, namely, its tendency to reduce the crystal size of the zones in which it occurs. In addition to the stiffening and keying effect of the actual *beta* particles there often exists, therefore, the additional influence of zones of very small crystals (see Fig. 57, p. 85), which will reduce still further the ductility of the sheet as a whole.

Whether or not the presence of a certain proportion of *beta* in a given condition will cause sheet to fail under the press will depend upon the safety margin which exists in any sequence of drawing operations. Often this safety margin has to be made fairly large in order to accommodate a certain proportion of sheet which contains free *beta*, thus limiting the depth of draw which can be accomplished. Because of this, and because it is often responsible for actual failure under the press, the user must regard free *beta* as a serious defect which the supplier should make every effort to eliminate in the sheet which he produces. All too often suppliers regard free *beta* as a defect of academic rather than industrial importance, and object to sheet being rejected purely by reason of its presence. Even when the harmful influence of free *beta* is acknowledged, there is a tendency for the onus to be laid upon the user for specifying sheet of low copper content. The user, being in a position to compare the product of different suppliers over a long period, knows that sheet having the copper content he specifies *can* be produced free from *beta*, and he therefore maintains that the supplier ought to find out what causes free *beta* to be produced (and retained) and to take the necessary steps to prevent its existence in delivered sheet.

Non-metallic Inclusions. Users of brass sheet are fortunate in that troubles attributable directly to the presence of non-metallic inclusions in this metal are comparatively rare. Indeed, in shops where both brass and steel sheet are drawn, the absence of both large masses of slag caused by piping, and also of the smaller yet often seriously injurious elongated particles of sulphide and mixed inclusions, leads to "inclusions" in the non-ferrous metal being regarded as a defect of little consequence.

This enviable state is caused by the absence of severe "piping" in most industrial brass ingots, by the fact that no slag comparable with that used in steel-making is present to become entrapped, and by the relatively greater cleanliness which is usually maintained in the casting shop. This last condition is, it must be admitted, often due more to natural causes than to the exercise of greater care, and the use of electric induction furnaces has helped to reduce still more the introduction of undesired foreign matter into the molten metal.

On the other hand, the relatively low melting point of the non-ferrous metal tends to prevent the solution—still less the adequate

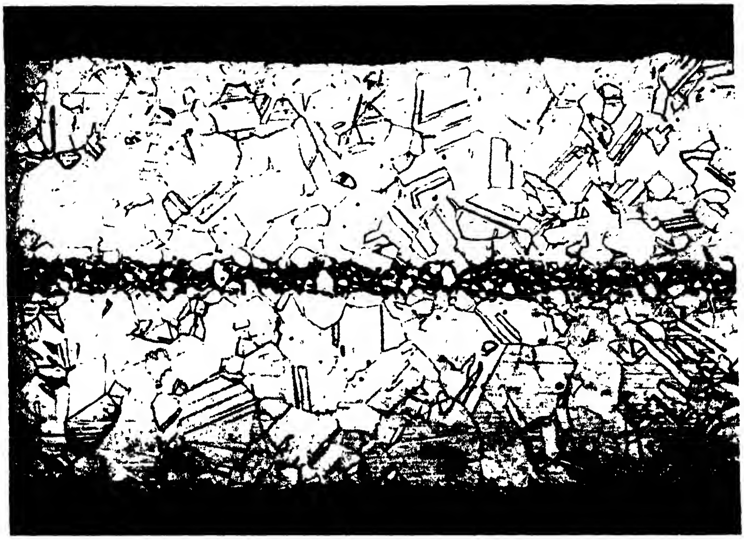


FIG. 98. Central core of unabsorbed *beta* in brass strip containing approximately 63 per cent. of copper.

Microsection cut normal to surface of sheet and parallel to direction of rolling. × 75.

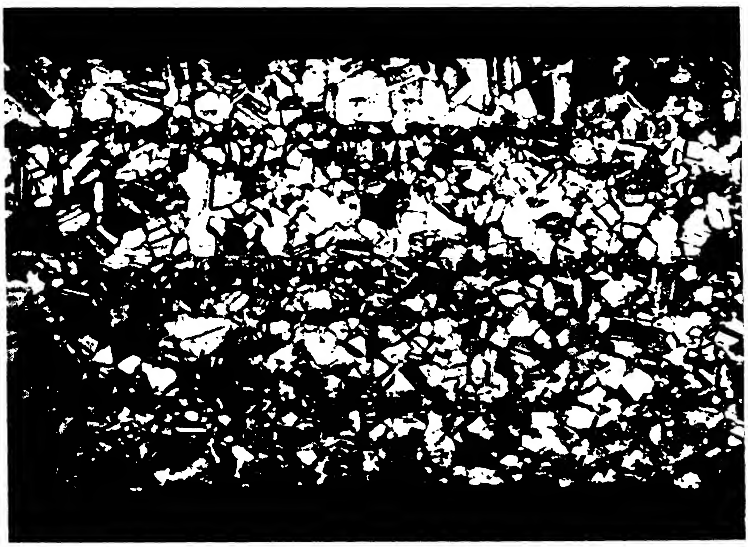


FIG. 99. Planes of unabsorbed *beta* in brass strip containing approximately 63 per cent. of copper.

Microsection cut normal to surface of sheet and parallel to direction of rolling. × 75

[*To face p.* 146.

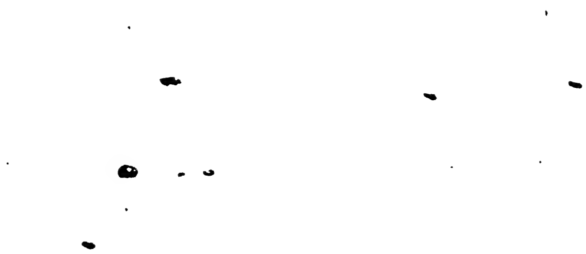


Fig. 100. Isolated non-metallic inclusions in brass.
Unetched microsection cut normal to surface of sheet. × 200.

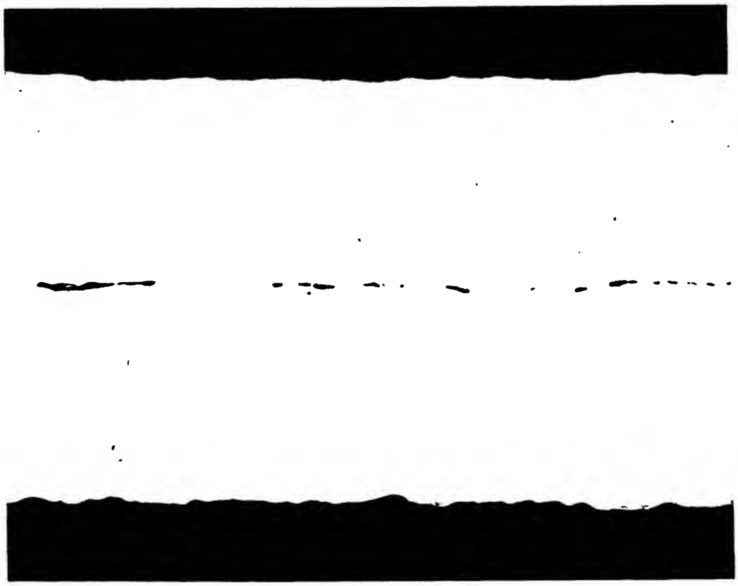
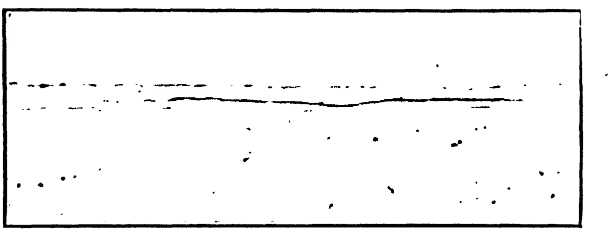


Fig. 101. Elongated non-metallic inclusions in brass.
Microsection cut normal to surface of sheet. × 75.



[*By courtesy of Genders and Bailey.*

Fig. 102. Unetched microsection showing sub-surface discontinuities in rolled brass sheet.

Microsection cut normal to surface of sheet. × 100.

[*To face p.* 147.

dilution—of inclusions of high melting point, such as pieces of steel concealed in bundled scrap; and not many years ago it was not uncommon for particles of iron to be a genuine cause of trouble in the brass sheet supplied to the press-shop.

Typical examples of inclusions in brass sheet are given in Figs. 100 and 101. The small, isolated inclusions shown in the first photomicrograph are unlikely to cause trouble in most pressing or deep drawing operations; their comparative rarity leads sometimes to undue importance being attached to them. Large inclusions such as those shown in Fig. 101, which resemble in appearance those commonly observed in steel, can sometimes constitute a primary cause of the failure of sheet under the press, because their presence is unexpected and allowance is not made for the loss in ductility which they will cause. It is of interest to record that the author has not come across a single failure due to the presence of inclusions in brass sheet rolled from ingots poured from electric-induction as distinct from fuel-fired furnaces.

Surface Blemishes. Surface blemishes on sheet caused by defects in the ingot such as cold-laps, laminations, spills or gas bubbles and the many variations of these defects known by colloquial names often peculiar to certain localities still cause trouble sometimes, although both their frequency and their severity have lessened during recent years. Reasons for this have been described in Chapter I; the principal ones are, probably, the exercise of more care in the choice and application of mould dressings, in the casting operation itself, in the maintenance of mould surfaces and in the wider use of copper-faced moulds and the practice of machining the surface of ingots or slabs.

Serious cold-laps or laminations produce obvious surface defects which lead to the rejection of rolled sheet by any reputable supplier, but small spills or gas bubbles may not be visible on the surface of the anish-rolled sheet or, if they are, may be masked by the burnishing fiction of the rolls. Like genuine sub-surface defects, hidden blemishes of this kind only become visible when they are opened up by the elongation of the metal in the press. Fig. 55 (p. 79) shows a spill which has opened up during a first press operation, and Fig. 102 shows the appearance of this kind of defect on a polished microsection cut through cold-rolled but unpressed sheet. True spills often contain non-metallic particles, generally believed to be oxide, and sometimes are of a multiple, laminated nature. Their nearness to the surface of the sheet determines whether they will open up while the sheet is being rolled or will remain hidden until the sheet has been worked by the consumer in his forming processes.

If a defect of the spill type is relatively slight, it may escape detection by casual examination until the pressed article has been pickled. This is unfortunate, because it often means that pressings have to be scrapped right at the end of a long series of press operations, with added loss to the consumer. Fig. 103 shows a typical spill defect, of a fairly mild nature, which escaped detection in the sheet and even in the deep-drawn articles until it was made clearly visible by bright-dipping, an operation which was not included in the production sequence until the containers had had tops soldered to them and a number of other fabricating operations had been performed. This shows that sometimes the consumer is well advised to inspect the sheet he purchases very carefully indeed in order to lessen the likelihood of a relatively expensive fabricated article—or even assembly—having to be scrapped, as in this instance.

When it is suspected that a consignment of metal is "spilly," a light pickle will instantly reveal any but genuine sub-surface defects. Before being pickled the surface shown in Fig. 104 was such that only very close inspection by a trained man would have shown that anything was amiss and enabled the sheet to be rejected before being sent to the press-shop. Immersion for a few seconds in a "bright-dipping" solution at once revealed the "spilly" surface shown in the photograph. The effectiveness of this test is well-known ; if it is not used, consumers ought not to grumble at the cost of operations carried out on articles which in the end have to be scrapped solely on account of the defect it reveals.

Consumers who purchase from several sources are often struck by the difference in the surface soundness of the brass sheet made by different suppliers. The regular excellence of the product of some suppliers shows that surface blemishes of the kind just illustrated can be almost eliminated if sufficient care is observed, but it seems that only continued insistence on the part of consumers will lead to the necessary precautions being taken.

Gas Cavities. Surface defects of the spill variety may or may not be caused by gas bubbles. If they are, the bubbles often occur in strings or colonies and are caused by gases generated at the mould surface, usually by combustion of the mould dressing or by the expulsion of gas held in cracks or pores in the mould surface. In this section it is proposed to discuss a rather different form of gas cavity, namely, that which occurs anywhere in the section of the ingot due to the expulsion of gas held in solution in the metal or, sometimes, entangled in the molten stream while the metal is being poured into the mould.

Troubles due to the occurrence of gas cavities in the original ingot, although far less prevalent now than a few years ago, are still encountered occasionally. The study of gas cavities in brass ingots does not appear to have received the intensive collective study afforded to cavities in steel ingots and, whatever may be the extent of individual findings, there seems by comparison to be a relatively small volume of established common knowledge. Considerable experimental work on

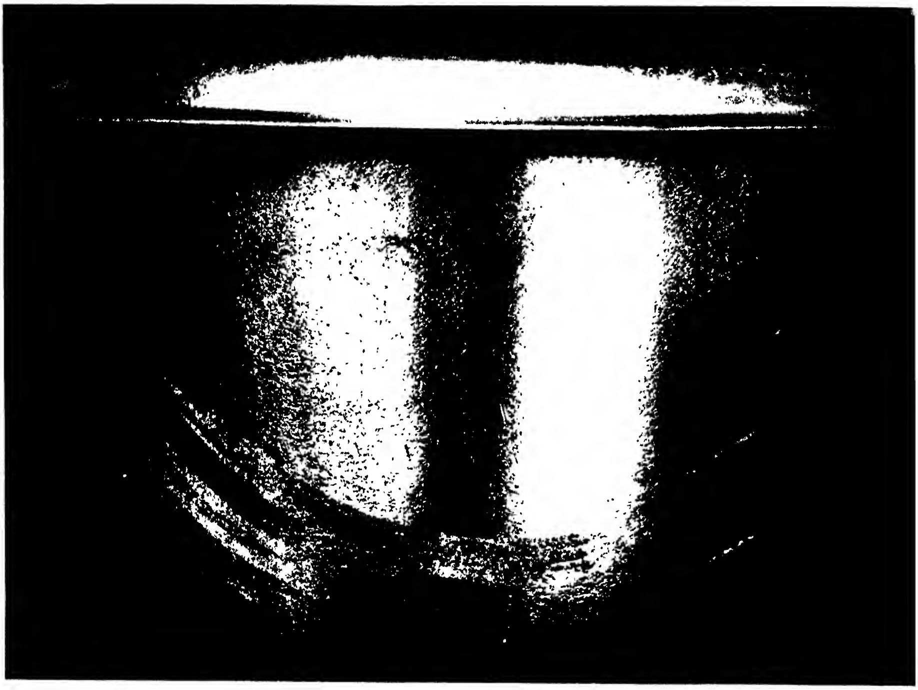


FIG. 103. Part of wall of deep-drawn container showing "spill" defect which opened up in apparently sound brass strip. (Actual size.)

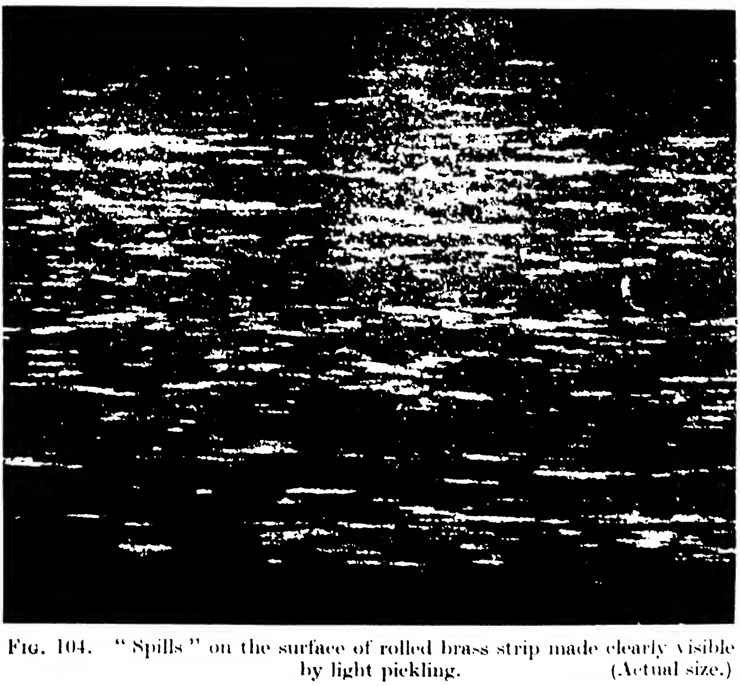


FIG. 104. "Spills" on the surface of rolled brass strip made clearly visible by light pickling. (Actual size.)

[To face p. 148.

[*By courtesy of Genders and Bailey.*

FIG. 105. Unetched microsection showing gas cavities in cast brass ingot.
Microsection cut normal to surface of sheet. × 25.

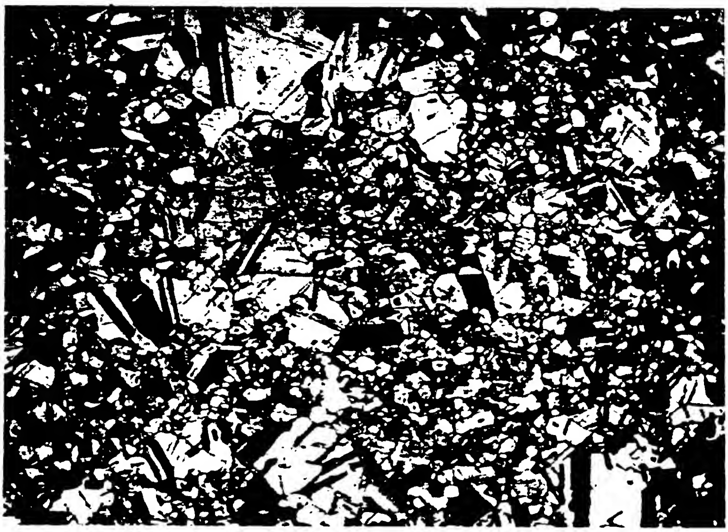


FIG. 106. Highly irregular crystal structure in deep-drawing quality brass strip.
Microsection cut parallel to surface of sheet. × 75.

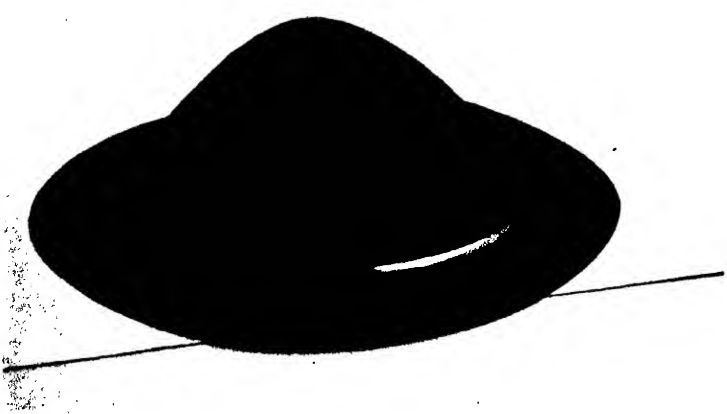


FIG. 107. Typical example of "waving" defect developed by one draw in brass shell.

[*To face p.* 149.

pouring procedure has been carried out by nearly every casting shop, yet the effects on ingot structure produced by various conditions of pouring and solidification are not yet generally known. In many instances it is to be feared that the experiments have been made with the immediate, though possibly necessary, object of overcoming some prevalent trouble rather than with the object of obtaining fundamental knowledge on ingot production.

The formation of gas cavities in brass ingots is different from that of those formed in solidifying rimming steel ingots; chemical action is relatively slight, and the principal mode of formation is by the expulsion of dissolved gas during cooling and solidification and by entanglement during pouring. When ingots of thick section are sliced into slabs prior to rolling, internal gas or contraction cavities naturally become of increased detriment to surface finish. Gas cavities of this type will be detrimental in proportion to their size and to their nearness to the surface of the finished sheet.

Typical gas cavities in a cast brass ingot are illustrated in Fig. 105. During the rolling of the ingot into sheet, cavities of this kind will be flattened into very thin planes of discontinuity unless hot-rolling produces partial welding of the surfaces when the cavities are free from oxide. Whether or not these internal discontinuities will lead to failure of the sheet under the press will depend upon their nearness to the surface of the sheet, their size relative to the thickness of the sheet and, naturally, upon the severity of the deformation inflicted upon the sheet by the consumer.

Piping. In well-cast brass ingots the pipe, meaning the contraction cavity at the top of the ingot, is small and free from slag, although included dross or a coating of oxides may prevent the welding-up during hot-rolling (when given) of any shrinkage cavities which exist. The small extent of the major pipe present in a well-cast brass ingot renders complete removal by cropping a matter of slight expense; defects in finished sheet traceable to it are rare.

Crystal Structure. The influence of crystal structure, meaning more particularly the size and uniformity of size of the crystals, upon the behaviour of sheet metal under the press has been discussed in the preceding chapter. As brass offers no exceptions to the general statements made it is unnecessary to repeat these with special reference to brass, and it is proposed merely to show what faults in crystal structure are specially common to this widely-used metal.

Two faults stand out pre-eminently in the crystal structure of much of the deep-drawing quality brass sheet now supplied to press-shops :—

(1) The size of the crystals is highly irregular; that is, in any given area, small and large crystals exist side by side.

(2) The "average grain size" is seldom constant or within the range for which the user asks.

Irregular Crystal Size. Fig. 56A (p. 84) shows the kind of crystal structure which would be welcome in every press-shop in which severe demands are made upon the metal and a smooth surface desired on the finish-drawn article. Fig. 56B on the same page shows a structure typical of much of the brass sheet now supplied for deep drawing and pressing and, unhappily, often alleged by suppliers to be quite satisfactory. Allowing for the natural variation in the size of the crystals visible on any plane section cut through a crystal aggregate, it will be evident that the size of the crystals in Fig. 56A is reasonably constant, and that the variation in size between the largest and the smallest crystals in Fig. 56A is far less than that in Fig. 56B. Readers are reminded that, taking the type of crystal structure shown in Fig. 56A as a standard, that shown in Fig. 56B will possess less ductility yet will exhibit a rougher surface on drawn work even when its " *average* grain size " is adjudged to be similar to that of the first. It is the predominance of the second type of crystal structure which explains why the appearance of drawn work or of the Erichsen dome itself is distinctly rougher than either the depth of the Erichsen impression or the "average grain size " estimated by casual inspection appears to warrant.

Fig. 106 shows a still more irregular crystal structure. Comment upon its failings is hardly necessary : this photomicrograph is included merely to confirm that, even to-day, it is not unknown for brass having such a microstructure to be delivered—in the particular instance associated with this photomicrograph in considerable quantities—by suppliers of repute equipped with modern plant and purporting to carry out extensive routine examination.

Fig. 57 (p. 85) shows a rather different form of crystal irregularity, namely, stringers or planes of tiny crystals existing in a matrix composed of crystals of reasonably regular size. Sometimes the stringers or planes are numerous and of short length, sometimes they are few in number on any cut section yet run for a considerable distance ; but it is unusual to find numerous, long stringers. Occasionally a single central plane or " core " may run through a considerable length of strip. Whatever the form in which they occur, the regions of tiny crystals are often associated with unabsorbed *beta* phase to the presence of which it is quite likely they owe their existence, although another possible cause which must not be forgotten is segregation of iron or of phosphorus. The ductility of sheet possessing a structure of the kind shown in Fig. 57 will, clearly, be considerably less than that normally associated with the matrix.

This particular defect seems to be confined to sheet of low copper content, but to it the user of basis quality brass sheet can justly ascribe many of the failures which he experiences under the press. Even when routine examination is carried out, the selected samples may be relatively free from this defect, which sometimes varies greatly in intensity within a short length of strip, and hence from blank to blank.

The influence of stringers and planes of tiny crystals upon "directionality" in sheet brass can be imagined from Fig. 57 (p. 85), a glance at which will suffice to show that this influence can be appreciable because the ductility of the sheet will be impaired less in a direction at right angles to that of rolling than in a direction parallel to it.

"*Average Grain Size.*" It has been pointed out that as the irregularity of the size of the crystals composing an aggregate increases, the significance of the property termed "average grain (or crystal) size" diminishes and the difficulty of estimating and expressing it as a single numeral increases so rapidly that it soon becomes virtually impossible. Owing to the regrettable tendency, just illustrated, for the crystal structure of a considerable proportion of the brass supplied to the press-shop to be decidedly irregular, it is often surprising that estimated "average grain size" values prove to be of real help in predicting the behaviour of sheet under the press.

It is almost impossible to give even a range of suitable "average grain sizes" for deep drawing or pressing quality brass sheet because the best size will depend upon the severity and the nature of the draw, on the degree of smoothness desired in the roughest parts of the finish-drawn article and on the regularity of the crystal structure. If, in order to reduce polishing costs, a smooth surface is desired on a finish-drawn article, an "average grain size" of approximately 0·03 mm. may be satisfactory; but the ductility of the sheet will be distinctly less than that associated with one of 0·045 mm. For the majority of small and medium size articles, an "average grain size" of 0·035 to 0·045 mm. will be found to give a fair compromise between good ductility and smoothness of drawn surface. For large articles not needing a smooth surface a value of 0·05 to 0·06 mm., and in some instances even 0·1 mm., is preferred by some users, but it must be borne in mind that although the ductility of the sheet increases as the "average grain size" increases, the tenacity decreases; because of this there will be an increased tendency, with some press operations, for the walls of the shape to thin and break instead of transmitting stress to the undrawn parts of the blank or shape.

The values just given apply only when the size of the crystals is reasonably uniform. When good ductility is needed, the presence of many tiny crystals will entail the selection of brass having a larger adjudged "average grain size" than usual and, in consequence, the production of an unusually rough surface on drawn work. When, on the other hand, a smooth surface is of primary importance, it may not be possible to reach the desired standard unless the sheet selected has such a small "average grain size," and in consequence such poor ductility, that the usual sequence of press operations cannot be carried through.

When rolled brass strip is annealed in more or less closely wound coils of some size, it is common for the " average grain size " to decrease toward the inner end of the coiled strip because the centre of the coil heats up less quickly than the outer turns. This and other causes of variation in " average grain size " throughout the length of coils or flat lengths of strip have been examined already. The fault may have serious consequences for the user, and a variation in " average grain size " from, say, 0·03 to 0·045 mm. according to whether blanks are cut from the outer or the inner end of a coil, may account for a fair percentage of failures in a difficult series of press operations.

Directionality. Directional properties in brass sheet tend to be less pronounced, and therefore less harmful, than in steel; but their existence can be discerned in the flow of most blanks—for example, the one shown in Fig. 60 (p. 87)—and quickly verified at any time by the simple tear-length test described elsewhere.

Directionality in brass sheet is caused mainly by the orientation and directional properties of the crystals: the supplementary effect, important in steel, of pronounced chemical segregation and elongated non-metallic inclusions is normally absent although, as has been pointed out earlier, the influence of stringers of small crystals may be appreciable in brass of low copper content.

The position of " ears " on drawn shells and also tensile tests made on undrawn sheet show that in brass of industrial quality the position of minimum ductility lies at 45 degrees to that of rolling. Cook,[19] describing an interesting study of the effect of various rolling and annealing procedures on directionality, states that by special treatment the direction in which ears form can be changed and as many as *six* ears formed in the drawing of a cylindrical cup. Brass having such special properties is not likely to be met with in industry at present, but users, who naturally would welcome brass sheet having less marked directional properties, will learn with interest that this end may be achieved by a careful planning of mill sequence on the part of suppliers.

" Waving." A form of surface defect known by a variety of names such as " rippling " and " waving," a typical example of which is shown in Fig. 107 (p. 149), sometimes causes serious trouble. This defect assumes the form of depressions, running parallel to the direction of rolling, which appear on the outer surface of drawn articles and, when the defect is severe, on the inside, the depressions on the inner and outer surfaces usually coinciding to form an actual elongated " neck " in the metal. Such markings can cause much upset to production schedules insufficiently elastic to accommodate the necessary increased polishing time, particularly when automatic polishing is employed. Indeed, when this type of surface marking is at all pronounced, it is often entirely uneconomical to attempt to polish articles which exhibit it.

Although the cause of this defect does not yet seem to have been established definitely, at least two possible sources are sufficiently probable to merit mention. Firstly, it is an observable fact that *beta* stringers (see Fig. 96, p. 149), if not always stringers of small crystals (see Fig. 57, p. 85), are frequently visible in drawn articles which exhibit "waving"; also, that when stringers are not visible, isolated particles of *beta* usually are. It is held by some workers, but disputed by others, that the "waving" defect occurs chiefly in brass of low copper content and that the increased use of such brass has coincided with the increase in the prevalence of this particular defect. This evidence seems at first sight to suggest localised effects produced by internal streaks of actually visible, or of incipient, *beta* constituent as a very probable cause of "waving." Supporters of this explanation must, however, concede that brass containing very distinct stringers of small crystals or of unabsorbed *beta* may sometimes prove immune from this particular type of surface defect, whereas under the same tools another batch of metal containing less pronounced stringers and less visible *beta* may develop it. As it seems doubtful whether such segregation and separation can always be avoided in commercially produced brass sheet in which the *beta* phase is approached, the only real remedy for "waving," if—as is not certain—this effect really arises from these particular defects, would seem to be the use, on articles prone to epidemics of this type of marking, of brass of higher copper content than that normally employed.

For the second possible cause it is held by some workers, who claim the important consideration that the defect can be produced from this cause at will, that oxides absorbed or rolled-in during the early stages of ingot processing are responsible for this form of surface defect notwithstanding the fact that no visible trace of such oxide can be seen under the microscrope in the finished sheet. As evidence in favour of this cause it may be pointed out that the observed prevalence of the defect in sheet of 63 per cent. copper content is accommodated by the frequent hot breaking down of this type of brass, whereas cartridge metal, in which the defect is rarely encountered, is usually broken down in the cold state. The remarkable penetrative power and influence of oxide on the surface of copper ingots and slabs is definitely established, and may be cited as an indication of the possibility of some similar effect in brass. If this second source is indeed the one from which "waving" defects arise, more careful control of the atmosphere in the furnaces used for heating ingots prior to hot breaking down, or even for annealing, would seem to be necessary, as also would a more complete knowledge of the action of furnace atmospheres of varying types on the properties of brass exposed to them.

Fire-cracking. "Fire-cracking" is the term often used to denote the cracking of cold-worked brass—or other metals—when heated suddenly, for instance when rolled, drawn or pressed products are thrust into an annealing furnace maintained at or near the full annealing temperature. It is a defect which is now far less prevalent than in past years, due principally to the increased purity—notably with regard to iron—of brass of ordinary industrial quality.

Lead as well as iron is liable to cause fire-cracking, and it is likely that special care may have to be taken with leaded brasses if, as is suggested in a later chapter, these come to be used for parts which are deep-drawn to shape prior to being machined. The obvious precaution of gently warming articles before placing them in a muffle at the full annealing temperature may not be so effective with leaded brass as with other metals; the particles of lead must melt whether heating be slow or rapid, but, by relieving some of the strain existing in the severely cold-worked crystal aggregate *before* the particles of lead melt, slow heating may at least prevent their action being disruptive. It seems likely that the disruptive action of particles of molten lead will depend upon their size, number and position, that is, whether they exist within a crystal or at its boundary. It has been shown that the size and dispersion of lead particles in leaded brasses can be controlled; the leaded brass of the future with its uniform dispersion of tiny particles may, therefore, prove less prone to fire-cracking than brass in which lead occurs as an unwanted and unexpected impurity.

Annealing. The inter-stage annealing of drawn brass articles calls for no special precautions. Yet, in spite of the fact that brass is not susceptible to serious critical-strain crystal growth, that it is not abnormally sensitive to annealing conditions, and that its relatively low temperature of recrystallisation helps in the design and maintenance of annealing plant, incorrect inter-stage annealing has been responsible for a large proportion of the trouble experienced in many press-shops. The cause of this trouble has usually been either ignorance, lack of care or, in some of the older types of furnace, inability of the plant to subject the whole of its charge to the desired conditions even though these are recognised.

As the inter-stage annealing of drawn work is discussed in some detail in another chapter, no elaboration will be attempted here concerning the annealing process itself and the reasons why an unsuitable treatment is sometimes inflicted upon work in furnaces of old—and, unhappily, sometimes of new—type; a few additional details relating specifically to brass may, however, usefully be included in this section.

As with other metals, inadequate annealing will not restore the ductility of cold-worked brass sufficiently to enable further severe plastic deformation to be inflicted, while over-annealing—the more common fault—will produce an unnecessarily rough surface on work after further drawing and, sometimes, actual breakage under the press, as illustrated in Fig. 85 (p. 120).

It is very difficult to tell whether annealing has been carried out satisfactorily except by actual trial of annealed work under the press. Most partly-formed articles are of such a shape that an Erichsen test cannot be made even by destroying selected samples, while indentation hardness tests are an uncertain indication because the values obtained vary to an appreciable degree with the crystal size of the annealed metal, and this will be determined to some extent by the crystal size before annealing. The following relationships between "average crystal size" and Vickers pyramid hardness numeral have been offered as an approximate guide for fully annealed brass of 70/30 composition [20] :—

"Average Crystal Size"	*V.P.N.*
0·030 mm.	75
0·050 mm.	65
0·10 mm.	55

Be this as it may, a hardness greater than 80 V.P.N. can usually be taken as an indication that annealing has not been carried to completion, while a value below 60 V.P.N. usually means that through over-annealing or other causes the crystal size has become too large for many drawing operations. It must be admitted, however, that tests are of small use and, under industrial conditions, the only way to obtain correct annealing seems to be to take every necessary precaution to ensure that each part of a furnace charge receives as nearly as possible that heat-treatment which previous experience with any particular article and annealing plant has shown to be best.

It is impossible to lay down any narrow range of temperature as the one most suitable for the inter-stage annealing of drawn brass articles because this range will vary according to the chemical composition of the brass used, its crystal size, the time of annealing, the degree of cold work inflicted, and the degree of softening desired. As a very general indication, approximately 550° C. is suitable for many purposes, but this temperature may need to be decreased to 500° C. or increased to 600° C. according to circumstances. If the brass is of high purity, 480° C. is sometimes adequate. When phosphorus or iron is present in appreciable proportion an increase approaching 50° C. in the annealing temperature may be needed ; should the proportions of both phosphorus *and* iron be high, a still higher temperature and a lengthened "soaking" period will usually be required. It is hardly necessary to point out that if regular response to a standardised annealing treatment is desired, it is important to ensure that brass of uniform chemical composition, and if possible uniform crystal size, is used. If this is not done, even modern furnaces equipped with efficient temperature-controlling apparatus cannot ensure the production of uniformly annealed work.

The influence of crystal size upon annealing temperature is not of great importance in most industrial inter-stage annealing, because the irregularity in size of the crystals composing the sheet drawn is usually so large that the effect tends to be masked. The tendency, undoubtedly true in theory, for the necessary annealing temperature to increase as the crystal size increases can, however, sometimes be discerned under industrial conditions now that the control of annealing processes is becoming more accurate.

The period during which work is held at the full annealing temperature is usually of less importance than the temperature itself in determining the crystal size of the annealed metal. By this it is not meant that work can be soaked for long periods with impunity, nor that time of soak need not be taken into consideration in conjunction with temperature when annealing procedure is being considered: under most conditions, however, small variations in time of soak will produce less effect than small variations in temperature. Exception to this statement must, of course, be made for "short time" annealing in which work is passed rapidly through a furnace maintained at a temperature above that which the work normally attains. Under these conditions an increased time of soak will raise the temperature of the work and produce a coarsened crystal structure. One of the uses of additions of phosphorus to brass is to reduce the rate of crystal growth and, hence, to minimise the influence of period of soak upon the crystal structure of the annealed work.

Experience suggests that the best crystal structure is produced in ordinary brass by a fairly rapid, but as uniform as possible, rate of heating to a temperature sufficiently high to produce the desired anneal after only a short period of soaking. As pointed out elsewhere, these conditions seem to be met most closely by forced-circulation air furnaces and least closely by large furnaces having an undisturbed atmosphere and only a few heating zones. At present there seems insufficient evidence available to show whether similar conditions are also best for special brasses containing phosphorus or comparable additions to reduce the rate of crystal growth; it is possible that with brasses of this kind a longer heating period at a lower temperature may give results which are sufficiently good for all practical purposes. If so, much annealing plant which would otherwise have been rendered obsolete by the ever-increasing demands of production methods may acquire a new lease of life.

It is perhaps desirable to repeat the warning given in Chapter III that although incorrect inter-stage annealing of brass can ruin a good crystal structure, and can aggravate still further undesirable characteristics in a bad one, the most carefully planned and executed interstage annealing cannot transform an irregular crystal structure into one having a desirable degree of regularity.

The prevention of surface oxidation during the annealing of brass is a problem which has been tackled in many ways. Water-sealed muffles have in the past produced work which, if not truly bright, was at least devoid of scale and, unless the heated charge was quenched at too high a temperature, reasonably satisfactory in other respects. "Clean-annealing" in controlled-atmosphere furnaces, often of continuous type, is now coming rapidly into favour and, at the risk of anticipating a later chapter, it may be said that a continuously regenerated atmosphere of burnt ammonia seems to be replacing the various gases which now hold the field, such as cracked ammonia or partially burnt town's gas.

Rate of cooling after annealing is usually assumed to be of no consequence with brass. Because of this belief, which is often disproved by observed facts, brass is sometimes quenched in water in order to save time, to give the metal a clean surface and to keep the temperature of the annealing-shop as low as possible. One interesting effect of quenching brass from, or near, the annealing temperature will be examined later under the heading of "Quench-roughness," but it is appropriate in this discussion of annealing to draw attention to another defect which quenching may produce, namely, the appearance of free *beta* phase in brasses of low copper content. The harmful influence of free *beta* upon the ductility of brass destined for drawing under the press has been explained earlier in this chapter. Reasonably rapid cooling, for example by an air blast, seems to have no harmful effect on either high or low grade brass ; this treatment may, therefore, be substituted for the more drastic one of water-quenching when rapid cooling is desired. Experience suggests that below about 400° C. water-quenching has no harmful effect on brass.

Quench-roughness. It is maintained by many workers, yet disputed by others, that when brass sheet which has been water-quenched from the neighbourhood of the annealing temperature is worked under the press it develops a peculiar form of surface roughness resembling an orange. An "orange peel surface" is the phrase often used to describe the appearance of articles drawn from brass—or other metals—having an unusually large crystal size, yet the similarity is markedly more striking in the case of quench-roughness. It is important to notice that this particular form of roughness can occur in an equally pronounced form in brass having either a small or a large crystal size.

As a result of as yet unpublished investigations, Johnston [21] thinks that quench-roughness in brass is confined to two zones the peaks of which lie at approximately 63 and 75 atomic per cent. of copper on the equilibrium diagram, the second being the more marked. Erichsen tests made by the author on a number of quenched specimens show that quench-roughness undoubtedly does occur sometimes, but that besides the copper-content factor suggested by Johnston, other factors, not yet isolated, seem to be needed to explain why the effect does or does not appear on different consignments of brass quenched under apparently similar conditions. Ordinary microscopical examination fails to reveal any difference between the microstructure of specimens of quenched brass which do and do not exhibit quench-roughness.

A point of academic interest, and also of possible industrial value, is that experiments show that the cause of quench-roughness can be removed if the affected brass is re-annealed and cooled normally.

The harmfulness of quench-roughness will depend upon the purpose for which drawn articles are required ; when they have to be polished it is sometimes cheaper to discard a whole batch of abnormally rough pressings than to polish them and cause a serious delay in the normal flow of work through a polishing-shop working to its full capacity.

Quench-roughness exhibited by purchased metal can usually be traced to coiled strip having been sprayed with a hosepipe immediately it has been taken out of a muffle. The trouble has occasionally been traced to the action of water-sealed muffles, but usually the temperature of the annealed metal falls to a safe value before it reaches the water. According to Johnston [21] the temperature below which quench-roughness has not been seen is in the region of 400° C., but near the middle of the two ranges of copper-content already indicated the limiting temperature seems to be considerably higher.

It is interesting to notice that Johnston's zones showing what compositions on the equilibrium diagram for brass are liable to quench-roughness bear a striking resemblance to zones found by Hume-Rothery [22] in the gold-zinc system. By quenching gold-zinc alloys within these zones the atomic structure, as shown by X-rays, is changed, although no difference can be seen in the microstructure.

" Orange Peel " Surface. An unusually rough surface on drawn work is often termed " orange peel " by workers in the press-shop. It has already been pointed out that unusual roughness may be caused either by too large a crystal size or, under certain conditions, by quenching brass from near the annealing temperature. The similarity between the appearance of the more severely drawn parts of an article and an orange can be far more striking in the second instance.

Pickling. Brass pressings are usually pickled with one of two distinct objects : to remove scale or stains after an inter-stage annealing operation, or to give a clean, golden appearance to finished articles before they are lacquered or plated or, sometimes, even when no protective or decorative finish is given.

The first object is generally attained by immersing work in a warm solution of sulphuric acid in water containing approximately 10 to 20 per cent. sulphuric acid. The strength of the solution is not of great importance and, because of this, pickling baths are often neglected and merely " made up " when they cease to function. Because of this neglect, solutions sometimes become badly contaminated and the vats charged with a considerable quantity of deposit. When this happens there is a danger of pickled brass acquiring the well-known defect termed "red stain," which is nothing more than areas of electrolytically-deposited copper. Its deposition is determined by at least three major factors: local differences of potential between one part of the brass surface and another; between two or more metals in contact in the bath, such as may arise from widely differing copper contents in two brass strips; or from concentration cells set up by local differences of concentration of copper salts. Whenever a foul bath contains sludge of oxides and sulphates, such differences may become very serious. When brass was less pure the danger of red stain was much greater, due mainly to the higher percentage of iron, an element which as is well known readily displaces copper from solution. With modern brass, containing less than 0·05 per cent. of iron, red stain seldom occurs unless the pickling vats are in serious need of attention, or unless the brass being pickled is of a higher grade than the usual " 70/30 " cartridge metal.

In some works a practice is made of adding a little nitric acid to the ordinary sulphuric acid solution to increase the vigour of the pickling and, sometimes, a small percentage of chromic acid or a dichromate salt to improve the colour of the pickled brass. The last-named additions, although often harmless, must be watched with care because they form a very thin chromate film upon the pickled surface. This film is very hard and tenacious and may lead to two distinct troubles: unusually rapid wear of drawing dies if the pickled brass has to go through further press operations, and difficulty in soldering. The author recalls an instance where a certain proportion of brass pressings gave persistent trouble in soldering; the brass, the forming operations, the annealing and the soldering were the same with all the pressings, but it was found that some of these were being pickled in a vat containing chromic acid and the others in a vat free from this addition.

When the primary object of pickling is to give that golden, lustrous finish which is often held in high esteem by purchasers of the finished product, a stronger acid solution, usually used cold, is preferred and the operation is then known as "bright-dipping." The strength of the solutions used varies widely; a solution containing 30 per cent.

of nitric acid and 30 per cent. of sulphuric acid is popular, the work being immersed for less than a minute, washed and dried quickly. Another recipe is a stronger solution of the one already described for ordinary pickling, namely, a sulphuric acid solution containing additions of chromic acid or a dichromate salt such as potassium dichromate. This gives a more golden colour than the pure, mixed acid solution, but the disadvantages already described naturally tend to be accentuated as the strength of solution is increased.

Occasionally brass articles are pickled by being passed on a conveyor through a tunnel in which sprays of acid impinge upon them from several directions. Provided that the disposition and efficiency of the jets is good and that the duration of spraying is sufficient to ensure adequate pickling, this method possesses many advantages when the shape of the article allows it to be used.

With the exception of " red stain " and possible difficulties due to the formation of a chromate film, pickling is rarely the cause of trouble. Quite often, however, it is blamed for the production of a rough, " orange peel " surface which, although existing previously, is made clearly visible on the clean, bright surface produced by pickling. It has already been explained that the true cause of a rough surface of this kind is a large crystal size in the metal itself or, occasionally, quenching brass from too high a temperature after annealing.

Another common defect for which pickling obviously ought not to be blamed is the disclosure of surface blemishes, such as small spills, which previously have escaped notice on the dull, unpickled surface. A surface condition only slightly less bad than that illustrated in Fig. 104 (p. 148) can, for example, often pass unnoticed on cold-rolled strip fed to the press; and, even though small blemishes open up during pressing, the presence of drawing lubricant may mask them unless a close examination is made.

Concluding this review of defects and difficulties peculiar to brass, readers are reminded again that the *general* defects and difficulties described in Chapter III apply to brass as to any other metal; their omission in this chapter must on no account be taken to mean that they do not occur with brass. Season-cracking, a serious defect to which brass is particularly susceptible, will be studied separately in the next chapter.

CHAPTER V

THE SEASON-CRACKING OF BRASS

When sheet metal has passed successfully through the vicissitudes of the press-shop and of any finishing, protective or decorative processes which may be given to the drawn and trimmed shape, the troubles of consumers are usually ended. Not so those who work in brass, for after the product has left their works in an apparently satisfactory condition it may still fail after a time owing to what is termed "season-cracking."

Although more wide-spread appreciation of the cause of season-cracking and of its remedy has resulted in some diminution in the number of failures attributable to it, sufficient trouble is still experienced in the deep drawing and pressing industry to justify a critical review of present knowledge concerning its nature, the condition under which it occurs, and how it can best be avoided. For more detailed consideration readers are referred to the papers of Moore and Beckinsale,[23] Moore, Beckinsale and Mallinson,[24] Crampton,[25] to the many works mentioned in the bibliographies to these papers, to various articles in technical periodicals; such as that of St. John,[26] and, for consideration of the mechanical aspect of internal strain in cold-wrought metal, to the classic contribution of Heyne.[27]

Nature and Cause

Season-cracking is the not wholly appropriate term commonly employed to describe the spontaneous cracking of deep-drawn, pressed or otherwise cold-worked metal, particularly brass, after a lapse of time. Unless influenced by the shape of the article or by special conditions, season-cracks usually follow an erratic, zig-zag path; in metal which is in a condition of high internal stress, cracks may spread to form an intersecting network which will allow pieces of metal to fall away, leading to actual disintegration of a drawn article.

Season-cracks often resemble cracks produced by the action of mercury and many molten metals, for example, tin or solder. These active agents penetrate stressed brass along its crystal boundaries, and microscopical examination shows that in *alpha* brass season-cracks are also inter-crystalline, as shown in Fig. 108 (p. 164). This finding suggests that they are caused by the inter-crystalline penetration of some external agent whose action is similar to, though usually much less rapid than, that of mercury or molten tin. The statement that season-cracks are inter-crystalline applies only to *alpha* brass : it has been shown [25] that in *alpha-beta* brass season-cracks run between the phases and that in *beta* brass the cracks are trans-crystalline.

Although it is often stated that season-cracking is caused by the action of internal stresses left in the metal as a result of cold-working, it cannot be said that the exact process by which cracks are formed is known. Moore and Beckinsale [23] have shown that brass in a severe state of internal stress will not crack if exposed to air from which the usual traces of contaminatory substances have been removed and, furthermore, that it will not crack in a *contaminated* atmosphere if it is covered with a non-porous electrically-deposited coat of nickel. This indicates that actual contact with some external corrosive agent is necessary for season-cracking to take place. Ammonia is an agent of proved virulence, and it is known that a large proportion of the season-cracking which occurs is caused directly by the action of this substance, of which mention will be made later.

It is possible that some ageing effect, comparable to that which occurs in non-deoxidised steel, may occur in brass and form a contributory cause of the visible phenomenon termed season-cracking. Elsewhere [28] the author has advanced a suggestion concerning the possibility of the precipitation of a certain amount of *beta* phase in the lower grades of drawing-quality brass ; whether such precipitation, or the precipitation of some other constituent, does actually produce or assist season-cracking is at present purely speculative, but the increase in hardness which precedes the softening produced in cold-worked brass by annealing [23] does suggest the possibility of such phenomena.

Season-cracking is influenced by at least four factors, namely :—

(1) The chemical composition of the metal, both as regards major constituents and any impurities which may be present ;

(2) The magnitude of the residual internal stresses ;

(3) The character of the surroundings, and

(4) The shape of the article.

(1) Chemical Composition. Brasses of low copper content are without doubt more prone to season-cracking than are ones of high copper content. Indeed, it is asserted sometimes that brass containing over 80 per cent. of copper is immune from season-cracking ; but this is definitely not so. Moore, Beckinsale and Mallinson [24] fix the limiting proportion at 94 per cent. copper ; Pinkerton and Tait [29] record marked season-cracking in copper containing 0·44 per cent. of arsenic, but none when the proportion of this element is reduced to 0·01 per cent. ; although Johnston [30] has recorded apparent season-cracking in (commercially) pure copper free from arsenic.

The fact that, other conditions being the same, the tendency of brass to season-crack diminishes as the copper content increases, may be due to the greater capacity of the high-copper brasses for cold deformation, to the less likelihood of free *beta* being present in the brass in the purchased condition or, as has just been tentatively suggested, to the less likelihood of obscure precipitational effects taking place in the cold-worked metal after some time. Wurstemberger [18] has shown that traces of *beta* phase in the crystal boundaries of an assumed wholly *alpha* brass increase its susceptibility to corrosive attack by many agents and, furthermore, that any attack proceeds by way of the *beta* particles in the crystal boundaries. As season-cracking is known to be a form of inter-crystalline penetrative attack, it seems only natural that brass containing traces of *beta* in its crystal boundaries should be more likely to suffer from season-cracking than one of similar chemical composition and degree of internal stress but free from *beta* ; a theoretical argument which is confirmed by observation.

In the proportions in which they occur normally, lead, iron, aluminium, manganese and nickel seem to have no appreciable influence on the tendency of brass to season-crack. Phosphorus, on the other hand, definitely does retard season-cracking, and on the Continent this element is sometimes added to cartridge metal in proportions so high—for example, 0·15 per cent.—that some ductility has to be sacrificed. It is doubtful, however, whether very small proportions of phosphorus, of the order of 0·004 per cent. popular with some suppliers, really do exert the noticeably beneficial influence which is commonly claimed for them.

It needs to be established whether the retarding influence of phosphorus is caused by some action of the element itself, presumably upon the crystal boundaries, or merely by the recognised influence of this element upon the crystal size of the aggregate. Crampton [25] states that in brass of 70/30 composition or over, a small proportion of tin definitely reduces the tendency to season-crack, a fact of special interest when the well-known increased resistance to corrosion shown by brass containing 1 per cent. or so of tin is called to mind. Although present knowledge is insufficient to indicate by what precise means phosphorus and tin retard season-cracking, their influence upon possible precipitational effects must not be overlooked.

(2) Magnitude of Internal Stress. In the past it has been assumed that this factor is of paramount importance because experience shows that brass which is free from internal stress, or in which residual stresses left from previous cold-working operations have been partly released by low-temperature annealing, shows little tendency to season-crack in the usual way. For the purpose of this review it is not proposed to challenge this assumption, yet it must be said that occasionally evidence is seen which suggests that some form of cracking —which for want of a better description will be called " corrosion-cracking "—can happen in the entire absence of stress under certain conditions.

It has been observed that season-cracking often occurs in some part of an article yet not in other parts which have certainly been more severely cold-worked. This, together with a somewhat loose use of the terms " magnitude of internal stress " and " residual stresses " has led to some confusion of thought. The important factor is, surely, the magnitude of the *unbalanced* residue of stress occurring in any part of an article. This is aptly demonstrated by the season-cracked shell illustrated in Fig. 109, in which the walls have cracked badly yet the rim at the top, which was rolled over without any local annealing of the wall, shows no trace of cracking although, clearly, the metal in it has been deformed much more severely than that in the walls. Here then, as often happens, the magnitude of the unbalanced residual stresses in the wall of the shell may well have been reduced by the infliction of still more cold-work.

In the middle portion of the shell season-cracks of a typical character occur, the irregular, zig-zag fractures, suggestive of inter-crystalline separation on a large scale, being well defined. In the bottom portion, which has been soft-soldered, bold, straight cracks, one of which has produced complete rupture and opening-up of the shell, are apparent The degree of distortion or " spring " in the wall shows how great must have been the unbalanced stresses present in it before fracture occurred.

Grimston [31] is of the opinion that when the circumferential (hoop) stress is less than 12,000 lbs. (5·4 tons) per square inch it is unlikely that drawn brass tubes of fairly high copper content will fail by season-cracking ; yet, so far as the author is aware, no scale of " threshold " values below which season-cracking will not occur has been published for any one alloy under stated conditions of exposure. Perhaps such a scale would be of but little use industrially, for it would of necessity postulate the existence of a uniform stress throughout the wall of an article and in industrial articles this condition is seldom found. To give one example, fully-annealed—and by inference stress-free—shells which will not normally season-crack will sometimes do so when the outer surface is burnished, yet this operation only work-hardens the outer skin and probably leaves the *average* stress in the wall section well below the threshold value just mentioned. This point is often overlooked and, as a result, lightly deformed yet locally highly-stressed brass is passed out without the usual stress-relieving anneal, sometimes with disastrous results.

(3) Character of Surroundings. It has already been stated that season-cracking is believed to be caused by inter-crystalline penetrative attack by an external agent. In view of this it will be obvious that the surroundings in which an article is kept may exert a profound influence upon its life—life meaning in this instance the time taken for season-cracking to occur. When, as is hardly possible except under

FIG. 108. Ends of season-cracks in 70/30 brass.
Microsection etched and lightly re-polished. × 200.

FIG. 109. **A typical example of season-cracking: a drawn brass shell, edge-rolled at the top and soft-soldered at the bottom.**

laboratory conditions, the surrounding medium is kept free from all traces of active agents, even severely stressed brass will not season-crack. Going to the other extreme, if the surrounding medium carries only traces of a very active agent, for example, mercury, the article may disintegrate in less than a minute, while in a molten metal such as tin its life may be only a few seconds. In between these two extremes there exists a whole range of intermediate conditions found in the various uses to which cold-worked brass is put, and it is with certain of these more normal utilitarian conditions that the following observations are concerned.

The cause of season-cracking in what, judged by ordinary standards, must be described as " clean " air is believed by many authorities to be the presence, perhaps only intermittently, of traces of ammonia. Although this explanation certainly seems a likely one it should be accepted with an open mind because, as far as the author is aware, it has not been proved in the laboratory by observation of stressed brass kept for a really long period in an atmosphere containing only the minute proportion of ammonia found in air drawn from the open countryside.

It is generally accepted that, other conditions being equal, the likelihood of failure by season-cracking is greater at the sea-side than in inland country districts unless abnormal industrial atmospheric pollution exists. In the past this has usually been attributed to the presence in sea air of an appreciable proportion of ozone, but it is now believed that it is the presence of amines which causes season-cracking to occur, as it certainly does, in an atmosphere alleged to contain ozone. Tri-methyl amine, which causes the smell popularly believed to be that of ozone itself, may be the active agent. The author has seen unusually bad season-cracking in brass articles used by workers in salt mines, while in Great Britain a spell of cold weather during which salt is sprinkled on the roads to make them less slippery quickly finds out any stressed brass on the low-lying parts of automobiles. The inference is that the presence of salt in sea air may supplement the influence of amines ; but that either an amine or salt, singly, can cause season-cracking.

Occasionally season-cracking occurs when stressed brass is kept in contact with rubber ; for example, when brass press-studs are used to fasten articles of rubber clothing. A probable explanation of these unexpected failures is that rubber is sometimes treated with anti-oxidising and anti-flex-cracking agents which contain a small percentage of some amine, *e.g.*, an aldehyde amine or a ketone amine. Another unexpected cause of season-cracking is under-cured bakelite which may lead to the failure of brass parts in moulded electrical fittings through the action of a trace of ammonia having its origin in the organic " accelerator " mixed with the moulding powder.

It is well known that the atmosphere in the vicinity of stables and farm-yards is a very dangerous one for stressed brass, and in olden times a car garaged in farm buildings often exhibited many season-cracked brass parts. It is not such common knowledge that the urine of rodents and of some other animals—for example, cats—quickly produces season-cracking, and many tons of cold-drawn brass have been ruined annually owing to the unwelcome attention of mice and rats in old warehouses before the immediate cause of the cracking was realised. Apart from special causes such as this, seemingly ordinary conditions of storage have been known to cause season-cracking owing, it is believed, to the presence of traces of ammonia. Among the causes which have come to the author's notice are sawdust sprinkled on a damp floor and certain kinds of concrete when used as storage floors before they have dried thoroughly.

It has been found that stressed brass is liable to crack if placed in a closed or semi-closed container in which sparking occurs, as in electrical equipment. This is commonly attributed to the action of the nitric acid which is known to be produced by successive stages of oxidation of the nitrous oxide (the first product) in the presence of water, but it seems more likely that the true cause of cracking under these conditions may be traces of ammonia formed in the presence of a catalyst and moisture.

Liquids can act more rapidly than air owing, presumably, to the likelihood of a greater concentration of the essential corrosive agent. Drawing-lubricant contaminated with residual traces of pickling solution can cause season-cracking in a period of hours and, as already pointed out, solutions of mercury can produce cracking within a period of minutes and sometimes seconds. Molten metal, such as tin, can also produce rapid disintegration, but it is not certain whether this special form of attack, although inter-crystalline and influenced by the degree of internal stress existing in the metal, ought to be regarded as true season-cracking because some metals which are not susceptible to ordinary season-cracking will fail under these special conditions.

It is sometimes asked whether the tendency to season-crack is greater when internally-stressed brass is exposed to elevated temperatures during service. It has been shown [24] that the tendency to season-crack is not increased by raising the temperature of the surrounding atmosphere to 100° C. or more, at which temperature no release of internal stress is stated to occur within a period of at least a year, if at all. On the other hand, a low temperature increases the tendency to crack; this is often demonstrated by epidemics of failure among partly-drawn shapes left standing during unusually cold weather.

Grimston [31] has shown that a moist atmosphere accelerates failure, a fact which is to be expected in view of the recognised greater activity of liquids as contrasted with dry air in producing season-cracking.

Investigations as yet unpublished [32] suggest that moisture is a factor of hitherto unsuspected importance, because preliminary experiments show that season-cracking does not occur when stressed brass is exposed to anhydrous ammonia or pyridene in clean air freed from moisture, although cracks occur at once if a trace of moisture is introduced. The true significance of this discovery is not yet established; but it is, clearly, one of fundamental importance which must hold the clue to the precise action of some of the active agents which are known to cause season-cracking under ordinary atmospheric conditions.

(4) Shape of Article. This factor is of importance in that it determines, in addition to the magnitude of the *residual* stresses left in the walls of an article as a result of its shaping by cold deformation, the chances of gradual relief or adjustment before failure occurs and, in particular, the concentration and direction of action of these stresses. So much work has been published upon the influence of the shape of engineering components upon concentration of stresses that elaboration of this aspect is unnecessary here.

It happens sometimes that an observer has difficulty in deciding whether cracks in an article returned from service ought to be attributed to season-cracking or entirely to the action of service stresses. In such instances it is helpful to notice whether the cracks appear to have started at points where *service* stresses are concentrated, and tend to follow a definite path, or whether they seem related more closely to the probable magnitude and location of *residual* stresses in the drawn shape, and follow an erratic path. Often it is, unfortunately, very difficult to distinguish with certainty between season-cracks and fatigue cracks in a used article not of simple shape.

Unless the influence of local "stress-raisers"—such as holes and abrupt changes of section—or of the general shape of the article is very strong, season-cracks usually form at right angles to the direction of the residual stress. The simplest example of this is to be seen in a drawn, circular tube, which cracks in perfectly straight lines from end to end. In rods the direction is the same, but the cracks also penetrate on radial planes. Exceptions to this generalisation are sometimes found when cracks are produced by a form of corrosion-attack rather than by true season-cracking.

Detection

It is fortunate that there is available a simple, reliable, quickly-made test which will reveal whether the stresses existent in cold-worked brass are of a magnitude which is likely to cause the brass to season-crack after a period of time.

The Mercurous-nitrate Test. If deep drawn or pressed brass articles are cleaned by a brief acid dip and then immersed in a solution containing mercury, cracks of a type similar to those produced by natural, non-accelerated season-cracking will become visible after a period of time dependent upon the severity of the residual internal stresses existent in the metal. This test, which the author believes was discovered by Rogers (see discussion to Moore and Beckinsale's paper [23]), has been known for many years, and is widely used to determine the stress-condition of samples selected from a batch of articles.

Although other solutions have been tried, mercurous nitrate remains by far the most commonly used of any, an aqueous solution containing 1 per cent. of mercurous nitrate, previously acidified by the addition of 1 per cent. of concentrated nitric acid, having become an almost standard test in Great Britain. In the United States a 10 per cent. solution of mercurous nitrate is often used, but there is no evidence to show that the time taken by a brass specimen stressed a given amount to crack decreases as the strength of the solution increases. It seems probable that the solution ought to be regarded as a carrying vehicle for mercury atoms rather than as a corrosive agent, and that, provided a certain limiting concentration of mercury atoms is exceeded, the desired action will occur after a time determined by the degree of internal stress in the specimen and not by the concentration of the mercury atoms in the test solution. Experiments made by the author on a number of shells drawn in the same tools failed to distinguish between the action of a 0·1, a 1 per cent. and a 10 per cent. solution. As a 1 per cent. solution is adequate, there seems to be no object in using one having a higher concentration.

On the other hand, the concentration of the nitric acid in the solution *is* important. Should this be too high, the time taken by any given specimen to crack is shortened, but it is uncertain whether this is due to some special action of the acid or whether it is due merely to an increase in temperature brought about by the normal action of the acid on the brass. It follows that the test solution should always be used cold, preferably at room temperature.

In Germany a solution containing 1 per cent. of mercurous chloride acidified with 0·4 per cent. of hydrochloric acid is sometimes used instead of one of mercurous nitrate. In the opinion of some authorities the chloride solution is the more active of the two, but the author has failed to find any such difference.

When making up the standard mercurous nitrate solution it is desirable to acidify the water before adding the mercurous nitrate. If this is not done, a basic mercurous nitrate is formed which is insoluble and the solution is spoiled. A convenient procedure is to moisten the crystals of mercurous nitrate with strong nitric acid and then add the water.

In spite of the simple nature of the mercurous-nitrate test, considerable misunderstanding often occurs owing to variation of the conditions under which it is carried out and of the interpretation of the

FIG. 110. Characteristic failure produced by the mercurous-nitrate test: a drawn and rolled rim in brass of 64 per cent. copper content, inadequately low-temperature annealed.

[By courtesy of Birmingham Electric Furnaces Ltd.

FIG. 111. Forced air circulation furnace for annealing brass pressings. Observe charging baskets and automatic temperature controlling and recording apparatus.

[To face p. 168.

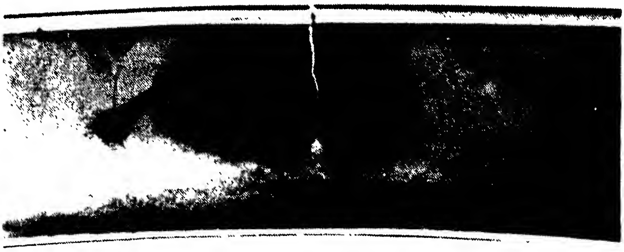


FIG. 113. Season-crack in unplated area, due to presence of an entrapped air bubble, on a drawn and rolled rim in brass of 64 per cent. copper content.

FIG. 114. Inter-crystalline cracks produced in soft brass by action of soldering flux residue.

Microsection cut normal to surface and beyond the actual soldered area. × 200.

Top : unetched.

Bottom : etched.

[*To face p.* 169.

results obtained. Confusion arises, for instance, because some observers record the time of immersion required to produce the first sign of a crack, whereas others await the appearance of clearly visible cracks such as are apparent in the drawn and rolled rim illustrated in Fig. 110, a condition which developed after five minutes' immersion. Needless to say, this rim has not received an adequate stress-relieving treatment. Again, certain specifications stipulate that, in order to pass the test, work must not crack after having been immersed for a certain period, for example, fifteen minutes, and then washed and allowed to hang suspended in air for a certain number of hours, possibly twelve or even twenty-four. Those familiar with the test know that, very frequently, articles which will withstand immersion for a fairly short time will crack badly during subsequent standing. Clearly, for useful comparison to be made, *the conditions of the test must be specified* ; it would be an advantage if certain conditions could be standardised and accepted internationally.

Even the significance of a straightforward immersion test is interpreted differently by different workers. For instance, St. John [26] suggests the following relationship :—

Time taken to Crack in Mercurous Nitrate Solution.	*Behaviour during Service.*
Less than 2 minutes . . .	Failure certain.
Between 2 and 5 minutes . .	Failure probable.
Between 5 and 15 minutes . .	Failure possible but unlikely.
More than 15 minutes . . .	Failure unlikely.

As a result of their own experience other workers may not accept this scale of behaviour during test and probable service behaviour ; similar scales both below and above it have been drawn up to represent opinions which, obviously, will be influenced by the type of article and the service with which the originators are concerned. Having regard to the unreliability of any scale of this kind it seems safest, unless service conditions are known to be unusually constant, to give all brass articles a proper stress-relieving treatment and not to allow them to pass out in a state such that any slightly abnormal circumstance may make them crack.

To summarise, the mercurous-nitrate test is of very great value for determining simply and quickly, although by destruction, whether any particular sample has received a specified low-temperature annealing ; but the adequacy of this treatment and the conditions of the test must remain at present matters for judgment by individuals fully conversant with the service requirements of any particular article.

Other Methods of Test. Besides the mercurous-nitrate test there are two others which justify mention. Of these, one is the classic method for the investigation of internal stresses used by Heyne,[37] in which careful measurements of a specimen are made before and after the removal—usually by machining—of successive layers, thus gradually releasing unbalanced stresses. This method is always a difficult one to use on non-circular or thin specimens ; in shells drawn from thin sheet it becomes virtually impracticable, although useful information can often be gained by carefully cutting completely through the wall of a drawn shape in one or more places and observing the "spring" or distortion which occurs. A fine-tooth saw should always be used for making the necessary cuts ; shears or tin-snips invariably distort the wall and mask some of the true deformation.

The second method is the rather more elaborate one of X-ray examination. Its great and unique advantage is that it is non-destructive, but the apparatus is expensive and it must be admitted that, in spite of the optimism of some of its protagonists, precise measurement of strain by means of X-rays is at present hardly possible in industry if, indeed, in the experimental laboratory. This subject is dealt with in rather greater detail in Appendix B.

It is important to notice that whereas the mercurous-nitrate test is simple, cheap, can be made by almost unskilled labour, reveals even a small danger-zone in an otherwise satisfactory article and enables an immediate decision to be made, the measurement of strain by either mechanical or X-ray methods needs skilful manipulation, is usually open to considerable experimental error, and examination is confined to some small area of an article which may give a misleading indication of the condition of other parts. Even when measurement has been made the results are of questionable value until such time as precise and well-proved correlation has been established between strain—expressed numerically—and tendency to season-crack. For this reason, in spite of its failings, the mercurous-nitrate test will probably remain the standard industrial test for season-cracking.

Prevention

Stress-relief. The only really effective preventative for season cracking is the release, or rather reduction to a safe magnitude, of such internal stresses as remain in the metal as a result of the cold deformation to which it has been subjected subsequent to its last annealing. The effect produced by additions of tin and phosphorus to the metal itself, or by electro-plating the finished article, is insufficient to justify recognition as effective preventatives, although the possible value of their mitigating influence must not be overlooked.

Because the potential danger of season-cracking has at last attained almost universal recognition throughout the deep-drawing industry, failure attributable to this phenomenon can usually be traced either to the intentional omission of a low-temperature annealing operation by individuals concerned more with the speed than with the quality of output, or else to the non-attainment of the assumed annealing temperature due to unsatisfactory heating conditions in the furnace employed. Of these two causes the former is inexcusable but the latter is, unfortunately, often difficult to avoid by reason of the very unsatisfactory design of many furnaces, and of the less excusable lack of appreciation of such conditions by responsible persons. The development of continuous furnaces having a heating zone of fairly small section relative to the size of the articles passing through it has helped, but, without doubt, the use of "forced" as distinct from "disturbed" air circulation in furnaces of suitable design offers the most certain cure for dangerously uneven heating conditions.

In furnaces of this type, one of which is shown in Fig. 111 (p. 168), hot air is continually circulated at considerable velocity over heater elements, which may be disposed on the inner walls of the furnace chamber or in an entirely separate chamber, and through the basket or charge of work. By this means the whole contents of the basket attains the desired temperature in a very short time, a matter which presents considerable difficulty when shells of any size have to be heated wholly by radiation, or even by the slow-moving air in "disturbed" air furnaces, to the low temperatures now under consideration. By disturbed air furnaces is meant furnaces of conventional design as regards heating arrangements, but having fans installed in them which, although they agitate the air in the chamber, do not cause it to circulate rapidly over heating elements and through the charge.

The treatment usually given to drawn or otherwise cold-worked articles to prevent season-cracking is a low-temperature anneal for about half an hour at between 250 and 350° C. The exact time and temperature will depend upon the severity of the deformation which has been imposed upon the metal, upon the degree of softening which can be permitted in it, upon the nature and surroundings of the anticipated service of the article, and upon the percentage of copper in the brass. Annealing by immersion in boiling water does not appear to be adequate in the majority of instances; a temperature of at least 250° C. and often higher is usually required to produce the necessary degree of stress-relief.

It is very necessary that a stress-relieving treatment be given to articles after the *final* cold-working operation. Drawn articles which have been quite satisfactorily low-temperature annealed may season-crack in service through internal stresses produced as a result of some burnishing or other finishing operation given after the annealing treatment.

Even though the necessity for low-temperature annealing is appreciated and such treatment is actually included on the production lay-out of articles, cracking can still occur should this treatment be delayed. There can be no excuse for not giving finish-drawn articles an immediate anneal, but, in some factories, it is not easy under existing conditions to avoid a lapse of days if not weeks between certain successive drawing operations. In such instances the inclusion of extra low-temperature annealing operations prior to anticipated periods of standing would prevent the formation of much scrap. Articles stored in the open are more prone to such failure than are ones stored under cover and at a normal indoor temperature; during exceptionally cold weather it is quite common for a considerable loss of drawn work to result from the cracking of partly-formed articles awaiting further drawing.

Drawing-lubricant left in contact with stressed brass can produce cracking if a stress-relieving anneal is delayed for some hours. In this connection Grimston [31] has recorded the high activity of "suds" which have become contaminated with sulphuric acid from traces of pickling solution left on brass surfaces. The remedy is obvious.

Relationship between Time and Temperature of Stress-relieving Anneal. Although it is possible from experimental determinations to

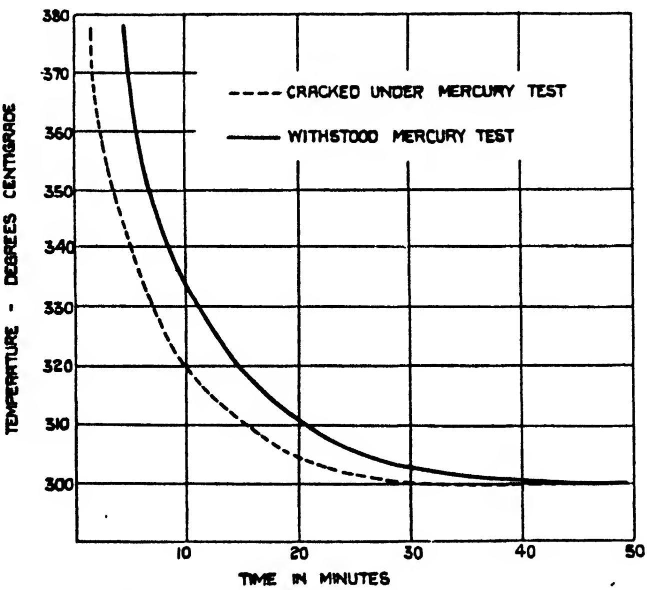


FIG. 112. Curves illustrating relationship between annealing temperature and time of soaking required to remove dangerous internal stresses, as revealed by the mercurous-nitrate test, from certain shells drawn in brass containing 63 per cent. of copper.

draw a curve representing the times of annealing at various temperatures between 250° and 400° C. which are necessary to produce immunity from season-cracking in any given article as shown by the mercurous-nitrate test, the fact must not be lost sight of that, under production conditions, it is far easier to secure uniform heating of a furnace charge, or even of a single article, for *thirty* minutes at 250° C. than for, say, *three* minutes at 400° C.

Fig. 112 shows such a curve plotted from the results of experiments made with shells of the kind illustrated in the frontispiece deep-drawn from 0·027 inch-thick brass containing approximately 63 per cent. of copper. It will be observed that in this instance the curve tends to become asymptotic at about 300° C., whereas with some articles an adequate degree of stress-relief can be obtained at a somewhat lower temperature. This illustrates the caution, given previously, that it is impossible safely to predict minimum times and temperatures for low-temperature annealing: each article must be treated individually.

Effect of Stress-relieving Anneal on Hardness of Cold-worked Brass. Very frequently it is desired to retain the hardness which has been imparted to an article by deep drawing and, for this reason, stress-relieving treatment is sometimes purposely omitted by persons unappreciative of the dangers of residual internal stress. It is impossible to make specific statements as to annealing temperatures which will produce a certain degree of softening or of stress-relief, because both these effects will vary with the amount of cold-work which has been imposed, with the magnitude of the internal stresses and with the composition of the brass.

It is not recognised generally that when cold-worked brass is annealed, an increase in hardness precedes the usual decrease. Moore and Beckinsale [23] have shown that an increase in hardness of from 8 to 12 per cent. is the first reaction of cold-drawn brass of 70/30 composition to an annealing treatment, this increase being attained in approximately the following times at the stated temperatures :—

100° C.	30 days.
200° C.	2 hours.
275° C.	30 seconds.

The (presumed) initial increase in hardness at temperatures higher than this was too rapid for measurements to be made. These workers are of the opinion that an adequate relief of stress can be produced by an annealing treatment controlled so that the peak hardness is just passed and the final hardness is no less than that existing prior to annealing.

Although this may be possible in certain instances, the author has come across very many drawn brass articles with which, for example, a soaking of thirty seconds at a temperature of 275° C. is not sufficient to render them immune or even unlikely to season-crack. Quite often the annealing treatment necessary to secure a fair measure of immunity from season-cracking will produce only a slight, and often negligible, softening; but it is desirable clearly to recognise that, with some articles, appreciable softening may be inseparable from a desirable measure of stress-relief.

There is evidence to show that, to secure a given measure of stress-relief, a short anneal at a high temperature tends to produce more softening than a longer anneal at a lower temperature, while very sudden heating to 400° C. or over may itself produce cracking in severely stressed brass even when the proportions of iron and lead are low.

Electro-plating as a Means for Preventing Season-cracking. In view of the fact that the action of some external accelerating agent, such as a minute proportion of ammonia in the surrounding atmosphere, is apparently necessary to produce season-cracking, it may well be asked why this action cannot be prevented by coating internally-stressed articles with some protective covering. Apart from the obvious possibility of the local destruction of such a coating by abrasion during service, it has been demonstrated [24] that ordinary paints and lacquers are not impervious to the agents which cause season-cracking. Plating, on the other hand, can offer a fair measure of protection, and a thick, *continuous* coating of nickel does ensure immunity from season-cracking under conditions which without it would quickly produce failure. Unfortunately, it must be conceded that the nickel plating of commerce is not always thick or continuous; and, although there is no doubt whatever that the common practice of plating drawn brass articles plays an unsuspectedly useful *rôle* in minimising the likelihood of season-cracking in unannealed articles, the deliberate use of plating as a substitute for stress-relieving treatment is unwise. Furthermore, instances are on record of highly stressed articles having cracked when plunged into the plating bath, due possibly to the presence of ammonium salts in the solution.

Convincing practical demonstration of the ability of nickel plating to prevent season-cracking is often to be found in articles which bear an area which has not been properly plated, for, when such an article season-cracks, the cracks usually start in, and are often confined to, the unplated area. An example of this is illustrated in Fig. 113 which shows a portion of a drawn and edge-rolled rim on the inner and unseen surface of which there remains a small unplated area caused by the entrapment of an air bubble when the rim was suspended vertically in the plating vat. The crack shown in the photograph is the only one visible on the rim, which in its entirety is similar in shape to that illustrated in Fig. 110 (p. 168), and it will be seen how they are confined to the circular, unplated area, and how no cracks have occurred even in the corroded areas, seen as dark marks in the photograph, produced by contact with rusty steel. As these rims do not usually give trouble when the plating is continuous, the protective power of the plating is clearly demonstrated.

The conclusion must therefore be reached that, as producers of deep drawn and pressed articles are not able to stipulate what kind of atmosphere their products will be subjected to in service, their only safe remedy against possible failure by season-cracking lies in giving to each and every article an adequate low-temperature annealing treatment after the last cold-working operation, be it deep-drawing, pressing, rim-rolling, expanding, folding, or even severe burnishing. For the reasons already stated, furnaces employing forced circulation seem to offer the best available means for giving this treatment, which need not always cause a serious reduction in the hardness of the drawn shape.

Cracking of Soldered Brass

Trouble is experienced sometimes owing to brass cracking in the vicinity of soldered joints after a period of time. This kind of failure, particularly when it occurs in drawn articles, is often casually dismissed as season-cracking, yet it is by no means certain that this conclusion is always entirely true. Season-cracking implies the existence of internal stress ; as cracks sometimes occur in the vicinity of a soldered joint made in brass which is fully annealed and unstressed in service, it seems necessary to attribute these failures to some kind of pure "corrosion-cracking" which, clearly, may also accelerate the true season-cracking of stressed brass.

Cracking is generally caused by the action of the soldering flux used or of its decomposition products, not by that of the solder itself. Indeed, it is noticeable that failure usually occurs well beyond the area covered by solder, from which it may be reasoned that the solder seems actually to protect the underlying brass from the action of the flux. Fig. 114 shows typical cracks in soft brass produced by the action of the residue of a proprietary alleged "non-corrosive" flux beyond the soldered area. It would be difficult by inspection of photomicrographs to distinguish between these cracks and ones due to season-cracking of stressed brass, and it seems likely that fundamentally the two kinds are similar, for both are caused by the inter-crystalline penetration of an external agent.

The corrosive action of soldering fluxes has received a considerable amount of study during recent years, and readers interested in this subject are advised to study the many papers and articles which have been published. It is regrettable that a certain amount of loose thinking and loose description has become associated with the terms "non-corrosive flux" and what is described as "neutralising" a flux. Barber,[33] in an excellent and acute review, maintains that damage is caused not by the acid nature of a flux but by the electrolytic action of the residue ; that acidity resulting from hydrolysis cannot be completely neutralised, and that neutralising agents often spread the flux over a wider area and do more harm than good.

Complete removal or transformation of " corrosive " or hygroscopic fluxes is usually a difficult matter under industrial conditions. In the light of present knowledge, the only way to avoid all possibility of cracking in the vicinity of soldered joints seems to be to use a rosin flux.

At the end of this review of the season-cracking and—to coin a new term—the solder-flux-cracking of brass, readers are reminded that some of the other industrial copper alloys, notably the nickel silvers, suffer from the first though not always from the second defect. Although this tendency will be mentioned and suitable stress-relieving treatments described when the properties of a number of industrial metals and alloys are discussed in subsequent chapters, no further study of the phenomenon of season-cracking will be attempted because the general observations made in this chapter apply in principle to other alloys.

Another warning must be given lest season-cracking be confused with stress-cracking. Season-cracking seems to be confined to alloys containing copper and needs the action of some external corrosive agent as well as the influence of internal stresses in the metal. Stress-cracking, on the other hand, may take place in any severely cold-worked metal or alloy irrespective of whether copper is or is not present, and does not need the action of an external agent.

NOTE. Since the above survey was written results of some interest have been published by Johnston.[136] From these certain general facts seem to be established. Ammonia appears to be the only corrosive agent which can, with certainty, be stated to be essential to cracking in service. The presence of moisture is also a *sine qua non*, for ammonia in dry conditions fails to produce any effect. Free oxygen is also necessary ; experiments in which attempts were made to exclude oxygen showed that ammonia and water alone were not sufficient. Cracking in service is always preceded by tarnish or darkening of the metal surfaces, and when this was prevented cracking failed to appear even after two years' exposure to cracking conditions. Where traces of ammonia were combined with an acid, and the resulting salt was prevented from dissociating, no cracks were formed even under apparently severely corrosive conditions. When the dissociation of the salts was encouraged cracking also appeared. Johnston's experiments link these results with a type-equilibrium

$$(NH_4)_2CO_3 \rightleftharpoons CO_2 + H_2O + 2NH_3$$

which, if caused to move to the right, accelerates cracking, but if moved to the left inhibits it. Pyridine and methylamine, wet or dry, failed even to produce tarnish. The wide-spread belief that snow and frost accelerate cracking receives support from work quoted on the ammonia content of snow and hoar-frost. The paper should be consulted as it is suggestive of further lines of research.

CHAPTER VI

DEFECTS AND DIFFICULTIES (STEEL)

In this chapter it is proposed to examine a number of defects, such as chemical segregation and slag inclusions, which are specially prevalent in steel sheet; and also certain peculiar difficulties which are encountered when it is deep drawn or pressed, for example those occasioned by critical-strain crystal growth, stretcher-strain markings and ageing.

Chemical Composition

If the term "chemical composition" is interpreted as the percentage of the carbon and common impurities as usually estimated by chemical analysis, it can be said that chemical composition is not often directly responsible for trouble in the press-shop. On the other hand, localised segregation or concentration of impurities, the intensity of which in thin sheet cannot be estimated by ordinary methods, does sometimes account for the actual failure of sheet under the press. Typical illustrations of various forms of segregation are given in the section devoted to this particular defect. When considering the effect of chemical composition upon deep-drawing properties, it is well to bear in mind that it is most unlikely that the *average* proportions of harmful impurities in low-carbon sheet of industrial quality will ever be reduced to such low values that segregation will not prove harmful.

A study of the influence of chemical composition upon the deep drawing and pressing properties of low-carbon steel sheet falls automatically into a study of the influence of impurities; and it is proposed to examine separately the action of each of the more common elements when these are present in the proportions normally found in sheet of industrial quality. As some of these influences, for example that of manganese in rendering sulphur relatively harmless, are complicated and in some instances not yet understood fully, the following comments are to be regarded as entirely general and elementary; for a more erudite treatment of this very important subject readers are referred to some of the newer text-books on the metallurgy of steel. Particular attention is drawn to the fact that the *combined* influence of impurities is often of greater importance than that of single impurities assumed to act individually. For proper discussion of this very complicated and in many instances incompletely understood aspect, advanced readers are again referred to modern literature.

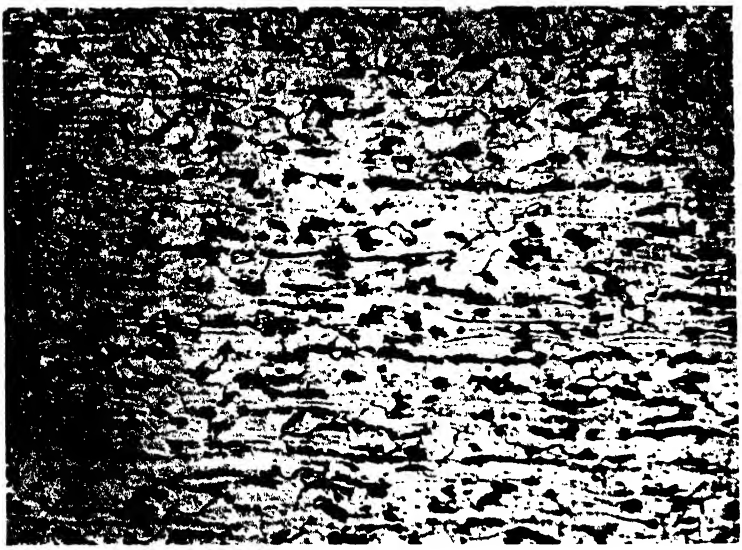
Carbon. Although carbon is usually regarded as an essential constituent rather than an impurity in most steels, it is permissible to class it as an impurity in the special instance of the low-carbon varieties of sheet manufactured specially for deep drawing and pressing. The influence of increasing carbon is nearly always injurious to true deep-drawing properties, and the severity of this influence will depend partly on the proportion of carbon present and partly upon the condition in which it exists in the finished sheet. An exception to this statement must be made for special varieties such as "panel steel," in which a relatively high carbon content, perhaps of the order of 0·2 per cent., is specified purposely to increase the strength of a pressed shape which can be made by imposing only a relatively small amount of deformation on the original sheet in the press.

In the very low carbon steel sheet which is widely used for deep drawing and pressing, the condition in which the carbon exists is usually of far more importance than the actual percentage revealed by chemical analysis. A very small percentage of carbon will go into solution in ferrite, and for practical purposes this part is often assumed to be of no importance; yet, as the solubility of carbon in *alpha* iron falls rapidly from its maximum at about 720° C. (see equilibrium diagram in Fig. 134, p. 202), it may be that the condition of the precipitated carbide has an unexpectedly large influence upon ductility even though the particles are too small to be seen under the microscope.

The bulk of the carbon occurs as iron carbide (Fe_3C), and it is the condition and manner of dispersion of this compound throughout the crystal structure of the finish-rolled sheet sent to consumers which is the important factor. For the ductility of the sheet to be at its maximum and directional properties at a minimum, the carbide must exist as infrequent, small, isolated globules, a state which follows either from the continued separation and balling-up of "divorced" pearlite or from annealing below the critical range after quenching from above it. For most purposes the ductility of sheet containing a lower percentage of carbon will not suffer appreciably if this separation and spheroidisation does not proceed to its final stages, and the carbide globules are allowed to remain in small colonies or discontinuous stringers, as illustrated in Fig. 115A.

When the carbide exists as areas of pearlite, the number, size, shape and position of these areas in the crystal structure will each influence the ductility, and in some instances the directional properties, of the sheet. (Pearlite is the name given to a common micro-constituent of carbon steels cooled slowly from above the critical range, and consists of alternate lamellæ of carbide and ferrite; prolonged annealing may cause the lamellæ of carbide to "ball up" and become "divorced.") Carbide is very much harder than ferrite and possesses no useful range of plastic deformation, therefore the hardening and keying action of the carbide particles or pearlite areas upon the crystal aggregate in

A



B

FIG. 115. Photomicrographs showing two forms in which carbon occurs in annealed low carbon steel sheet.

A : Stringers of carbide particles. × 500.
B : Elongated particles of pearlite. × 250.

Microsections cut normal to surface of sheet and parallel to direction of rolling.

[*To face p.* 178.

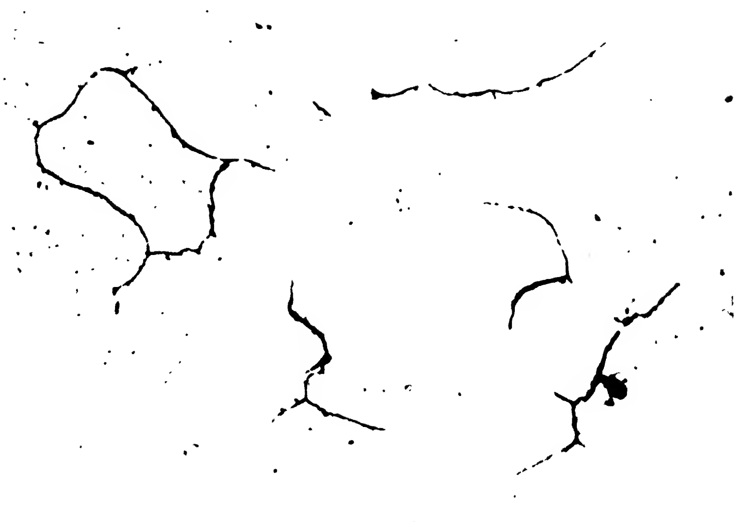


Fig. 116. Grain boundary envelopes of carbide in annealed low carbon steel sheet.

Microsection cut normal to surface of sheet and etched to throw carbide into contrast. × 200

[*To face p.* 179.

which they exist increases as their number and size increases. In contrast to the sheet shown in Fig. 115A, the effect of the pearlite areas upon the ductility of the sheet shown in Fig. 115B will be unmistakable; and when, as in this specimen, the areas are elongated, the "directionality" manifested by the sheet will be increased for obvious reasons. In normalised low-carbon sheet there is a tendency for the carbide to exist as small areas of pearlite situated at the junction of crystal boundaries (Fig. 54B, p. 68) and not as discontinuous stringers of partly-divorced pearlite trailing through perhaps a number of crystals. The carbon content of most deep-drawing quality sheet is, however, so low that the influence of pearlite in this "normalised" condition, although not the one associated with maximum ductility, is of no serious consequence and indeed often preferable to stringers if these are of any size and frequency.

One other condition in which carbide may occur remains to be considered, namely, in the crystal boundaries. This condition, in contrast to the relatively mild influence of those already examined, is seriously injurious to deep-drawing properties. The reason for this will be clear if it is remembered that what appears under the microscope as a continuous, line network outlining the crystal grains is only the appearance, on a two-dimensional plane micro-section, of what in reality are actual envelopes surrounding the crystal grains in three dimensions. When the envelopes, no matter how thin they are, consist of a hard, brittle substance such as iron carbide, the ductility of the structure as a whole is certain to be impaired in all directions, perhaps seriously. A typical example of carbide segregation in the crystal boundaries of low carbon sheet is shown in Fig. 116. Although not an abnormally bad example, the segregation shown caused the sheet to fail during the first attempted press operation.

So far, only the influence of carbon in the combined form, that is as cementite (Fe_3C), has been discussed; but a very small percentage of carbon often exists in true solution in *alpha* iron (ferrite). This percentage is likely to be highest after rapid cooling from above 720° C., for example, when thin sheet has been cooled from the normalising temperatures in perhaps less than two minutes. The reason for this is the change in solubility of carbon in *alpha* iron with temperature which is shown in the equilibrium diagram in Fig. 134 (p. 202).

Very little is known about the influence of carbon in this condition, but it seems likely that differences both in the ageing properties—a matter discussed later—and also in the stiffness and general deep-drawing properties of low-carbon sheet are caused by differences in the percentage of carbon held in solution in the atomic form.

Silicon. Silicon goes into solution in ferrite, hardening it and reducing its ductility. In the proportions in which this element is usually found in deep-drawing quality low-carbon sheet its direct influence as an alloying element is of little consequence, for in fully killed steels the percentage may be no higher than 0·05, while in rimming steel only a trace is to be expected. When the percentage of silicon rises to about 0·15 per cent., an appreciable drop in the ductility of the sheet will become evident. When—as in some electrical irons—1 per cent. is added, little or no deep drawing can be accomplished by ordinary methods and, when the proportion is increased still more, it becomes impossible to carry out pressing and, eventually, even bending operations. Silicon is an element which is not subject to pronounced segregation, although when it does segregate it is extremely difficult to diffuse again.

The indirect influence of silicon is profound because, in conjunction with manganese and sometimes other elements, it assists the deoxidation of steel during manufacture. As pointed out elsewhere, present knowledge suggests that the proportion and condition of the oxygen has a most important influence upon the ductility and general behaviour of deep-drawing quality steel sheet. Beyond serving as an indication whether the steel is of fully-killed, semi-killed or rimming type, the percentage of silicon existing in any sheet cannot be regarded as a factor of importance unless it is well outside the normal range for these three respective varieties. It may be remarked that 0·10 per cent. of silicon raises the critical range in steel by about 12° to 15° C.

Manganese. The direct effect of manganese as an alloying element is small, because in steel of ordinary deep-drawing quality the proportion which goes into solution in the ferrite will be small. When for any reason the percentage of manganese rises above 0·6, the hardening influence of this element becomes distinctly noticeable in the behaviour of the sheet under the press. The percentage of manganese usually found in deep drawing and pressing quality steel of good class is often about 0·30 per cent. in " rimming," and up to about 0·45 per cent. in " killed," steel. 0.5 per cent. of manganese depresses the critical range of steel by about 25° C., a fact which is often forgotten.

The indirect action of manganese is of the greatest importance. Firstly, a small proportion forms manganese carbide (Mn_3C) which is always present in solution with iron carbide (Fe_3C), the effect of which constituent has already been indicated. Secondly, in conjunction with silicon and sometimes other elements, manganese deoxidises the steel with the important consequences which have been explained already. Thirdly, excess manganese prevents the formation of iron sulphide (FeS) a compound which, because it forms envelopes surrounding the crystal grains, is highly detrimental to ductility at both high and low temperatures.

The beneficial action of manganese in converting nearly the whole of the sulphur present into slag is, however, partly offset by the harmful influence of the particles so formed. It is desired that prior to solidification of the steel the manganese shall convert the sulphur and that, being lighter than and immiscible with molten steel, the particles of slag formed in conjunction with manganese oxide and silicates shall rise to the top of the bath, ladle or teemed ingot. Unfortunately in practice many particles invariably remain in suspension until their escape is prevented by the solidification of the surrounding metal, and the size and number of these entrapped particles affects the deep drawing and pressing properties of the finished sheet in the manner explained in the section headed " Inclusions."

Sulphur. The precise influence of sulphur upon the deep drawing and pressing properties of low-carbon steel sheet cannot be related directly to the percentage of the element revealed by ordinary chemical analysis. Because of well-recognised associated defects, for example brittleness and red-shortness, it is usual to hold this element to a low figure, generally about 0·045 per cent. maximum, although the actual percentage present in good deep-drawing quality steel is usually appreciably less than the specified maximum.

The direct action of sulphur as an alloying element need not be considered, because for all practical purposes it can be assumed that the whole of the sulphur present enters into the slag in the presence of manganese or, if—as is unusual—the proportion of manganese is insufficient, exists as iron sulphide. Owing to its tendency to form envelopes surrounding the crystal grains, iron sulphide renders steel very brittle ; its presence is usually avoided by the addition to the molten metal of an adequate proportion of manganese which, it is commonly held, should be at least five times that of the sulphur present, because the action is a complicated one and not, as was believed at one time, the *direct* formation of the simple chemical compound manganese sulphide. As a primary cause of the failure of low-carbon steel sheet under the press, the presence of iron sulphide can be dismissed.

The indirect action of sulphur as particles of slag in the presence of manganese sulphide is easily understandable. If these particles are few, small, isolated and well distributed, little harm will result ; when numerous or large, the deep-drawing properties of the sheet will be impaired and, if genuine segregation has occurred, seriously affected sheet may fail altogether even though only a light draw be attempted. Illustrations of various forms of slag inclusion are given in the section which deals with inclusions.

Phosphorus. Phosphorus dissolves in ferrite, making it harder and less ductile. An influence usually attributed to the presence of an unusually high proportion of phosphorus is that of diminishing the normal size of the ferrite crystals either throughout the whole " core " of a sheet rolled from rimming steel, or in the narrow segregated planes of high phosphorus content which often occur within the core. It is held by some that this influence on crystal size is caused not by phosphorus but by oxygen, the proportion of which element usually follows that of the phosphorus in any steel. Whatever the true explanation, it follows that where a high percentage of phosphorus occurs the crystal size will tend to be unusually small, and the deep drawing and pressing properties of the steel will be influenced by this in the usual way as well as by the hardening effect exercised by the phosphorus held in solution in the crystals themselves.

A peculiarity of phosphorus is the striking way in which a relatively small percentage will raise the limit of proportionality of low-carbon steel while affecting the hardness, tensile strength and impact value to a much smaller degree. This property is taken advantage of in some structural steels, but in sheet which has to be deep drawn or pressed an unusually high limit of proportionality is often a disadvantage.

As explained later, the attitude of metallurgists toward the hitherto assumed harmful effect of phosphorus in steel has changed. It is now believed that it is not the phosphorus itself which is necessarily harmful, but other effects or conditions which usually accompany an inefficient removal of phosphorus during open-hearth steel-making. In the special high-phosphorus steels just mentioned the molten metal is treated in the usual way to reduce the proportion of impurities, including phosphorus, to normal values, and phosphorus is then added at the appropriate stage to raise the percentage of this element to the desired figure. In other words, the high percentage of phosphorus present in finished steel of good quality is not caused by an inefficient carrying out of the normal steel-making processes.

As yet these high-phosphorus steels have not found their way to the press-shop, and a high phosphorus content in deep-drawing quality steel can still be regarded as an indication that the steel is of decidedly inferior quality. Sheet of good quality will seldom contain more than 0·03 per cent. of phosphorus; sheet containing more than 0·05 per cent. should be regarded with suspicion. It must be emphasised, however, that *average* percentages estimated in the usual manner give no indication whatever of the principal danger associated with phosphorus in deep-drawing quality steel sheet, namely, the high concentration which this element assumes when, as often happens in rimming steels, it segregates in the ingot and is rolled out into thin planes having low ductility in the finished sheet. This defect, which will be discussed later under the heading of "segregation," is a serious one and is dependent not so much upon the average percentage of phosphorus present in the steel as upon the manner in which the ingot solidifies.

Nickel, Chromium and Copper. Each of these three elements is soluble in ferrite, slightly increasing its hardness; chromium may also form a double carbide even though the percentages of carbon and chromium present are very small.

Owing to the increasing amount of alloy-steel scrap which is melted down, it is becoming more common for the proportions of nickel, chromium and copper in assumed plain carbon steel sheet to reach a value sufficiently high to cause a small yet noticeable diminution in ductility. It may soon be necessary to specify a maximum content for these three impurities, particularly nickel, when sheet having maximum ductility is desired.

Nickel exerts a marked influence upon the rate at which austenite crystals grow when steel is soaked at a temperature above the critical range, and quite a small percentage of this element will retard the rate of crystal growth considerably. Even the small percentages of nickel which, due to the increasing use of nickel-steel scrap, are becoming common in the dead-mild steel used in the press-shop will prevent excessive crystal growth when the steel is normalised at a relatively high temperature. In this sense the presence of nickel is beneficial.

Tin. Tin is rarely responsible for difficulties encountered in the press-shop, because the presence of an unusually high proportion of this element makes the steel difficult to hot-roll. If by any chance an ingot of high tin-content should survive the hot-rolling stage, the sheet produced may contain surface cracks which will become filled with oxide during annealing treatments and produce the troubles usually associated with cracks of this kind.

Gases. The effect of gases, whether in solution, occluded or present in combined form such as oxides or nitrides, is not yet understood fully. It is possible that the phenomen termed " ageing " which causes the ductility of low-carbon sheet to fall after a period of time, or unexplained inherent low ductility in certain batches of sheet of apparently normal structure and chemical composition with respect to the common elements, may be caused at least in part by the direct or indirect action of gases, particularly oxygen and nitrogen.

Oxygen is believed to be the most important of the gases usually found in steel sheet of industrial quality. In the light of present knowledge theories explaining the influence of oxygen must for the most part be regarded as tentative, but it seems fairly certain that one important influence is to hinder the removal of ingot structure during forging, rolling and annealing, giving more sharply defined zones of chemical segregation. Its influence on ingot structure, as exemplified by deoxidised (killed) steels and incompletely deoxidised (rimming) steels, has already been described in Chapter II when the manufacture of steel was being described.

In low-carbon steel a high percentage of oxygen tends to give a relatively large austenitic crystal size. This influence is of greater importance than might be imagined, because upon it depends to some extent the disposition of carbide and other particles which will be forced to the austenitic crystal boundaries, there to remain as a "shadow" outline of the original structure after annealing has produced an entirely new set of ferritic crystal boundaries. Indeed, it may be shown eventually that this shadow outline, normally invisible under the microscope, may have an influence upon deep drawing and pressing properties comparable in magnitude with that which, under the guise of "inherent grain size," it exerts upon hardening properties.

It is often stated that the absence of carbon in the familiar planes or "bands" rich in phosphorus (see Fig. 119, p. 187) is caused by the carbon having been thrown out of solution by the phosphorus. Most evidence goes to prove that this belief is erroneous and that it is the high *oxygen* content of these planes of phosphorus segregation which drives the carbon from them, thus helping to accentuate and preserve the intensity and sharpness of existing segregation throughout forging, rolling and annealing.

In addition to these influences, oxygen reacts, often in a complicated manner, with iron, manganese, silicon, aluminium and sometimes other elements. Upon the degree and nature of these reactions depends the size, nature and disposition of certain sub-microscope particles which may have an unexpectedly great influence upon deep-drawing properties. Further comment would be unsafe.

The influence of nitrogen upon the deep drawing and pressing properties of low-carbon steel is still largely speculative, but it is believed that both "blue brittleness" and "ageing," two defects which are often the cause of much trouble with this class of sheet, are at least partly attributable to the action of this element. A high percentage of nitrogen is also known to increase the distinctness of stretcher-strain markings.

Hydrogen plays an even more uncertain part in determining deep-drawing properties, although this element has been included—with many others—as one having a possible influence upon ageing. It is well known that hydrogen absorbed or occluded during acid-cleaning processes often causes a serious loss in ductility with most varieties of steel. This particular form of embrittlement can usually be removed by a low-temperature anneal, and often merely by allowing the steel to stand for a considerable time. Sometimes, however, the full original ductility cannot be restored in this way, and it may be that hydrogen is at least partly responsible for occasional puzzling instances of low ductility. Little seems to be known of the chemical as distinct from the physical action of hydrogen, yet the chemical aspect must not be regarded as of insufficient importance to warrant careful study.

Segregation

Segregation, meaning a local concentration of elements and impurities which takes place in the cast ingot prior to complete solidification, can have a most injurious influence upon the behaviour of steel sheet under the press. The reason for this is that, during the reduction of the ingot to sheet form, any zones of segregation which exist are rolled out into thin planes or layers which may extend through many feet of sheet or strip. These planes, which appear as bands or streaks on a microsection cut through the thickness of the sheet, are harder and distinctly less ductile than the remainder of the sheet. Because of this these hard layers will fracture when the sheet is severely worked under the press, and the small internal cracks formed in this way will quickly spread through the whole section of the sheet, causing it to fracture before the completion of press operations which are withstood satisfactorily by sheet free from marked segregation. Suppliers are often loath to regard even marked planes of segregation as a definite defect which will justify the rejection of deep drawing and pressing quality sheet, yet the user knows from experience that the presence or absence of pronounced planes of low ductility in the sheet he offers to his presses often decides the success or failure of that sheet to withstand the desired amount of mechanical deformation.

Segregation is more pronounced in rimming steel that in killed steel owing to the difference, already explained, in the way in which ingots of these two varieties of steel solidify. Its severity also varies from place to place in the ingot, and it is because of this variation that sheet of the very best deep-drawing quality is rolled only from selected portions of good ingots. Segregation of slag will be examined later under the heading of "Inclusions"; it is to the segregation of chemical constituents to which attention will now be given. Two items have to be considered: segregation of carbon and segregation of impurities, principally of phosphorus, and perhaps oxygen and nitrogen.

Segregation of Carbon. In fully killed steel, the distribution of carbon throughout the section of the ingot, and therefore of the sheet rolled from it, is usually relatively uniform although it does vary a little from the centre to the skin and also according to the position of any chosen cross-section in the ingot. In rimming steel both the carbon and the impurities tend to segregate into a central "core," leaving what is relatively a very pure skin on the outside of the ingot. The relative thickness of this skin, which is one of the main features of rimming steel, depends upon the oxygen content of the steel as well as the conditions under which the ingot is cast and allowed to solidify. Fig. 117 (p. 186) shows a longitudinal section cut from typical rimming steel sheet of mediocre quality in which the surface zone is thicker and less pure than usual.

It will be seen that the crystal size of the core is distinctly smaller than that of the surface zones ; this is usual and is explained by the restraining action of carbon and impurities upon the crystal size of ferrite, assisted perhaps by their influence on the critical temperature. This variation in crystal size is important because if the difference between the size of the crystals of the core and the surface zones is considerable one of two things may happen. If the crystal size of the core is unusually small, the ductility of the sheet as a whole will be less than usual, and fracture may occur. If on the other hand the crystal size of the core is normal, that of the surface zones may be so large that an unusually rough surface, giving an unsightly appearance or greatly increased polishing costs, may be produced on deep drawn or pressed articles. From many aspects it is desirable that the crystal size of the surface layers and the core of steel sheet offered to the press should be nearly the same ; for this to be so, segregation of carbon and impurities into a " core " must be as slight as possible.

Quite apart from its influence upon crystal size, segregation of carbon to the core of rimming steel sheet will naturally make the core less ductile than the surface layers due to the stiffening action of the pearlite areas or carbide particles, thus aggravating the influence of crystal size. Usually, however, the carbon content of deep-drawing steel sheet of good quality is so low that the effect of carbon segregation is not seriously harmful.

Turning from common to occasional forms of carbon segregation, Fig. 118 illustrates one which, due to the low ductility of the high-carbon zones, usually causes sheet to fail under the press. It is a defect which, like other forms of segregation, arises in the ingot stage of steel-making, and one which may occur only in sheet rolled from certain portions of an ingot, other portions yielding sheet having a microstructure of normal homogeneity.

It must be pointed out that other impurities, such as oxygen and phosphorus, are the true cause of carbon segregation. In a pure steel carbon diffuses with considerable rapidity at rolling temperatures, and its uniform dissemination is only prevented when the migrating carbon atoms encounter planes of ferrite containing a relatively high percentage of dissolved impurities.

Segregation of Impurities. The influence of segregated impurities, which is generally far more serious than that of segregated carbon, is two-fold. Firstly, general segregation to form a " core " will reduce the ductility of the affected zone by reason of the hardening action of the dissolved or suspended impurities and also by reason of their restraining action upon crystal growth. Secondly, a very high local concentration of impurities will give narrow layers or bands possessing very low ductility and productive of failure, in the manner already described, when sheet containing them is worked under the press.

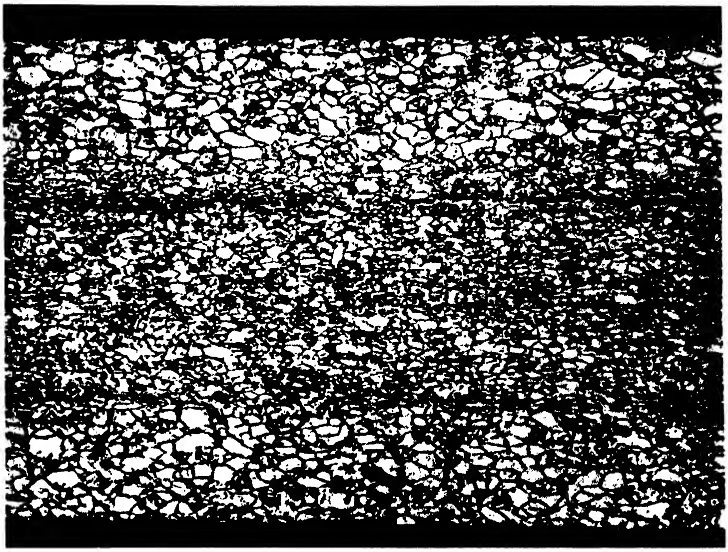


FIG. 117. Microstructure of rimming steel sheet showing relatively pure surface zones and core containing a higher percentage of carbon and impurities. Observe smaller crystal size of core.

Microsection cut normal to surface of sheet and parallel to direction of rolling. × 75.

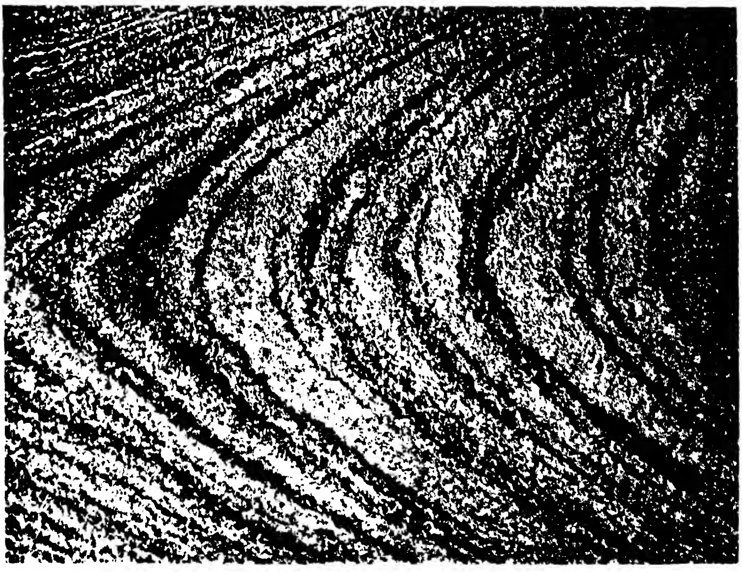


FIG. 118. Microstructure of steel pressing which fractured in the press due to poor ductility engendered by planes of carbon segregation in the sheet used.

Microsection cut parallel to surface of pressing. × 20.

[*To face p.* 186.

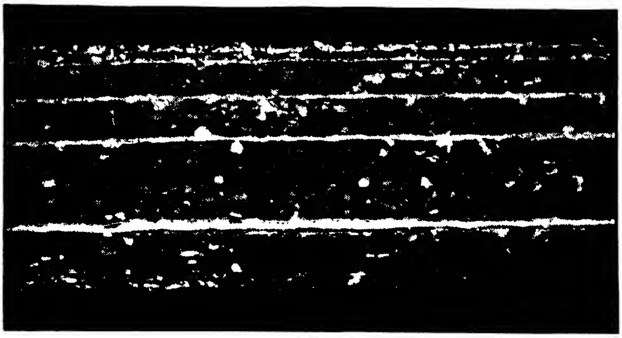


FIG. 119. Pronounced layers of phosphorus segregation in low carbon steel sheet.

Microsection, cut normal to surface of sheet and parallel to direction of rolling, has been etched specially to throw regions of high phosphorus content into contrast. × 75.

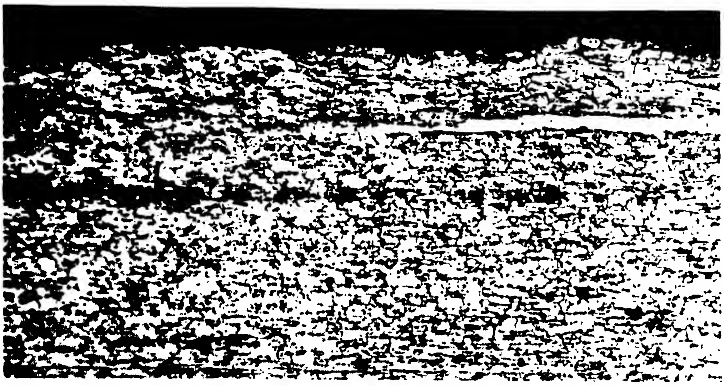


FIG. 120. Minor inclusions and segregation rolled out into narrow stringers near surface of low carbon steel sheet.

Microsection cut normal to surface of sheet and parallel to direction of rolling. × 50.

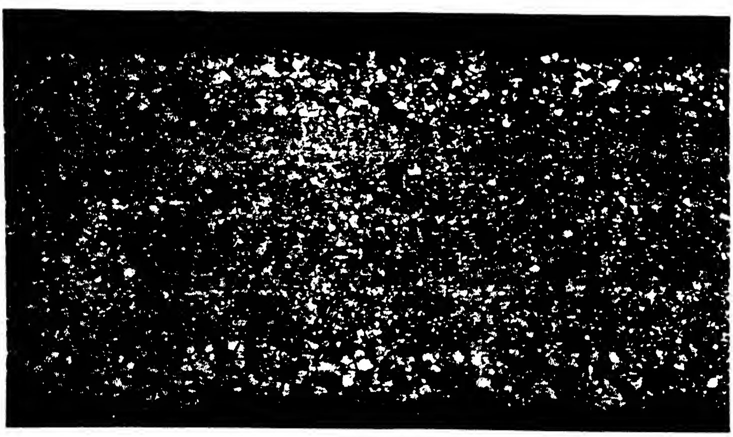


FIG. 121. Planes of chemical segregation in steel sheet.

Microspecimen cut normal to surface of sheet and parallel to direction of rolling. × 75.

[*To face p.* 187.

This particular form of local segregation, which appears as carbon-free bands of light colour on microspecimens etched in the usual way, is usually termed "phosphorus banding," but it is known that the affected zones are also high in oxygen and perhaps other elements. A typical example of pronounced phosphorus banding is shown in Fig. 119; the microspecimen illustrated has been etched specially to throw into contrast zones high in phosphorus. The ductility of the sheet from which this microspecimen was taken was so much below normal that a very high percentage of failures occurred under the press.

Occasionally it happens that what may be termed small, local segregations cause trouble. An example of this near the surface of sheet—that is away from the usual zones—is shown in Fig. 120, in which numerous small segregations of slag associated with phosphorus-rich areas caused the surface of the sheet to open up under the press. A common position for segregation of all kinds is the junction of the pure "case" and impure "core" in rimming steel sheet. Sheet which is satisfactory in other respects may contain two pronounced planes of intermittent discontinuities, slag inclusions or continuous phosphorus segregation at this critical place, as shown in Fig. 121. The position of these dangerous planes in the cast ingot has already been indicated in Fig. 51 (p. 65).

This discussion has dealt mainly with rimming steel because it is in this variety in which pronounced segregation is most often responsible for failure in the press-shop. When seriously harmful segregation is found in killed steel it is usually a sign that the sheet has not been rolled from those portions of the ingot which are normally chosen for the production of deep drawing and pressing quality sheet.

To summarise, chemical segregation—whether appearing as a thick core or as narrow layers—reduces the ductility of steel sheet in proportion to the severity of the segregation and the harmfulness of the segregated impurity. Phosphorus is often held to be the most injurious of the common elements which segregate, but the influence of the others needs to be investigated more fully. A secondary effect which must not be overlooked is that segregation of carbon and impurities into a "core" may leave the surface layers of sheet so pure that critical-strain crystal growth readily takes place in them, as shown in Fig. 139 (p. 208), although the size of the crystals in the core remains normal owing to the restraining influence of carbon and impurities.

Inclusions

Inclusions, which are nearly always non-metallic and consist principally of silicates, oxides and sulphides, constitute a very serious defect in deep drawing and pressing quality steel sheet. In the present state of knowledge it is best to describe these inclusions as "slag," because their precise constitution, including that of the familiar bluish-grey particles usually termed "manganese sulphide," is not really known. Less common varieties of inclusion are particles of alumina formed during deoxidation of the steel in the ladle if aluminium is used, and particles of refractory lining separated from the lining of the furnace or ladle.

The effect of non-metallic inclusions is to reduce the ductility of the sheet in which they occur. The seriousness of this reduction depends upon the size and number of the inclusions and not upon their chemical composition because, from the aspect of mechanical strength, all non-metallic inclusions can be regarded as particles of hard and usually very brittle substance, lacking in ductility, incapable of transmitting stress, and likely to start cracks in the matrix in which they are embedded.

It will be convenient to examine inclusions under two headings, namely, segregated inclusions and isolated inclusions, although this division is one of degree and implies no difference in the nature and influence of the inclusions themselves in most instances.

Segregated Inclusions. In the opinion of most consumers the presence of segregated masses of non-metallic inclusions is a defect which accounts for more failures of steel sheet under the press than all other defects put together, and is a source of continual irritation to suppliers and consumers alike. Suppliers will usually replace obviously defective sheet, but the cost of blanking, pressing and general upset of production schedules has to be borne by consumers, while the cost of the returned defective sheet must, ultimately, be reflected in the purchase price of sheet.

Sheet which contains continuous or semi-continuous planes of non-metallic inclusions is commonly said by press-shop operatives to be "laminated." Badly laminated sheet will nearly always fail during a severe press operation. Under less severe conditions the same sheet may withstand the desired amount of mechanical deformation without breaking, but its surface will have that characteristic rumpled or blistered appearance which usually occurs near the fracture in "laminated" sheet which has actually fractured. A faintly blistered appearance on the surface of finish-rolled sheet often enables the presence of internal discontinuities caused by slag to be detected by a practised inspector before the sheet is sent to the press-shop, and consumers often feel that closer inspection of finish-rolled sheet by suppliers would reduce the percentage of defective sheets delivered. A quick, practical test to reveal the presence of bad lamination is to cut a strip from the doubtful sheet, bend it over a fairly sharp radius and then straighten. If an internal discontinuity exists, the surface will blister at the bend as shown in Fig. 122.

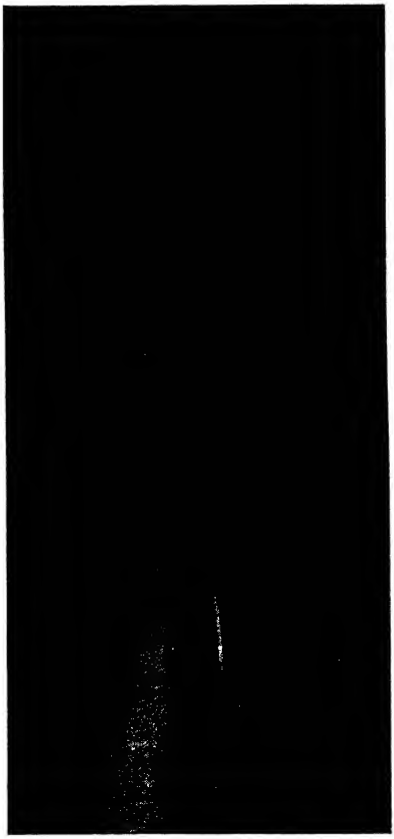


Fig. 122. Blister produced by bending and straightening steel strip containing an internal discontinuity. × $\frac{2}{3}$.

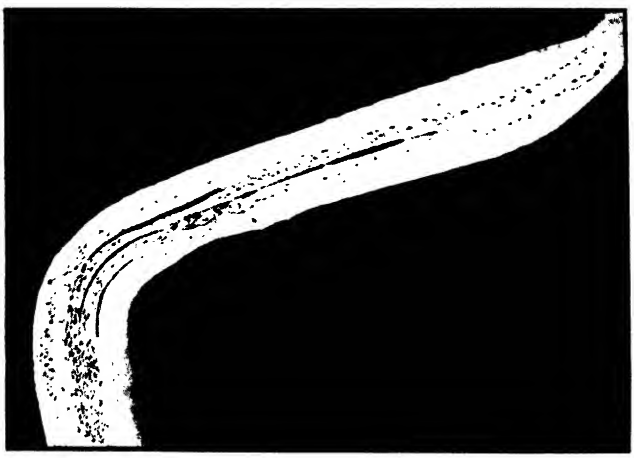


Fig. 123. Section cut from wall of fractured steel pressing showing various types of slag particles and segregation. Unetched. × 8.

[*To face p.* 188

FIG. 124. Sub-surface discontinuity in steel sheet opened up during the deep-drawing of the cup illustrated. $\times \frac{2}{3}$.

[*To face p.* 189.

It must be pointed out that, because it does not extend to the edges of rolled strip of nearly full original width, an internal layer of slag is not discernible on the sheared sides; even on sheared edges which run at right angles to the direction of rolling, and therefore cut through any such defect, the smearing action of the shears often masks all evidence of even a bad internal discontinuity.

The photomicrograph in Fig. 123 shows an example of segregated non-metallic inclusions in a steel sheet which failed under the first press operation. Pronounced as these particular inclusions are, they are by no means unusually bad. Indeed, it is common for the micro-specimen to divide into two parts along the plane of segregation when being cut from the sheet or fractured pressing. This particular specimen was chosen because it illustrates at least five typical forms of slag inclusion which do not always occur together. These are: large masses of irregular shape situated at or near the centre of the sectioned sheet; continuous or semi-continuous planes, located at or near the centre of the sheet, which may extend through many feet; similar planes not located at the centre of the sectioned sheet, usually of shorter length than centrally-located planes which, in killed steel, are often the residue of a true "pipe"; numbers of isolated particles of small size located near the centre of the sheet and, lastly, isolated particles of small size which may occur anywhere in the section.

Consumers often attribute all but the last of these five types of inclusion to the presence of "pipe" in the top of the original ingot; in other words, to inadequate cropping. While this assumption may be true in killed steel, it must be borne in mind that rimming steel ingots usually contain no true pipe and that the origin of seemingly major slag inclusions found in rimming steel sheet is often isolated slag pockets in positions other than the top of the ingot. This tendency is illustrated in the diagrams in Fig. 51 (p. 65).

Relatively short planes of inclusions, often discontinuous, are sometimes found at the junction of the rim and the core of sheet rolled from rimming steel. Although these may not be sufficiently bad to make the sheet fail under the press, they often produce blisters or rumples on the surface of the pressed article which, because they cannot be polished out, are as harmful as actual fracture. Fig. 120 (p. 187) shows stringers of small slag inclusions accompanied by chemical segregation near the surface of rimming steel sheet. It will be seen that internal fracture on planes of weakness of the kind illustrated may easily occur when the sheet is severely worked under the press. Once formed, these local sub-surface cracks may spread in all directions and lead to the complete failure of the sheet or partly formed shape.

The effect of this kind of sub-surface defect when it is of a more serious nature is shown in Fig. 124. During the deep-drawing of the cup illustrated, the thin surface layer covering the internal discontinuity ruptured, exposing the flaw in the manner shown. The appearance of this failure is, naturally, not unlike that of a bad " spill " on a deep-drawn article of copper or copper alloy (see Fig. 55, p. 79).

Fig. 125 shows a characteristic failure which occurred, during a first press operation, solely due to the presence of a pronounced layer of segregated slag in sheet of otherwise satisfactory nature. The " laminated " appearance of the fracture is clearly discernible in this photograph, which is an enlarged view of part of the fracture shown in Fig. 70 (p. 99). Bounding the fracture in this enlarged view there can be seen the rumpled surface which, as has already been explained, may occur even when sheet containing internal discontinuities does not actually break.

It has already been explained that, although in killed steel pronounced slag segregation of this kind is usually confined to the main pipe and ought therefore to have been discarded in a properly-cropped ingot, in rimming steel there is a strong tendency for isolated slag pockets to form as the ingot solidifies. It is these pockets which, when rolled out, produce the marked but not necessarily centrally disposed internal discontinuities which consumers may unthinkingly class as " pipe."

Isolated Inclusions. The action of isolated particles of slag is quite different from that of the segregated planes and large masses just considered. Planes of slag are virtual internal discontinuities and cause sheet to fail under the press partly because they cannot transmit stresses and partly because sheet containing them tends to separate along them to give a " laminated " appearance. Isolated particles of slag, on the other hand, exert a stiffening action and also form points of stress concentration from which cracks may start when the surrounding matrix becomes severely work-hardened. Furthermore, if the particles are of fairly large size in relation to the thickness of the sheet, they form points of weakness, and a fortuitously situated chain of particles may engender localised necking leading to fracture, as shown in Fig. 126.

It will help readers to visualise the action of slag particles if they remember that the hardness of these particles prevents them being thinned down with the sheet during its cold-working in rolls or press ; they can be compared to glass marbles embedded in a slab of dough. Because of this, intense local stress concentrations, leading to the formation of cracks, are set up in their immediate vicinity. It is not generally known that high-power microscopical examination of carefully prepared microspecimens of cold-worked steel usually reveals tiny cracks at the ends of lenticular, and even of nearly spheroidal, slag particles. The more the metal becomes work-hardened, the greater will be the tendency for these tiny cracks to spread

FIG. 125. Fractured wall of steel pressing showing severe internal discontinuity of "lamination." (Actual size.)

FIG. 126. Section cut through localised fracture in steel pressing, showing how path of fracture follows slag inclusions. Unetched. × 15.

[*To face p.* 190.

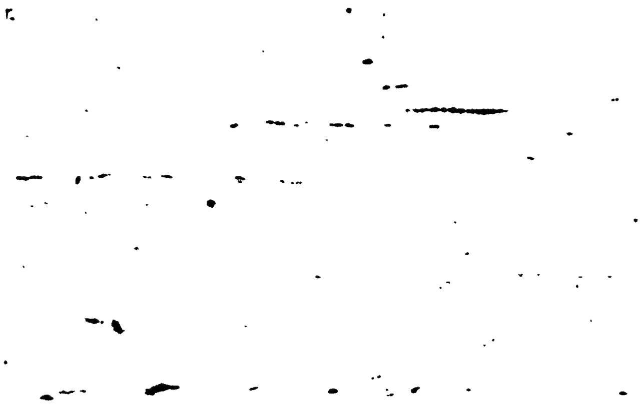


FIG. 127. Illustrating stages in the elongation, transverse fracture, and separation into smaller particles of streaks of slag in low carbon steel sheet. Each type of inclusion shown is typical of those commonly found in low carbon steel sheet.

Microsection cut normal to surface of sheet and parallel to direction of rolling Unetched. × 50.

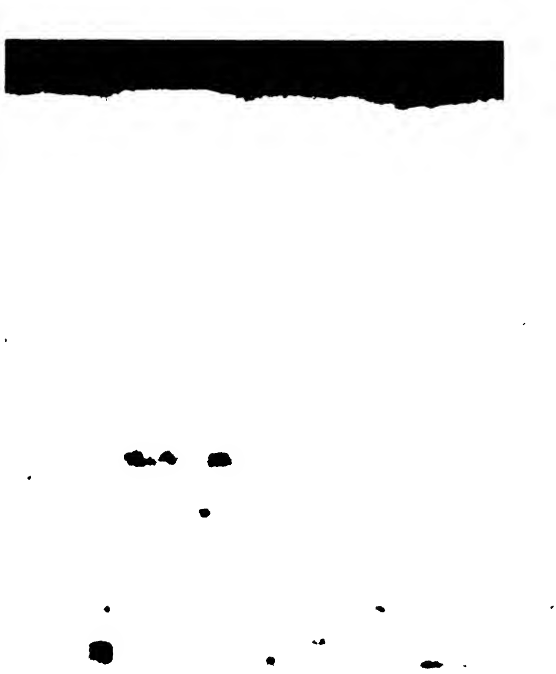


FIG. 128. Non-metallic inclusions in steel deoxidised with aluminium.

Microsection cut normal to surface of sheet and parallel to direction of rolling. Unetched. × 300.

[*To face p.* 191

and thus reduce the normal ductility of the sheet in which they occur.

Isolated slag inclusions vary widely in size, shape and frequency of occurrence. Usually they are small in relation to the thickness of the sheet in which they are found; if so, they may not be seriously harmful unless they occur in considerable numbers. Their shape may vary from almost spherical globules, through the common lenticular particles, to fine threads which often exist as a discontinuous string and represent the first stage in the breaking up of a plane or stringer of slag as a result of rolling. It will be appreciated that during the reduction of an ingot to sheet form by rolling, a mass of slag will be gradually elongated and attenuated until a thin plane or stringer is formed. Continued rolling may break up this plane or stringer, which will be very brittle when cold, and particles so formed become separated further and further, perhaps sub-dividing again, until the particles become truly isolated. Various stages in the process of such disintegration are shown in Fig. 127.

Not all isolated particles of slag are formed in this way: some come direct from the original ingot in which, owing to their small size, they failed to rise or segregate prior to the solidification of the surrounding metal. Slag inclusions of this kind are sometimes very small and numerous; when a "cloud" formation of tiny, hard particles occurs, the work-hardening tendencies of the matrix become considerably increased, with the natural result that the ductility of the sheet is much less than normal and failure under the press is likely. Sometimes these "cloud" particles are so small that individual particles become almost sub-microscopic; their effect upon the ductility of the matrix then becomes remarkably pronounced. In the opinion of some authorities, the presence of very small, or even sub-microscopic, inclusions in the crystal boundaries has a profound influence upon the ductility of steel sheet, and is held to account for some of the marked variation in behaviour under the press for which no other apparent reason can be found.

Inclusions of alumina in aluminium-killed steel or of refractory lining in steel of any kind, although responsible for the failure of an isolated sheet or even of a whole batch of sheets, are seldom responsible for frequent or large-scale failure of sheet or pressings. They usually occur as disconnected stringers of irregular or angular-shaped particles and are easily distinguished from the particles of normal slag which, unless broken up by cold-rolling, have a smooth surface. Fig. 128 shows particles of this kind in finish-rolled sheet.

Surface Blemishes

The majority of the surface blemishes which cause trouble on steel sheet sent to the press-shop can be divided into one of three main kinds: those caused by casting defects on the surface of the original ingot, those caused by sub-surface discontinuities and slag inclusions, and those caused by the action of mill-scale formed during the rolling of the ingot into sheet. Each of these three kinds of defect is actually existent in the sheet supplied to consumers, but others, for which consumers must be held wholly responsible, are sometimes produced by excessive scaling during inter-stage annealing, by unsatisfactory pickling or by the action of drawing lubricants.

When the methods used to produce steel sheet are contrasted with those used to produce brass sheet, it seems surprising that surface blemishes caused by ingot or casting defects are not more common in steel. The surface of brass ingots is often machined all over to remove surface defects, whereas local grinding or trimming with pneumatic gougeing chisels is the only treatment given to steel ingots and slabs, and this can remove only those blemishes which are sufficiently large and obvious to catch the eye of the operator.

Surface defects may be produced by irregularities on the mould surface, by the action of the mould dressing, by entrapped particles of refractory lining torn from ladle or dozzle, by " shells " formed by the molten stream splashing against the walls of the mould, by thermal cracks and by other familiar casting defects which may occur at any time. During subsequent hot-rolling, cracks may be formed—for example through the use of too much cooling water—which, becoming filled with oxide, will produce serious defects often extending for some distance beyond any visible surface manifestation in the finish-rolled sheet.

The severe hot-working coupled with the very great total reduction which a large steel ingot suffers before it is transformed into thin sheet certainly helps to spread out, and to some extent to lessen, the seriousness of the various defects just mentioned; but fortunately for consumers the resultant blemishes are usually plainly visible on finished sheet and therefore get no further than the inspection department of reputable suppliers.

Blemishes caused by sub-surface discontinuities seldom become visible until the sheet has been stretched under the press, when they open up into the familiar scabs and blisters, often revealing interiors coated with slag or oxide. Sometimes the blisters do not burst, and local areas of rumpling are produced on the surface of the pressing above the internal plane of discontinuity. Fig. 129 shows typical surface blemishes on steel sheet caused by sub-surface discontinuities attributable to unwelded gas cavities or slag segregation. In this instance the defect is plainly visible on the cold-rolled, unpressed sheet; the fact that sheets exhibiting blemishes of this kind can be passed out in considerable numbers by sheet mills of repute can be construed by consumers only as evidence of serious lapses, or of a

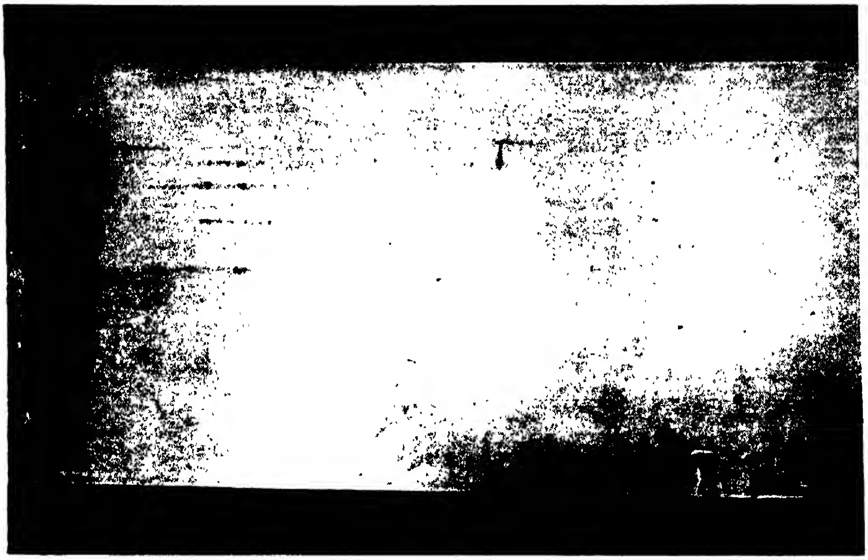


FIG. 129. Surface of cold-rolled steel strip as received from mill, showing blemishes attributable to sub-surface discontinuities. × ½.

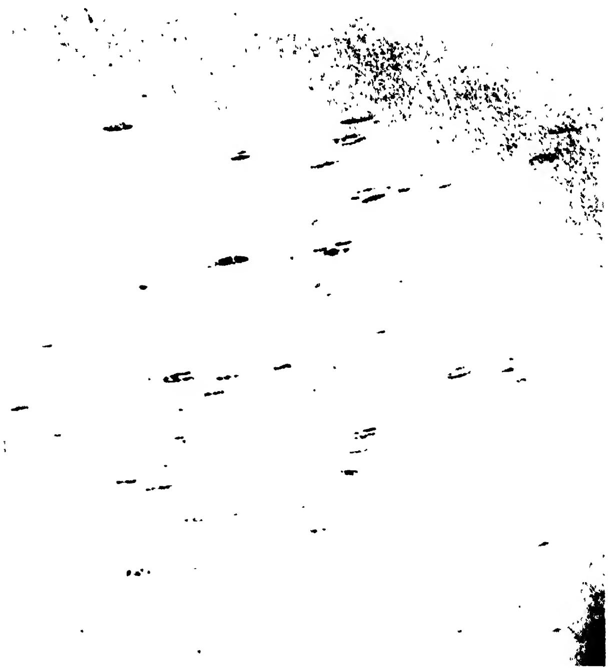


FIG. 130. Surface blemishes on steel pressing caused by cavities left by mill scale. × 2.

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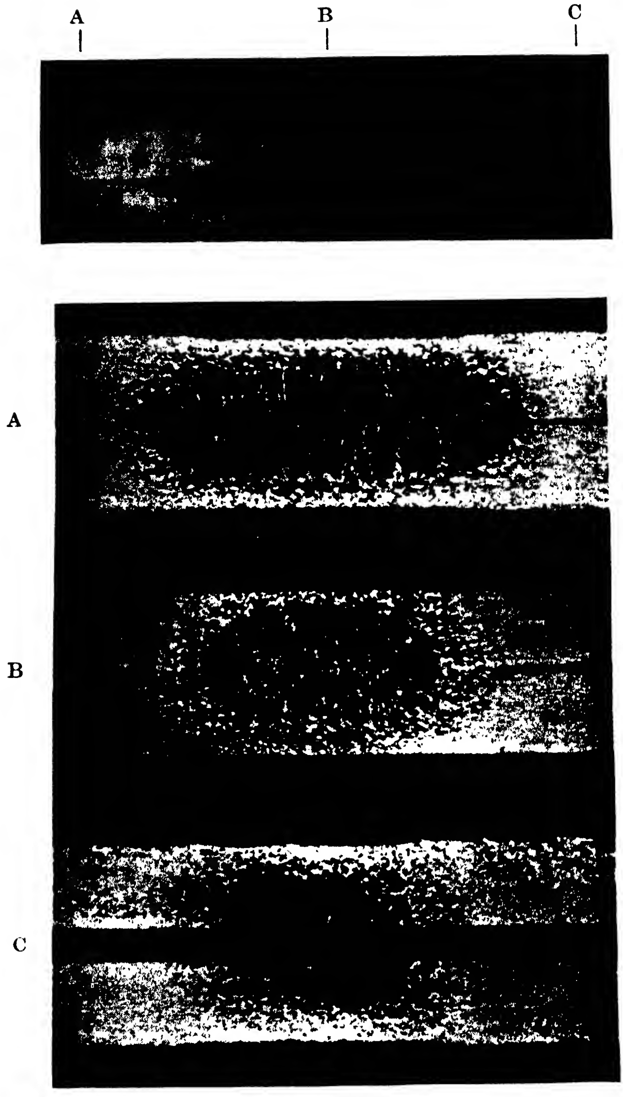


Fig. 131. Sections of spot welds made under constant machine-setting on specimens cut from the indicated positions on the oxide colour band on close-annealed mild steel sheet. × 10.

[*To face p.* 193.

price so cut that final inspection is sometimes confined to an inadequate percentage of the total output.

The last cause of surface blemishes which needs to be examined is rolled-in mill-scale. This type of blemish is usually invisible until the sheet is worked in the press, during which operation the surface opens up into the kind of blemish shown in Fig. 130. Although small, these markings will spoil the appearance of any pressings which have to be pickled, dipped, polished, plated or enamelled ; often, therefore, they are as harmful as actual fracture. This defect is caused by small particles of mill-scale being rolled into the surface of the sheet and then dissolved away by pickling solution. Often the cavities formed in this way are closed up by subsequent cold-rolling which, although it makes their detection in finish-rolled sheet difficult even with the aid of a hand lens, in no way heals them or alters their behaviour when the sheet is deep drawn or pressed.

Surface Condition

Even though the surface of steel sheet is free from actual blemishes of the various kinds just examined, its condition may be directly responsible for difficulties encountered in the production of a pressed article. In the past the degree of mechanical smoothness of both cold-rolled and close-annealed steel sheet has often been regarded as unsatisfactory by consumers ; this is due to the methods of production adopted, such as excessive pickling, to marks due to strongly-adherent patches of scale, or to an indifferent surface finish on the finishing rolls themselves. Owing to improved methods of production—particularly the growth of controlled-atmosphere annealing and the giving and maintaining of better roll surfaces—this complaint is on the decline. It can, indeed, be said that the methods of consumers do not always allow them to take full advantage of the excellent surface finish found on a good proportion of the better grades of steel sheet manufactured for deep drawing and pressing.

One genuine cause of trouble is the oxide coating which occurs near the edges of pack-annealed sheet if the purging atmosphere used in the container has not done its work thoroughly. The close contact made between the sheets composing a large pack owing to their own weight prevents the ingress of oxidising gases to the central zones of the sheets during the annealing process, but less pressure near the edges allows a little gas to penetrate for a distance of some inches. This produces the familiar coating of coloured oxide, which ranges from a deep blue at the edge of the sheet to a pale straw colour as it gradually fades away at the inner visible edge of the surrounding band.

This oxide edging is harmful for two reasons. First, the oxide quickly spoils and even wears the polished surface of press-tools, while particles of oxide become detached and mix with the lubricant to form an abrasive paste which scores the surface of the sheet being drawn. Secondly, the adhering oxide is very injurious to efficient spot welding, a process which is being used more and more to join together pressed steel shapes in quantity production.

The difficulty lies not so much in the *presence* of oxide, for a fairly good spot weld can often be made between oxide-coated sheets if the coating remains constant in thickness : it is the *variation* in the coating from place to place which is so troublesome. The electrodes of a spot or seam welding machine may travel over a surface having practically no oxide, thin oxide and heavy oxide within the space of a few inches when welding shapes pressed from sheet having an edging of oxide; therefore when the machine works at a constant setting, some bad welds are certain to be made. Various automatic devices have been devised with the object of controlling the operation of spot-welding machines to compensate for variation in oxide, grease or other forms of surface coating; but, attractive as some of these schemes appear on paper, variation in the thickness of the surface coating on steel sheet still seems to constitute a very real source of trouble in practical spot welding.

At the top of Fig. 131 is shown one end of a strip cut from a close-annealed mild steel sheet. In this photograph the right edge of the strip is the edge of the original sheet, and the left edge of the sample strip is located well beyond the extent of the characteristic oxide colour band, which is distinguishable in half-tone in the printed illustration. Using a constant, thyratron-controlled machine setting, spot welds were made in successive positions from the edge to the oxide-free portion of the strip, and the resulting welds sectioned and examined under the microscope. Space allows only three specimens, taken from the positions indicated by the letters, of this series to be reproduced.

"A" represents the central, oxide-free area of the original sheet; here a reasonably good weld has been achieved. "B" represents an intermediate area where the sheet bears a relatively thin coating of oxide; here the area of the weld is distinctly smaller than at "A," yet the zone of affected metal surrounding the central area of columnar crystals is thicker. "C" represents the specimen cut from the extreme edge of the original sheet where the oxide coating was thickest yet, let it be emphasised, typical of that encountered near the edges of much normal, commercial-quality close-annealed sheet. The adhesion of this attempted weld was insufficient to withstand the light stresses produced by sawing the specimen into two parts.

It must be conceded that this series forms a convincing illustration of the very important influence exercised by variation in thickness of oxide coating upon the welding properties of commercial mild steel sheet, and shows how very desirable it is to use clean sheet unless some really adequate automatic compensating device can be obtained.

It will be appreciated that in this instance no useful compromise can be struck, for, as will be seen, the weld at " A " is satisfactory, although if anything slightly over-heated, while the weld at " C " is unworthy of its name. If conditions were adjusted so that a good weld was produced at position " B," welds at " A " would be badly overheated yet welds at " C " would still be poor.

In view of the harmful effect of an oxide coating on the surface of steel sheet, it may seem strange that when the surface has been " de-scaled " by the action of a reducing atmosphere in a normalising furnace, its behaviour under the press is sometimes unsatisfactory. This is explained by the fact that when the oxide is reduced it leaves a layer of pure, spongy ferrite which tends to " foul " or " load " steel tools more readily than a normal surface. When sheet is deep drawn or pressed immediately after it has been " clean-normalised," instead of being allowed to stand for a while, its behaviour is even worse, because the surface is then approaching a " chemically clean " condition which facilitates the localised welding together of the sheet and steel tools known as " loading." Quite often this difficulty is not encountered; but, when sheet is truly " clean-normalised " and the press operation is a severe one, trouble is likely to occur unless a specially good lubricant and very hard tools are used.

A very polished surface is not good because it does not " hold " lubricant. It is rather ironical that now, largely to please consumers, suppliers are producing cold-rolled sheet having a beautifully smooth, bright surface, it has been found advantageous to shot-blast this surface. This gives a very smooth, fine matte finish which is excellent for many deep drawing and pressing operations because it " holds " lubricant and also lessens the distinctness of stretcher-strain markings.

To summarise, a heavy coat of oxide is very bad because it injures tool surfaces and produces scores on the work; either a heavy or a light coat of oxide is bad for resistance welding; a " chemically clean " surface is likely to cause fouling, and a very polished surface is bad because it increases the difficulty of adequate lubrication. An ordinary " clean " surface bearing only the usual invisible film of oxide which always forms on steel exposed to air seems best for most purposes, and a very smooth, yet finely " matte " finish is preferable to a genuine polish.

Crystal Structure

As with brass, it is intended here merely to indicate the faults in crystal structure which are most common in steel sheet; the general influence which various forms of crystal structure exerts upon the deep drawing and pressing properties of sheet metal is dealt with in detail elsewhere. Three faults stand out pre-eminently:

(1) The occurrence of isolated crystals, or zones of crystals, of abnormally large size.

(2) A marked difference between the size of the crystals in the surface layers and the core of sheet rolled from rimming steel ingots.

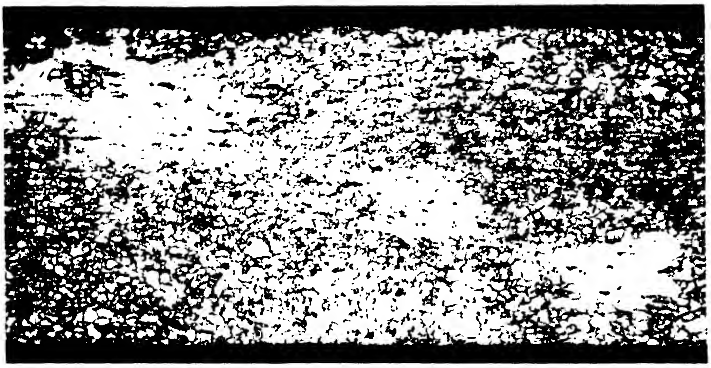
(3) An unsuitable " average grain size " even though the two faults just mentioned are not pronounced.

(1) Crystals of Abnormally Large Size. Compared with its condition a few years ago, the crystal structure of annealed sheet, if not always as regular as that of normalised sheet, now tends to be reasonably good. However, occasional lapses from the normal standard still occur, and two typical examples are shown in Fig. 132.

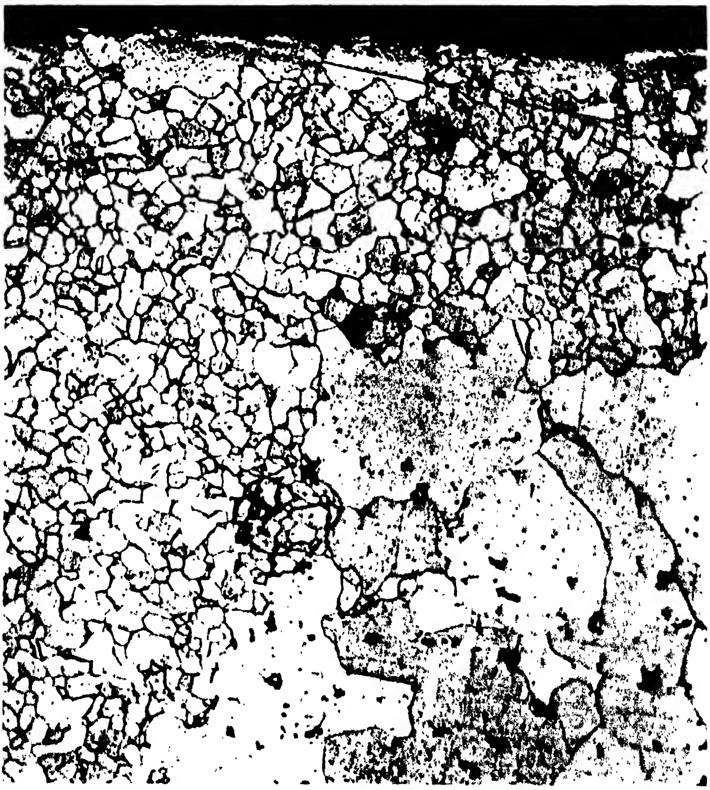
Abnormally large crystals of ferrite possess unusually low tenacity. Because of this, their presence is likely to cause sheet to fail under the press due to intensified local " necking " through conveniently situated chains or zones of large crystals. If actual failure does not occur, the surface of deep drawn or pressed work is likely to be particularly rough.

The formation of abnormally large ferrite crystals in low-carbon steel which has been cold-worked and annealed is believed to be due to " critical-strain crystal growth," a phenomenon discussed later. While this cause may be the principal one in many, and a contributory one in some, instances, it does seem as if other important causes are needed to explain many observed microstructures. For example, in the sheet illustrated in Fig. 132A abnormal crystals are isolated and occur anywhere from the surface to the centre of the sheet section. In cold-rolled sheet it might be expected that regions in which the strain has reached the critical range of values—values which, incidentally, are usually greatly exceeded in normal cold-reduction—would be confined to certain zones parallel to the surface of the sheet, even if a condition of critical strain did not extend throughout the entire section. Furthermore, it will be noticed that the understandable and recognised influence of chemical segregation has not tended to confine the large crystals to the relatively pure surface layers of the sheet. As with copper sheet (see Fig. 171, p. 287), some other explanation besides critical-strain phenomena is needed to explain why isolated large crystals should be formed in apparently random positions throughout the section of annealed steel sheet.

(2) Variation in Crystal Size. It has been pointed out that in brass a marked difference between the size of the smallest and largest crystals in the microstructure of sheet constitutes a serious defect in a considerable proportion of industrial sheet. In steel, owing mainly to the action of carbon and of non-metallic inclusions, it is unusual to find a mixture of very large and very small crystals throughout the section of the sheet; but, particularly in rimming steel, it is common for the average crystal size of the core to be considerably smaller than that of the surface layers. Fig. 117 (p. 186) shows a not unduly pronounced example of this variation in structure.



A



B

FIG. 132. Examples of crystals of abnormal size in annealed low carbon steel sheet.

A : Large isolated crystals. × 75.
B : Zone of large crystals. × 50.

Microsection cut normal to surface of sheet and parallel to direction of rolling.

[*To face* p. 196.

Fig. 133. Ears formed in steel cup at 0 and 90 degrees to the direction of rolling (marked with white strip).

[*To face p.* 197.

It is evident that even though the " average grain size " of the core is satisfactory in a structure of the kind illustrated, that of the surface zones may be sufficiently large to produce an undesirably rough surface on deep drawn or pressed articles. If, on the other hand, the " average grain size " of the surface zones is satisfactory, that of the core may be so small that the ductility of the whole section proves insufficient for the desired press operations to be performed without the sheet breaking. When the claims of rimming steel are being judged it must be borne in mind that this variation in crystal size is always likely to occur ; the severity of this defect—for defect it certainly is from the aspect of the press-shop—may play a large part in determining whether the behaviour of any sheet under the press is satisfactory or unsatisfactory. When the microstructure of sheet having this kind of variation in its crystal size is being described, separate values for " average grain size " should always be given for the core and surface zones. To state an estimated mean value for the surface layers and the core can often be most misleading and gives no true indication of the probable behaviour of the sheet under the press.

The principal cause of this sharply-defined variation in crystal size throughout the section of sheet is a difference in the chemical composition and in the number of non-metallic inclusions in the core and in the surface zones. The higher carbon content, the higher percentage of impurities and the greater number of inclusions in the core tend to reduce the size of its crystals ; the higher purity of the surface zones, which contain few inclusions, no layers of chemical segregation, and often a very low carbon content, favours the growth of crystals to a size larger than that of the crystals in the core.

Another cause, which is of increasing importance now that clean-annealing in controlled-atmosphere furnaces is becoming more widely used, is complete decarburisation of the surface zones of thin sheet by the action of the protective atmosphere at elevated temperatures. This tends to produce a surface layer of very low carbon content in killed steel sheets which previously had a homogeneous structure, and to accentuate existing differences between the core and the surface zones in rimming steel sheet. In both types of sheet the practical effect is to increase the tendency for the crystals in the surface zones to grow in size under suitable thermal conditions more rapidly than those of the core.

(3) Unsuitable " Average Grain Size." The influence of an unsuitable " average grain size " upon the deep drawing and pressing properties of sheet metal has already been described, and no special qualifications need be added with respect to steel.

In a good proportion of steel sheet the " average grain size " is reasonably close to the desired value, a beneficial attribute which is helped by the relative regularity of crystal size in any sheet if pronounced "cored" structures are excluded. It is impossible to give definite recommendations for the best "average grain size" because these will vary according to the nature of the shape to be made, the processes used to make it, the degree of temper-rolling given to the sheet, the harmfulness of stretcher-strain markings on the particular article being made, the carbon content, the percentage and severity of segregation of impurities, and even the size and number of slag inclusions. As an approximate guide, 0·035 to 0·045 mm. is satisfactory for many deep drawing and pressing operations; but, in clean steel free from chemical segregation and low in carbon, surprisingly deep draws can be made in sheet having an "average grain size" as small as 0·025 mm. Above 0·05 mm. "average grain size" the roughness of surface of deep-drawn, pressed or even bent steel sheet increases rapidly.

Directionality

Directional properties in steel sheet vary widely in severity and are often sufficiently pronounced to cause serious trouble. This happens because marked "directionality" produces uneven flow of the blank in a fairly symmetrical shape and, in both symmetrical or unsymmetrical shapes, increases the likelihood of the sheet breaking in regions of high stress.

The influence of "directionality" upon the flow of sheet metal in press-tools has been illustrated in Chapter III, and the causes of this unwelcome manifestation are discussed at some length in Chapter XIII; but it is necessary to remind readers at this point that, in steel sheet, directional properties attributable solely to crystal structure are usually supplemented, and often aggravated, by others attributable to elongated planes of chemical segregation, non-metallic inclusions and sometimes particles and stringers of pearlite. It is these additional causes which make the directional properties of steel sheet more pronounced than those of good quality brass sheet.

The position of "ears" on drawn shells and also tensile tests made on undrawn sheet show that in steel the direction of minimum ductility usually lies at 45 degrees to that of rolling. This direction varies with the treatment which the sheet receives in the rolling mill; with certain percentage reductions prior to annealing it is found to lie at 90 degrees, and very occasionally at intermediate angles, to that of rolling in steel sheet of industrial quality.

Fig. 59 (p. 86) shows splits in the walls of a drawn steel cup attributable entirely to unusually pronounced directional properties in the original sheet. In this instance the direction of minimum ductility is the most usual one, namely, at 45 degrees to that of rolling. Fig. 133 (p. 197) shows a mild example of ear formation on the untrimmed periphery of a deep-drawn steel cup ; here again the direction of minimum ductility is the common one. Both these articles are small, but it will be appreciated that, in large pressings whose size is measured in feet instead of inches, variation in the severity of directional properties from batch to batch of sheet may produce a difference in flow of several inches at certain critical regions of the blank periphery even though they do not produce failure in the worst instance.

The influence of directionality upon stretcher-strain markings will be illustrated later.

Annealing and Normalising

As the inter-stage annealing of deep drawn and pressed articles has already been discussed in a general way and also with special reference to brass, it is only necessary to describe the methods used for steel and to draw attention to certain peculiarities in the behaviour of this metal when it is annealed.

Two distinct methods are in common use for restoring ductility to cold-worked steel ; these are annealing and normalising, both these terms being used in the proper metallurgical sense. "Patenting," a special form of annealing often given to high-carbon steel wire and sometimes strip, is not given to the low-carbon steel sheet commonly used in the press-shop.

Annealing. Annealing consists of heating articles in a furnace, either free or in a container, to some predetermined temperature usually below the critical range, soaking at this temperature for a certain time and then cooling slowly. The fundamental principle upon which the annealing of cold-worked low-carbon steel depends is that strained ferrite will recrystallise at a relatively low temperature and that the tiny crystallites will grow to a size which is dependent upon time, temperature and the purity of the ferrite. Pure ferrite, if very severely cold-worked, will recrystallise at as low a temperature as 550° C., but under normal industrial conditions a considerably higher temperature is nearly always needed.

The temperature actually used varies from about 650 to 850° C., depending upon the kind of plant consumers have at their disposal, whether or not a protective atmosphere is available, the degree of cold work given to the steel, the nature of subsequent forming operations and, unhappily, the fancy of the individuals responsible for the annealing treatment. Temperatures near the lower limit of the temperature range just mentioned can only be used when the steel has been cold-worked uniformly and very severely, for example by cold-rolling sheet or strip, or when complete restoration of ductility is not needed ; a temperature of about 820° C. is popular for general work if the soaking period is fairly short. If higher temperatures are used the tendency for a coarse crystal structure to be developed increases and, unless an efficient protective atmosphere is used, surface oxidation is likely to be so serious that cleaning by ordinary pickling methods will prove difficult.

It is a common belief that in the inter-stage annealing of steel articles there is less need to exercise the same degree of care that is necessary with brass. This impression is entirely erroneous ; incorrect annealing has been, and still is, the cause of a large proportion of the troubles which are met with in the deep drawing and pressing of steel. If steel is annealed at too high a temperature or for too long a time, an undesirably large crystal size will be produced, in exactly the same manner as with brass, which will engender unusual softness associated with low tenacity and the formation of a rough surface during subsequent pressing. Indeed, because the added danger of critical-strain crystal growth has to be met, there is at least an equal need for the exercise of careful control in the annealing of ferrous as of non-ferrous metal.

Normalising. Normalising consists of heating steel to above its critical range for a short time to obtain uniformity of conditions—perhaps for only a few minutes if the sheet is thin—and cooling fairly quickly ; "cooling in still air" is the true metallurgical definition. With low-carbon steel a temperature of 920° C. is adequate, but no harm will be done if this temperature is exceeded by a considerable margin. Indeed, it is often desirable to do this in order to heat work rapidly through the critical range, to overcome the effect of thermal hysteresis and to ensure that no part of the furnace charge fails to attain the critical temperature.

In continuous normalising furnaces an indicated furnace temperature of 950° or even 1,000° C. is perfectly satisfactory for normal rates of progress through the furnace, and upon several occasions the author has normalised thin steel shells in a copper-brazing furnace, working at an indicated furnace temperature of 1,120° C., with entirely satisfactory results even though the work was held at maximum temperature for at least ten minutes. It need hardly be added that with these high temperatures an efficient protective atmosphere is essential ; even at 920 to 950° C. this aid is a virtual necessity for articles of thin gauge whose surfaces have to be preserved in reasonably good condition.

This recommendation to keep normalising temperatures on the high side must not be misinterpreted. There is no advantage in using a *needlessly* high temperature which will increase furnace maintenance costs without giving an improved product ; the point it is desired to emphasise is that quite often it is genuinely necessary to use an indicated furnace temperature considerably above the theoretical critical temperature of the steel if the whole of the charge is to be normalised properly.

In the modern slit-type continuous furnaces of the type illustrated in Fig. 44 (p. 55) designed for normalising steel sheet and strip it is easy to obtain almost ideally uniform heating and temperature control. In large-aperature furnaces such as those illustrated in Fig. 312 (p. 680) designed to take pressed or drawn articles of some size, it is not always possible to ensure that all parts of an article are heated to exactly the same temperature, because one part may be close to, and another relatively far from, the heating surfaces of the furnace tunnel. The same difficulty arises with baskets of small articles. As explained elsewhere the maximum temperature which the work attains is not of great importance, and perfectly satisfactorily normalising can be obtained by running the furnace at a temperature sufficiently high to ensure that the coolest part of the charge is heated to, preferably, not less than 20° C. above the theoretical normalising temperature of the steel.

Provided that surface oxidation is prevented by the use of a protective atmosphere in the furnace, the superiority of normalising as distinct from annealing seems indisputable, because a much more uniform product is obtained and, assuming proper control of time, temperatures, heating and cooling rates, difficulties arising out of critical-strain crystal growth are reduced to a minimum and the time of the heat-treatment cycle is made much shorter.

It is true that, for reasons explained in Chapter II, normalising may produce a slightly lower ductility than annealing, but this is more than counter-balanced when the condition of softened pressings can be predicted and produced with regularity, a procedure which cannot be followed when annealing is used except, perhaps, in special instances. Furnaces are now available which will normalise steel articles and deliver them in a genuinely, indeed often chemically, clean condition. Since surface decarburisation is usually of no detriment in articles deep-drawn in dead-mild steel, the atmospheres of these furnaces can when desired be so adjusted that an actual de-scaling action is produced, thus eliminating the unpleasant operation of pickling.

Another very good reason why it may be better to normalise partly-formed steel shapes than to anneal them below the critical temperature is that the temperature at which recrystallisation begins is dependent upon the amount of cold work which has been given. For example, according to Goss,[34] low-carbon steel strip given a reduction in thickness of 10 per cent. fails to recrystallise within half an hour when held at 600° C., whereas when the reduction in thickness is 20 per cent. recrystallisation is partially completed under the same conditions. When the reduction is 80 per cent. recrystallisation, as indicated by X-ray examination, is complete after only one minute at a temperature of 650° C.

In view of this and similar evidence it will be clear that, during the annealing of a deep drawn or pressed steel shape which has not suffered the same amount of cold work over the whole of its area, uneven re-crystallisation may readily occur even without the incidence of critical-strain growth effects. Proper normalising will ensure complete and more uniform recrystallisation, and will prevent critical-strain crystal growth occurring.

Principles of Normalising. It is often said that refinement of crystal structure takes place as steel cools through the critical range, and that the final crystal size is dependent upon the rate of cooling.

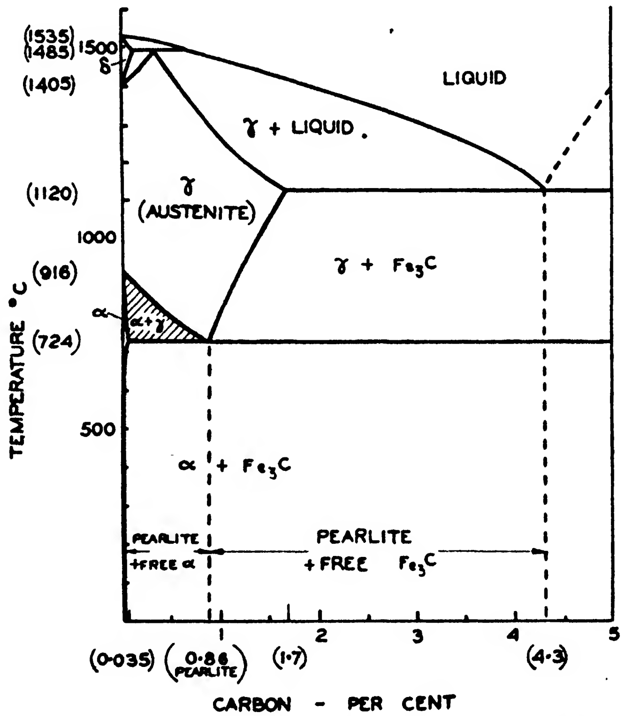


FIG. 134. Iron-carbon equilibrium diagram. The cross-hatched area represents the "critical range" which is of importance in the normalising—and other heat-treatments—of hypo-eutectoid steels.

These statements show that even technical men are often unfamiliar with the true principles of normalising, for the first is untrue and the second misleading because, under most industrial conditions, the rate of cooling is too rapid to influence the crystal size to any appreciable extent. The true facts, which may be deduced from a study of the iron-carbon equilibrium diagram shown in Fig. 134, are these :

Normalising implies three successive stages ; heating to and above the critical range,* soaking at a temperature above it, and cooling

* The critical range is indicated by cross-hatching on the equilibrium diagram in Fig. 134.

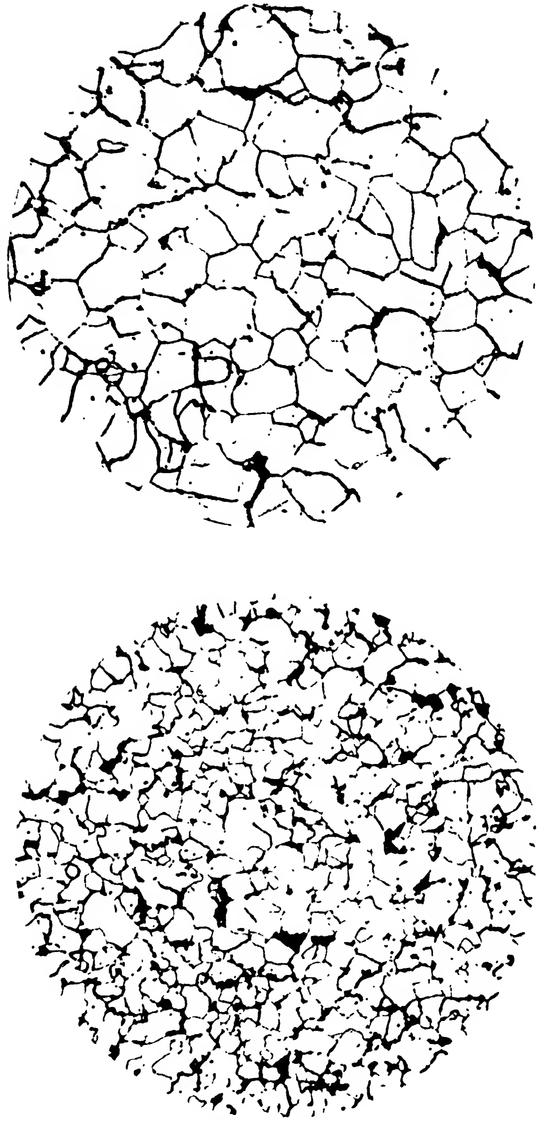


FIG. 135. The influence of oxygen content upon the crystal size of normalised low carbon steel sheet. *Top*, 0·06 per cent. carbon "rimming" steel; *bottom*, 0·08 per cent. carbon "killed" steel. Both sheets have received the same normalising treatment. × 150.

[*To face p.* 203.

through it down to about 650° C., below which temperature the rate of cooling ceases to be important. In cold-worked steel of low carbon-content the changes which occur during these three stages are briefly as follows :—

Heating. As the temperature rises, the cold-worked ferrite crystals recrystallise and then grow in size, recrystallisation starting, as in annealing, at a temperature dependent upon the amount they have been strained. As the temperature rises through the critical range, recrystallisation and refinement will take place as soon as thermal hysteresis has been overcome, the crystal structure of the matrix changing from the *alpha* or body-centred cubic lattice structure (ferrite) to the *gamma* or face-centred cubic lattice structure (austenite). The structure is now " refined." The size of the austenitic crystals will depend upon the " inherent crystal size " of the particular steel being treated, not upon the rate of heating or the degree of strain which existed in the cold-worked ferrite, and the inherent crystal size will depend partly upon the thermal and mechanical history of the steel and partly upon its chemical composition, particularly the oxygen content. Fig. 135 shows the different ferritic crystal size produced by normalising a high-oxygen " rimming " steel and a low-oxygen " killed " steel under identical conditions.

When the lattice structure changes from the body-centred to the face-centred cubic arrangement the carbon—whether present in the form of pearlite or of isolated particles of carbide—will be dissolved, for, as is evident from the equilibrium diagram, *gamma* iron dissolves carbon forming the solid solution known as austenite. The solution and subsequent uniform diffusion of carbide takes place rapidly but, as pointed out before, diffusion of carbon is hindered or even prevented by the presence of zones of austenite containing in comparison relatively high percentages of impurities.

At the end of the heating stage, therefore, the cold-worked ferrite crystals have changed to " equi-ax " polygonal austenite crystals having a size determined primarily by the properties of the steel being treated, and the carbon has dissolved and diffused as uniformly as the chemical heterogeneity of the steel allows.

Soaking. This commences when the steel passes through the lower limit of the critical range, continues through the upper limit to the maximum temperature of the soaking period, and ends when it cools through and to just below the lower limit.

During this stage the size of the austenite crystals will increase at a rate dependent upon the temperature reached and the period of soaking. As this rate is a relatively slow one at temperatures only slightly above the critical range, little increase in austenitic crystal size occurs even when the time of soaking is prolonged well beyond the few minutes used in normal industrial practice.

Cooling. The cooling stage starts when the temperature of the steel falls through the critical range, and is conveniently studied in two sub-stages.

During the first stage the temperature falls through the critical range and, at the lower limit of this range, ferrite crystals separate from the *gamma* lattice (austenite) which itself changes to the *alpha* lattice (ferrite) and at the same time rejects very nearly the whole of the dissolved carbide from solution. The size of the ferrite crystals will depend on the relative size and position of the austenite crystal boundaries during the austenite–ferrite transformation, not upon the rate of cooling.

The size and number of the pearlite areas will depend, naturally, upon the percentage of carbon present but—assuming this to be some fixed value—also upon the maximum soaking temperature, the time of soaking above the critical range and the rate of cooling through the critical range. A fine distribution of pearlite areas is assisted by careful control of these factors ; yet in the very low carbon steels used in the press-shop, the influence of the size of the pearlite areas upon deep drawing and pressing properties is usually very small.

During the second sub-stage, which commences at the instant the temperature falls below the critical range, the ferrite crystals formed during the first cooling stage will tend to grow in size until the temperature drops to about 650° C. At the same time the pearlite areas will tend to "ball-up," as during annealing. However, little change usually occurs under industrial normalising conditions because this period is fairly short and, in the absence of strain produced by cold work, the rate of growth of ferrite crystals from other causes is relatively slow, as is that at which carbide becomes spheroidised. When the rate of cooling is so slow that the steel takes about two hours to cool from 900 to 700° C., a noticeable increase in crystal size will occur. Therefore although in theory the rate of cooling is an important factor in determining the crystal size of normalised steel, in practice this influence is nearly always too small materially to affect the final crystal size which, as has already been explained, is determined primarily by the crystal size of the austenite.

Pickling

When inter-stage annealing or normalising of deep drawn or pressed steel articles is not carried out in an efficient protective atmosphere, it will be necessary to pickle these articles before returning them to the press. The solution used is usually warm dilute sulphuric acid, and it may be observed that the temperature of the bath has a greater influence upon its speed of action than its strength. The process by which scale is removed from steel in a pickling bath has already been described, and it will be recalled that the process is not one of simple solution in the acid.

When a proper inhibitor is not added to the bath, over-pickling—perhaps on localised areas—may occur, leading to thinning of the walls of the article. Very energetic action in the pickling bath will increase the amount of hydrogen absorbed by the steel and will thus accentuate the well-recognised phenomenon of hydrogen-embrittlement. As a rule normal ductility is restored if embrittled steel is allowed to stand; but, if it is desired at once to press steel which has been pickled in an active bath, it may be necessary to give a preliminary low-temperature anneal to drive off the hydrogen and restore normal ductility.

A defect for which pickling is often blamed entirely without justification is the production of a rough surface, often on certain localised regions, on an article. The true cause of a rough surface is an undesirably large crystal size, either general or localised, caused by critical-strain crystal growth: pickling only reveals more clearly existing surface roughness produced by this growth.

Other defects revealed, but not caused, by pickling are pitting attributable to the presence of oxide forced deep into the surface by mechanical pressure, as shown in Fig. 130 (p. 192), and blisters. Blisters are caused either by acid penetrating to sub-surface discontinuities of the kind already described and illustrated, or else by hydrogen penetrating to internal discontinuities having no outlet to the surface.

Hydrogen-embrittlement

It has just been said that serious loss of ductility may be produced in low-carbon steel sheet by pickling under unsuitable conditions. Although this defect is not a common one in the press-shop, brief mention of the phenomenon of hydrogen-embrittlement can hardly be omitted.

The exact way in which dissolved or occluded hydrogen produces embrittlement is not known with certainty. One theory is that the presence of hydrogen atoms actually in solution strains the crystal lattice, thus producing hardening and embrittlement. This explanation is rather discounted by the fact that steel containing hydrogen up to the limit of solubility, which is a very low percentage, is not excessively brittle: a much higher percentage of hydrogen is necessary to produce the effect known as hydrogen-embrittlement. Proof that the bulk of the absorbed hydrogen is not in true solution in the lattice has been given by Moore and Smith,[35] who have shown that when hydrogen-embrittled iron is heated gradually the hydrogen comes off in a series of sudden evolutions bearing no apparent relation to the conditions of heating.

Another theory is that hydrogen penetrates into, but cannot escape from, minute internal discontinuities and thus generates a high pressure which causes these to enlarge and spread to form serious cracks, perhaps aided by the chemical action of the hydrogen upon non-metallic inclusions such as slag and iron oxide. Although an action of this kind may occur and may explain why the original measure of ductility cannot always be restored to hydrogen-embrittled steel, it does not seem to account for the extreme brittleness exhibited in the first instance nor for the temporary hardening which occurs.

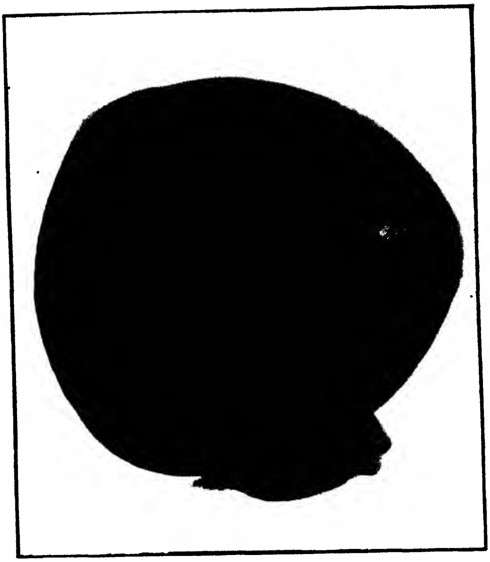
In support of this last theory it must be said that the manner in which absorbed hydrogen is evolved when the iron is heated fits in with what Moore and Smith term "rift occlusion"; also that the volume of hydrogen absorbed by iron is so large that the whole cannot exist actually in the lattice; in other words, the bulk *must* exist—presumably under considerable pressure—in mechanical discontinuities or in places where the lattice is broken up, for example at crystal boundaries or, which is specially important, in the blocks of distorted lattice known as slip or cleavage planes.

The fact that cold-worked iron can absorb more hydrogen than annealed iron supports the belief that at least some of the hydrogen atoms lodge in cleavage planes. It can well be imagined that the presence of a large proportion of hydrogen atoms in the broken-up lattice of cleavage planes—and also of the crystal boundaries—may produce sufficient stress to explain the brittleness which occurs. However, until more knowledge is gained it is best to regard all the theories here mentioned as having a possible and perhaps cumulative influence.

Critical-strain Crystal Growth

Critical-strain crystal growth, meaning the formation of crystals of abnormally large size in sheet or pressed shapes which have been strained a certain "critical" amount, is a phenomenon of great interest to the metallurgist. Industrially, however, the phenomenon is always unwelcome and it causes a lot of trouble in press-shops where annealing and not normalising is used to restore ductility to partly formed steel shapes.

It has already been explained that sheet metal having a very large crystal size will either fail under the press owing to lack of tenacity—tenacity meaning an ability to transmit stresses and so prevent localised necking and rupture in highly stressed regions—or, when failure does not occur, will emerge from the press with a very rough surface. An example of localised fracture accompanied by pronounced surface roughness, both defects being attributable entirely to critical-strain crystal growth, in a region near the apex of a small conical steel shell is shown in Fig. 136. This example is very typical as regards the appearance of the "necked" fracture, the accompanying roughening of the surface and the confinement of the affected zone to a small portion of the pressed or drawn shape. A somewhat similar example, interesting because it exhibits *several* zones which have been strained



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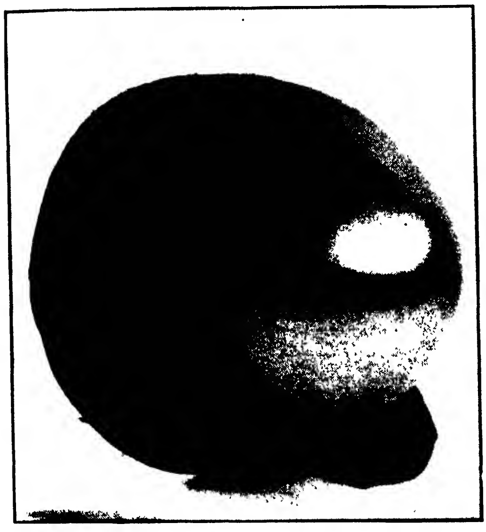

B

FIG. 136. Failure in drawn steel shell due to critical-strain crystal growth.

A: Roughened surface and fracture due to abnormal crystal growth in zone of critical strain.

B: Shell drawn in the same tools but normalised instead of annealed between press operations. × $\frac{2}{3}$

[*To face p.* 206.

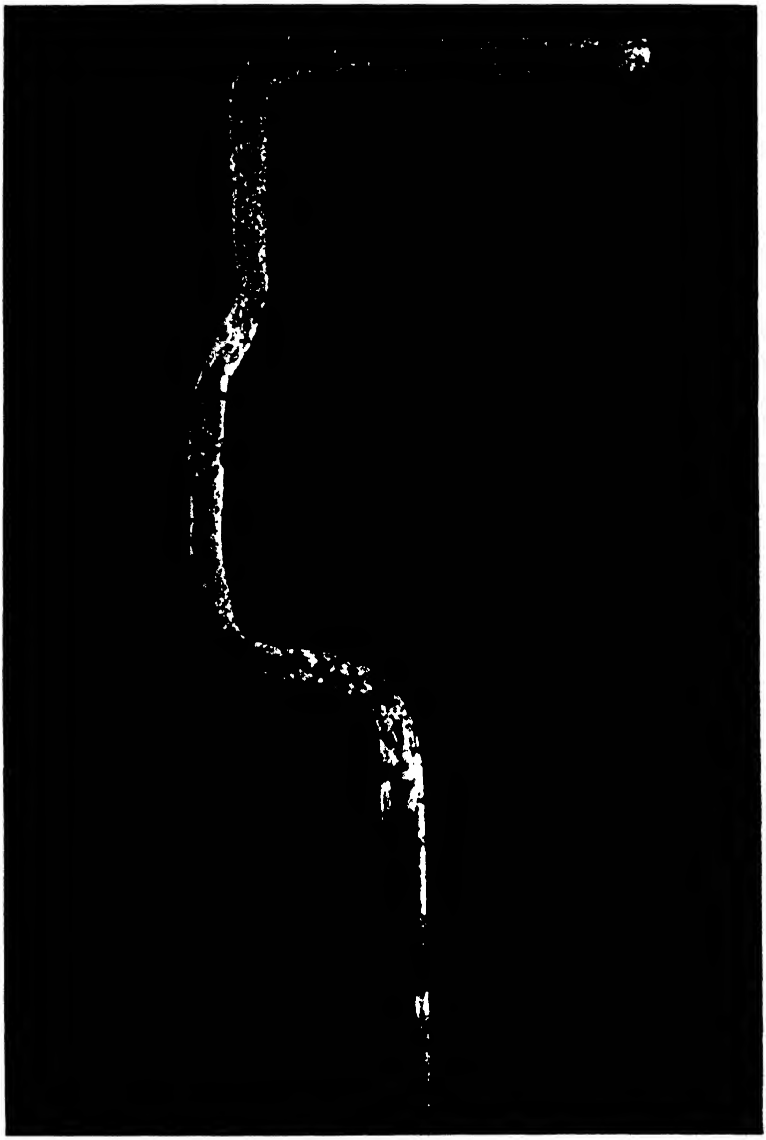

Fig. 137. Section through portion of annealed steel pressing showing critical-strain crystal growth in certain areas. × 3.

[*To face p.* 207.

within the critical-stress range, is illustrated in Fig. 142 (p. 217). Had the draw which followed the inter-stage anneal which produced critical-strain crystal growth been more severe, failure would have undoubtedly occurred in one of the affected zones.

Turning from outward appearance to microstructure, Fig. 86 (p. 123) shows an example of highly localised critical-strain crystal growth in a part of the wall of a pressing where the deformation prior to annealing has amounted to little more than a slight bending. It is interesting to observe that the boundary of the affected zone follows the contour of zones of equal stress usually found in elasto-plastic stress maps of a bend of this kind. During subsequent extension these pressings fractured at the bend illustrated owing to low tenacity of the very large crystals existing at that region.

Fig. 137 shows part of a section cut through the wall of an annealed steel pressing in which critical-strain crystal growth has occurred in several well-defined regions and has produced fracture in another part of the article. It will be seen that although the " average grain size " of the remainder of the pressing has remained normal at about 0·035 mm., some of the crystals in the affected zones extend half-way through the wall, which is over 2 mm. thick. This is not uncommon and, under favourable conditions, crystals will extend from face to face of much thicker sheet if their growth is not hindered by layers of chemical segregation or slag inclusions and if the carbon content of the steel is very low.

In general, critical-strain crystal growth is more common in shallow pressings than in deep-drawn articles, because in the latter the critical range of strain is usually exceeded in most, although not always in all, parts of their walls. In a deep-drawn flat-bottomed cup, for example, abnormal crystal growth is often confined to a narrow circular zone in the bottom. The experience of the author leads him to suggest that the prevalence of critical-strain crystal growth, not always of so pronounced a nature as that evident in the specimens here illustrated, is the source of an unsuspectedly large proportion of trouble during the deep drawing and pressing and subsequent polishing of steel articles.

Considerable interest in the phenomenon of critical-strain crystal growth in steel has been shown by academic as well as industrial workers, and many investigations have been made to determine the conditions most conducive to the growth of crystals of maximum size. Most authorities consider that the most favourable range of strain—which, to the industrialist, is the most dangerous—lies between 10 and 20 per cent. elongation, but there is evidence to show that in the press-shop the dangerous range may extend from at least 5 to 30 per cent. *apparent* elongation. It should be borne in mind that when, as often happens, the wall of a pressed or drawn article has been subjected to both tensile and compressive stresses, the apparent final elongation may not be a reliable indication of the real amount of total deformation which the metal in the wall has actually suffered. This may be the sum of tension and compression, the net external result of which, in terms of apparent strain, may be zero in some parts of the walls of a deep-drawn article of irregular shape.

Turner [36] has published a curve, illustrated in Fig. 138, which relates annealing temperature to degree of strain required to produce maximum crystal growth in steel of 0·10 per cent. carbon content. Although this particular curve may not represent the behaviour of *any* low-carbon steel, as the size and rate of crystal growth is dependent

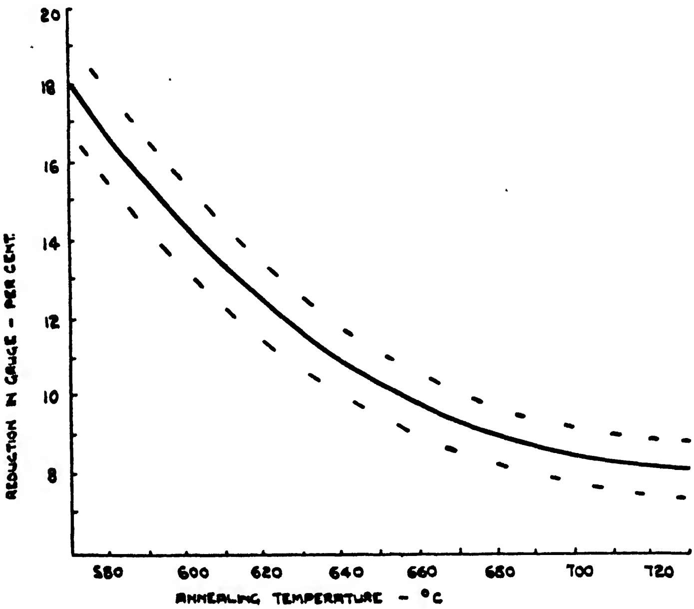

FIG. 138. Curve relating degree of strain (expressed as percentage reduction in thickness produced by rolling) to annealing temperature required to produce maximum growth of crystals in steel containing 0·10 per cent. carbon. [*Turner.*

upon the percentage of carbon and of other elements, it is interesting because it shows the kind of relationship which exists.

The susceptibility of sheet to critical-strain crystal growth increases rapidly with decreasing carbon content. Because of this it often happens that crystals of abnormal size are formed in the surface layers of rimming steel sheet when the core, with its higher percentage of carbon and impurities helped by the retarding influence of slag particles and layers of chemical segregation, retains a normal crystal size. Fig. 139 shows a section through the wall of a pressing which exhibits this rather striking happening. The type of structure illustrated leads to the formation of a very rough surface on pressed or deep-drawn work and sometimes to failure because the core is unable

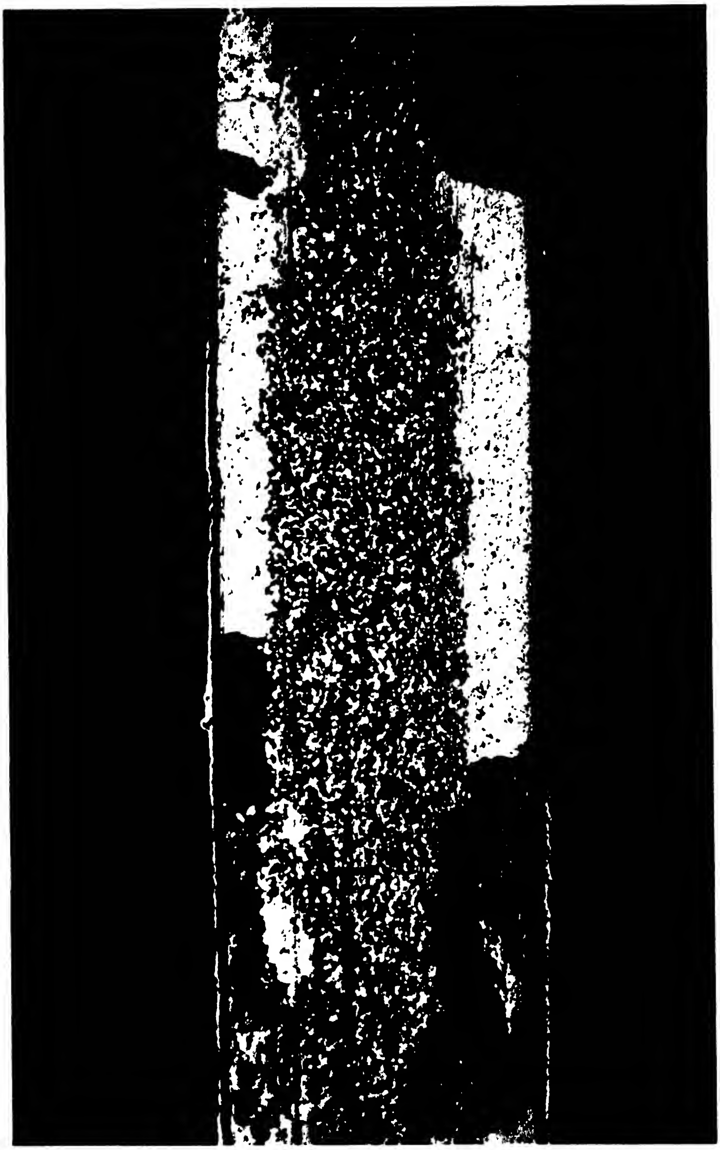

FIG. 139. Section through wall of annealed pressing in rimming steel sheet. Observe abnormal crystal size of surface zones although that of the core is normal. × 20.

[*To face p.* 208.

to carry the added load imposed upon it owing to the lower tenacity of the surface zones.

Remedies for abnormal crystal growth resulting from critical amounts of strain are, at present, three in number. First, and only partly effective, is the reduction of the time of annealing to the shortest possible period followed by fairly rapid cooling. Second, is the very careful apportionment of successive draws so that the dangerous range of strain is as far as possible avoided, a matter of considerable difficulty if not genuine impossibility in many instances. Third, and most effective, is the substitution of proper normalising—which, by definition, implies heating through the critical range followed by fairly rapid cooling—for annealing, because annealing is almost certain to give some opportunity for critical-strain crystal growth to take place.

Fig. 136 (p. 206) shows an annealed shell roughened and fractured owing to the occurrence of a zone of critical-strain crystal growth. The only alteration in the production operations needed to make the wholly satisfactory shell illustrated in the lower photograph of the same figure was the substitution of normalising for annealing before the final press operation.

Ageing

The term "ageing," when applied to low-carbon steel sheet, implies a change in physical properties which occurs when steel which has been cold-worked—for example, sheet which has been cold-rolled or pressed—is allowed to stand for some time.

It is best to distinguish this particular kind of change by calling it "strain-ageing" in order to discriminate between it and "quench-ageing," in which a somewhat similar change in physical properties is induced by quenching instead of by cold-working. This distinction is not as superfluous as it may at first seem, because although an oil or water quench is rarely given to low-carbon steel sheet by either the maker or the consumer, rapid cooling in air or gas from normalising temperature may induce a mild form of quench-ageing.

Strain-ageing. Strain-ageing sometimes leads to serious difficulties in the press-shop because, particularly under the production conditions obtaining in many small works, it is often impossible to feed sheet to the presses as soon as it is delivered by the supplier or, even when this can be done, to complete a number of successive press operations within a short space of time. Not the least difficulty in the way of overcoming these adverse conditions is the fact that the ageing propensities of different batches of sheet vary very widely; comment has already been passed upon the type of individual who, when variation occurs in the properties of the metal he has to handle, dismisses the trouble as being attributable solely to "bad" metal and cannot be persuaded that at least a partial remedy for his trouble often lies in his own hands.

Strain-ageing is a most interesting phenomenon to the scientific student, but to those actively engaged in the deep drawing and pressing industry it constitutes a three-fold evil because it increases the hardness of sheet, may seriously reduce its ductility, and destroys the effect of temper-rolling or roller-levelling given to minimise stretcher-strain markings.

Examining the first two of these three items, the curves reproduced

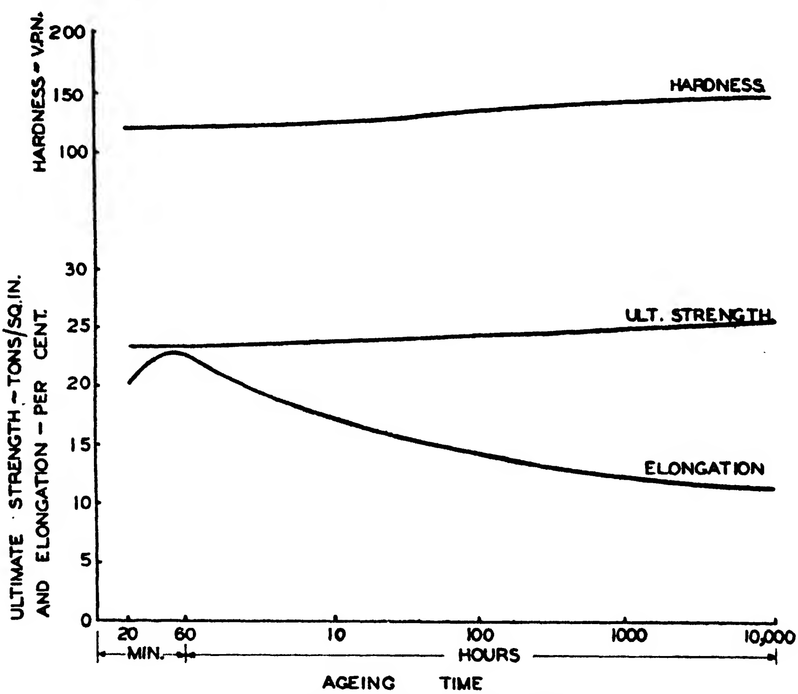

FIG. 140. Typical curves showing changes in percentage elongation, ultimate strength and hardness which take place when strained low-carbon steel sheet is allowed to stand at room temperature.

in Fig. 140 show the kind of change which takes place in ultimate strength, percentage elongation and hardness when annealed and lightly cold-rolled low-carbon steel sheet is allowed to stand at room temperature. Confusion sometimes arises because it is assumed that any loss of ductility will be accompanied by an appreciable increase in hardness as measured by indentation hardness tests. This assumption is incorrect, for both experience in the press-shop and physical tests made in the laboratory show that a serious loss in ductility, reflected in a fall in cupping-test values and in percentage elongation as determined by tensile tests, may occur accompanied by only a relatively small increase in hardness and ultimate tensile strength.

For this reason hardness tests cannot always be used to determine whether the failure of certain pressings is due to strain-ageing ; with unpressed sheet a tensile or cupping test may give a useful indication.

Rodgers and Wainwright [37] have published a number of curves relating the indentation hardness, ultimate tensile strength and percentage elongation of various low-carbon steel sheets strain-aged after various amounts of cold reduction. These results provide clear proof of the fact that changes in percentage elongation are not reflected in changes in indentation hardness nor, sometimes, in ultimate strength. They also confirm those of other investigators in showing what industrial workers have suspected, namely, that the rate of strain-ageing tends to be greater, and the fall in elongation more erratic, with normalised than with annealed low-carbon sheet, and that the loss of ductility seems to be greatest at small amounts of strain equivalent to a reduction by cold-rolling in the region of 5 per cent. With reductions of less than 10 per cent. there is clear indication of an initial *increase* in ductility, as indicated in the curve for percentage elongation shown in Fig. 140, prior to the start of the major decrease.

The general tendencies illustrated in Fig. 140 do not represent extremes, but even here it will be seen that when the elongation has fallen from the original value of 25 per cent. to the final value of 15 per cent., thus completely spoiling the sheet for the purpose of deep drawing or pressing, the hardness has only increased from 125 V.P.N. to 150 V.P.N. Quite often a degree of strain-ageing sufficiently severe to render sheet unusable under the press is accompanied by a considerably smaller increase in hardness than that indicated by the curve shown in Fig. 140.

Besides producing the changes in physical properties just indicated, strain-ageing gradually restores the " yield-point elongation " step to the smooth stress-strain curve of cold-worked low-carbon steel (see Fig. 148, p. 230) ; an effect which, for reasons explained in Chapter VII, is often most unwelcome in the press-shop. The harmfulness of strain-ageing is therefore twofold, for it impairs the actual deep drawing and pressing properties of sheet and also increases the tendency for stretcher-strain markings to be formed.

It is interesting to notice that the greater the degree of temper-rolling, the longer is the time required for the yield-point elongation step in the stress-strain curve to return. Because severe temper-rolling itself causes a serious reduction in ductility, the seemingly simple expedient of increasing the reduction given during temper-rolling to 10 per cent., a value above which the yield-point elongation does not return after a lapse of time, cannot be used except on sheet which has to withstand only very light pressing operations.

Temperature has a marked influence upon the rate at which strain-ageing proceeds. To give a practical rather than a scientific illustration, if cold-worked sheet is held at a temperature of approximately 100° C. for three hours, the change in physical properties may be as great as if the sheet had stood at ordinary temperature for six months. This explains the observed fact that more trouble due to the formation of stretcher-strain markings on temper-rolled sheet is experienced in hot than in cold weather, because in hot weather the effect of temper-rolling passes off more rapidly. On the other hand, the possible advantage of keeping temper-rolled sheet in cold-storage does not seem to have been investigated.

Turning from the effects of strain-ageing to a consideration of its cause, it cannot be said that the true origin or even the mechanism of the process is understood fully. For some time the phenomenon was attributed by different investigators to precipitation-hardening caused directly or indirectly by carbon, oxygen, nitrogen and even hydrogen. Practical experience shows that rimming steel tends to strain-age more than killed steel, thus suggesting that oxygen is of primary importance. Several independent investors, for example Davenport and Bain [38] in the United States and Pfeil [39] in Great Britain, have published evidence to show that the tendency to strain-age seems to be closely related to the degree of deoxidation given to steel either when it was made or at a later stage by special treatment, such as heating in hydrogen. It has been established that when steel which, as a result of careful deoxidation and special annealing, does not show normal strain-ageing tendencies is heated in air, it absorbs sufficient oxygen to enable it to strain-age in the usual manner even though it was not subject to this phenomenon previously.

Daniloff, Mehl and Herty [40] suggest that the influence of oxygen upon ageing is two-fold, and that it is due partly to an assumed direct effect of oxygen held in solution and partly to an indirect effect attributable to the known influence of oxygen upon crystal size, an influence already mentioned during discussion of the microstructure of rimming and killed steels. On the other hand, Edwards, Jones and Walters [41] are of the opinion that oxygen is *not* a primary cause of strain-ageing, and suggest that the amount of strain-ageing which a low-carbon steel undergoes is a function of the amount of deformation which occurs at the yield-point, and is therefore related to crystal size.

Swinden and Bolsover [42] have produced evidence to show that steel having a fine " inherent grain size " is much less susceptible to strain-age-embrittlement than steel having a coarse " inherent grain size," irrespective of the method by which the steel is produced ; but that, for a given grain size, Bessemer steels are more susceptible to this defect than open-hearth steels. This finding also points to oxygen, perhaps in the form of FeO, being a factor of prime importance. These investigators have also found that in a fine-grained steel an increase in nitrogen content from 0·005 per cent. to as high as 0·018 per cent.

does not materially increase strain-age-embrittlement in the steels they examined; whereas in a coarse-grained steel an increase in nitrogen from 0·005 per cent. to 0·010 per cent. increases the strain-ageing effects, although beyond this value any further effect is comparatively slight.

The influence of nitrogen is the probable explanation of the recognised greater tendency to strain-age exhibited by low-carbon steel made by the Bessemer as compared with that made by the open-hearth process. Sometimes this property is turned to advantage, for example in wire used to make cheap cold-drawn wire for upholstery springs or in sheet for shallow-pressed parts for domestic culinary utensils in which really high ductility is of little importance and the extra hardness of the worked and strain-aged product is an important advantage. At other times the property is unexpectedly harmful; for example, cable conduit made from cold-formed and welded Bessemer steel cannot be bent as readily by fitters as similar conduit made from open-hearth steel.

Returning to the consideration of the causes of strain-ageing, Edwards, Phillips and Jones [137] have shown that the occurrence of this phenomenon can be prevented in low-carbon steel by the addition of some special element having a strong affinity for carbon, provided that sufficient is added to combine with all the carbon present. This discovery suggests that strain-ageing is caused primarily by carbon, presumably by actual or incipient precipitation from solid solution; yet the recognised influence of other elements, for example nitrogen and oxygen, ought not to be forgotten even though future work proves beyond doubt that their action is of only a contributory or modifying nature.

The additions examined by the workers just mentioned are molybdenum, manganese, chromium, vanadium, niobium and titanium. This order is one of increasing affinity for carbon; thus the investigators state that in low carbon steel 2 per cent. of molybdenum served only to minimise the normal degree of strain-ageing, that 0·55 per cent. of vanadium reduced it to a practically negligible amount, and that 0·36 of niobium or 0·21 per cent. of titanium eliminated it.

It has been said that some of the deoxidised steels now manufactured industrially seem relatively free from strain-ageing tendencies, and during recent years attempts have been made deliberately to produce non-ageing steels suitable for use in the press-shop. These attempts have proved successful on a laboratory scale in Great Britain and, according to technical literature, on at least a semi-production scale in the United States. The sheet is said to be rolled from fully-killed steel deoxidised with aluminium and titanium; and a special heat-treatment, which presumably has for its object the complete precipitation of constituents held in solid solution, has to be given after the final rolling if the best results are to be obtained. This heat-treatment usually takes the form of an anneal at a temperature in the region of 650 to 700° C. maintained for several hours, followed by very slow cooling at a rate of not more than 15° C. per hour. To prevent the occurrence of critical-strain crystal growth, a preliminary normalising is generally given to finish-rolled sheet prior to the annealing and slow cooling just described.

Until such time as the price and deep-drawing properties of genuine non-ageing steel sheet approach those of the ordinary varieties which consumers now use, the only way in which they can minimise troubles attributable to strain-ageing seems to lie in endeavouring to complete all deep drawing or pressing operations before a serious loss of ductility takes place or the effect of temper-rolling passes off. It is true that ductility can be restored to most age-hardened sheet by heating it to a temperature of about 650° C. or more; but as this treatment also removes the effect of temper-rolling, and may therefore lead to the formation of severe stretcher-strain markings during subsequent pressing, its value is often small with unused sheet if not always with partly-drawn articles. It is true also that the formation of stretcher-strain markings in strain-aged sheet can be prevented by further roller-levelling, but this treatment will not restore the associated lost ductility.

Quench-ageing. If low-carbon steel is cooled rapidly from a temperature of about 550 to 700° C. and then allowed to stand for a period of days at room temperature the hardness will gradually increase and the ductility will fall, sometimes to a very marked extent. The changes which take place are of a complicated nature as shown by the fact that the first change is often a *fall* in hardness, and that when the sheet is aged at a raised temperature the hardness quickly rises to a maximum and then falls, often to a value lower than that of the sheet before it was quenched. Normal properties can be restored to the steel by normalising or annealing.

It is believed that quench-ageing is caused by carbon, not, as seems probable with strain-ageing, by oxygen; but in the opinion of some authorities both oxygen and nitrogen may accentuate the effect of the carbon. According to Davenport and Bain,[38] quench-ageing is greatest when the percentage of carbon lies between 0·05 and 0·06, and for practical purposes becomes negligible when it falls to 0·02 per cent. or less.

Andrew and Trent[43] suggest that the cause of quench-ageing in low-carbon steel is the retention of a small amount of "low-carbon austenite" in the assumed wholly-ferritic microstructure. This retained austenite is naturally unstable and in time changes to martensite, a very small proportion of which distributed throughout the matrix would account for the recognised increase in hardness,.

and more particularly loss of ductility, it is sought to explain. This hypothesis is supported by certain experimental evidence and is one which needs careful study.

It is particularly interesting to observe that this explanation of quench-ageing can be extended to strain-ageing which, as already explained, is a much more serious cause of trouble in the press-shop. In the light of present knowledge it seems certain that a very high temperature is attained momentarily on the crystallographic "slip planes" upon which movement takes place when a crystal is deformed plastically in the cold. It is therefore conceivable that, although of such brief duration, this sudden large increase in temperature changes at least a portion of the crystal lattice in the vicinity of the slip-planes from the *alpha* to the *gamma* form of iron and also causes a certain amount of carbon to go into solution in it. Once formed, the new lattice will persist because the rate of cooling will certainly be more rapid than during a drastic water quench. On standing this carbon will tend to be precipitated, a state which would produce the change in physical properties termed strain-ageing. This change would be accelerated if the temperature were raised slightly, and this is in accordance with observed facts.

At present the importance of quench-ageing to users of steel sheet lies in a possible loss in ductility due to rapid cooling after normalising, but it is not unlikely that in the future this seemingly harmful phenomenon may be turned to good account. For instance, it may be found possible even under industrial conditions to press quenched sheet at the time when the temporary increase in ductility which precedes the subsequent permanent decrease is at its maximum or, again, to produce quenched and aged sheet having better ductility than that of sheet manufactured by present methods.

Blue-brittleness

Blue-brittleness, which must not be confused with hydrogen-embrittlement, is the name given to a peculiar, and often very pronounced, form of embrittlement developed by many low-carbon steels which have been cold-worked and then heated to a temperature between 150 and 300° C. Laboratory tests made on a section having sufficient thickness to enable Izod impact specimens to be machined show that it is not uncommon for low-carbon steel having an Izod impact value in the region of 90 foot-pounds to have this value reduced to less than 10 foot-pounds when severe blue-brittleness is developed.

It need hardly be explained that the defect termed blue-brittleness derives its name from the fact that it is often associated with the attainment of a temperature at which the blue of the range of temper-colours is formed on steel heated in air. This defect is well known in the enamelling, japanning and hot-galvanising industries and, indeed, in any in which cold-worked low-carbon steel has to be heated to the temperature just mentioned. The susceptibility of different steels to blue-brittleness varies very greatly, and some appear to be relatively immune. Because of this the defect often causes most trouble when steel obtained from a new source is suddenly introduced into a works in which steel which does not demand the taking of special precautions has hitherto been used, a happening which explains the failure illustrated in Fig. 141. This particular failure, which is representative of a whole batch of stove-enamelled articles normally made without difficulty by rolling the walls of a deep-drawn shell from which the bottom had been severed, must be attributed to the combined influence of blue-brittleness and strain-ageing, for the hardness of the cracked articles proved to be no less than 180 V.P.N., an abnormally high value for low-carbon steel cold-worked to the extent shown.

Many explanations have been advanced to explain blue-brittleness. One explanation is that blue-brittleness is the ferrous equivalent of season-cracking in brass and certain other copper alloys. This belief is certainly incorrect for, although both these defects are caused by the action of residual stresses in cold-worked metal, season-cracking requires the presence of some external agent, such as traces of ammonia in the atmosphere, whereas blue-brittleness requires no external agent. This proves that the two defects are different.

Another explanation is that blue-brittleness is a form of ageing, or loss of ductility, a defect already discussed. Those who hold this belief will doubtless find fresh support in the explanations advanced by Andrew and Trent [43] and Andrew [44] to account for the more usual forms of ageing; but, if any relationship exists, blue-brittleness is such a particularly virulent form of ageing that special explanations seem necessary.

Yet another explanation is that raising the temperature to some 200 to 300° C. causes recrystallisation to take place on the atomic slip planes on which movement has occurred as a result of cold-deformation. This might cause the space lattice of the crystal to be severely strained, thus engendering the brittleness it is sought to explain.

An interesting fact, observed by a number of independent investigators, is that when steel which develops blue-brittleness is strained in a tensile testing machine within a certain range of temperature near 200° C., the stress-strain curve shows violent vertical fluctuations for some distance past the yield-point. It has been suggested that this is due to some action taking place on the slip planes in the crystal aggregate; for example, that, at this temperature, the rate of work-hardening is barely sufficient to enable the slipping planes to " re-set " and transmit stress to adjacent crystals. Above and below this

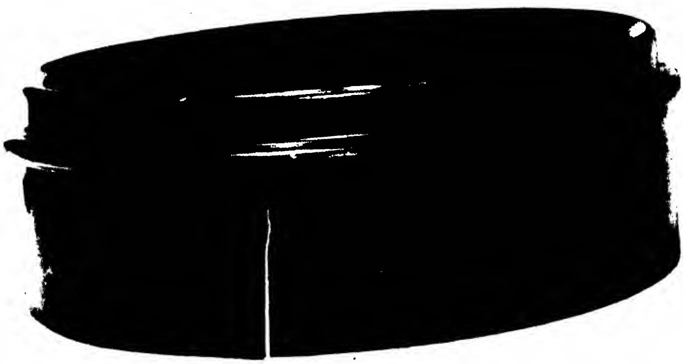

FIG. 141. Crack caused by "blue-brittleness" induced by stove-enamelling a deep-drawn steel cover.

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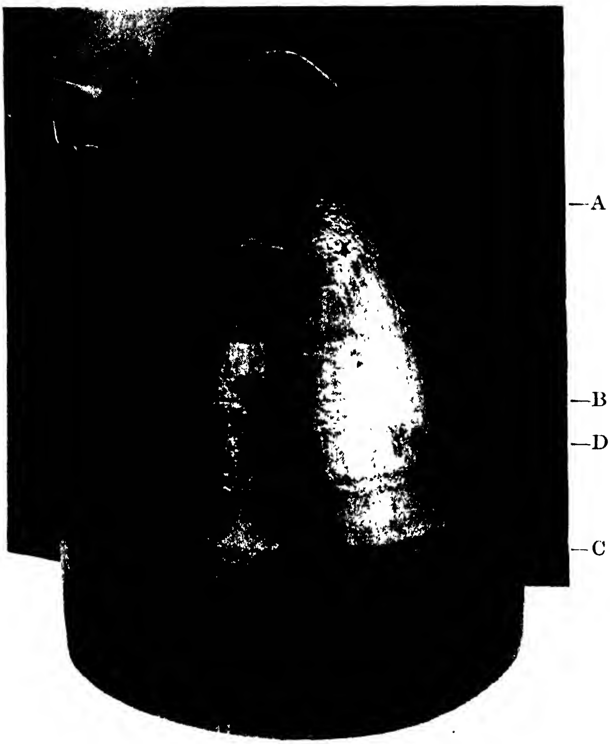


FIG. 142. Combination of defects in a pointed shell deep drawn to a depth of 12 inches from steel sheet 0·035 inch thick. × $\frac{1}{3}$

[To face p. 217.

temperature-range the stress-strain curve is smooth and of normal shape.

Carbon, phosphorus, oxygen, hydrogen and nitrogen have each been put forward from time to time as the probable cause of blue-brittleness, but in some instances reports are conflicting and it may be that a certain form or combination of these impurities is necessary, or that they merely aggravate some other property or condition not yet isolated. A certain percentage of carbon seems to be an essential, because pure ferrite and medium-carbon steels are not subject to blue-brittleness to anything like the same degree as low-carbon steels of the kind used in the deep drawing and pressing industry. However, available evidence points to the fact that carbon alone does not cause blue-brittleness, else all low-carbon steels would develop this defect. The condition of the carbon, for example the amount retained in true solution, may be an important factor, but evidence on this point is lacking.

Phosphorus is often held to be the cause of blue-brittleness, and it is true that steels containing a relatively high percentage of this element seem unusually prone to develop this defect. For this reason the percentage of phosphorus is often kept specially low in sheet destined for enamelling, but this precaution is no guarantee that blue-brittleness of a serious nature will not occur sometimes and it seems, therefore, that phosphorus is a contributory and not a principal cause of this defect.

Turning from solid to gaseous impurities, the *rôles* of oxygen and hydrogen are not yet known. It is possible that much of the suspected influence of oxygen may be due to other causes to which the percentage of oxygen is incidental, while effects ascribed to hydrogen can seldom be reproduced under controlled conditions when the separate defect of hydrogen-embrittlement is excluded. Nitrogen, on the other hand, is probably the most important of any known factor and, unlike phosphorus, its influence is so certain that it can be predicted with safety that any low-carbon steel containing a relatively high percentage of nitrogen will be liable to blue-brittleness. Epidemics of cracking in the enamelling and hot-galvanising industries have repeatedly been traced to the sudden introduction of basic Bessemer steel which, for reasons already described, contains a relatively high percentage of nitrogen.

A peculiar feature of blue-brittleness is that, like critical-strain crystal growth and unlike ageing, the conditions of temperature and degree of strain are fairly critical. Tensile tests indicate that a strain of approximately 15 per cent. followed by heating at about 250° C. produces the greatest brittleness of which any particular steel is capable; after a strain amounting to either 10 or 20 per cent., brittleness is usually somewhat less pronounced. When interpreting these laboratory findings into press-shop practice it must be remembered that, owing to the very complicated stresses and flow of metal produced by many deep drawing and pressing operations, the apparent total elongation measured between two points on the wall of a pressed shape does not always indicate the amount of deformation which has actually occurred in the sheet. The influence of temperature is rather less critical than that of strain.

Until the true cause of blue-brittleness is established, and perhaps after, consumers who do not wish to give a stress-relieving anneal prior to stoving or hot-galvanising are well advised to avoid Bessemer steel and, as an additional precaution, to use steel having as low a percentage of phosphorus as possible.

An Unusual Combination of Defects

At the end of this review of defects prevalent in steel sheet and of special difficulties encountered when it is pressed and drawn, it is interesting to study the shell illustrated in Fig. 142, which deserves the title of "The press-man's nightmare, or how not to do it." Owing to the depth of the pressing, which is in sheet 0·035 inch thick, and to the pointed contour of its apex, it had to be formed in easy stages with frequent softening which, it must be emphasised, was attained by annealing instead of normalising. These circumstances resulted in the formation of three distinct zones of critical-strain crystal growth, marked A, B and C in the photograph, produced during the final draws. Another, marked D, which was produced at an early stage, has elongated into a zone of wavy "orange peel" texture. It will be seen that in one of these zones—B—local necking has almost produced fracture during the final draw.

Stretcher-strain markings are visible in a number of zones; the sharply-defined markings are the ones produced after the final annealing, those less sharply defined have been formed earlier and—owing to causes already explained—have persisted in spite of the fact that the zones in which they occurred have subsequently been elongated beyond the critical value at which they normally disappear.

Lastly, wrinkling has extended for some distance into the wanted part of the shell. This is attributable to the fact that the low tenacity of the zones of abnormal crystal growth made it necessary to use a very low pressure-plate loading in order to prevent fracture in these zones.

Summarising this chapter, it can be said that internal discontinuities—known in the press-shop as "laminations"—often tend to be more serious than any other defect, and that "directionality" is also serious sometimes. Chemical segregation, unsuitable crystal size and ageing constitute occasional sources of trouble, and the peculiar defect of " blue-brittleness " may cause much difficulty in certain kinds of work. Critical-strain crystal growth, productive of a rough surface if not always of actual breakage in the press, always lurks ready to trap unwary consumers who persist in annealing instead of normalising between press operations, and, as explained in the foregoing pages, many minor yet often serious defects are met with in sheet of industrial quality.

Readers are reminded that, as with brass, the *general* defects and difficulties reviewed in Chapter III are also experienced with steel; mention of them has not been made in this chapter merely to avoid repetition. A peculiar defect encountered with low-carbon steel in the press-shop is that known industrially as "stretcher-strain markings." Because of the importance and, incidentally, considerable scientific interest of this defect it will be studied separately in the next chapter.

CHAPTER VII

STRETCHER-STRAIN MARKINGS

THE term " stretcher-strains " has been coined to described characteristic surface markings, usually of a wedge-shaped, flamboyant pattern, which appear during the early stages of the plastic elongation of soft mild steel. " Lüder's lines," " strain figures," and—proposed by the present author [45] as being more suggestive of solidity—" distortion wedges " are other names which have been used to describe the same effect.

Similar markings, sometimes termed " coil-breaks," can be formed during the coiling of soft strip or, when they are often termed " flutes," in the handling of flat sheet. Every care should be taken to prevent the formation of these marks because, once formed, they may persist through several shaping operations in a surprising manner and may form detrimental blemishes on the surface of the finished article.

Although the nature and mode of formation of stretcher-strain markings seem to be well established, the avoidance of this defect is so difficult that many press-shop operators engaged in the production of articles containing areas in which the deformation is small would place it at the top of a list of current troubles. The difference in level which actually exists between the levels of distortion wedges and the adjacent plateaux of undistorted metal is extremely small, often less than 0·001 inch in thin sheet, yet it is always very costly—and often quite uneconomic—to grind and polish the whole surface flat prior to plating, spray-painting or dipping. On the other hand if no smoothing is attempted, stretcher-strain patterns may so spoil the appearance of an article as to make it of no value commercially : hence the seriousness of this defect.

It seems certain that the surface markings occasionally observed on certain non-ferrous metals strained in tension, for example aluminium and bronze, are in no way related to the peculiar method of plastic deformation of low-carbon steel which gives rise to stretcher-strain markings. The marks on non-ferrous metals are caused by a form of macroscopic deformation, also observed on steel after the yield-point is passed, which in its ultimate and most pronounced manifestation appears as the " contractile cross " observed by many investigators. These marks appear as narrow, parallel bands crossing the surface of the parallel part of the ordinary tensile test piece obliquely, and differ essentially from stretcher-strain markings in that they are

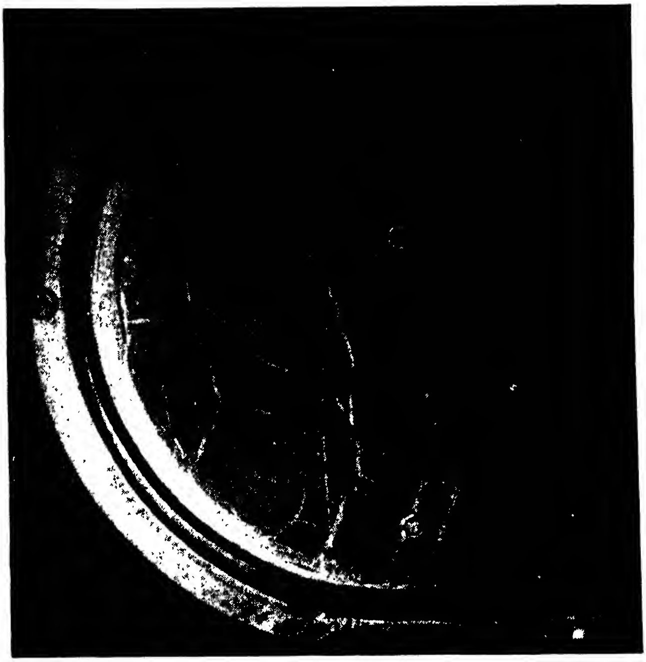


FIG. 143. Stretcher-strain markings on bottom of shallow pressed-steel tray.

[*By courtesy of G. L. Smith and Vauxhall Motors Ltd.*

FIG. 144. Stretcher-strain markings on automobile panel.

[*To face p.* 220.

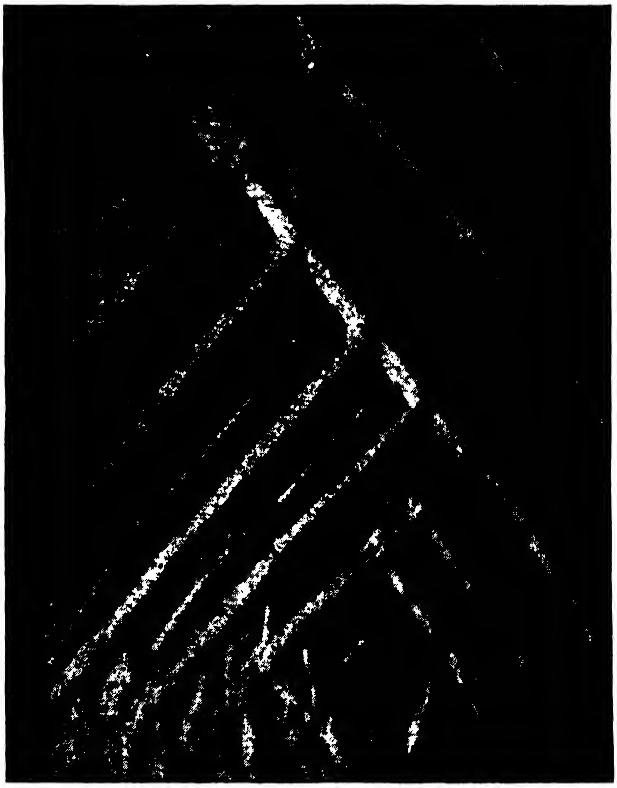


FIG. 145. Stretcher-strain markings on steel sheet; a typical configuration. × 7.

[To face p. 221.

not bounded by a sharp step marking a change in level, do not extend and widen, often are not visible until long after the yield-point is passed, and do not merge and disappear even when the stress rises to near the ultimate value. Fracture occurs by the continued necking of one of these bands.

Nature and Mode of Formation

Expressed as simply as possible, stretcher-strain markings are the surface manifestation of actual "necking," or localised reduction in cross-sectional area, produced by the action of tensile-stresses on the sheet upon which they appear. Fig. 143 shows typical markings formed upon the flat bottom of a pressed-steel tray, while Fig. 144 shows markings produced in an automobile body panel as a result of pressing and forming the raised ridges seen in the photograph. Fig. 145 shows, at a higher magnification, a characteristic pattern formed on a nearly flat surface.

Before the formation of stretcher-strain markings can be described, it is necessary to examine an important peculiarity in the stress-strain curve of fully annealed low-carbon steel. This peculiarity takes the form of a definite kink in the curve which occurs at the so-called yield-point of the steel, as indicated in Fig. 148 (p. 230). It will be seen that the first and normal part of the curve rises in a straight line indicative of elastic deformation up to what is known as the "upper yield-point," at which it falls at once to the "lower yield-point"—which is held by many authorities to be the true one—then rises, often in a rather erratic manner, to the upper yield-point, after which it continues in a smooth curve of normal shape.

The existence of the upper yield-point, a value which is influenced by rate of straining, is thought by some investigators to be caused by a curious "lag" which ferrite exhibits in changing from a condition of elastic to plastic strain. Once this lag has been overcome, plastic deformation starts and the stress sustained by the yielding ferrite falls momentarily to the true yield-point; afterwards increasing gradually, as work-hardening takes place, until the zone of yield or slip becomes sufficiently work-hardened to transmit a stress having a value just in excess of the upper yield-point to the surrounding undistorted areas of the test piece. When this happens, yield takes place in another zone, the cycle of "Yield—Work-harden—Yield elsewhere" being repeated until no part of the strained specimen contains any sizable zone of virgin crystals to give a lag, and plastic deformation proceeds in a uniform manner as indicated by the smooth contour of the stress-strain curve once the yield-point irregularity is passed.

Bearing in mind this brief description of the peculiar nature of the yield-point of annealed low-carbon steel, it becomes possible to visualise the process by which stretcher-strain markings of an elementary kind are formed under simple stresses; complication, although altering the pattern of the stretcher-strain markings produced, in no way alters their fundamental nature. In Fig. 146 an attempt has been made to depict what the author believes to be the true form of stretcher-strain markings formed in a homogeneous rectangular steel bar stressed axially, and to indicate their angular relationship to the direction of applied tensile stress. This hypothesis is based on extended industrial observations following laboratory experiments in which specimens of many shapes were strained small amounts by various methods and the resulting distortion wedges revealed by special etching.[46, 47] The five flat tensile test bars shown in Fig. 147, selected from a series of ten, are typical of the strain-etch figures obtained.

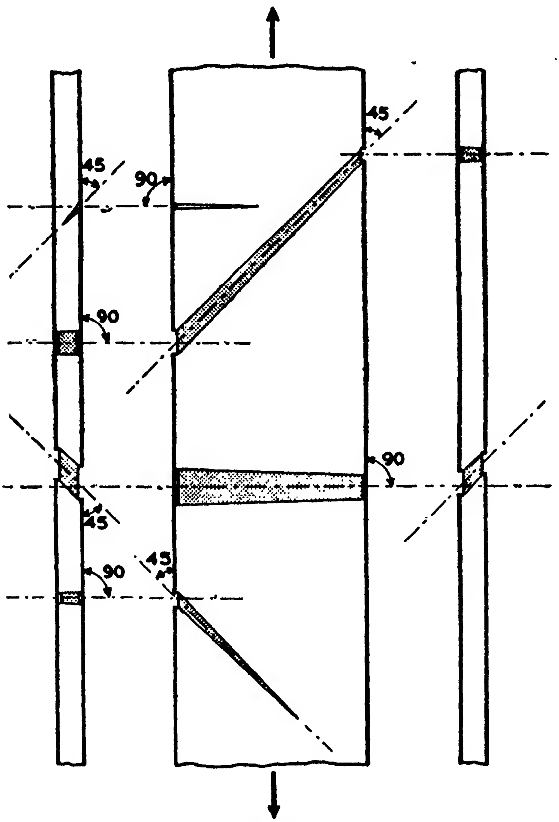


FIG. 146. Drawing showing form and angular disposition of "distortion wedges" formed in a flat rectangular bar of mild steel strained in tension. (Third angle projection.)

When the upper yield-point of the steel is exceeded, a single distortion wedge forms at a point of stress concentration, usually at a corner of a rectangular tensile test piece, as indicated by the uppermost wedge in Fig. 146. If a local "stress-raiser," for example, a small hole or even a centre-punch mark, is present on the face of the specimen, a wedge may start at it instead of at a corner where, in a homogeneous specimen, the stress will be highest.

Having started, the distortion wedge grows rapidly in length, but relatively slowly in width, and proceeds across the face of the specimen either at 90 or at 45 degrees to the direction of applied tensile stress. When it grows in the 90 degrees direction on the face, it will grow at

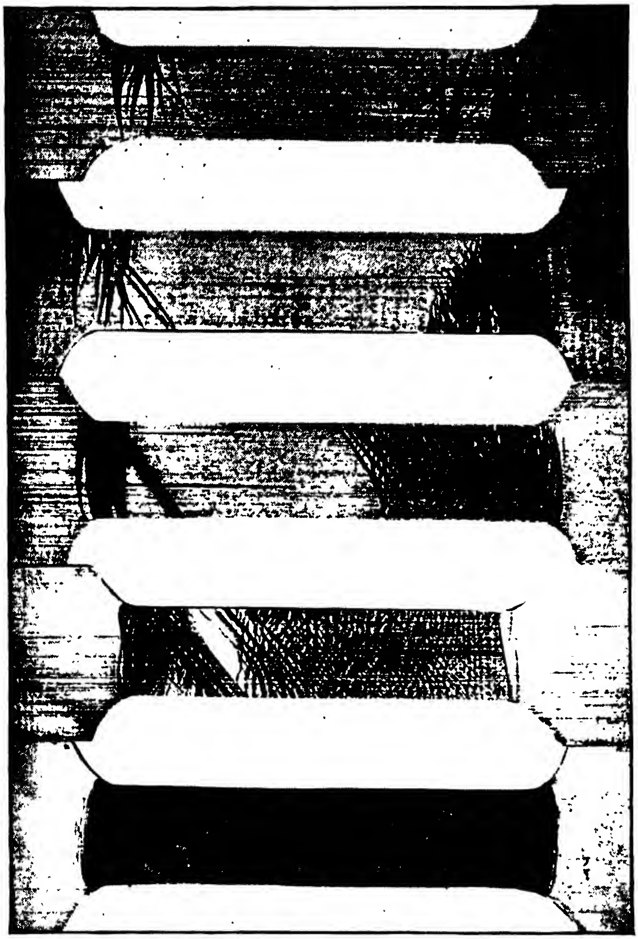


FIG. 147. Spread of distortion wedges when annealed low-carbon steel is strained from the yield-point to 4 per cent. elongation. The photograph shows a series of flat tensile test bars strained to the indicated percentage elongation (on 4 inches) and etched to reveal zones of plastic deformation. × ½.

[*To face p.* 222.

45 degrees on the side, and *vice-versâ*, as illustrated in Fig. 146. In thin specimens cut from sheet the wedge usually penetrates the whole thickness very soon after its formation, and it is difficult to detect the two distinct orientations which are seen clearly on the side of a thick bar.

A distortion wedge is a block of metal in which, the " lag " at the yield-point of the steel having been overcome, yield—meaning a small amount of *plastic* deformation resulting from actual slip in some of the crystals composing the aggregate—has taken place. This is proved by many properties of the wedge metal such as an increase in hardness, a change in rate of solution by etching reagents and an alteration in the angle of reflection of an incident beam of light, for it can be shown by rotating a specimen that the visible difference is not explained by the surface of the wedge having become " matte " or roughened. As the block or distortion wedge continues to deform plastically it naturally becomes reduced in cross-sectional area, giving the " step " which is one of the principal characteristics of stretcher-strain markings and, in this process, gradually work-hardens until it becomes able to transmit a stress in excess of the upper yield-point value, whereupon another distortion wedge forms elsewhere and the process is repeated. This answers the question, so often asked, why, having become localised at one distortion wedge or stretcher-strain marking, plastic deformation does not continue within the confines of this one wedge until excessive local reduction in cross-sectional area leads to failure.

When the rate of straining is relatively rapid, several wedges may appear at what, to the unaided eye, appears to be the same instant and, even at slow rates of straining, fresh wedges may appear and start to grow before existing ones have finished growing.

It will be clear from what has been said that the severity and distinctness of distortion wedges is likely to be proportional to the size of the yield-point " kink " in the stress-strain curve. As will be shown later this is indeed so, but it seems certain that other factors, not yet understood fully, play a part in determining to what size individual wedges grow before they harden sufficiently to transmit stress to the surrounding metal.

An interesting fact is that, in growing, a distortion wedge frequently passes without apparent hindrance through an existing wedge lying in its path. It might be thought that the strain-hardened barrier would stop or at least deflect the new wedge, and it is interesting to speculate whether the new wedge penetrates the old so readily because, owing to its different orientation, slip proceeds upon different sets of planes in the crystal aggregate.

Returning to the consideration of our rectangular tensile test bar, distortion wedges continue to grow in number and, at a later stage, in size until no areas remain which have not suffered plastic as distinct from elastic deformation. In the series of tensile test pieces already mentioned, complete merging of distortion wedges took place at an elongation of approximately 4 per cent. measured on the 4-inch gauge length of the specimens. When this stage is reached, no plastically-unstrained crystals remain to give a "lag" or upper yield-point effect, and the test piece extends in a uniform manner. It is important to notice that, setting aside the evidence of stretcher-strain or distortion-wedge markings, tensile tests show how, when projected on the axis of the familiar graph, the length of the kink in the stress-strain curve already mentioned corresponds to an elongation of the test piece of between 4 and 5 per cent., the value at which complete merging of distortion wedges occurs.

The straight, precisely-oriented distortion wedges of the hypothetical tensile test bar shown in Fig. 146 bear little relation to the stretcher-strain markings found on many commercial pressings, for these patterns are often straggling and individual wedges curved instead of straight and in some places may have no apparent angular relationship to the applied stress or even to the shape of the pressing, although some degree of symmetry is usually maintained. The reason for this difference is that the stress system in any one area of the wall of a pressing is generally complicated, continually changing and, moreover, the contour of the pressing is also altering while the distortion wedges are growing. This explains why the markings seen on commercial pressings are often curved and apparently oriented fortuitously, although often the markings in any one area will conform quite closely to the theoretical pattern distorted uniformly as, for example, in the pressing illustrated in Fig. 145 (p. 221).

Even in rectangular tensile test bars strained axially, distortion wedges do not always grow in straight lines owing to the heterogeneity of the steel, to the presence of small stress-raisers and other causes; yet the general tendency seems sufficiently marked to justify the assumptions made.

It has been stated that stretcher-strain markings, which are actually the surface manifestation of solid distortion wedges, multiply in number and size with increasing stress until the sheet has suffered a total elongation of approximately 4 per cent. At this value, no undeformed areas remain and the markings have merged to give a uniform appearance to the surface. This statement, although true in substance, needs qualification in at least two respects.

Firstly, industrial observers find that stretcher-strain markings often persist in their full strength up to an elongation somewhat greater than 4 per cent. This apparent discrepancy between laboratory findings and industrial observations is explained by the fact that, owing to the complicated nature of the stresses imposed on a pressing, the apparent elongation measured between two points on the wall of a pressed article may be either greater or less than the true elongation which the sheet has actually suffered. Because of this, in practical press-shop design a calculated apparent elongation which exceeds 4 per cent. by only a small margin must not be taken as a guarantee that stretcher-strain markings will not be formed on a pressed steel surface.

Secondly, traces of individual markings are sometimes faintly visible at elongations greatly exceeding 4 per cent. These seem to be caused by very small steps or differences in level rather than by local differences in the texture or appearance of the strained surface, and may really be small differences in level of the original individual stretcher-strain markings or to effects where differently oriented distortion wedges intersect.

It is interesting to observe that although, when first formed, flutes, coil-breaks, stretcher-strain or distortion-wedge markings sink below the normal surface of sheet or pressing—as indicated in the diagram shown in Fig. 146 (p. 222),—occasionally they may be seen standing " proud " to this surface if the sheet or pressing bearing them is pressed after it has stood for some time. The explanation of this is that the work-hardened crystals which compose the distortion wedges may age-harden during standing to a greater degree than the relatively undistorted crystals in the surrounding sheet. Because of this, the distortion wedges will not elongate so much as the surrounding sheet when some area of the sheet or pressing is subjected to a uniform stress, and will therefore tend to be thrown into relief as the adjacent sheet stretches and thins.

Although work-hardening in stretcher-strain markings or, as the author prefers to call them in theoretical discussion, " distortion wedges " has been postulated for some years, many early investigators —including the author [45]—failed to detect it experimentally owing to the use of insufficiently sensitive testing apparatus. Fell,[48] in 1927, appears to have been the first to record the hitherto assumed increase which, in his particular experiments, amounted to nearly 7 per cent.; later Rawdon [49] and also Fowler [50] detected hardening up to 8 per cent. An increase of this order seems, therefore, to occur; although by using different methods Moser [51] estimated an increase of no less than 18 per cent. Stanley [52] reports increases of from 15 to 25 per cent., adding the caution that this is probably a maximum. It seems likely that increases of this order, that is 15 to 20 per cent., represent the hardness after a considerable amount of work-hardening, perhaps accentuated by subsequent age-hardening, has taken place rather than the hardness of distortion wedges when first formed. The last-named investigator has also measured the depth to which stretcher-strain markings sink below the surface of flat, normalised, low-carbon steel sheet 0·040 inch thick, and finds this to be of the order of 0·0005 to 0·001 inch after the sheet as a whole has suffered an apparent elongation of 3·5 to 5·0 per cent.

To summarise, it seems established that stretcher-strain markings are the surface manifestation of localised, sharply defined, straight-sided, solid blocks or " wedges " of plastic deformation in the underlying sheet which appear at the upper yield-point of annealed low-carbon steel and persist until the sheet has suffered a *true* elongation of about 4 per cent., at which value wedges have increased in size and number and have merged to give a sheet free from non-plastically-deformed areas ; that this method of plastic deformation is attributable to a peculiar " lag," revealed on a stress-strain curve as a kink, which annealed low-carbon steel exhibits at its yield-point ; that the wedges or markings are appreciably harder than the surrounding non-plastically-deformed metal, and that, except in very special instances, the surface markings are sunk beneath the normal surface level of the sheet.

The hypothesis which has been outlined does fit in with observed facts, and it offers at least a reasonable explanation of the way in which stretcher-strain markings are formed owing to the influence of the " lag " in the transition of the crystal aggregate from a condition of elastic to plastic strain. Possible explanations of the origin of this peculiar lag will be examined later.

Properties of Steel Sheet which influence Stretcher-strain Markings

The nature and mode of formation of stretcher-strain markings having been established, the question naturally arises why some steel sheet exhibits this phenomenon whilst other does not, or does so in less degree.

Many attempts have been made to correlate the tendency to form stretcher-strain markings with some definite properties or condition of the sheet, and a considerable amount of research work has been undertaken in the United States where the huge production of automobile bodies and wings has intensified the seriousness of stretcher-strain markings. The fundamental origin of these markings which, as has been explained, are the surface manifestation of solid distortion wedges in the underlying metal, certainly lies in some property reflected in the " lag " which low-carbon steel exhibits in changing from a condition of elastic to plastic strain. The lag is revealed in a kink of the stress-strain curve at the yield-point, and the property which produces it, together with other properties which modify the severity of the stretcher-strain markings produced, will now be examined.

The old idea that stretcher-strain markings are caused by the dissimilar properties of the surface layers and the core in sheet rolled from segregated steel ingots must be abandoned. Reasons for this will now be clear but, neglecting the modern conception of stretcher-strain markings, there is abundant evidence to show that these markings occur in sheet virtually free from segregation. The influence of a cored microstructure *per se*, if worthy of notice, must be very small indeed.

Another early explanation suggested that stretcher-strain markings were caused by the natural slight heterogeneity of all steel. It was said that, because of this, small stress concentrations occurred at various inclusions or structural characteristics, producing localised deformation in the form of stretcher-strains. Like that of the cored structure, this explanation must be abandoned because it fails to explain many observed facts, including the influence of small amounts of cold-work upon yield-point elongation.

Some relationship has been established between the chemical composition of steel and tendency to form stretcher-strain markings, particularly with respect to the percentages of carbon, nitrogen and oxygen. Of these three elements only carbon acts in a truly direct way ; the others seem merely to modify the intensity of the markings produced.

The percentage of carbon is of primary importance academically if not industrially. Pure iron does not exhibit a kink in the stress-strain curve at the yield-point. In the past several investigators *have* noticed a kink, but this seems to have been caused by the iron used in the experiments not having been really pure. The work of Edwards and Pfeil,[53] Kuroda [54] and others shows that the stress-strain curve for pure iron is a smooth one and, therefore, that stretcher-strain markings will not be formed. The presence of only a very little carbon is sufficient to produce the all-important kink at the yield-point. Industrial users know to their dismay that severe stretcher-strain markings often occur in steel having the lowest percentage of carbon normally encountered under industrial conditions, a value usually in the region of 0·04 per cent. Under laboratory conditions it has been shown that 0·02 per cent. of carbon is sufficient to give a yield-point kink in steel having a normal crystal size.

Within the range of carbon content usually found in sheet used for deep drawing and pressing, that is about 0·05 to 0·11 per cent., the severity of stretcher-strain markings tends to decrease as the percentage of carbon rises, but the decrease is insufficient to be of much importance industrially. As the percentage of carbon rises above 0·2 the severity of the markings diminishes, and medium-carbon steels are free from visible stretcher-strain markings when deformed within the dangerous range of 0 to 4 per cent. true elongation. A possible explanation of the way in which carbon exercises its recorded influence will be given later when the nature of the kink in the stress-strain curve is examined.

The influence of nitrogen is not known with certainty, but it is a fact that there is a tendency for low-carbon steels containing a high percentage of this element to show more sharply defined stretcher-strain markings than steels in which the percentage is relatively low. For this reason more trouble is experienced in the press-shop with Bessemer steels than with those made by the open-hearth process. The action of nitrogen is believed to produce a stiffening action in the ferrite crystals and also in the crystal boundary material, as explained later.

The direct action of oxygen is at present a somewhat controversial subject. It is a fact that as a rule "rimming" steels, which are relatively high in oxygen, tend to exhibit more pronounced stretcher-strain markings than "killed" steels, but this may be due to causes other than oxygen content, for example a lower carbon content or a larger crystal size.

The indirect action of oxygen, probably nitrogen and perhaps carbon upon the tendency of low-carbon sheet to develop stretcher-strain markings when pressed under industrial conditions is quite definite. By indirect action is meant the influence exerted by each of these three elements upon "ageing," a term used here to imply the passing-off of the effect of the cold-working treatments which are commonly given to sheet of industrial quality to prevent the formation of stretcher-strain markings. Even here the precise action of these elements is not understood fully, and investigators in several countries are studying this important subject.

Many attempts have been made to correlate hardness, as indicated by indentation hardness tests, with tendency to form stretcher-strain markings. Although a measure of apparent success may seem to have been obtained in some instances, it cannot be stated too strongly that indentation hardness values, as such, do *not* form a reliable indication of tendency to form stretcher-strain markings. When correlation of these two properties has proved apparently successful, the truly essential factors have been either crystal size or degree of cold work and, except under very restricted conditions, hardness tests cannot be used with safety to measure these two factors; when they are used indiscriminately for this purpose, misleading results are sure to be obtained. Other conditions being equal, hardness tests do give an indication of "average grain size" and degree of temper-rolling if the sheet has not strain-aged; therefore, in a fixed series of sheet-production operations, hardness tests can sometimes be used as a rapid means to determine the *probability* that different batches of sheet have received the same treatment in the mills of the supplier. Only in this indirect way can hardness be said to be related to tendency to form stretcher-strain markings.

Whenever an attempt is made to relate hardness to degree of temper-rolling, it must be borne in mind that when the reduction during temper-rolling has been very small the resulting increase in hardness will also be very small. For example, an extension of 0·2 per cent. by rolling may increase the hardness of soft low-carbon steel sheet by only 3 Rockwell B points or 4 V.P.N. Therefore, unless the hardness of sheet prior to alleged temper-rolling is known, the hardness of that sheet at some subsequent time does not form a reliable indication as to whether or not the alleged temper-rolling has actually been given or, if it has, in what degree. This fact is often overlooked by consumers.

The state of strain of low-carbon steel is of the utmost importance in determining whether or not stretcher-strain markings will be formed. Unless very special circumstances obtain, any fully annealed or normalised low carbon sheet will exhibit stretcher-strain markings when strained to an elongation not exceeding 4 per cent., but the infliction of very light cold-working will—for a time—eliminate the kink in the stress-strain curve and, in consequence, stretcher-strain markings will not be formed.

It is sometimes stated that stretcher-strain markings will not be formed in low-carbon steel which has been given a " fibrous " structure by cold-work. This statement, although true, can be misleading because stretcher-strain markings can be prevented by a degree of cold-working so small that no " fibrous " structure is produced, even though this term be interpreted in its widest academic meaning. On the other hand, cold-worked sheet which *has* a fibrous structure is not in a fully annealed or normalised condition, and this condition is the one postulated if stretcher-strain markings are to be formed. The influence of small amounts of cold-work will be studied more fully later.

From what has been said it will be clear that tensile properties, or at least some of them, are of the utmost importance in indicating—if not explaining—the tendency of any sheet to develop stretcher-strain markings. When expressed in numerical values, the commonly-measured tensile properties do not indicate the inherent tendency of soft low-carbon steel sheet to form stretcher-strain markings when pressed. If, on the other hand, an accurate stress-strain curve is made, the shape of this curve does provide a reliable indication of this otherwise elusive tendency.

It has already been explained that the property of low-carbon steel which is the true cause of stretcher-strain markings is manifested in the peculiar kink which occurs at the yield-point of steel of the kind under consideration. It has also been explained that this peculiar property may be due to a " lag " in the transition of the crystal aggregate from the elastic to the plastic state, to the ease with which slip, having started, proceeds owing to the unusually large number of " slip planes " which exist in a ferrite crystal, or perhaps to both these factors. Leaving these theoretical considerations, the very important fact remains that, as shown by Kenyon and Burns [55] and other workers, the *size* of this kink in the stress-strain curve is a reliable guide to the severity of stretcher-strain markings formed during pressing. Sheet which gives a curve of the shape shown at A, Fig. 148, is certain to develop severe stretcher-strain markings; sheet which gives a curve approximating to the shape shown at B in the same figure is likely to develop this defect to a definite but much smaller degree, while sheet which gives a smooth curve, as shown at C, is likely to be free from

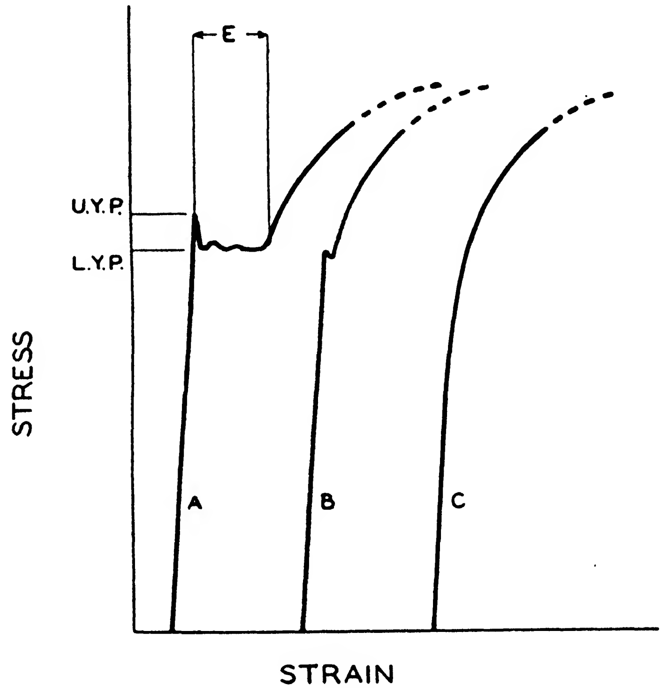


FIG. 148. Stress-strain curves representative of low carbon steel in different conditions :—

A : Fully annealed or normalised.
B : Lightly cold-rolled or cold-rolled and partly aged.
C : Freshly cold-worked (E indicates " yield-point elongation ").

distinct stretcher-strain markings under all conditions of pressing. As will be explained later, curve A is typical of fully annealed or normalised low-carbon steel, whereas curve C is typical of such sheet immediately after it has been lightly cold-worked, for example by being either rolled, repeatedly flexed in a series of leveller rolls, or stretched.

Winlock and Leiter,[56] in a paper which throws much light upon the properties of steel sheet which determine tendency to form stretcher-strain markings, have shown that this tendency is directly proportional to the length of the yield-point kink in the stress-strain curve. By length is meant the length of the irregular part of the curve projected upon the horizontal axis of the usual graph. This length, denoted by E in Fig. 148, is termed "yield-point elongation," and can be expressed as a percentage elongation, thus giving a definite measure of the tendency of sheet to develop stretcher-strain markings. The importance of this proved relationship between magnitude of yield-point elongation and severity of stretcher-strain markings cannot be overemphasised : no other easily-measured physical property yet discovered gives such a reliable, and in fact quantitative, indication of these markings. It should be observed that in fully annealed or normalised low-carbon sheet of normal "average grain size" the yield-point elongation is approximately 5 per cent. of the gauge length of the tensile test piece.

Stanley [52] points out that when sheet specimens are bent under standard conditions the radius of the bend so made varies in direct proportion to the magnitude of the yield-point elongation : that is, the bigger the yield-point elongation, the bigger the radius. If this simple test proves sufficiently sensitive, it will provide a most welcome aid because it can be made outside the laboratory, far more quickly, and on many more samples than the full tensile test needed to determine numerically the yield-point elongation even though only the essential part of the full stress-strain curve be drawn.

Having established that the fundamental cause of stretcher-strain markings is some characteristic of low-carbon steel reflected in the measurable property termed yield-point elongation, the nature of this fundamental characteristic must be examined. It is, clearly, an unusual method of plastic deformation peculiar to fully annealed or normalised low-carbon steel, and several ingenious explanations have been advanced to account for its existence.

One of these, namely, the "lag" hypothesis, has already been indicated. This postulates that when unstrained ferrite crystals are subjected to a gradually increasing strain, the stress rises to a value exceeding the true yield-point, in the same way that a solution can be cooled below the temperature at which saturation is complete or a molten metal can be cooled below its true solidification temperature. When the "upper yield-point"—a value which depends upon the rate of straining—is reached, the crystal will suddenly slip upon the most favourably oriented slip planes, the stress will fall to the "lower—or true—yield point," and will not rise until the crystal has work-hardened sufficiently to transmit to adjacent crystals a stress equal to the upper yield-point.

At first sight this explanation seems to fit in with many recorded facts, but it must be remembered that neither really pure ferrite nor medium-carbon steel behave in this way ; therefore a definite range of carbon must be postulated if this hypothesis is admitted. In other words, what has been termed " lag " is caused not, as is commonly held, by some property of the ferrite crystal but by one of ferrite containing a certain proportion of cemenite (iron carbide Fe_3C). To justify this explanation it seems necessary to postulate some keying action exerted by sub-microscopic particles of cementite distributed throughout the space lattice of the ferrite or by some other mechanism. One objection to it is that it fails to explain clearly why light cold-working entirely removes the property known as yield-point elongation, and why this property usually returns to cold-worked steel after a period of time. This behaviour may, however, be due to cold-work breaking down or using up the available keying action in the crystals and to small atomic movements—which it is known can occur in steel at ordinary temperature—restoring this keying action after a period of time.

When considering the " lag " hypothesis it is of interest to bear in mind that, owing to the change in solid solubility of iron carbide (cementite) in *alpha* iron (ferrite) with temperature shown in the equilibrium diagram (Fig. 134, p. 202), the ferrite in industrial low-carbon sheet is usually super-saturated. Although the determinations of different investigators are not in entire agreement, it is likely that the proportion of carbon held in solution in *alpha* iron is approximately 0·04 per cent. at 700° C., 0·006 per cent. at 200° C. and not more than 0·004 per cent. at ordinary temperature. In a super-saturated solid solution the space lattice is strained by the solute atoms trying to precipitate, and it is possible that the condition of very slight internal strain which is here postulated even in annealed low-carbon steel may account for the keying of the crystallographic slip planes and the consequent " lag " in plastic deformation.

This action may be additional to that exerted by minute carbide particles actually precipitated. A point of special interest is that cold-work, by increasing the energy of the crystal aggregate and perhaps by temporarily raising the temperature, may remove or at least reduce the postulated condition of lattice strain and may even cause minute particles of cementite to be taken *into* solution. The effect of this would be to reduce the keying action within the crystals and hence the phenomenon of yield-point elongation, and it is likely that as time passes the disturbed super-saturated lattice would tend to revert to its previous condition, thus causing the property of yield-point elongation to appear again.

From these remarks it will be seen that the " lag " hypothesis is capable of a fairly wide interpretation. It may be that only one or else that several causes—for example lattice strain and minute precipitated particles—are necessary to explain all the observed facts if this hypothesis is actually the true one.

Another suggested explanation is based on the fact that ferrite crystals have three groups of crystallographic slip planes, namely, the dodecahedral (110), icositetrahedral (112) and octrahedral (113). Of these there are in number forty-two; yet, owing to the fact that the direction of slip is the octrahedral direction and that the dodecahedral planes contain two directions, there are actually forty-eight directions of possible slip in a ferrite crystal. Most of the common metals have far fewer; for example, copper and many copper alloys slip on only one group of planes—the octrahedral—giving only twelve possible directions of slip.

Because of this a very large proportion of crystals in an aggregate of ferrite crystals will have slip-planes so oriented to the direction of applied stress that some are very close indeed to the most favourable orientation for slip to take place. Therefore it is suggested that, when the stress rises to the yield-point, the slip which then occurs will be sudden and relatively large before these favourably-oriented slip planes work-harden sufficiently to enable the stress to rise and slip to occur on less favourably oriented slip-planes. This, it is said, gives the horizontal part of the stress-strain curve which indicates the property of yield-point elongation.

It is assumed that, in crystals containing relatively few planes of slip, the few favourably situated crystals in which slip first takes place quickly work-harden and become able to transmit an increasing stress to adjacent less favourably oriented crystals before any noticeable yield-point elongation has occurred in the aggregate measured as a whole. It should be observed that this explanation does not necessarily discredit the "lag" hypothesis already explained; the two could conceivably exist together.

The ingenious "honey-comb" hypothesis advanced by Kuroda [54] to explain the existence of the property of yield-point elongation, and hence of stretcher-strain markings, in low-carbon steel deserves careful study. Starting with the known fact that neither pure ferrite nor cementite has a yield-point elongation, Kuroda suggests that this phenomenon has its origin in a special structure composed of ferrite crystals surrounded by envelopes of cementite. In proof of this it is shown that the property of yield-point elongation is caused to disappear by treatments calculated to destroy the cementite envelope, such as quenching, excessive crystal growth or—which is less easy to understand—cold-working. Conversely, it can be caused to re-appear by treatments calculated to restore the cementite envelope, such as annealing or—which needs explanation—standing at room temperature.

It is suggested that when this postulated ferrite-cementite "honeycomb" structure is strained, at first both the ferrite crystals and the cementite envelopes act together to sustain the stress by elastic deformation. The upper yield-point is held to be the stress at which the cementite envelope breaks down, throws the whole strain on to the ferrite crystal and causes the stress to fall to the lower yield-point, this being the stress which the unstrained ferrite crystal itself can sustain. In order to transmit a higher stress the ferrite crystal must work-harden, which it does under an almost constant stress (*cf.* the preceding hypotheses) which corresponds to the nearly horizontal part of the stress-strain curve during the yield-point elongation. When, as the result of work-hardening, the crystal becomes strong enough to transmit to its neighbours a stress equal to that of the upper yield-point, the process is repeated in adjacent crystals.

In further proof of this hypothesis, Kuroda shows stress-strain curves obtained by pulling composite tensile test pieces made of annealed and hard-drawn copper strips, and others made of annealed copper wire and quenched steel wire, to correspond to the ferrite and cementite constituent in annealed low-carbon steel. Test pieces of this kind containing a suitable proportion of harder wires give stress-strain curves having a shape which resembles that given by annealed or normalised low-carbon steel, the essential features of the upper and lower yield-points and even a semblance of yield-point elongation being discernible.

Striking though the experimental evidence is, the "honey-comb" explanation of the origin of yield-point elongation needs critical examination. In the first place, it is by no means certain that in industrial sheet of good quality the ferrite crystals are always enclosed in envelopes of cementite. When such envelopes are visible under the microscope, the percentage elongation is invariably very low and the sheet is of little value for deep drawing and pressing. In view of accepted views concerning the hardness and brittleness of cementite, it seems likely that its harmful influence would persist even though the envelopes were so thin as to be invisible under the microscope, and it is difficult to see how the "honey-comb" explanation can apply without modification when only isolated particles and not a continuous envelope of cementite exists in the crystal boundaries.

The tensile strength of cementite is believed to be approximately 16 tons per square inch and its elongation practically nil, while that of pure ferrite having a normal crystal size is about 18 tons per square inch and its elongation may approach 60 per cent. At first sight these known facts do not appear to fit in with the "honey-comb" hypothesis which postulates that the ferrite crystals are only able to sustain elastically a *lower* stress than the cementite envelopes. The important factor is, however, limit of proportionality, not ultimate strength; that is the stress at which plastic slip begins, not that at which actual breakage occurs. The limit of proportionality of cementite lies very close to the ultimate strength, whereas that of unworked ferrite is always considerably below the ultimate strength. Therefore, the cementite envelope would not deform plastically until it was stressed practically to its ultimate strength, when it would break and the stress would fall to the limit of proportionality, not the ultimate strength, of the ferrite crystal within. This is in accordance with the hypothesis.

If the " honey-comb " hypothesis is modified to include what may be termed general crystal boundary conditions instead of cementite envelopes, interesting speculations are possible. In pursuing these it must not be forgotten that, in the light of present knowledge, a certain small proportion of cementite is essential and that boundary effects which take no account of cementite cannot be accepted as a complete explanation of the yield-point elongation phenomenon. For example, effects due to nitrogen, oxygen, or to some crystallographic arrangement of the ferrite atoms at the crystal boundaries are inadmissible in any fundamental explanation, because these effects must occur in ferrite of high purity, a substance which does not exhibit any yield-point elongation.

As with the " lag " hypothesis, it is difficult to reconcile the " honey-comb " hypothesis with the known effect of small amounts of cold-work followed by standing at ordinary temperature upon the yield-point elongation. If the complete cementite envelope hypothesis is accepted, one explanation is that cold-work shatters the hard, brittle envelope structure, and that this structure is reformed by migration of carbide atoms during a period of standing at room temperature which, in roller-levelled sheet, may be as short as twenty-four hours. If, on the other hand, special boundary conditions are postulated instead of a cementite envelope, explanations of known effects must be still more speculative. Perhaps the influence of lattice strain, solute atoms or even discrete particles may function in the manner suggested when the " lag " hypothesis was being discussed. It is interesting to examine the " honey-comb " hypothesis in the light of the one advanced by Andrew and Trent,[43] and Andrew,[44] to explain the ageing of low-carbon steel. The ideas of these investigators concerning the retention and breakdown of austenite and the solution and precipitation of atomic carbon purely as a result of cold-work may lead to a useful extension of the " honey-comb " hypothesis.

With this brief review of the three tentative explanations descriptively termed the " lag," the " easy-slip " and the " honey-comb " the important subject of yield-point elongation must be left. Each of these three hypotheses seems only partly convincing, and future investigations may show that some part of each—and perhaps others not yet conceived—will have to be incorporated in a completely satisfactory explanation of yield-point elongation, and hence of stretcher-strain markings in soft low-carbon steel sheet.

Crystal size, meaning what is known industrially as the " average grain size " of sheet, has a marked influence upon tendency to form stretcher-strain markings, but it seems likely that this is due primarily to the influence of "average grain size" upon the obscure property of the crystal aggregate manifested as yield-point elongation. Be this as it may, industrial experience shows that stretcher-strain markings increase in severity, and laboratory investigation shows that the yield-point elongation value increases, as the crystal size of the sheet

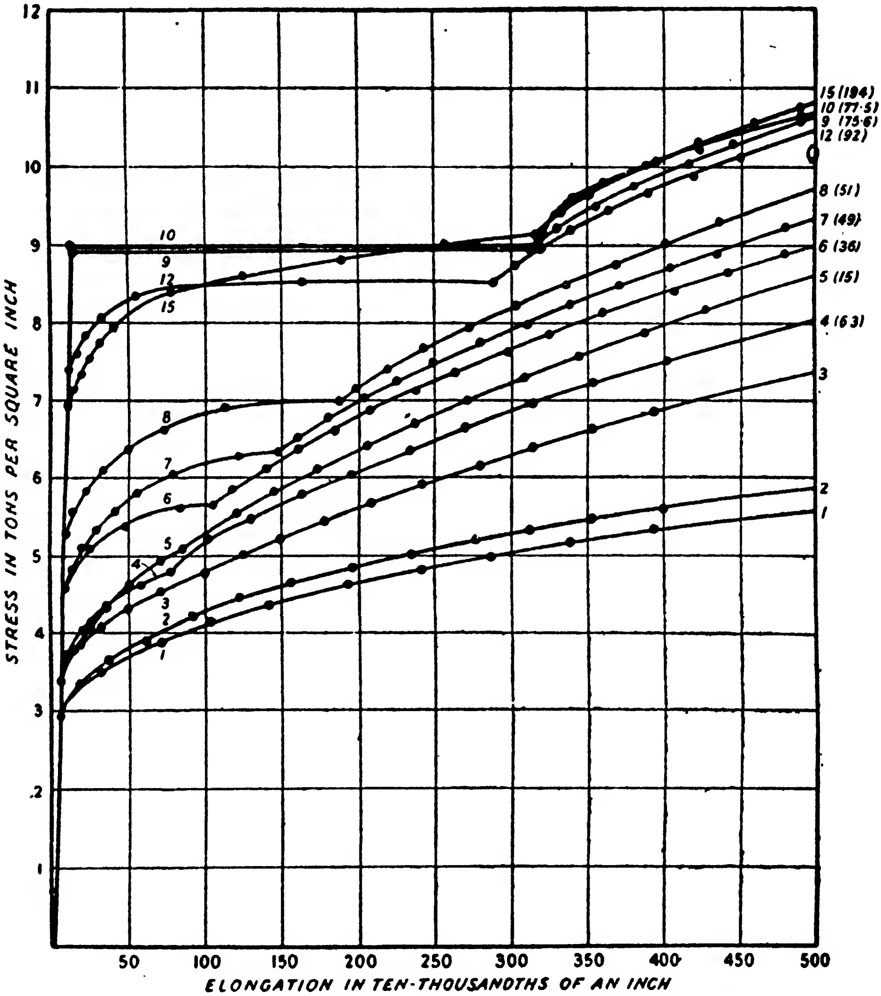


FIG. 149. Influence of crystal size of pure ferrite upon the shape of the stress-strain curve. [*Edwards and Pfeil.*

decreases. Edwards and Pfeil [53] have shown that no yield-point elongation can be detected in a single crystal of pure iron, and that no abrupt step in the curve occurs until the crystal size has fallen to about ten per square millimetre ; a size which is still far too large for sheet destined for industrial deep drawing and pressing. Fig. 149, reproduced from the paper just cited, shows the interesting relation-

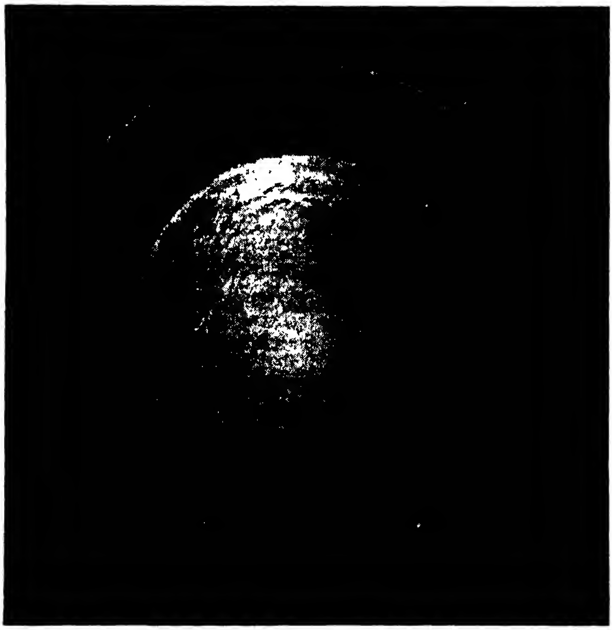


FIG. 151. Stretcher-strain markings on the flat bottom of a circular pressed-steel cup. The ovality of the affected zone is due to directional properties in the original sheet. × $\frac{2}{3}$.

[*To face p.* 237.

ship found between yield-point elongation and crystal size at, it should be added, a constant and not abnormally slow rate of straining.

The rate at which straining is carried out has a most important influence upon the magnitude of the yield-point elongation, and hence upon the severity of the stretcher-strain markings formed, and also upon the stress at which the yield-point occurs. This influence is illustrated graphically in the hypothetical stress-strain curve shown in Fig. 150, which is reproduced from a paper by Winlock and Leiter.[57] The existence of this speed effect must always be borne in mind when examining any suggested explanation of the true origin of stretcher-

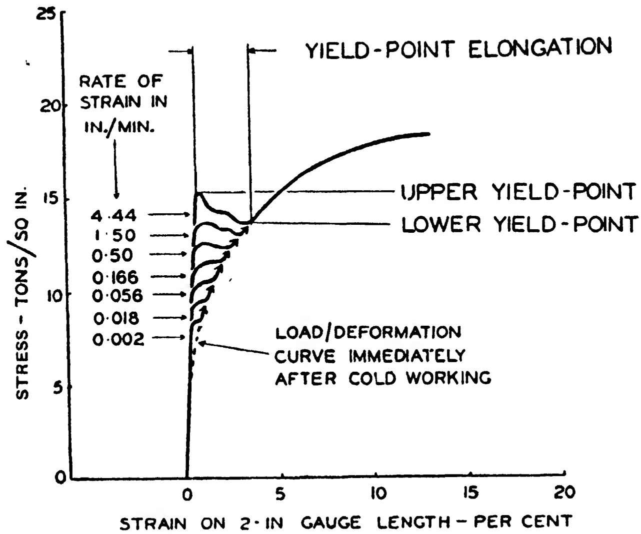


FIG. 150. Composite stress-strain curve illustrating influence of rate of straining upon yield-point elongation of annealed low-carbon steel.
[*Winlock and Leiter.*

strain markings. Any explanation which does not account for the speed effect cannot, on the available evidence, be accepted.

A property of steel sheet which influences the shape, as distinct from the severity, of the stretcher-strain pattern formed on any pressing is directionality. Fig. 151 shows a photograph taken of the inside face of the flat bottom of a circular cup, and it will be seen that distortion wedges have been formed in a fairly narrow, oval area in which, it can be assumed, the sheet has elongated not more than about 4 per cent. Inside this oval the elongation has been very small; outside it, where the radius of the cup is approached, the elongation has been sufficiently large to obliterate the pattern which was produced in the early stages of pressing. The interesting point is that although the cup is *circular*, the band of distortion wedges is plainly *oval*, owing to the influence of directional properties existing in the sheet pressed.

Uneven flow caused by directional properties is manifested as "ears" on the severely worked rim of a deep-drawn cup; in the specimen illustrated the shape of the band of distortion-wedges provides interesting evidence that the flow of the sheet in the slightly-worked flat bottom is also influenced quite distinctly by directional properties. Similar evidence can often be seen in the stretcher-strain patterns produced on pressings of all sizes and shapes.

Prevention

Having studied the influence of certain properties of low-carbon steel sheet upon tendency to form stretcher-strain markings, it remains to be seen to what degree these properties can be controlled by either the suppliers or the consumers of sheet in order to minimise, and if possible to prevent, the formation of stretcher-strain markings when sheet is pressed.

Most authorities are of the opinion that, within the ordinary range, chemical composition has little direct influence upon the initial tendency of stretcher-strain markings to form in annealed or normalised sheet. It has already been said that within the range usually found in industrial sheet, that is about 0·05 to 0·11 per cent., carbon has only a small influence upon the severity of the stretcher-strain markings formed, and that the influence of nitrogen, although noticeable, is also relatively small. According to Kuroda [54] the condition, as distinct from the proportion, of the carbide is of paramount importance; yet, if the "honey-comb" hypothesis already described is correct, almost any low-carbon sheet produced by present industrial methods must contain sufficient carbide in the crystal boundaries to cause stretcher-strain markings to be formed in the manner suggested by this investigator.

It is sometimes stated that the oxygen content of steel has a marked influence upon tendency to form stretcher-strains. This statement is misleading because, as far as the author is aware, no evidence exists to justify this claim if it be interpreted literally, that is, that the percentage of oxygen influences the tendency for stretcher-strain markings to form when annealed or normalised sheet is worked under the press. What oxygen does do is to increase the ageing properties of low-carbon steel in the sense that, the higher the percentage of oxygen, the more quickly the effects of preventive treatments such as temper-rolling pass off. It would therefore be more correct to say that the percentage of oxygen influences the permanency of certain cold-working, and perhaps thermal, treatments given to prevent the formation of stretcher-strain markings.

Major differences in oxygen content usually arise from the use of either "killed" (deoxidised) or "rimming" (partially deoxidised) steel, and the recognised differences in behaviour of sheet rolled from either of these two varieties of sheet with respect to permanence of temper-rolling are caused mainly by a difference in the percentage of oxygen which they contain. It is not yet known what effect oxygen has upon the precipitation, probably in a sub-microscopic form, of certain constituents which, in the opinion of some authorities, influence ageing.

Attempts are being made to produce so-called "non-ageing" steel in which the effects of cold work given to prevent the formation of stretcher-strain markings will be relatively permanent. One method is to select sheet rolled from fully-deoxidised steel, to give the sheet a final anneal followed by very slow cooling, and then to temper-roll in the usual way. The resulting product does not develop stretcher-strain markings, yet this defect has only been suppressed in a more than usually permanent manner; its true or initial cause has not been eliminated. Another method, already described (p. 213), is to add a small percentage of some special element which has a strong affinity for carbon. By converting all the carbon into discrete particles of carbides additions of this kind leave the ferritic matrix in a virtually pure condition; and, as has already been said, pure ferrite exhibits no kink at the yield-point and hence does not develop stretcher-strain markings. In theory this seems a more convenient and more reliable method than the one based upon the very slow cooling of sheet rolled from deoxidised steel, yet unfortunately it possesses serious practical difficulties. Relatively large additions, for example of molybdenum or vanadium, would seriously lower the ductility of the sheet, and the cost of the additions would be considerable. Furthermore, these additions would transform the steel into the "killed" as distinct from the "rimming" kind, with the consequent inferior surface finish which at present seems to be an inherent disadvantage of the last-named variety of steel sheet.

It has been said that the "average grain size" of sheet has a marked influence upon tendency to form stretcher-strain markings. This is true, but unfortunately the "average grain size" above which the yield-point elongation becomes negligible for practical purposes is of the order of 1 mm., a size which is quite useless for most press-shop operations because the tenacity of the sheet would be very low and the surface after pressing would be extremely rough. Industrial experience confirmed by laboratory evidence suggests that for most purposes sheet having an "average grain size" of approximately 0·035 mm. gives the best compromise between a reasonably smooth surface, which is favoured by a small crystal size, and minimisation of stretcher strain markings, which is favoured by a large crystal size. This is fortunate, because an "average grain size" of this particular value (0·035 mm.) also gives a useful compromise in mechanical properties.

It is sometimes stated that tendency to form stretcher-strain markings can be altered by varying the thermal and mechanical treatment given to sheet in the hot-rolling mill. The author has failed to obtain any evidence to substantiate the truth of this statement which, considered from the theoretical aspect, seems improbable if applied to sheet of industrial quality produced by the usual methods. Treatment of a very special nature can delay or even prevent *ageing* in deoxidised steel, and the thermal and mechanical history of sheet in the mill will determine its " average grain size " ; both these factors have an influence on tendency to form stretcher-strain markings, but the statement here being criticised is invariably used to imply a much

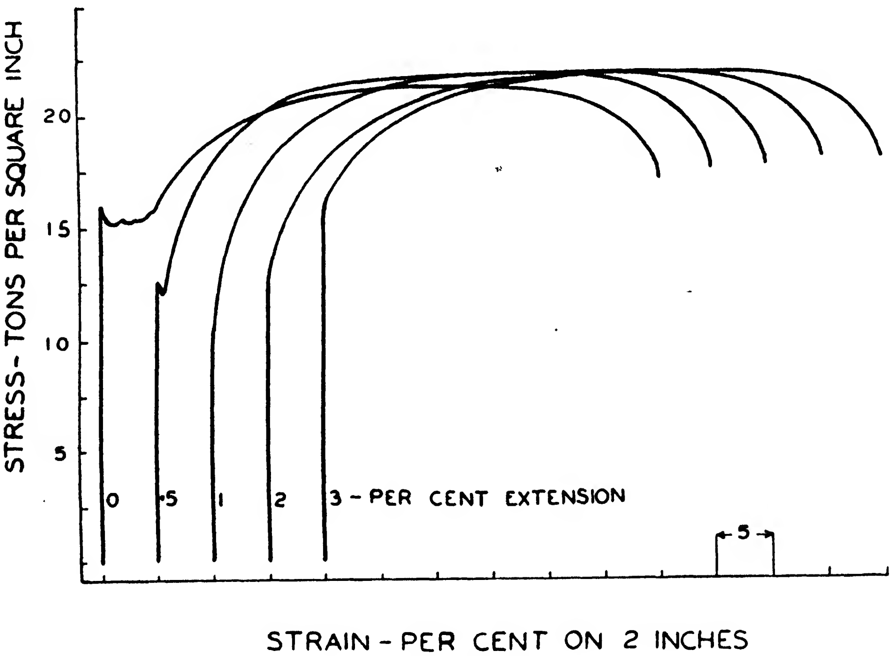


FIG. 152. The influence of cold-rolling upon the shape of the stress-strain curve of annealed low carbon steel. The five curves represent sheet temper-rolled to the percentage extensions indicated.

[*Griffis, Kenyon and Hayes.*

more direct influence than this. Very rapid cooling from a normalising temperature, as obtained by quenching in oil, will usually reduce the yield-point elongation of very low-carbon steels to a very small value and thus greatly reduce the tendency of stretcher-strain markings to form. However, this procedure does not represent industrial practice and therefore does not alter the opinion just expressed.

It is established that tendency to form stretcher-strain markings is directly related to magnitude of yield-point elongation ; therefore any treatment which reduces the last-named property to a very small value will be most helpful in combating stretcher-strain markings. The yield-point elongation exhibited by annealed or normalised low-carbon steel can be eliminated by giving sheet a very small, controlled amount of cold work. Industrially this is done by one of the three methods mentioned in Chapter II when the production of steel sheet was being described, namely, stretching between moving heads or grips, repeating flexing between a series of staggered " leveller-rolls " as depicted in Fig. 47 (p. 59) and, lastly and most commonly, ordinary cold rolling. Because of the very light reductions used, cold rolling given for the express purpose of preventing the formation of stretcher-strain markings is usually distinguished by a special term such as " temper-rolling," " skin-pass " or " pinch-pass."

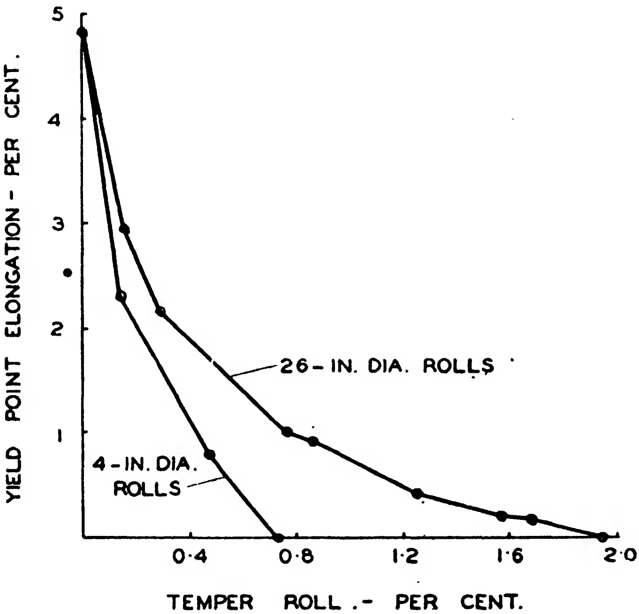


FIG. 153. Curves illustrating the influence of roll diameter upon the yield-point elongation of annealed and temper-rolled low-carbon steel sheet. [*Hayes and Burns.*

When annealed or normalised low-carbon steel sheet is very lightly cold-rolled, important changes are produced in the stress-strain curve in the vicinity of the yield-point. When an elongation of the order of 1 per cent. is approached in sheet of normal quality, the upper and lower yield-points merge into a single, less abrupt change and the yield-point stress falls appreciably. If rolling is continued the yield-point stress rises until, when rolling has produced an elongation of approximately 3 per cent., it reaches the value of the original upper yield-point of the unworked sheet without the ultimate strength or hardness of the sheet being greatly affected.

Fig. 152, based on curves obtained by Griffis, Kenyon and Hayes,[58] shows the effect of various amounts of cold reduction upon the yield-point stress and the shape of the stress-strain curve. These curves and the values given in the preceding paragraph must be regarded as illustrative and not as applicable in all instances because, as demonstrated by Hayes and Burns,[59] the amount of temper-rolling needed to diminish the yield-point elongation by a given amount depends upon at least three factors, namely, the "average grain size," the smoothness of the surface of the sheet and the diameter of the rolls used. The smaller the "average grain size," the bigger the yield-point elongation and the greater the amount of reduction by temper-rolling which must be given to eliminate this characteristic. Fig. 153, taken from the paper just mentioned, shows the influence of roll diameter upon temper-rolling; the smaller the roll diameter, the less the reduction needed to produce a given decrease in yield-point elongation. As regards the third factor, the smoother the surface of the sheet the more temper-rolling will be necessary, other conditions being equal.

Reputable suppliers of steel sheet for pressing have developed temper-rolling to a very closely controlled process and, provided that consumers can press their sheet before the effects of temper-rolling begin to pass off—as they do—with time, this process constitutes a very valuable remedy for troubles attributable to stretcher-strain markings. From what has been said it will be clear that no definite percentage reduction can be said to be the optimum, because this value will vary according to the properties of the sheet and the diameter of the rolls used, as already described. As a general rule percentage reductions of the order of 0·5 to 1 per cent. are given, but this will be varied by conscientious suppliers to suit the particular needs of individual consumers in addition to fulfilling requirements dictated by the mill and by each batch of sheet rolled.

This practice has led to the establishment of very close contact between the consumer and his supplier. Indeed, in order to ensure uninterrupted production of a certain pressing, a consumer is often compelled to use sheet which has been prepared by some particular supplier—perhaps after numerous trials and rejections—to meet the particular demands of this article. For many reasons this is undesirable from the viewpoint of the consumer, and constitutes one of the drawbacks to the useful remedy of temper-rolling.

The remedies considered up to the present have been ones which only the steel-maker or the sheet-roller can apply. The consumer can do relatively little, but attention must be drawn to five possible ways in which he can at least help to combat the defect of stretcher-strain markings, namely, by using sheet as soon as possible after it has been temper-rolled by the supplier, by roller-levelling sheet or blanks in his own works immediately before pressing, by modifying the shape of the article or the stages in which it is formed, by reducing the speed of pressing and, lastly, by co-operating with the sheet supplier as closely as possible.

Dealing with the first item, much trouble is caused because consumers forget that the effects of temper-rolling or some equivalent mechanical treatment pass off after a period of time which may vary from one day to several months depending upon the properties of the steel and the temperature of storage. In warm weather the rate of ageing is accelerated appreciably, and it is common for a noticeable increase in troubles due to stretcher-strain markings to occur. The phenomenon of ageing has already been discussed in Chapter VI.

Roller-levelling, the second of the enumerated aids, has nearly the same practical effect as temper-rolling; but, because of the relative cheapness of the plant and the simplicity of the operation, roller-levelling can be done by the consumer himself. The great advantage of this is that sheet or even cut blanks can be roller-levelled immediately before use, thus enabling the maximum benefit which this treatment can give to be secured. For obvious reasons it may be difficult always to ensure that sheet from a rolling mill in a distant part of the country reaches the press of the consumer in a desirably short space of time, but there can be no justifiable excuse for allowing a long rest between roller-levelling and pressing in the consumer's own works.

Although roller-levelling as usually carried out does not lend itself to such precise control as temper-rolling, the greater ease of ensuring rapid progress from rolls to press renders the former in some ways the safer operation when severe draws have to be accomplished. The cost and time of roller-levelling is very small, and the more extensive use of this simple operation in the works of the consumer would be an advantage, if only as an insurance against trouble with certain kinds of work even with sheet which has been temper-rolled. It is not generally known that to obtain the fullest possible benefit from roller-levelling, sheet or blanks must be passed through the rolls lengthways, sideways and preferably diagonally as well.

Compared with temper-rolling, roller-levelling possesses one serious disadvantage, namely, that its effect passes off very quickly. The effect of temper-rolling may last for a number of weeks if the sheet is kept at a low temperature, but that of roller-levelling may pass off in a day. For this reason roller-levelling cannot be used by sheet suppliers as an alternative to temper-rolling, although it is often given as a supplementary treatment.

The true cause of this striking difference does not seem to have been established. It may be that the explanation lies in the different way in which the cold-work, which is the net practical result of both treatments, is imposed. In ordinary rolling, the sheet is cold-worked in a relatively uniform manner throughout its section; in roller-levelling, the sheet is merely bent first one way and then the other or "flexed" a number of times without suffering any reduction in thickness. Because of this, a "strain gradient" exists in roller-levelled sheet, the strain being at its maximum at each surface and zero at the centre of the cross section of the sheet. Experiments with cold-drawn tubes and with electro-deposited coatings of hard—and by reason of this fact severely strained—coatings over soft coatings, for example chromium and nickel over copper, show that under such conditions a redistribution of strain occurs even at ordinary temperatures. It is therefore not unreasonable to suggest that in roller-levelled sheet the initial uneven distribution of strain tends to become more uniform throughout the thickness of the sheet and that, as a result, the surface layers soon return to a condition which allows the formation of stretcher-strain markings. This explanation is offered as a purely tentative one because the author has seen no other advanced to account for the recognised difference between the permanence of the effect of temper-rolling and that of roller-levelling.

These conditions may explain a recognised difference in the appearance of the surface of temper-rolled and roller-levelled sheet after pressing. Properly temper-rolled sheet often shows a relatively smooth surface after it has been pressed within the critical range of percentage elongation, whereas lightly roller-levelled sheet often exhibits what seems to be a multitude of very fine stretcher-strain markings of insufficient depth or distinctness to be detrimental.

It is often assumed that roller-levelling eliminates the yield-point kink in the stress-strain curve in the same way that temper-rolling does. Unless the roller-levelling treatment is unusually severe, this assumption is not true. The yield-point elongation, that is the length of the horizontal part of the yield-point kink, is greatly reduced *but not eliminated*, a fact explained by the hypothesis just described which postulates a core or neutral axis of nearly unworked metal—which will still exhibit a yield-point elongation—and surface layers of metal cold-worked a sufficient amount to eliminate the yield-point elongation. Furthermore, the shape of the stress-strain curve of roller-levelled sheet does not alter materially within the short period of about twenty-four hours during which the practical effect of the treatment passes off. In temper-rolled sheet, on the other hand, the gradual return of stretcher-strain markings is accompanied by a return of, and proportional increase in, yield-point elongation. This fact alone shows that there must be an important difference in the full explanation of what, when examined casually, may seem to be the similar practical effect of temper-rolling and that of roller-levelling.

The third method open to consumers whereby they can minimise stretcher-strain markings is by so designing and shaping their articles that areas in which the true elongation is less than 4 per cent. are avoided. The shape of many articles renders this ideal unattainable, but an important and often attainable condition arises from it. This is that in multi-draw procedure it can sometimes be arranged, when the need is appreciated, that in the first operation large areas of low elongation are avoided or reduced in size. This is most desirable because, once formed, stretcher-strain markings may persist through subsequent shaping operations, particularly if time is allowed for the distortion wedges to age-harden.

It must always be borne in mind that, for reasons already stated, an apparent elongation measured from point to point on a pressed or deep-drawn shape is not always a true indication of the elongation which has actually taken place. For this reason, if and when such planning is possible, the empirical safety limit of 4 per cent. should always be exceeded by as large a margin as possible.

It will be appreciated that after partly-drawn shapes have been annealed the steel will again be in the condition most favourable for the formation of stretcher-strain markings. For this reason the avoidance of areas in which the true elongation falls within the dangerous range is even more important during the draw following annealing than during the first draw from flat sheet, for no temper-rolling or roller-levelling can be given to a drawn shape. Fig. 142 (p. 217), shows a shell in which stretcher-strain markings have been formed in certain areas as a result of a draw following inter-stage annealing.

A reduction in the speed of pressing, the fourth item mentioned, is, unfortunately, one which offers little help in modern press operations, for every effort is made by production engineers to increase rather than to decrease the speed of pressing. The influence of rate of straining upon magnitude of yield-point elongation, and hence severity of stretcher-strain markings, has been illustrated in Fig. 150 (p. 237). It will be seen from this that a rate sufficiently slow to give the desired effect is one which would be deemed uneconomic in modern industrial production operations.

Close co-operation with their suppliers is the fifth of the suggested ways in which consumers can minimise troubles caused by stretcher-strain markings. After what has been said concerning the critical operation of temper-rolling, the reasons for this will be obvious; yet some consumers still order steel sheet without specifying that it shall be temper-rolled or, even if they do this, without availing themselves of the help which the supplier with his wider experience is always ready to give to determine as quickly as possible the amount of temper-rolling which will give the best compromise between avoidance of stretcher-strain markings and reduction in ductility.

This ends an attempt to summarise present knowledge concerning the phenomenon of stretcher-strain markings in low-carbon steel sheet.

The author has explained what he believes to be the true nature and method of propagation of "distortion wedges," of which stretcher-strain markings are merely the surface manifestation; a number of hypotheses purporting to explain the fundamental cause of the peculiar method of plastic deformation which produces these distortion wedges have been described and discussed, and methods whereby stretcher-strain markings can be prevented or at least minimised under industrial conditions have been described. Readers specially interested in this subject, which is of considerable importance industrially and of intriguing interest academically, can pursue its study through the references given to papers which deal with separate aspects in greater detail.

CHAPTER VIII

THE DEEP-DRAWING OF METALS OTHER THAN BRASS AND STEEL

ALTHOUGH preceding chapters have been confined mainly to a study of brass and mild steel, it will be evident that much that has been said concerning press-shop practice—and also concerning some of the properties, defects and conditions peculiar to these two most widely used metals—will be applicable with perhaps only slight modification to other metals.

In this chapter there will be considered some of the outstanding points of importance relating to the deep drawing and pressing of a number of other metals, some of which are finding their way into the press-shop in rapidly increasing tonnages for the production of a large variety of articles destined for engineering, industrial and domestic purposes. For each metal there will be examined first any properties which are of importance from the aspect of deep drawing and pressing and, secondly, any essential points of difference between the technique which it requires and that which is established for the common metals, brass and steel.

To avoid tedious repetition, attention will be directed only to those defects which are peculiar to, or specially prevalent in, each individual metal. Because of this readers are urged to keep continually in mind that most of the general defects reviewed in Chapter III, and also some of those illustrated with special reference to brass and steel in Chapters IV and VI, can occur in the metals about to be discussed. Of these defects the most common are, perhaps, an unsuitable crystal structure ; non-metallic inclusions ; too high a percentage of harmful impurities ; pronounced directional properties, and variation in thickness.

ALUMINIUM AND ALUMINIUM ALLOYS

During recent years aluminium and, still more recently, aluminium alloys have found their way into the press-shop in ever-increasing quantities, at first owing to the use of the pure metal for domestic utensils and, latterly, owing to the demands of road and, in particular, aerial transport. Because there are essential differences between the technique used for deep drawing and pressing the two major groups of aluminium alloys, it will be convenient to divide discussion into two distinct sections dealing with :—

(*a*) Non-precipitation-hardening alloys which do not have to be heat-treated apart from ordinary inter-stage annealing, and

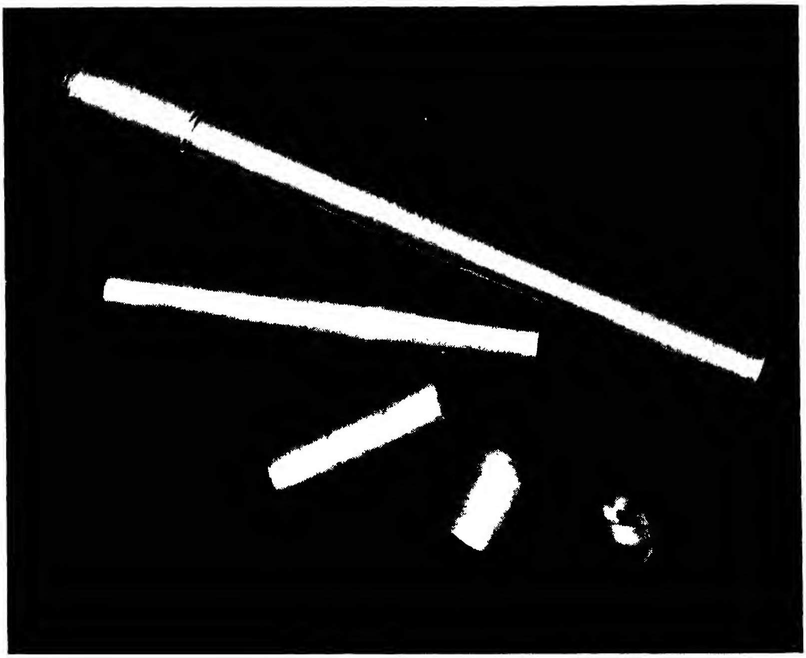
(*b*) Precipitation bardening alloys which have to be heat-treated in order to induce sufficient ductility to enable deep drawing and pressing to be carried out and, sometimes, afterwards in order to produce the high mechanical strength which is a feature of alloys of this kind.

Those of the first group, in which must be included the pure metal, have much better deep drawing and pressing properties than those of

Table I.

	Approximate chemical composition.						Condition.	Tensile properties			Hard-ness : V.P.N.
	Cu	Ni	Mg	Mn	Si	Fe		0.1 per cent. proof stress tons/sq. in.	Ultimate strength : tons/sq. in.	Elongation: per cent. on 2 in.	
Aluminium, industrially pure	—	—	—	—	—	—	Annealed . .	—	5–6	32-38	22–25
							" ¼-hard " . .	—	6–7	10–14	27–30
							" ½-hard " . .	—	7–8	8–10	32–35
Aluminium alloy	—	—	—	1·5	—	—	Annealed . .	—	6–7	28–32	26–30
							" ¼-hard " . .	—	7–8	10–12	34–38
							" ½-hard " . .	—	9–10	7–8	38–42
Ditto . .	—	—	1	1·3	—	—	Annealed . .	—	10–11	18–22	42–45
							" ¼-hard " . .	—	12–14	10–12	50–55
							" ½-hard " . .	—	14–16	8–10	60–65
Ditto . .	—	—	2·5	—	—	—	Annealed . .	—	14–16	20–24	—
							" ½-hard " . .	—	16–18	6–10	—
Ditto . .	—	—	7	—	—	—	Annealed . .	—	20–23	20–24	—
							" ½-hard " . .	—	25–28	16–19	—
Ditto, single-heat-treatment (Duralumin) type	4	—	0·6	0·5	0·5	0·4	Annealed . .	5–7	16–18	16–20	60–70
							Solution - treated at 495° C. and quenched . .	6–8	19–20	18–22	70–80
							Solution - treated at 495° C., quenched and aged for 5 days at room temperature .	15–17	25–28	20–24	115–125
Ditto, double-heat-treatment type	2	1	1	—	1	1	Annealed . .	6–8	12–15	20–25	45–55
							Solution - treated at 525° C. and quenched . .	10–13	22–26	15–22	80–100
							Solution - treated at 525° C., quenched and aged for 20 hours at 160° C.	21–23	27–30	10–15	120–135

the second, which are used only when the finished article must have high mechanical strength. The number of slightly differing alloys in both of these groups which are used industrially is large, but Table I gives the chemical composition and mechanical properties of a few representative alloys from which the average properties of the two groups can be assessed. It is to be regretted that the majority of the aluminium alloys used for sheet are marketed under trade names which give no clue to their chemical composition, and users are apt to be bewildered unless they make frequent reference to lists, such as that given by Zeerleder,[62] in which the chemical composition and mechanical properties of many proprietary alloys are given.



[*By courtesy of the Apex Inflator Co. Ltd.*

Fig. 154. Stages in the deep drawing of a bicycle inflator tube from aluminium sheet.

[*By courtesy of the British Aluminium Co. Ltd.*

Fig. 155. Meter cases pressed in pure aluminium sheet.

[*To face p.* 248.

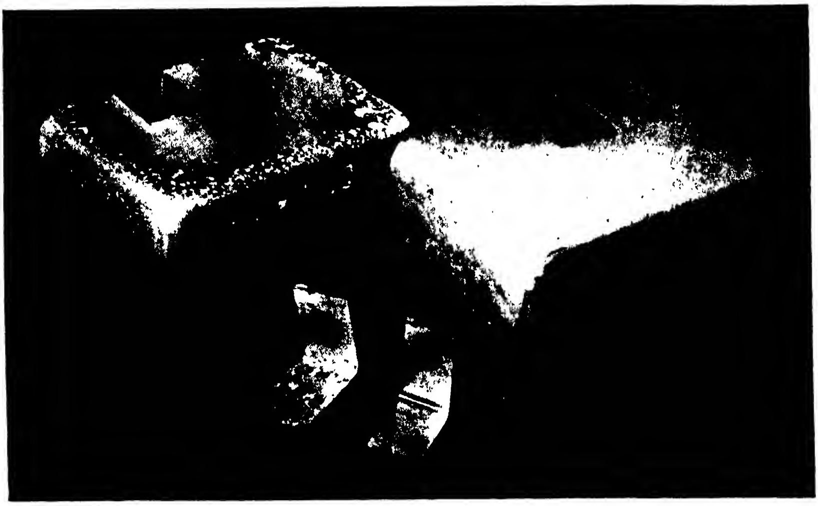


Fig. 156. Critical-strain crystal growth produced by the inter-stage annealing of boxes deep-drawn in magnesium-aluminium alloy sheet (left). The box on the right was deep-drawn without any annealing, and has cracked on the radius nearest the camera.

[*By courtesy of the British Aluminium Co. Ltd.*

Fig. 157. An illustration of the low rate of work-hardening of aluminium. Some of the 13 stages used to deep-draw the 1-inch diameter blank seen on the left into the $\frac{5}{32}$-inch diameter tube seen by its side without any inter-stage annealing.

[*To face p.* 249.

Aluminium and Non-precipitation-hardening Aluminium Alloys

In the past, attempts to press and deep-draw aluminium often resulted in failure or, at best, mediocre success. This was owing to the fact that a technique similar to that established as a result of long experience with brass and steel was adopted and seldom modified sufficiently to meet the somewhat different requirements of aluminium. Indeed, notwithstanding the fairly extensive range of deep drawn and pressed articles which are now produced in this metal, it cannot be said even now that a sound technique has been arrived at, although the bicycle inflator illustrated in Fig. 154, the hot-water bottle shown in Fig. 291 (p. 604) and, perhaps most conclusively, the tube illustrated in Fig. 157 show that very severe draws can be accomplished provided that a proper technique is used. The meter cases shown in Fig. 155 are of interest as typical moderately-deep draws which can be accomplished in one operation. Other familiar examples are saucepans and similar domestic articles which are often deep-drawn to the full depth—though, for reasons explained later, not always finished to size—in one operation; although sometimes articles of this kind are made by spinning.

The principal difficulties which have to be overcome are the natural inclination of aluminium to foul steel tools, to pucker and wrinkle to an unusual degree as illustrated in Fig. 75 (p. 105) and, particularly when the metal used is of very high purity, to break owing to its low tenacity and low rate of work-hardening. With precipitation-hardening aluminium alloys, the added difficulties associated with a rather critical heat-treatment often prove a stumbling block to those unaccustomed to treating these particular alloys and, which usually follows, who do not possess suitable furnaces.

Procedures based more closely upon the information revealed by special forms of stress-strain curves and laboratory types of practical drawing tests are likely to facilitate the deep drawing and pressing of aluminium sheet under industrial conditions in the future. For example, Gwyer and Varley [60] have shown that for a straightforward cupping operation performed in two stages, aluminium of so-called "hard temper" of about 9 tons per square inch ultimate tensile strength can be drawn into a deeper cup than annealed sheet of about 5 to 7 tons per square inch tensile strength. How soon the desired application of theory to industrial practice will take place must depend upon the enthusiasm shown by both theorists and industrialists.

Apart from any increased depth of draw, there is another reason why, under industrial conditions, the use of sheet which has received a certain amount of cold work is desirable if the shape is one which cannot be formed without the help of inter-stage annealing. Aluminium is subject to critical-strain crystal growth; therefore, when annealed sheet is used, a partly-formed shape will usually contain critically-strained regions in which annealing will produce crystals of abnormal size. During subsequent operations these regions will "neck" and cause failure; but, if the original sheet is cold-worked beyond the critical amount of strain, abnormal crystal growth will not occur in any part of the article during annealing, and subsequent operations can be carried out without fear of breakage. If abnormal crystal growth does not cause actual failure, it may make the surface of a finish-drawn article so rough that polishing costs will be excessive; furthermore, the harder the aluminium, the easier it is to polish. So marked is the phenomenon of critical-strain crystal growth in aluminium, that specimens of bent bar or tapered tensile test pieces of this metal are often used as museum or lecture-room exhibits to show the confinement of abnormal crystal growth to certain areas. Although various smaller ranges have been postulated as the critical one, 5 to 20 per cent. elongation may be regarded as the one wherein it is possible that abnormal growth may occur under industrial conditions in commercially-pure aluminium.

The critical-strain crystal growth shown in Fig. 156 is typical of that encountered in the press-shop. The cover on the left was deep-drawn in two stages with an inter-stage anneal, with the result shown; that on the right was drawn without the help of annealing, and it will be seen that cracks have developed in the radius bounding the flat top. Subsequently, by slight alteration to the tools, it was found possible to produce sound covers without any inter-stage annealing. In this instance the sheet is not pure aluminium but an alloy containing 3½ per cent. of magnesium; this illustrates the susceptibility of the various common aluminium alloys to critical-strain crystal growth, although often not in such virulent form as in pure aluminium.

It need hardly be pointed out that no remedy exists for critical-strain crystal growth in aluminium if sheet strained within the critical range is annealed: no easy preventative, as exists for steel—that is the replacement of annealing by normalising—can be taken advantage of. For this reason, when the production of any aluminium article requires the help of inter-stage annealing, every effort should be made to exceed at least 20 per cent. elongation in all its parts prior to such annealing.

Unfortunately it is not always possible to use hard "tempers" of aluminium sheet for all deep drawn or pressed articles. If, for example, the rim of a deep-drawn cup or shell has to be rolled over or the parallel walls of a shell bulged or otherwise deformed, or it is not desired to anneal on account of cost or because the remainder of the shape would thereby be made too soft to withstand ordinary usage, it may seem preferable to form the shell from annealed sheet. Again, the tendency to "pucker"—always pronounced with aluminium—

increases as the hardness of the sheet increases ; this fact alone may preclude the use of hard sheet for the production of shapes from which puckers cannot be removed by a final coining or stamping operation.

A well-recognised natural characteristic of aluminium is its tendency to foul steel dies and even steel punches. This characteristic might not be anticipated, because fouling is essentially a welding process and, due to its coating of tenacious and relatively infusible oxide, aluminium is at all times a difficult metal to weld unless special means are adopted to break or remove the oxide skin. The explanation offered by Egeberg and Promisel [12] to account for the marked tendency to foul shown by nickel-silver (see p. 304) may also apply to aluminium; but, pending further investigation, this ingenious hypothesis should be held *sub judice*. Whatever may be the true explanation of the precise mechanism of fouling, the fact remains that this phenomenon tends to be unusually pronounced with aluminium and that it constitutes a serious difficulty during the manipulation of this metal and some of its alloys in the press-shop.

During recent years the purity of commercial aluminium sheet has increased considerably, and it is now unusual to find more than 0·6 per cent. of total impurities, of which about 0·4 per cent. is generally iron. The effect of this is to increase the ductility but to decrease still further the naturally low tenacity of sheet received in the press-shop; so that in some respects present-day sheet is more difficult to shape under the press than the less pure sheet of by-gone days, a failing which has hastened the introduction of aluminium-alloy sheet for purposes of deep drawing and pressing. The advent of sheet of high purity has also increased the likelihood of critical-strain crystal growth and lowered the temperature at which cold-worked sheet recrystallises, a fact which is not always appreciated by those responsible for annealing procedure.

One of the practical difficulties with which the press-shop has to contend is that the crystal structure of the aluminium sheet it has to manipulate is sometimes far from satisfactory because, using ordinary industrial annealing furnaces, it is not easy to anneal aluminium sheet in such a way that the best deep-drawing properties are secured regularly. This is due to a natural " lag " in the recrystallisation of cold-worked aluminium coupled with a rapid rate of crystal growth once recrystallisation has started. Because of this, both the " average grain size " and the uniformity of crystal size of aluminium sheet often varies rather widely. It is therefore fortunate that, owing to the low rate of work-hardening of aluminium and to the fact that it is often used in a slightly cold-rolled condition, the influence of both " average grain size " and uniformity of crystal size tends in many instances to be less pronounced than in many other metals. One result of this is that an unusually large " average grain size " does not always cause failure under the press by the familiar process of localised "necking," although the rough surface which invariably is associated with a large crystal size may render a deep-drawn article unusable even though it has been shaped without failure. Conversely sheet having a small "average grain size" may possess a sufficient margin of safety to be successfully deep-drawn into the desired shape. Useful though this accommodation is, it ought not to be made an excuse by users for omitting proper acceptance examination or by suppliers for hindering the supply of sheet having a more satisfactory crystal structure.

In a most interesting investigation,[61] which may point the way to the better industrial annealing of sheet other than aluminium, Masurkawitz showed that if aluminium sheet is heated very quickly to the annealing temperature a much more uniform, and usually a smaller, crystal structure can be obtained than when orthodox methods are employed. The method employed by Masurkawitz was to pass the sheet at a fairly rapid rate through a continuous annealing furnace in which the entrance zone was maintained at a temperature of about 800° C., that is, well above the melting point of the sheet passing through it. In this way he heated cold-rolled sheet of 0·040 inch thickness to an annealing temperature of from 420° to 500° C. in approximately thirty seconds, and succeeded in obtaining Erichsen values considerably higher than those given by similar sheet annealed by ordinary methods at any temperature. Needless to say, the general introduction of this method of annealing for aluminium sheet destined for deep drawing and pressing would be gladly welcomed by those whose task it is to shape this sheet under the press.

Mention must be made of the value of the Erichsen test in estimating the deep dawing and pressing properties of aluminium and aluminium-alloy sheet. The usefulness and also the limitations of this test are discussed fully in Chapter XII, and all that need be said here is that with aluminium and aluminium-alloy sheet the results obtained tend to be more than usually erratic, and do not always form a reliable guide to the behaviour of sheet under the press. For example, the advantages of "$\frac{1}{4}$-hard" sheet for many press operations is established beyond question, yet the Erichsen value for the "$\frac{1}{4}$ hard" sheet may be distinctly less than that for the fully annealed, but in fact inferior, sheet. The smoothness of the surface of the dome is, however, a reliable indication of crystal size. For this reason, and because when used intelligently on sheet obtained from one source for the continued production of one article it does provide helpful indications, this simple and quickly-made test need not be excluded from acceptance examination.

In both aluminium and aluminium-alloy sheet "directional" properties tend to be troublesome. The severity of the "directionality" in any sheet can be measured by the appropriate tests described in Chapter XII.

Whether pure aluminium or an alloy is to be chosen will usually be decided by the strength which the finished article must have, yet sometimes it is worth while using slightly-alloyed aluminium in preference to the pure metal because, owing to the somewhat higher tenacity of the alloy, shapes deep drawn or pressed in it are less likely to break at the radius of the punch or by localised necking in the walls. As with the pure metal, many of the aluminium alloys containing only small amounts of alloying elements behave better under the press when used in the slightly cold-worked condition known industrially as "¼-hard temper," and it will often be found that these will survive almost as much plastic deformation as pure aluminium before annealing becomes necessary. Another advantage of the alloy sheet is that finished articles are less liable to be dented or deformed through handling or use in service.

Special mention must be accorded to the alloys containing from 2 to 7 per cent. of magnesium, often with a little magnanese (see Table I on p. 248) which combine tensile properties considerably better than those of pure aluminium with excellent corrosion resistance. The best deep drawing and pressing properties are found, naturally, in the alloy having the lowest magnesium content, yet the popular alloy containing 3½ per cent. of this element can be shaped nearly as well and, as is evident from the brake-drum illustrated in Fig. 285 (p. 595), a useful draw can be accomplished even with the 7 per cent. alloy.

"Super-purity" Aluminium. It is now possible to obtain aluminium sheet in which the percentage of impurities is usually of the order of 0·0025 per cent., consisting mainly of iron. Although this sheet is useful for anodising, it is less welcome in the press-shop than the ordinary variety because, as explained later, it has to be annealed under very closely controlled conditions in order to obtain a satisfactory crystal structure, and also because it is very prone to "foul" and to "load" steel tools.

Technique. Some indication of the special technique needed for the deep drawing and pressing of aluminium and aluminium-alloy sheet has already been given. It has, for example, been mentioned that aluminium is particularly sensitive to pressure-plate loading, to the size of the blank used to form a shape of given depth and to the hardness or "temper" of the sheet used. For these and other reasons the successful shaping of aluminium in the press-shop demands even closer study than may seem necessary with other metals, and careful consideration of the conditions relating to any particular operation in the light of such little information as has been published relating to general and, when possible, similar conditions. It is not unlikely that experience gained in the study of these particular factors with aluminium may prove of unsuspected benefit in the deep drawing and pressing of metals whose behaviour, it is sometimes imagined, is understood reasonably well. If only for this reason the study of aluminium is one to be pursued energetically in the laboratory.

All too frequently blanks of aluminium are substituted, as an experiment, for blanks of steel or brass in regular production tools set up for deep drawing or pressing these last-named metals, and their almost certain failure attributed, quite unfairly, to the unsuitability for presswork of the particular samples of sheet used and, by inference, even of aluminium in general. The failure of trials of this nature ought often to be attributed to the use of tools of unsuitable design, of an unsuitable size of blank or to an unsuitable combination of blank size and pressure-plate loading, particularly on the first draw.

The golden rule for the successful deep drawing and pressing of aluminium—and indeed of many of the aluminium alloys—is to let the sheet flow as freely as possible. To obey this it is often desirable to avoid the extra drag, caused by localised thickening of the walls of a shell, by easing the clearance between the punch and the die in the regions where thickening occurs—for example, at the corners of a rectangular shell—and by using shaped blanks designed to even-up the flow of metal into the region of high stress in the throat of the die. Pressure-plate loading should be kept to the minimum needed to prevent the formation of seriously injurious wrinkles; indeed, sometimes it is best to use a pressure so light that a certain amount of wrinkling occurs and to remove this by a subsequent drop-stamping operation, as explained later.

Aluminium is sensitive to the radius of the drawing die and, still more so, to that of the punch used in a cupping operation. When the radius of the punch is too small, the metal is likely to tear in the vicinity of its contact with this radius. If, on the other hand, the radius is too large, the punch tends to pierce the sheet instead of allowing it to fold over this radius and draw the rest of the blank through the die. The replacement of the usual radiused corner of the punch by a 45° bevel with suitably radiused corners is often most beneficial, particularly with annealed sheet. As the hardness of the sheet increases, this modification becomes less effective and, fortunately, less necessary.

Mijôn [63] and Fukui [64, 65] have published results showing that the replacement of the usual radiused drawing die by one of conical shape resulted in a reduction of the force needed to form a cup from a circular aluminium blank, and also lessened the tendency to wrinkle and pucker. This investigation illustrates the almost unexplored possibilities, commented upon elsewhere, associated with the replacement of the orthodox radius of drawing dies by contours of special shape; possibilities which, needless to say, are not confined to aluminium.

Although aluminium is quite amenable to "ironing," it is often preferable to form a deep shell by gradual reductions in diameter rather than by ironing the walls of a cup pressed to nearly the final diameter, because this procedure lessens the likelihood both of breakage in the walls and of fouling. For similar reasons the process of reversed drawing is of great benefit, and it is curious that it is not used more often.

Experience has shown that often it is well worth while to trim the tops of deep-drawn cups before proceeding to the next deep-drawing operation. This procedure, useful with all metals, is of particular benefit with aluminium; a rather unexpected finding having regard to the very low rate of work-hardening of this metal.

A factor of considerable importance which needs to be observed during the deep drawing and pressing of aluminium, particularly if the sheet is thin, is that of cleanliness. The unsuspected damage to both work and tools which can be caused by particles of abrasive foreign matter has already been commented upon and, later, a plea is advanced for the maintenance of a much higher standard of cleanliness in the average press-shop. The effect of abrasive particles is more noticeable with aluminium than with any of the other metals which are commonly used in the press-shop; its softness allows deep scores to be inflicted easily, its low tenacity renders any extra friction due to the action of abrasive particles likely to cause breakage and, lastly, its natural tendency to foul is aggravated by the presence of particles which rupture the protective film of drawing lubricant and simultaneously expose freshly scraped, unoxidised areas of metal to the tools. For these reasons it is desirable to take more than ordinary precautions to prevent the ingress of foreign matter to the tools *viâ* blanks, lubricant or the surrounding air.

Attention has already been drawn to the proneness of aluminium and aluminium-alloy sheet to "pucker" during pressing and drawing operations, and it is also true that the effect known as "wrinkling" tends to be troublesome because the pressure-plate loading required to prevent the formation of wrinkles often proves to be so high that, were it used, the depth of draw would be seriously reduced. To combat this difficulty, a common industrial practice is to allow a certain amount of wrinkling and puckering to take place, and, having obtained the desired depth of draw, to "coin" the finished shape between suitable dies under a drop-stamp. This last operation performs the double purpose of sizing the shape, sharpening up any corners and perhaps putting in certain desired ridges or indentations and, secondly, of removing wrinkles and puckers in a surprisingly effective manner. The dies used for this finishing operation are often of zinc, lead or white-metal, cast to shape around a finished article so that their cost of production is very low. In general their life and performance is quite satisfactory, and there seems no need to go to the considerable expense of making machine-cut dies unless the article to be stamped demands unusually close dimensional tolerances throughout the whole of a long production run.

The benefits associated with presses actuated by fluid-pressure instead of by a crank are more than usually evident when aluminium alloys of Duralumin type are being deep drawn or pressed. In particular the advantage of being able to limit the punch-pressure to a predetermined maximum prevents the production of a large proportion of scrap when improperly-normalised or partially-aged metal is inadvertently placed under the press. Should this happen the punch will stop, thus giving an opportunity for the partly-formed shape to be re-normalised and re-drawn, whereas slightly hard metal will assuredly fracture under the inflexible descent of the punch of a crank-actuated press. The non-harmonic motion and easily regulated speed of a fluid-pressure are also of great help. These and other matters are described more fully in Chapter IX, which deals with presses.

In Chapter XV there is described a special technique which is rapidly gaining in popularity for the shaping of sheet metal components. This is a combined drawing, pressing and stamping process, carried out in either a modified form of drop-stamp or an hydraulic press, in which the sheet is persuaded into the desired shape by a series of blows, squeezes or draws. Aluminium and aluminium-alloy sheet are particularly amenable to shaping by this process, and its adoption should always be considered for the production of pressings and, when the number to be produced does not justify the making of more orthodox tools, of deep-drawn articles of moderate depth.

Tools. It might be assumed that the softness of aluminium would render tool problems relatively unimportant. Up to a point this assumption is correct, and many articles are pressed in tools made of indifferently-hardened—and occasionally from soft—steel, of bronze, cast iron and zinc, and occasionally of wood. When the operation is of a true deep-drawing nature and a large number of articles have to be produced, it is usually necessary to use well-polished, hardened steel tools if production is not to be interrupted by fouling. When cost is an important consideration, case-hardened mild-steel tools are perfectly satisfactory unless for some reason pressures are unusually high. When, as in many pressing operations, contact pressures are not high, cast bronze of fairly high tin content may be used in place of hardened steel. Although a relatively expensive material, bronze possesses the great advantage that tools can be cast so closely to shape that very little machining is needed to finish them ; also, in the opinion of some users, bronze is less likely to foul than steel.

"Soft metal" tools are used extensively for shaping aluminium and aluminium-alloy sheet in pressing, in the new stamping process described elsewhere (p. 614) and sometimes for light deep-drawing operations. These consist of dies of zinc or zinc alloy and punches of zinc, zinc alloy or lead cast to shape in the manner described in Chapter X; they have sufficient durability for production runs of moderate length and have the great advantage that they can be made very quickly and at low cost.

Rubber is also widely used as a tool material to work against an opposite metal member, which may be either male or female, and is usually of zinc or zinc alloy. Sometimes the rubber is left relatively free; but sometimes sideways movement of the edges of the pad is prevented by a surrounding steel frame. In addition to being used for shaping, rubber is also used for blanking operations. Very high pressures are needed to shape some of the aluminium alloys, and the operation is usually carried out on hydraulic presses of large size. When small pressings have to be made on these large presses, several are usually shaped at one stroke of the press by mounting the dies on the lower table and having one large rubber pad for the upper tool, as shown in Fig. 300 (p. 618).

Punches, and occasionally dies, of large size are sometimes cast in aluminium or, particularly in Germany, in magnesium alloy. The principal advantage of this application is the lightness of these metals, which enables tools of large size to be handled with relative ease. This is particularly welcome in the aircraft industry where, owing to the small number of any one pressing which is needed at one run, tools have to be changed at frequent intervals.

The tools used for forming large light-alloy sheets by the "stretching" process (see p. 613) fall into a separate group because pressures are lighter than in deep drawing and pressing operations. Built-up wooden tools, sometimes having inserts or facings of zinc or mild steel, are used in the majority of instances, although tools cast in zinc, aluminium or magnesium keep their shape better and are, naturally, more durable.

Lubricants. A variety of lubricants ranging from paraffin to polishing "compo" are used on aluminium; often, as might be expected, with indifferent success. Why such unusual lubricants should be used with aluminium is not apparent: paraffin is a very poor lubricant and, in the experience of the author, almost useless. It is advantageous to use a lubricant when blanking or shearing aluminium; for *this* purpose, paraffin is excellent.

Ordinary "suds" can be used for light draws, the varieties which contain lard oil being the best. For more severe operations a lubricant containing a fair proportion of lard oil, as distinct from the few per cent. present in soluble oils, is of proved benefit, and, for pressing operations, vaseline is often used. A popular lubricant for pressing or light drawing operations on thin sheet is ordinary machine oil diluted with an equal bulk of paraffin.

For heavy draws when fouling is likely to occur, a "filled" lubricant containing chalk or other suitable filler is usually desirable, although tallow, mixtures of tallow with rape or machine oil, and sometimes pure castor oil have been used with success. The "evaporating" lubricants described later in Chapter XI have also proved very successful with aluminium, and still more so with light-alloy sheet of Duralumin type.

Annealing. The temperature at which aluminium will recrystallise is influenced by the amount of cold-work which has been imposed upon it and by the percentages of impurities, notably of iron and silicon, which the metal contains. In most metals the time of heating as well as the temperature needs to be considered in any annealing problem, but, in the case of aluminium, the influence of time is more than usually marked. This was established in a precise manner as early as 1917 by Carpenter and Tavener, who published a paper [66] containing tables showing the effect of heating specimens of cold-worked aluminium for various periods at a number of temperatures.

More recently Trillat [67] has shown that aluminium of 99·99 per cent. purity will recrystallise at as low a temperature as 170° C. if annealing is continued for a number of hours, and aluminium of 99·0 per cent. purity at from 200° to 230° C. The paper just mentioned is commended to users of aluminium sheet both for the interesting theoretical study therein described and for the excellent bibliography on the annealing of aluminium. Another paper worthy of close study is that of Hobrock,[68] which gives much valuable information upon the influence of degree of cold-work and other factors upon the annealing of cold-worked aluminium and a number of aluminium alloys.

Without usurping the function of these and other erudite and authoritative papers dealing with the theoretical aspect of the annealing of cold-worked aluminium and its alloys, it can be stated that, as far as the average press-shop is concerned, an annealing temperature of from 350° to 390° C. will usually be found the most satisfactory for aluminium of normal purity and for the commonly-used aluminium alloys. Unless the time of heating is very short—a condition which must introduce practical difficulties—it is usually unwise to use, as is still sometimes done, a temperature of 500° C. and even higher. Aluminium sheet of so-called "super-purity" needs to be annealed within the range of 340° to 370° C.; below 340° C. recrystallisation takes place very slowly, yet above 370° C. crystal growth takes place rapidly. Aluminium alloys containing from 2 to 7 per cent. of magnesium (see Table I on p. 248) are best annealed at a temperature of from 400° to 450° C.

Owing to the rapid rate at which crystal growth takes place, it is important that pure aluminium should not be held at or near the annealing temperature longer than is necessary to produce complete recrystallisation. As, for thin sheet, this may be only a few minutes, it will be appreciated that special precautions need to be taken to ensure that all parts of each charge—and indeed of each article—are heated as nearly as possible uniformly and at the same rate. The most satisfactory way to ensure this is to use forced-circulation air furnaces of the type already described, or oil baths : it is almost impossible to secure a desirably uniform heating in a short time in still-atmosphere furnaces unless these are of very large capacity in relation to the charge, and therefore bulky and costly. It is unnecessary to use any protective atmosphere during the inter-stage annealing of aluminium and its alloys.

The recommendations given in this section for the inter-stage annealing of articles deep-drawn from aluminium-alloy sheet must, naturally, be examined in the light of the interesting results obtained by Masurkawitz [61] in his study of the annealing of aluminium sheet (see p. 252). Masurkawitz showed that a smaller and more uniform crystal structure and a better Erichsen value could be obtained if cold-rolled aluminium sheet was heated very rapidly—that is in less than a minute—to the annealing temperature. Although it is not difficult to do this with sheet or strip in specially designed continuous furnaces, it will be appreciated that it will be far from easy to secure very rapid yet uniform heating of a shell of any size owing to the varying distance of its different parts from heating elements which, of necessity, must be maintained well above the melting point of aluminium. It seems therefore that, as applied to the press-shop, the findings of Masurkawitz must be regarded as confirmatory evidence of the fact, already emphasised, that the rate of heating during inter-stage annealing should be the highest which practical considerations will permit.

Concluding these remarks on annealing, it may be said that, if careful attention is given to tool design, lubrication and other relevant factors, surprisingly severe deep drawing and pressing operations can be carried out with pure aluminium—though not always with aluminium-alloy—sheet without having recourse to inter-stage annealing. Aluminium, particularly when of high purity, has a very low rate of work-hardening. This explains the really amazing amounts of deformation which can be inflicted before annealing becomes necessary, as shown by the tube illustrated in Fig. 157 (p. 249) which is deep-drawn from a round blank 1 inch diameter in no fewer than thirteen operations to a tube $\frac{5}{32}$ inch diameter with no annealing whatever.

Precipitation-hardening Aluminium Alloys

The essential feature of the many alloys in this group, which is of particular importance in the aircraft industry, is that by suitable heat-treatment they can be made sufficiently soft and ductile to enable sheet to be deep drawn or pressed into the desired shape and that this softened sheet can then be "aged" to give excellent mechanical properties greatly superior to those of aluminium and, in most instances, to those of the non-precipitation-hardening aluminium alloys. All the alloys can be softened by being heated to a suitable temperature, which is determined by their chemical composition and is usually in the region of 500° C., to make the precipitated constituents of the microstructure go into solid solution and then stabilising this solid solution by cooling rapidly to room temperature, usually by quenching. After the necessary shaping operations have been carried out the sheet is "aged," and here the alloys fall into two natural sub-divisions: those which age when, after solution-treatment, they are allowed to stand at room temperature, and those in which ageing has to be induced by heating them for a number of hours to a moderate temperature, sixteen to twenty hours at 160° C. being a common ageing treatment. Another important distinction between these two groups is that those alloys which age at room temperature begin to lose their ductility so quickly that shaping operations have to be completed within from half an hour to two hours of solution-treating depending on the severity of the deformation to be inflicted, whereas those alloys in which ageing has to be induced by heating retain their ductility for very long periods at room temperature.

This group of alloys can also be softened by annealing, usually at a temperature in the region of 380° C. When this method is used it is often necessary to "solution-treat" and age the shaped article in order to induce precipitation-hardening and thus to obtain the desired mechanical properties. The merits of these two methods will be discussed later.

Table I (p. 248) gives the chemical composition and mechanical properties of two representative alloys in this group, the first being a grade of "Duralumin" which is probably the most popular of any of the light alloys used in the press-shop in sheet form for the production of stressed parts for aircraft. For the purpose of simplification only the major alloying elements are given, and it must be emphasised that small variations in the proportions of these elements, in the proportions of each relative to the others and also in the proportions of impurities, particularly iron, influence the mechanical properties and in some instances the heat-treatment which has to be given.

In the application of light alloys to aircraft construction corrosion-resistance is a property of considerable importance. The precipitation-hardening alloys, such as Duralumin, are not particularly good in this respect, and for this reason Duralumin sheet is often "clad" with very thin surface layers of high-purity aluminium as shown in the photomicrograph in Fig. 293 (p. 609). In this way it is possible to secure the mechanical strength of the heat-treated alloy core, which constitutes very nearly the whole bulk of the section, coupled with the superior corrosion-resisting properties of the pure aluminium coating which can be increased still more by one of the popular anodic treatments. Owing to the softness and thinness of the " clad " coating great care needs to be taken during severe press operations not to damage the coat and expose the alloy core. This calls for very smoothly polished tools and for the avoidance of high contact-pressures and localised regions of severe deformation.

Elsewhere it is explained that the deep drawing and pressing properties of the precipitation-hardening aluminium alloys are not particularly good when judged by usual standards, and for this reason they should be chosen for articles needing severe shaping operations only when the mechanical properties of non-precipitation-hardening alloys of the kind set out in Table I are insufficiently high to satisfy the demands of designs engineers. Any press-shop which sets out to handle these alloys *must* enforce strict control of the necessary heat-treatment and, if accustomed to more easily worked metals such as brass and steel, must learn to think in terms of more gentle stages of deformation than those customary with such metals. Even then occasional failures may be encountered and, when the resources of a laboratory are available, such assistance as this can give will certainly help even though the problems are less simple than with many other metals because metallographic examination and mechanical tests will not always reveal the cause of failure or mediocre performance under the press.

It is, unhappily, particularly difficult to predict the deep drawing and pressing properties of aluminium-alloy sheet of the precipitation-hardening varieties from the results of the usual laboratory tests or to establish the true cause of failure in sheet proved by trial to behave in an unsatisfactory way under the press. One reason for this is, of course, that—except in the instance of annealed sheet—tests made on aged sheet enable its properties in the freshly-quenched condition, in which it is shaped, to be judged only by inference. The task of the metallurgist is not helped by the fact that by the time a sample of sheet which has failed has reached the laboratory it will certainly not be in the condition in which it was when placed under the press, and may have age-hardened appreciably. Apart from this, however, it must be admitted that the lack of prolonged industrial experience in the press-shop with sheet of this kind is a handicap and also that, in the light of existing knowledge, it is particularly difficult to correlate behaviour under the press with measured physical properties or with observed microstructure.

In the experience of the author the most common cause of failure is improper solution-treating, and this should always be checked before a full examination of the metal is undertaken. Often it will be found that a fall—or occasionally a rise—in the temperature of the salt bath or furnace is the cause of the trouble, or perhaps that the solution-treating temperature is correct yet the sheet has been allowed an insufficient soaking period.

Sometimes the indicating pyrometer may be reading correctly, yet, owing to temperature variations between one part of a bath and another, sheets or pressings are not being heated to the indicated temperature. Only when, with the guidance of pyrometers of known accuracy, representative samples of an alleged defective batch of sheet have been correctly solution-treated should more obscure reasons be sought to explain still unsatisfactory behaviour. In these days of automatic temperature control, recording pyrometers and stop-watch timing, this advice may seem strange, yet it is sound and helps to prove that, as many industrialists know, the human element is still a very potent factor and that coloured signal lights and expensive apparatus are of no avail when the lunch bell is about to ring or the merits of a certain football team have been questioned by some rival supporter.

When it has been ascertained that a batch of sheet really does exhibit abnormal behaviour, the investigator is faced with the choice of making tests on samples in the "as received" condition, in the solution-treated and aged or partly-aged-condition, or within a very short time of the solution-treating quench. Often the last is the most informative, but special facilities are usually necessary if, for example, a complete tensile test is to be carried out within a few minutes of quenching.

Reviewing the usual tests, Erichsen values tend to be most erratic although this test is useful in that it does reveal an undesirably large crystal size and also pronounced directional properties. Hardness tests, which are usually made on the Vickers machine, also tend to give rather erratic readings ; they offer very little help in assessing the deep drawing and pressings properties of soft—*i.e.*, solution-treated—sheet, but they are used quite extensively on aged samples or pressings as a quick check to show whether solution-treating and ageing have produced the desired mechanical properties. For example, it is commonly held that if the hardness of aged Duralumin is greater than 115 V.P.N. the full tensile properties have been induced. Although this may often be true as regards ultimate strength, it has been the experience of the author that no reliable relationship exists between hardness and proof stress, and indeed there are no theoretical grounds for assuming that one should. As in aircraft construction proof stress is often of greater significance than ultimate stress, the only safe check on heat-treatment lies in the heat-treatment, simultaneously with a batch of pressings, of flat strips *cut from the same sheets* on which proper tensile tests are made.

In hardness testing a careful watch should be kept for "clad" sheet and the surface layer of pure aluminium removed so that the indentation is made on the alloy core.

Tensile tests may give some helpful information for, although ultimate strength seems to have little influence upon deep drawing and pressing properties, an unusually low percentage elongation is a sure indication that sheet is not up to the desired standard and is likely to fail under the press. The reason for the low percentage elongations which are sometimes met with is not yet understood fully, although experience shows that the arrangement of the particles of the precipitated constituents has an influence upon this property. When the particles are isolated and distributed uniformly, the behaviour of the sheet under the press is usually good ; whereas when the particles are segregated into pronounced stringers (reminiscent of carbide segregations in high-speed steel) trouble is likely to be encountered. Typical examples of these two types of microstructure are shown in Figs. 158 and 159 (p. 264).

Light-alloy sheet of Duralumin type often possesses marked " directional " properties. For this reason when tensile properties are not measured both in directions parallel to and at right angles to that of rolling, the right-angle direction should always be chosen. Another point of some importance is that an 8-inch gauge length often reveals differences which are not discernible with a 2-inch gauge length. This means that tensile tests made parallel to and at right angles to the direction of rolling on two samples of light-alloy sheet having known good and bad behaviour under the press may show no difference when a 2-inch gauge length is used, whereas with an 8-inch gauge length a distinctly low percentage elongation will often be obtained in the transverse, as distinct from the longitudinal, direction on the unsatisfactory sheet.

Many specifications covering light-alloy sheet call for a 1-inch radius on tensile test specimens, this being the radius of the British Standards Institution test pieces illustrated in Fig. 250 (p. 504). There is some evidence to show that this radius is too small to give true results on age-hardened light-alloy sheet and, although the use of standard test pieces is to be encouraged, it is desirable to use a larger radius on test pieces in this and similar alloys. A radius of 3½ inches is specified for most light alloys in the cast condition, so, to avoid unnecessary multiplication of shapes, it would be a good thing if this radius were adopted as standard for light-alloy sheet of all kinds.

The crystal structure, meaning more particularly the " average grain size " of sheet of Duralumin type, is less likely to be unsatisfactory than that of pure aluminium upon which comment has already been made. An " average grain size " of about 0·035 mm. appears to be satisfactory for many operations.

A defect which seems more prevalent in aluminium-alloy sheet than in the other kinds of sheet commonly used in the press-shop is that of surface blisters. Occasionally these are to be seen on the surface of purchased sheet, as in the example illustrated in Fig. 160; and often it is hard to understand why sheet having an obviously defective surface passes suppliers' inspection departments. At other times no visible surface blemishes, or perhaps only faintly visible markings of a nature too indeterminate to warrant summary rejection, are visible on purchased sheet, yet heat-treating or annealing in users' works will cause blisters to appear owing, presumably, to the expansion of gas which is entrapped in mechanical discontinuities in the metal. A typical example is shown in Fig. 161. In this instance the internal discontinuity lies in the middle of the section and has produced blisters on each surface of the sheet, but often it is near to one surface and produces a blister on that surface only. In "clad" sheet (which, as explained later, is aluminium-alloy sheet to which a very thin layer of pure aluminium has been pressure-welded by hot-rolling) blisters are sometimes caused by local discontinuities situated at the junction of the sheet proper and its surface coating. The bend test described elsewhere (see p. 476 and Fig. 122, p. 188) is helpful in revealing whether suspected surface markings really do indicate internal discontinuities; but, as the size of the sheets used in aircraft work is often large, a suspected area cannot always be tested without cutting the sheet and thus rendering it useless for its allotted purpose.

Technique. Aluminium alloys of the precipitation-hardening varieties now being discussed do not possess good deep drawing and pressing properties; yet a proper understanding of their limitations and peculiarities will enable properly solution-treated or annealed sheet to be formed into all kinds of shapes by deep drawing, pressing or the new drop-hammer-cum-pressing technique already mentioned. This implied caution concerning heat-treatment is important, for unless the sheet is worked in its most ductile state, even moderately severe press operations are doomed to failure. It is essential that this fact be appreciated.

The deep drawing and pressing properties of these alloys in some ways resemble those of steel, although markedly less good than those of this relatively tractable metal. On the other hand they resemble those of aluminium in that the least possible restraint must be put upon sheet by pressure-plate loading or by "ironing" caused by localised thickening, for example at the corners of a rectangular shell. This fact explains the special value of rubber tools and of blanks carefully shaped to induce uniform flow. Marked "directional" properties are sometimes manifested, and this should always be borne in mind whenever it is possible to vary the relationship of a non-circular shape to the direction of rolling in the sheet.

Owing partly to the nature of the sheet and partly to the need for light pressure-plate loading, difficulty is often experienced with "wrinkling" and "puckering" (see, for example, the article illustrated

FIG. 158. Typical microstructure of Duralumin sheet having good deep-pressing properties.

Microsection cut normal to surface of sheet and parallel to direction of rolling. Etched, × 100.

FIG. 159. Microstructure of Duralumin sheet having poor deep-pressing properties. Observe stringers of precipitated constituent.

Microsection cut normal to surface of sheet and parallel to direction of rolling. Etched, × 100.

[*To face p.* 264.

FIG. 160. Blisters on surface of Duralumin sheet. × 4.

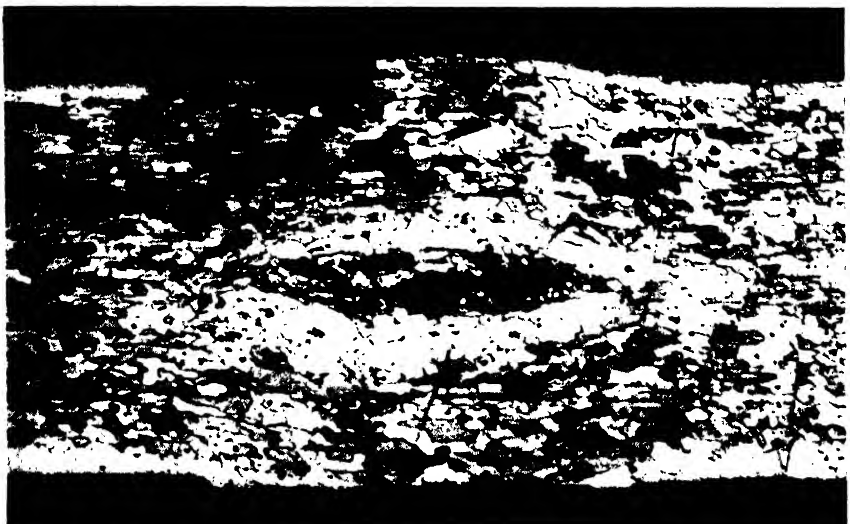


FIG. 161. Section through blister caused by central cavity in Duralumin sheet.
Microsection cut normal to surface of sheet and at right angles to the direction of rolling. Etched, × 100.

[*To face p.* 265.

in Fig. 75, p. 105). Although skilful tool design can do something to minimise the severity of these unwanted happenings their occurrence cannot always be prevented, and often it is advisable to remove these undulations or at least to reduce their severity by " coining " the shape between dies in a drop-stamp prior to the next press operation. With pressings of large size, when it would be too costly to have a series of coining tools, the judicious application of a wooden mallet wielded by a skilled man can achieve surprisingly good results. It need hardly be added that either of these treatments must be given before the metal has had time to age-harden to an appreciable extent.

When deep drawing and pressing operations are carried out on sheet in the annealed, as distinct from the solution-treated, condition, it is usually necessary to solution-treat and age the finished product in order to induce in it the excellent mechanical properties which are the principal attribute of this kind of light alloy. Quenching, however, is likely to produce serious distortion, and it is therefore preferable to solution-treat and quench immediately prior to the final press operation even though this be only a sizing operation. In this way the distortion produced by quenching can be rectified.

In the opinion of some workers it is desirable to use solution-treated sheet only for shapes formed at a single operation, or by several operations carried out in rapid succession, when the amount of deformation is not great. When the desired deformation is considerable the use of annealed sheet is often helpful, particularly as shaping operations can then be carried out at leisure instead of having to be completed within a short time of solution-treatment.

The practice of warming blanks to a temperature of about 100° to 180° C. is salutary, and has often enabled production to be continued without interruption when conditions were such that frequent breakage of cold blanks was being experienced. Naturally, proper heating in a bath of hot lubricant or other medium and not indiscriminate warming over a naked flame, or even a hot-plate, is virtually essential. In the case of solution-treated aluminium alloys the benefits of warm drawing can be combined in a most convenient way with a special pre-ageing treatment described later, which can be used to produce a temporary increase in ductility in sheets of suitable chemical composition.

The benefits associated with presses actuated by fluid-pressure instead of by a crank are more than usually evident when aluminium alloys of Duralumin type are being deep drawn or pressed. In particular the advantage of being able to limit the punch-pressure to a predetermined maximum prevents the production of a large proportion of scrap when improperly-normalised or partially-aged metal is inadvertently placed under the press. Should this happen the punch will stop, thus giving an opportunity for the partly-formed shape to be re-normalised and re-drawn, whereas slightly hard metal will assuredly fracture under the inflexible descent of the punch of a crank-actuated press. The non-harmonic motion and easily regulated speed of a fluid-pressure press are also of great help. These and other matters are described more fully in Chapter IX, which deals with presses.

Tools. The tools used for shaping light-alloy sheet of the precipitation-hardening kind often resemble those already described for the non-precipitation-hardening varieties. Owing to the higher loads which are imposed it is only natural that the more durable tool materials are needed sometimes, yet, as the shaping operations often have to be more gradual, relatively soft materials frequently give excellent service. " Soft metals " and rubber are, for example, used extensively for producing pressings for aircraft in sheet of Duralumin type ; for genuine deep-drawing processes dies of hardened steel, well polished, are usually desirable, and nitrided steels offer increased resistance to " fouling."

Lubricants. As with many of the less-common metals, little published information is available concerning the best lubricants to use with sheet of Duralumin type. For light operations light oils without special additions seem adequate ; for more severe operations a " filled " drawing lubricant offers advantages, and the " evaporating " type of lubricant has proved particularly helpful.

Mechanism of Precipitation Hardening

Before examining the technique for shaping and heat-treating light-alloys in the press-shop, brief mention must be made of the fundamental phenomenon which causes the change in mechanical properties, so useful industrially, which is brought about by solution-treating and ageing. In the confines of a few paragraphs only essential facts having industrial significance can be given ; readers desiring fuller details of the practical aspect are referred to the excellent and authoritative manual of Teed [69] and, for theoretical discussion, to the considerable bulk of scientific papers which have sought, often with considerable ingenuity, to explain the changes which occur.

Although the exact details of the age-hardening process are not yet known, it can be said that the precipitation of certain constituents from the state of solid solution induced by solution-treatment is believed to be responsible for the observed changes in physical and mechanical properties. However, these changes cannot be explained by the simple precipitation of one constituent, and it is recognised that the answer to this unsolved problem lies—at least partly—in the combined influence of several precipitations occurring either simultaneously or in sequence and probably overlapping for certain parts of the ageing period, and perhaps having their influence modified by other factors not yet isolated. In this statement the term " precipitation " is used, somewhat loosely, to cover both the state immediately preceding, and that of, true precipitation ; although a peculiar feature of these alloys is that the " precipitation " which takes place during ageing cannot be seen by ordinary microscopical examination. This fact is mentioned because, although it occasions no surprise to metallurgists who recognise the profound influence exerted by both nascent and sub-microscopic precipitation, it sometimes surprises practical men who, perhaps having limited metallurgical knowledge, assume that so great a change in mechanical properties will be accompanied by some clearly visible change in microstructure and, observing no such change, may jump to the conclusion that the particular sample at which they are looking has not aged in a normal manner. The microstructure illustrated in Fig. 158 (p. 264) is typical of the Duralumin sheet used in the press-shop.

In the instance of Duralumin, substances represented by the following chemical formulæ, and perhaps others, occur and can be taken into solid solution by proper solution-treatment: $CuAl_2$, Mg_2Si, $Al_{13}Cu_7Mg_8$ and $AlMn_3$. Obinata and Tabata [138] have shown that the solution velocity of these various substances differs, and state that a heating period of at least twenty minutes is needed to take all of them into solution at a temperature of 500° to 510° C. Another substance, $FeAl_3$, is not taken completely into solution during normal solution-treatment, and it is this which is seen as discrete particles when solution-treated Duralumin is examined under the microscope.

Heat-treatment of Precipitation-hardening Light Alloys

It has been explained that the special value of sheet made from the alloys in this group lies in the fact that it can be softened by suitable heat-treatment, deep drawn or pressed into the desired shape and then " aged " to produce mechanical properties outstandingly better than those of pure aluminium or of the non-precipitation-hardening aluminium alloys. As these alloys will find their way into the press-shop in increasing quantities, it behoves those in charge to become thoroughly acquainted with the practical details of the necessary heat-treatment and to grasp the important fact that sheet and pressings *must* be given exactly the specified heat-treatment, and that the control of temperatures to within a few degrees is usually essential. The three stages of the heat-treatment process, namely, solution-treating, quenching and ageing will be examined separately.

Solution-treating. This operation, which implies heating sheet or pressings to a specified temperature for a suitable period, is often known industrially as " normalising." The accepted use of this term is unfortunate because, industrially, it is often used to describe other treatments—for example low-temperature stress-relieving annealing—

and, to the metallurgist, it is a term reserved to describe a certain clearly defined heat-treatment applied to steel.

The whole secret of successful solution-treating light-alloy sheet and pressings lies in ensuring that all parts of a furnace charge reach the desired temperature and are maintained at this temperature for the desired time. Under industrial conditions this seemingly simple condition is, unfortunately, not always easily fulfilled owing, mainly, to the difficulty experienced in quickly heating all parts of a charge to a uniform temperature and in judging the temperature of different parts by means of the fixed pyrometers with which furnaces or baths are usually equipped.

The temperature of solution-treating, which will vary according to the chemical composition of the alloy, is usually stated in the specifications for the various standard alloys or, in the case of proprietary alloys, in the instructions issued by the suppliers. For Duralumin, the most popular alloy, a temperature of 495° ± 5° C. is usually specified in order to cover slight inaccuracies of temperature measurement, although actually a range of 485° to 510° C. is permissible; and, assuming that the true temperature can be measured accurately, it is always preferable to approach the upper limit. This advice applies also to those alloys in which a considerably wider temperature range is specified, for example to the 490° to 530° C. range often given for some of the "double-heat-treatment" alloys, particularly when it is desired to bring the sheet into its most ductile condition. On the other hand it is most important to avoid over-heating, because this will seriously injure any of the alloys; hence, in practice, the solution-treating temperature should be partly decided by the accuracy with which the true temperature of the actual sheet or pressings can be measured.

Examination under the microscope will show whether an alloy of the precipitation-hardening type has been heated appreciably beyond the upper limit of the specified range of temperature for solution-treatment, for the microstructure will contain numerous dark spots caused by the melting of particles of a constituent believed by some workers to be an aluminium/copper-aluminide eutectic. Fig. 162 shows the appearance of Duralumin sheet which has been over-heated; but it is unsafe to attempt either to predict the true limiting temperature or to deduce the exact temperature to which a visibly overheated sample has been taken, because the temperature at which this localised melting starts depends upon the exact chemical composition of any sample within the range covered by the usual specifications. The time of soaking also has some influence from the practical aspect, and there is some doubt as to whether heating to a temperature just high enough to injure the mechanical properties of the metal can always be detected under the microscope, at least by unpractised observers. The degree of embrittlement engendered by solution-treating at too high a

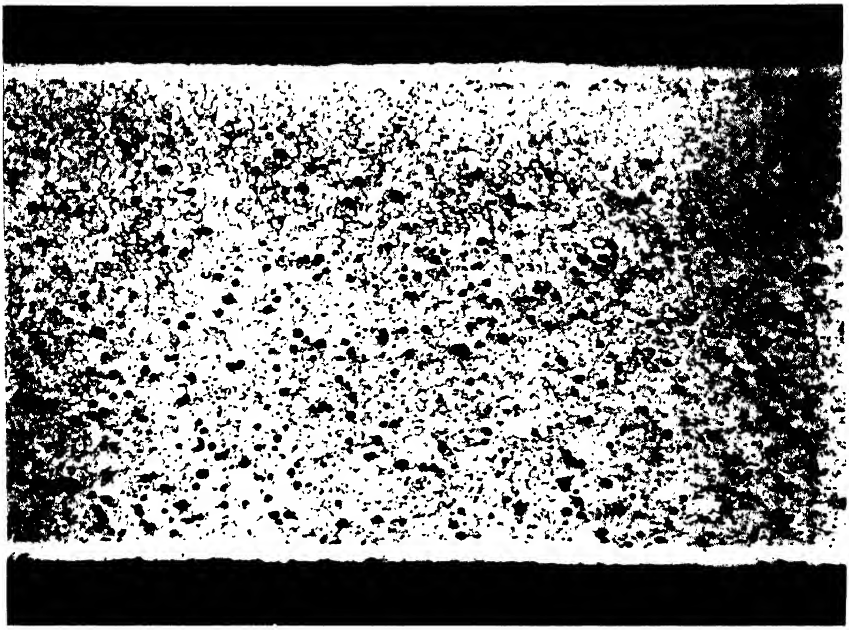


FIG. 162. Microstructure of overheated "clad" Duralumin strip illustrated in Fig. 163 showing numerous spots caused by localised fusion of one of the constituents in the alloy core.

Microsection cut normal to surface of sheet and parallel to direction of rolling. Etched, × 60

FIG. 163. Embrittlement of "clad" Duralumin strip caused by solution-treating at too high a temperature. × $\frac{1}{3}$

[*To face p.* 268.

temperature can be judged from the appearance of the piece of strip shown in Fig. 163.

Although the time of soaking at the solution-treating temperature is still a somewhat controversial subject, the following table is commonly cited as a guide to industrial practice. The times given apply to light-alloy sheet heated in salt baths ; when air furnaces are used the heating period must be increased by the time taken by the metal to reach the full solution-treating temperature, and this period will vary considerably according to the efficiency of the furnace used.

Soaking Periods for solution-treating

Gauge of sheet . .	22	18	14	10	6	3
Time of immersion (minutes) . .	10–14	13–19	16–22	22–28	28–34	30–38

It has been the experience of the author that these values ought to be regarded as minima and that, for reasons as yet unexplained, batches of sheet having abnormal properties are met with which fail under the press unless soaked for twice, and occasionally three times, the times given above. The observations of Obinata and Tabata,[138] already referred to, upon this point are interesting, and it seems likely that the soaking period is influenced by the exact chemical composition of the sheet as well as by the severity of the deformation which has to be inflicted upon it.

In view of this it is a wise precaution always to give sheet and pressings an ample soak at the solution-treating temperature. Alloys of this kind are far less susceptible to critical-strain crystal growth than pure aluminium, and experiments made by Teed [69] on Duralumin sheet show that soaking for as long as six hours caused no serious injury. As explained later, " clad " sheet does not possess this latitude.

Furnaces for " normalising " or " solution-treating " Duralumin are of two kinds, air furnaces of muffle type and salt baths. Air furnaces have the advantage that they are simpler, easier to operate and to maintain and are free from certain hazards associated with salt baths ; yet they possess the serious disadvantages that work is heated much more slowly in them than in salt baths, that it is more difficult to measure and to control the exact temperature to which work is heated, that in many instances heating tends to be irregular and that the surface of the work suffers discoloration. Each kind may be heated by either gas or electricity, but some efficient form of automatic apparatus for controlling, and preferably for recording, the temperature of the bath is essential. This comment may seem superfluous, yet the author has known instances in which the heat-treatment of Duralumin has been attempted, naturally without success, in furnaces which were quite incapable of giving the necessary degree of control of temperature or uniformity of heating.

Air Furnaces. It cannot be stated too strongly that the use of still-atmosphere furnaces for solution-treating light-alloy sheet or pressings is likely to lead to serious trouble owing to the temperature variations which invariably occur within them for some portion, and usually for the whole, of the heating of a charge. Furnaces having a "disturbed" atmosphere are somewhat better, yet it is a wise rule always to use proper forced-circulation air furnaces and, even then, to dispose the charge intelligently so that all parts can readily be reached by the circulating air, thus ensuring rapid and uniform heating. Furnaces of these two kinds are illustrated respectively in Fig. 164, p. 274, and Fig. 311, p. 679.

Salt Baths. Salt baths are deservedly popular for the solution-treating of Duralumin sheet and pressings. Although needing more attention than air furnaces, they possess the great advantage that large sheets or shaped pressings attain a reasonably uniform temperature very quickly and, what is equally important, that it is possible to measure this temperature easily and accurately. It cannot be emphasised too strongly, however, that the advantages of salt baths can be secured *only* when certain precautions are observed, and that attempts to use them without proper supervision are likely to cause continuous trouble in the press-shop and may end in disaster caused by early failure of the container or even by explosion.

Salt baths should always be of ample size for the work treated in them. When the ratio of the mass of salt to that of the work immersed in it is not adequate, the sudden introduction of the charge may lower the temperature of the bath below the minimum specified for the particular alloy being treated. Should this happen, it may not recover in a reasonably short time and the operator may not notice that the temperature has fallen below the safe minimum for some or even all of the usual heating period—one very good reason why the fitting of a recording pyrometer is a wise insurance.

It should be unnecessary to add the caution that baths must be sufficiently large to enable a part to be immersed completely; yet the author has witnessed vital parts for aircraft solution-treated in baths so small that portions projected above the surface of the salt, the operator being under the impression that subsequent immersion of the projecting portion of each part, with consequent exposure of the other end, would suffice. Clearly, manipulation of this nature cannot give satisfactory solution-treatment throughout the whole of a component. On another occasion one end of a solution-treated and aged part was immersed in a bath to facilitate certain forming operations at that end, without regard to the seemingly obvious fact that this treatment would produce a central softened zone which would not age-harden to give the desired physical properties. To many readers these stories may seem unbelievable; yet they are true and serve to illustrate the need for continuous supervision during the production of parts in heat-treatable light alloys, particularly in shops not accustomed to dealing with them.

It cannot be emphasised too strongly that a temperature indicated by a pyrometer fixed in one position in a bath ought never to be accepted as a true indication of the temperature in all parts of that bath. Tests made with the help of an exploratory pyrometer often yield surprising results and, particularly in gas-heated baths, enable adjustments to be made which will produce a reasonable degree of uniformity and will enable the average temperature of the bath to be judged more accurately from the reading of the fixed pyrometer. The provision of several fixed pyrometers is, obviously, advantageous in baths of large, and even medium, size, and their position in the bath should be chosen with care. The stems should be kept well away from the sides of the container and should be immersed to a reasonable depth below the surface of the salt. The favourite position of a corner of the bath where they are " out of the way " should never be tolerated, neither should one immediately opposite a hot zone caused by the impingement of gas flames on the outside of the container, unless it is placed there expressly to indicate the temperature in this position and not that of the bath as a whole.

An essential precaution is the frequent checking of pyrometers, for an alteration of only 5° C. may cause serious trouble which, as explained already, is often attributed incorrectly to a faulty batch of metal. A weekly check should be regarded as the minimum desirable for baths in continuance operation, and more frequent examination is preferable.

It is important that work should be both dry and free from grease before it is immersed in the salt. The presence of moisture may cause a minor explosion which, although seldom serious, may injure operators by flying salt. Grease tends to run into pockets which, owing to an exothermic reaction, may cause local overheating—and even melting—of the work. The continual introduction of grease into a bath will, moreover, convert the nitrates into the corresponding hydrates and carbonates, leading to corrosion of the work immersed in it and in time to a general upset. To avoid these undesirable happenings, work should always be degreased, and preferably warmed, prior to being placed in a salt bath.

The method used to suspend work in the bath is important. Sheets are often supported vertically in metal racks, but unless care is taken to prevent them touching one another the areas which are in contact are likely to split when the sheets are transferred to the press. For this reason sheets should never be placed one on top of another in a horizontal plane. The formation of these areas of low ductility is often attributed to delayed heating of the contact areas to the solution-treating temperature; yet, having regard to the excellent heat conductivity of aluminium alloys, it seems possible that, unless air is trapped, other factors not yet understood exert an influence. When bubbles rise intermittently to the surface of the bath for some time after work has been immersed it is a sure sign that air has been trapped, and the pieces should be agitated and an extra soaking time given.

Pressings and small sheets are best suspended by wires in order to avoid areas of contact with frames of perforated baskets. When small holes to take wires cannot be drilled without spoiling an article, it should be suspended in a cradle fabricated from thin Duralumin strip. The seemingly harmless practice of binding suspension wires round pressings, and even sheets, should be avoided because experience shows that cracks are likely to occur where the wire has made contact, a curious fact which may perhaps be explained by electrical effects. The uppermost parts of sheets or pressings should be at least 6 inches below the surface of the salt, and it is hardly necessary to add that pressings should not touch one another and should also be kept well away from the sides of the container, particularly when this is heated externally. When steel frames or wire baskets are used these should be of light construction so as to lower the temperature of the bath as little as possible.

Baths should be cleaned at regular intervals, preferably once a week, to remove sludge, scale, swarf and dropped parts. If an accumulation is allowed to form, the bath will deteriorate and there is a danger that an explosion may occur owing to a thermit action caused by Duralumin, present as either pressings or swarf, and scale in the presence of hot nitrates.

The medium used in baths of the kind under discussion consists essentially of either sodium nitrate or a mixture of this salt with potassium nitrate, but additions of small proportions of various acid salts—*e.g.*, sodium bicarbonate, or certain ammonium salts—to neutralise any alkaline substances which may be formed during the working of the bath are the subject of various patents. The modern tendency is to use straight sodium nitrate, but in the past a mixture was often used in order to secure the advantage of a lower melting point with consequent reduced strain on the steel container caused by thermal expansion when a cold, solidified bath was heated up. The approximate melting points of the substances mentioned are: potassium nitrate, 340° C.; sodium nitrate, 310° C.; eutectic mixture, containing 54 per cent. of potassium nitrate and 46 per cent. of sodium nitrate, 220° C. Additions of sodium nitrite, which are sometimes made to retard gradual decomposition of the nitrates, lower the melting point of the bath slightly. Pure salts should be used because the presence of small quantities of chlorides accelerates the rate of attack on the steel container.

Nitrate baths deteriorate gradually owing to decomposition into nitrites, oxygen and nitrogen. This deterioration is very slow at 500° C., but it is much faster at 550° C. and is accelerated by the presence of oil, grease, carbon and other contaminatory substances; hence the importance, stressed elsewhere, of avoiding localised overheating and of thoroughly cleaning all work prior to immersion. It is the practice in some works to determine the nitrite content of baths at regular intervals of a few weeks. The proportion of nitrite is not in itself of special importance, but the rate of increase forms a useful check on whether operating conditions are satisfactory. A sudden rise indicates that dirty work is being immersed or that local overheating, probably caused by incorrect burner adjustment if the bath be gas-heated, is occurring. This enables the fault to be remedied before serious damage is done.

In the past one of the disadvantages of salt baths has been rapid perforation of the steel container. The exact cause of this trouble is not known, and its elucidation is not helped by the conflicting evidence of experiments made under supposedly controlled conditions nor by the considerable variation found in the life of containers used under industrial conditions. Some facts have, however, been established. It is known that the chemical composition of the steel used for the container has some bearing on its life and that, other conditions being equal, Armco iron of very low carbon content gives a longer life than mild steel of ordinary commercial quality. The method of heating is also of importance, an influence proved by the long life of containers heated internally by electrical immersion heaters and by the short life of gas-heated containers when an unsatisfactory arrangement of the burners gives localised "hot spots."

It is quite clear, however, that other factors have to be considered, and it is known that the presence of as little as 0·2 per cent. of chlorides in the salt increases the rate of attack on the steel container. It is likely that electrical effects, to which little attention seems to have been given, may be found to be an important factor. A potential difference of several volts can sometimes be measured between a container and Duralumin articles immersed in it, and a fruitful field for investigation lies open in this direction.

A troublesome, though somewhat less costly, form of attack is that on steel baskets. These are often made from wire mesh or "expanded metal" welded to an angle-iron frame, and it is common for parts of the frame to be attacked rapidly leaving the wire mesh intact. Here again electrical effects may explain the curious happenings which are often encountered.

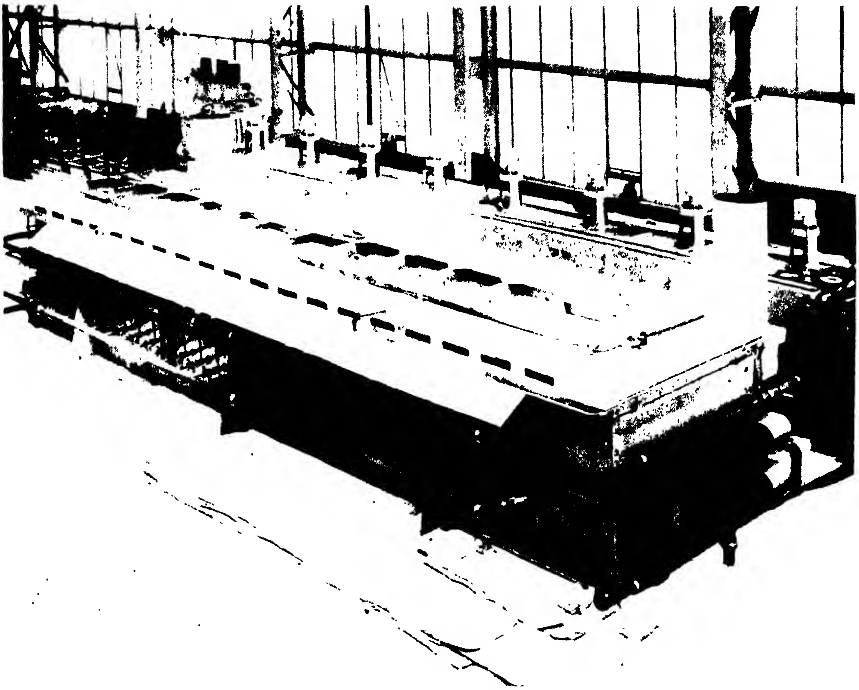
It has already been said that containers made of Armco iron have a longer life than ones made of ordinary mild steel, and experiments have shown that containers made of alloy steel, particularly ones having a high chromium content and free from nickel, resist attack even better, although in some instances brittleness has developed. Mild steel containers lined with nickel have also been tried; and only experience can decide whether the increased cost of large alloy-steel or composite containers is justified by the increase in useful life. More careful control over operating conditions, better design of gas-heated baths and, in particular, the adoption of internal electrical heaters may well lead to the continued use of plain steels of very low carbon content.

Salt baths are usually installed with at least a low brick wall built round them to prevent the spreading of molten salt should the container suddenly fail, and it is wise to make an adjacent catch-pit into which the salt can run. Syphon apparatus is available by means of which containers can quickly be emptied, and a multi-bath installation can be arranged so that one catch-pit and one syphon serves several baths.

With externally-heated salt baths it is most important that the heat be applied in as gentle and in as diffused a manner as possible in order to avoid " hot spots " which will cause premature failure of the container, rapid deterioration of the bath and, in extreme instances, explosions. Gas-heated baths usually have burners arranged to heat the sides of the container only, and adequate arrangements to prevent direct impingement of the flames on to the container are very desirable. Large containers need at least two rows of burners, one above the other, to enable a uniform temperature to be maintained without producing undesirably hot zones. Such an arrangement can be seen on the bath illustrated in Fig. 164, which also shows a useful pyrometric installation comprising six fixed thermocouples and one exploratory thermocouple. The flues of gas-heated baths must be cleaned regularly because, should soot be allowed to accumulate, there is a danger that it may react with explosive violence with any nitrate which finds its way—as it often does in spite of all precautions—into the flues.

Behind the salt bath illustrated in Fig. 164 there can be seen a typical electrically-heated air furnace having eight fans mounted on its roof to circulate the air within the closed chamber containing the heating elements and the charge. Furnaces of this kind are often used for ageing light alloys of the " double-heat-treatment " kind and, sometimes, for solution-treatment.

Although their first cost is considerably greater, salt baths heated by electrical immersion heaters possess certain advantages over externally gas-heated baths, among the most important being a longer life from containers owing to the absence of hot spots, more uniform heating of the bath and a higher output from a bath of given size.



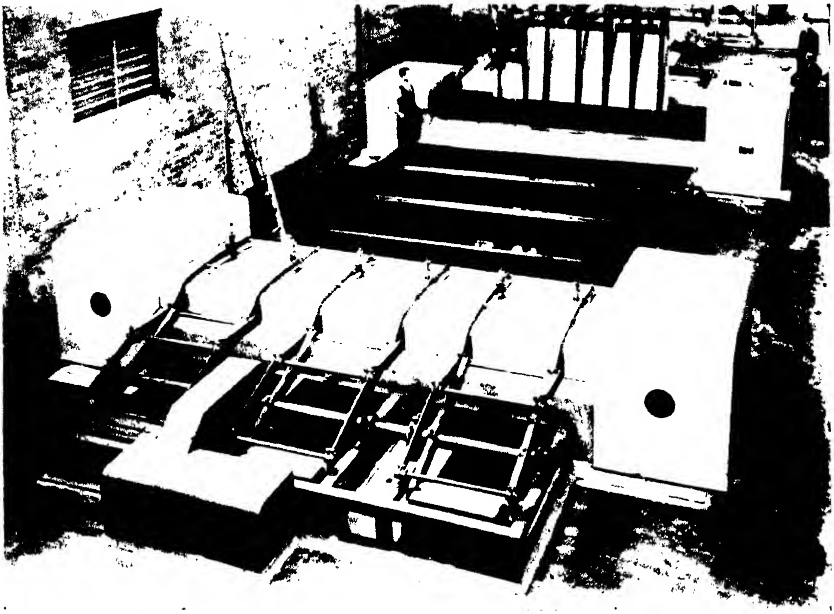
[*By courtesy of the Incandescent Heat Co. Ltd. and Birmingham Electric Furnaces Ltd.*

FIG. 164. Plant for heat-treating light-alloy sheet or products.

In front : Gas-heated salt bath. Observe double rows of burners, also six fixed, and one exploratory, thermocouple.

Behind : Electrically-heated air furnace with disturbed atmosphere induced by eight fans mounted on roof.

[*To face p.* 274.



[*By courtesy of Birmingham Electric Furnaces Ltd.*

FIG. 165. Plant comprising two salt baths heated by L-shaped electric immersion heaters with quenching and swill tanks and mechanically-operated cradles for solution-treating light-alloy sheet.

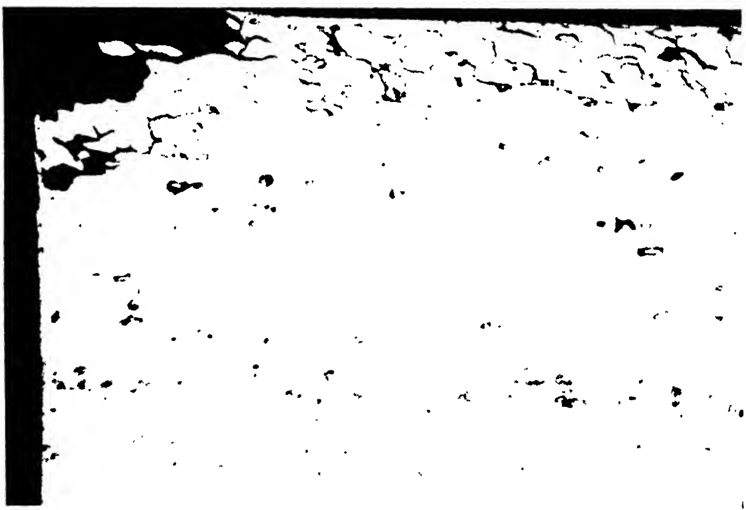


FIG. 166. Intercrystalline attack produced by action of salt solution on surface of Duralumin sheet which has had its corrosion-resistance impaired by somewhat slow cooling after solution-treating.

Microsection cut normal to surface of sheet, unetched, × 100.

[*To face p.* 275.

In the baths shown in Fig. 165 heat is supplied by a number of L-shaped immersion heaters which pass down the end face of the container and extend along the bottom of the bath under a protective grill. Any one of these heaters can be removed and replaced without having to shut down the bath.

A caution must be added regarding the starting up of a solidified bath from cold, because careless operation may strain the container to the point of cracking, and may cause minor explosions owing to the formation of trapped pockets of molten salt. It is a process which must never be hurried, and it is often advisable to cut out large cavities in the solid salt with pneumatic chisels so as to induce movement in the salt rather than to inflict severe thermal stresses on the container. When baths are not in use at night it is better to keep them molten than to allow them to solidify, because in this way repeated stressing of the container is avoided and a bath having a uniform temperature is available first thing in the morning. The cost of keeping baths hot overnight is not an important item because a considerable amount of heat is needed to raise the temperature of a cool bath to working temperature.

Lastly it may be wise to draw attention to the fact that light alloys containing a high percentage of magnesium should *never* be immersed in nitrate salt baths, because the resulting reaction may proceed with explosive violence.

Considered together the numerous cautions just given may convey the impression that salt baths are difficult and even dangerous to operate. In reality, this is not so when intelligent supervision is arranged, and the same may be said of many other forms of modern plant; yet the caution must be repeated that absence of proper supervision will certainly lead to the failure of sheet and pressings under the press and may cause still more serious happenings. Used intelligently, and with frequent checking of pyrometers, salt baths offer the best means yet available for heating Duralumin and light alloys of similar nature quickly and uniformly to the solution-treating temperature.

QUENCHING. In order that the full mechanical properties may be developed by solution-treatment and ageing, it is necessary that sheet or pressings be cooled from the solution-treating temperature fairly rapidly by quenching in water or oil or, in the case of very thin sheet, by cooling in air, and it is natural that the less rapid the quench the less will be the distortion of the quenched sheets or pressings. Unfortunately when the rate of cooling—although still sufficiently rapid to enable the desired mechanical properties to be attained after ageing—is relatively slow, alloys of Duralumin type become susceptible to a peculiar form of intercrystalline corrosion attack under conditions of use or storage which would not be harmful had the rate of cooling been more rapid. For this reason air-cooling can seldom be tolerated even for thin sheet.

It is possible to ascertain whether or not a sample of quenched Duralumin is liable to this form of attack by immersing a small piece for twenty-four hours in the following aqueous solution maintained at 20° C. :—

Common salt	58·45 gm. per litre
Concentrated hydrochloric acid .	27·50 ,, ,,

If after this period of immersion a section is cut and prepared in the usual way for metallographic examination, intercrystalline attack will be seen should the sample be susceptible. The result of too slow cooling, revealed by the method just described, is shown in Fig. 166.

Although it reduces distortion, oil quenching is seldom used for work which has been solution-treated in salt baths because of the danger of fire, and perhaps explosion, caused by the action of the oil on the adhering film of hot nitrate. Water is the preferred medium ; but the temperature of the bath should not be allowed to rise above 50° C. and, for reasons which will now be clear, it is important that the methods of manipulation and the position of the quenching bath allow work to be transferred to it from the solution-treating salt bath or furnace as quickly as possible. Unfortunately, some pressings form natural containers and make it difficult to avoid a serious " drag out " of salt which will rapidly contaminate the quenching bath, yet the temptation to pause for any appreciable interval with work suspended over the salt bath to allow it to drain before it is transferred to the quenching bath must be resisted. Owing to the relatively low temperature employed there is no visible colour change, as with steel, to indicate the fall in temperature of work during its transference from furnace to quenching bath.

In order to avoid subsequent corrosion, work should always be given one swill, and preferably two swills, after removal from the quenching tank, and the final swill should not be allowed to become contaminated with salt.

A certain amount of local staining or discoloration is sometimes apparent on the surface of sheet and pressings of Duralumin and similar alloys. At one time it was thought that this was caused by the action of the salt bath, and it was found that the addition of about 3 to 5 per cent. of potassium chromate to the bath minimised, but did not always prevent, discoloration. It is now known that this defect is caused largely by the action of the quenching water, and that it is particularly likely to happen when the heating bath is slightly alkaline and also when such alkalinity has been corrected by the addition of salts having an acid reaction, for example a dichromate. In the opinion of some workers the tendency of the quenching water to produce discoloration is directly proportional to its degree of alkalinity, and a patent [1] has been granted for the maintenance of a *p*H value below 7 by periodic additions of acids to the quenching bath. This patent provides that the acids used shall be of such a nature and in such a proportion that the salts formed in the quenching bath are of the same kind and in the same proportion as those transferred to the quenching bath on work from the salt bath, an example being nitric acid and chromic anhydride. In this way it is possible to recover the salts from the quenching tank by evaporation and to return them to the salt bath.

The principal difficulty encountered in the quenching of the precipitation-hardening light alloys, whether in the form of sheet or pressings, is distortion. This distortion is no mystery : it is attributable entirely to thermal stresses set up when different parts of a sheet are subjected to sudden changes in temperature, and its magnitude—although unhappily not always its distribution—can be calculated mathematically. Some idea of the dimensional changes which take place can be gained from the fact that a sheet 15 feet long, which is by no means small for an aircraft wing-pressing, may contract more than 2 inches on being quenched and that the region of the temperature gradient may be only a few inches wide. The ingenuity of overseers and the skill of operators in sliding sheets beneath the surface of the quenching bath at the best angle (which must be studied from a three-dimensional aspect) can do a lot to minimise distortion. Opinion is divided as to whether it is better to leave sheets or strips entirely free or to restrict their movement by means of jigs. Much depends upon the size and shape of the sheet or article and upon the skill and experience of the operators available for unrestrained quenching; but rigid restriction, as distinct from partial restraint, is seldom successful. Sheets which have not been degreased often buckle when being slid into the salt bath itself, hence another reason for the routine degreasing advocated earlier.

It will be obvious that if the whole area of a sheet could be cooled at a uniform rate no distortion would occur. This is impossible when a quenching bath is used, but experiments show that a reasonably uniform rate of cooling is given by "spray-quenching." In this method the hot sheet is placed end-on in a stream of "mist" formed by blowing cold air over suitable water-atomising jets which, although they may be situated in the cooling chamber, do not play directly on to the hot metal. In this way, clean, 16-gauge sheet can be cooled in from two to three minutes, which is sufficiently fast to produce the desired condition; but, as adhering salt hinders cooling and gives erratic results, the method is restricted to sheet heated in air furnaces.

Were it not for the fact that in some instances it may render alloys

[1] British Patent No. 533151 (1939).

of Duralumin type susceptible to the form of intercrystalline corrosion already described, spray-quenching would certainly have a great industrial future.

AGEING. After having been solution-treated, quenched, and subjected to the desired mechanical shaping processes, pressings have to be aged in order to develop the mechnical properties which are the essential feature of the precipitation-hardening type of light alloy.

As explained already the "single-heat-treatment" group of alloys age naturally when allowed to stand at room temperature for a period of about five days, and it is usual to make acceptance tests at the end of five and sometimes at the end of four days' ageing at room temperature. The ageing process is not entirely completed in this time, yet subsequent changes in tensile properties are too small to be of much practical significance. Hardness values, on the other hand, continue to increase very slowly for a long time.

The temperature at which ageing is carried out has a profound influence upon the rate at which this process proceeds and, though in rather less degree, upon the mechanical properties developed. Considering first the range covered by the rather vague term "room" temperature, in cold weather the rate of ageing may be so retarded that the usual five-day period may need to be extended before acceptance tests are made. Conversely in a very hot room the rate of ageing will be accelerated, but it should be observed that at ageing temperatures of 40° C. and over the corrosion resistance of the alloy tends to be affected adversely.

The lower end of the scale is of very great importance from the aspect of the press-shop because, by keeping quenched sheet or pressings at a low temperature, it is possible to lengthen the "period of grace" between quenching and the time when a noticeable fall in ductility begins. When sheet or pressings are held at room temperature, meaning in this instance in the region of 15° to 20° C., it is safest to carry out severe deep drawing or pressing operations within half an hour of quenching, although for less severe operations a lapse of an hour or more can sometimes be allowed. If the temperature of storage be reduced to 0° C., severe operations can be performed for quite twenty-four hours, and less severe operations for forty-eight hours, after quenching; and a decrease to − 17° C. enables full ductility to be preserved for several weeks The curves shown in Fig. 167 can be taken as being fairly typical for Duralumin of normal chemical composition aged at the temperatures stated.

In many press-shops the solution-treating plant forms a "bottle neck" to the uninterrupted flow of quenched blanks or partly-formed pressings to the presses, so that quite often it is most useful to be able to build up a stock from which small numbers can be drawn at intervals of, say, a quarter of an hour. This can readily be done by using the "cold chambers" which are marketed in various sizes and types to suit all needs. Proper refrigerator installations equipped with automatic temperature control are best when the size or number of sheets or pressings is large, yet for a limited number of small sheets or parts the double-walled cold-storage box is a popular, less-expensive, and entirely satisfactory alternative. These boxes, which were first used for storing Duralumin rivets, are generally designed to work with solid carbon dioxide, which melts at − 79° C., as the cooling agent. Quite often they form a valuable adjunct to a proper refrigerator because they can be located close to presses and can even be put on wheels so that they can be moved about and used to convey small stocks of sheets or pressings from a large central refrigerator to various press-shops.

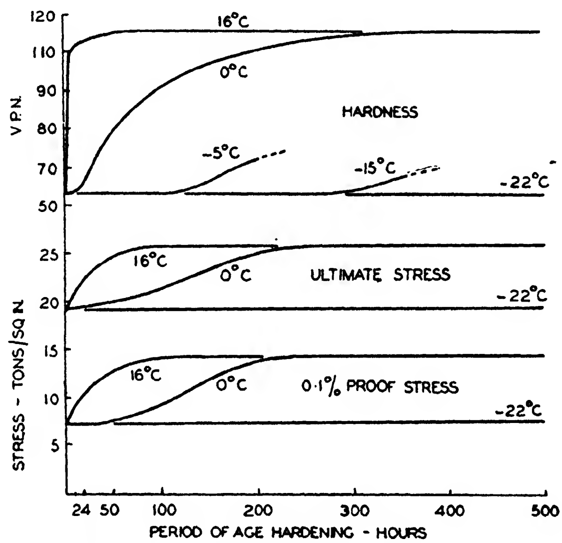


FIG. 167. Curves illustrating the hardness, 0·1 per cent. proof stress and ultimate tensile strength of typical Duralumin sheet solution-treated at 490° C. ± 5° C. for thirty minutes, quenched in water, and aged at temperatures of 16° C., 0° C., −5°, −15° and −22° C.

During the laboratory investigation of a number of age-hardening light alloys it has been observed by many investigators that the gradual hardening which occurs naturally, or which can be induced, after solution-treatment is often preceded by a distinct *fall* in hardness, a change not shown on the curves in Fig. 167 because the time scale is not sufficiently open. This phenomenon can be taken advantage of in the press-shop to impose greater amounts of plastic deformation on solution-treated sheet than would otherwise be possible: it can, for example, be induced in alloys of Duralumin type by heating solution-treated sheet to between 100° and 200° C. for from half to one hour immediately prior to pressing. The effect of this short ageing treatment is a marked fall in hardness, tensile strength and limit of proportionality and a corresponding increase in percentage elongation; yet this preliminary treatment in no way affects the values which the physical properties of the sheet attain after final ageing in the normal way.

At the other end of the scale, the effect of ageing alloys of Duralumin type at temperatures appreciably above room temperature is rather complicated and indeed not yet elucidated fully. The principal effect of raising the ageing temperature to 150° C. is greatly to accelerate the rate of ageing, to decrease corrosion-resistance, to increase the proof stress—often markedly, to alter the ultimate strength only slightly and to decrease the percentage elongation ; but in many alloys ageing has to be stopped after a certain period or the proof stress and ultimate strength decrease after reaching a maximum. As the position of this peak in relation to ageing time seems to be somewhat erratic, it is a practice which is not to be recommended for industrial use until more knowledge is available.

The " double-heat-treatment " group of alloys age very slowly at room temperature, a property which is often utilised by users to purchase sheet in the solution-treated condition thus leaving only the second, or ageing, treatment to be done after the sheet has been shaped under the press. The best ageing temperature varies according to the exact chemical composition of the alloy, but a typical treatment is to heat for twenty hours at 160° C. This secondary or ageing treatment is generally given in air furnaces heated by either electricity or gas, and it is most important that these should be designed so that all parts of a charge reach the proper ageing temperature.

ANNEALING. Useful though the results given by solution-treating the precipitation-hardening light-alloys are, still better deep drawing and pressing properties can usually be obtained when sheet is annealed. On routine production work it is sometimes preferable to have sheet delivered, preferably in cold storage, in the annealed condition, to deep draw and press it, and then to solution-treat and age the shaped article in order to obtain the desired mechanical properties.

It is said sometimes that annealed sheet does not age. This is incorrect; for, although ageing takes place far more slowly and not to the same extent as with solution-treated sheet, the ductility of annealed sheet does fall with time, particularly when it is allowed to cool in air instead of being quenched after annealing. For most press operations, annealed and quenched sheet can be kept for a period of two months at room temperature, and almost indefinitely at 0° C., before being used ; whereas a lower temperature is needed to preserve the full ductility of solution-treated sheet for the same period.

Consumers who wish to anneal Duralumin themselves are advised to use a temperature of between 330° C. and 350° C. A soaking period of thirty minutes is adequate, although a considerably longer period does not produce an undesirable increase in crystal size. With sheet of the thickness used in the press-shop, it makes little difference to the *immediate* mechanical properties whether sheet is allowed to cool in air or quenched after annealing ; but slow cooling in the muffle confers distinctly better ductility than either of these methods. If a salt bath is used, water-quenching has the advantage that it removes the adhering salt.

The superior ductility of annealed, as contrasted with solution-treated, Duralumin sheet deserves wider recognition in the press-shop. To enable comparison to be made, typical values for some mechanical properties of annealed, solution-treated and aged Duralumin sheet are set out in Table II. Particular attention is directed to the value for

TABLE II

Influence of Various Heat-treatments upon the Mechanical Properties of Duralumin Sheet

	Annealed at 390° C. for thirty minutes and cooled in air or quenched in water.	Annealed at 390° C. for thirty minutes and cooled in muffle.	Solution-treated at 490° C. and quenched in water.	Solution-treated at 490° C., quenched in water and aged for four days at room temperature.
0·1 per cent. proof stress .	6	5	8	16 tons/sq. in.
Ultimate stress . . .	17	14	20	27 tons/sq. in.
Elongation on 2 inches . .	18	25	22	24 per cent.
Vickers hardness . . .	65	55	75	115 V.P.N.

percentage elongation of the annealed and muffle-cooled sheet. It must not be forgotten that, owing to the intercrystalline attack described earlier in this section (p. 276), the corrosion resisting properties of annealed Duralumin sheet are much inferior to those of solution-treated and quenched sheet. Yet, as in the majority of instances pressings will be solution-treated and quenched after they have been shaped, this disadvantage should seldom prevent the use of annealed sheet in the press-shop when desired.

HEAT-TREATMENT OF "CLAD" DURALUMIN. The statements made regarding the relative insensitivity of Duralumin to conditions of heating do *not* apply to "clad" sheet, that is to Duralumin sheet having a thin coating of pure aluminium.

It is advisable to heat clad Duralumin sheet or pressings as quickly as possible and to soak for no longer than is necessary. If this precaution is not observed, the coating of pure aluminium may develop an undesirably large crystal size which will give a very rough surface after deep drawing or pressing, and may even open up into cracks. In the opinion of some authorities it is more important to heat rapidly through the range 200 to 350° C. than to limit the time of soaking; but this probably depends upon whether the sheet has been cold-worked within the range of "critical strain," that is from 5 to 20 per cent. extension. It is, therefore, preferable to heat clad sheet in salt baths rather than in air furnaces, because salt baths give more rapid heating.

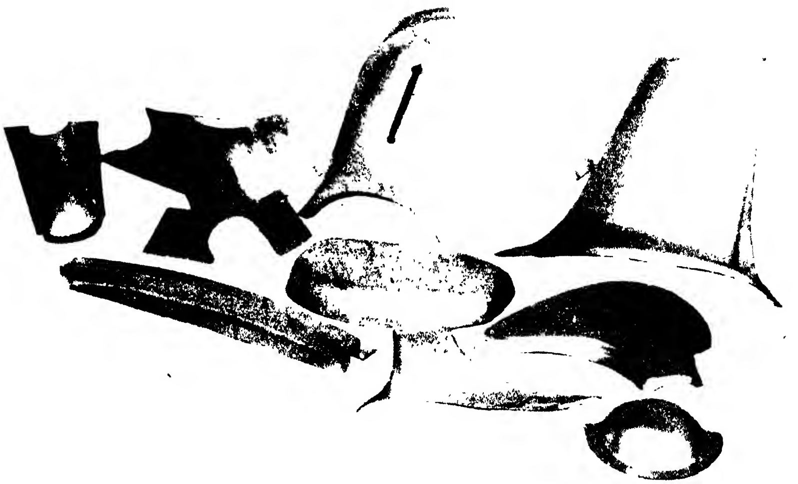
Reviewing what has been said, it will be evident that pure aluminium possesses extremely good deep drawing and pressing properties; but that because, as a rule, rather specialised technique is needed to take full advantage of these, users accustomed to brass and steel often experience considerable difficulty until they modify their procedures. The deep drawing and pressing of light-alloy sheet is more difficult, and much knowledge needs to be obtained concerning this comparative newcomer to the press-shop before it can be claimed that a satisfactory technique capable of general application has been established.

Magnesium Alloys

Magnesium alloy sheet, the latest arrival to the press-shop, has poor deep drawing and pressing properties judged by ordinary standards. For this reason its introduction into the average shop has sometimes been even less popular than was that of Duralumin a few years earlier; yet, because the demand for pressings in this ultra-light metal will certainly increase, it behoves those who have to deal with it to familiarise themselves both with its limitations and with the special technique which must be adopted if success is to be achieved in even simple press operations.

The outstanding feature of magnesium alloys is, of course, their very low specific gravity of only 1·8, that of aluminium being 2·8. This extreme lightness makes them of unique value in aircraft construction and, indeed, in any application in which lightness is important. The popular alloys of magnesium are covered by patents and are marketed under the trade name of "Elektron," with various alphabetical and numerical notations to distinguish different alloys.

Until recently the best available alloy for sheet to be shaped by deep drawing and pressing was one containing from 1½ to 2½ per cent. of manganese, the primary function of this element being to improve resistance to corrosion. It is established that the addition of 0·5 per cent. of cerium to this alloy improves its ductility, although the sheet needs more carefully controlled rolling, and it is likely that alloys having still better deep drawing and pressing properties will be developed. Neither of these alloys responds to solution-treating and ageing as do the ones containing from 6 to 10 per cent. of aluminium which are used for castings and forgings. Alloys containing 6 per cent. of aluminium, often with a little zinc, are sometimes used in sheet form, but their deep drawing and pressing properties are not equal to those of the manganese alloys just mentioned. The chemical composition and mechanical properties of these three alloys are set out in the



[*By courtesy of F. A. Hughes & Co. Ltd.*

FIG. 168. Group of pressings in magnesium-alloy (Elektron) sheet.

[*To face p.* 282.

following table, and Fig. 168 shows a group of small parts shaped under the press in tools of normal design.

"Elektron" grade.	Chemical composition.	0·2 per cent. proof stress: tons/sq. in.	Ultimate strength: tons/sq. in.	Elongation: per cent. on ·2 inches.	Erichsen value: mm.
AM 503	Mn 2%	5–7·5	13·5–15	8–16	2–3
AM 537	Mn 2%, Ce 0·5%	12–13·5	16–17	18–24	4–4·5
AZM	Al 6%, Zn 1%	11·5–13·5	18·5–21	16–20	2–2·5

The values given apply to soft sheet at room temperature, not at the elevated temperature at which, as explained later, magnesium alloy sheet has to be deep drawn and pressed. Erichsen values *decrease* as the thickness of the sheet increases—a most unusual feature—and, as with many other varieties of light-alloy sheet, tend to be very erratic and hence of relatively little significance industrially.

A peculiarity of magnesium sheet is that the highest mechanical properties are found in a direction at right angles to that of rolling and not, as is usual, in one parallel to it. This peculiarity, also found in zinc, is presumed to be related to the fact that these elements crystallise on an hexagonal lattice instead of on the more common cubic lattice.

Brief comment upon the fire hazard and the corrosion resistance of magnesium alloys is offered because during the industrial introduction of these alloys over-emphasis of these two dangers has led to much needless apprehension. Solid magnesium, as distinct from powder or fine swarf, does not catch fire readily even in contact with an open flame, and in the press-shop the risk of fire can be ignored. The caution may, however, be repeated that magnesium alloys will cause an explosion if placed in nitrate salt baths of the kind used for solution-treating Duralumin.

The resistance of magnesium alloys to corrosion is not so poor as is often thought. Press-shop products are usually given a protective coat by one of the various chromating treatments devised for this purpose, but it must be understood that this coat is not to be compared with the hard, impervious film produced on aluminium alloys by anodic treatment. Although often it suffices for articles destined for indoor service, for exposure out of doors it must be supplemented by a coat of ordinary paint, and for marine exposure or other special conditions by a coat of special paint.

Technique. It is useless to attempt to deep-draw magnesium-alloy sheet by ordinary methods. The most important feature is that both sheet and partly-formed shapes must be worked hot, and in most instances it is advisable to blank hot in order to prevent flaking and cracking at the sheared edge, particularly when the thickness of the sheet is greater than 0·060 inch.

It is necessary to heat the tools and, sometimes, the blanks or partly-formed pressings placed in them. Tools are often heated by surrounding gas flames issuing from small holes in suitably shaped pipes, although small electrical resistance heaters let into holes drilled in the tools sometimes enable the temperature to be controlled more accurately. Owing to the high thermal conductivity of magnesium, thin sheet is often heated by the tools so rapidly that prior heating is unnecessary, but thick sheet is best heated before the press operation in ovens placed at the side of the press. In the production of some shapes it is better to heat the die, and perhaps the blanks, yet to keep the punch relatively cool by means of an air blast, thus chilling the metal as it comes into contact with the punch and increasing its strength so that it is better able to draw the hot, weaker portions of the blank through the die without danger of excessive stretch or rupture of the area in contact with the lower part of the punch. It is difficult to give more precise instruction because the requirements of every article are different, but the principle should be kept continually in mind that, although heat at the drawing radius of the die is essential, its rapid dissipation after this zone has been passed is often desirable in order to stiffen up the metal and enable it to transmit stress to parts of the blank which have not yet passed the die radius.

Every effort should be made to allow the metal to flow with as little hindrance as possible. Pressure-plate loading should be kept to a minimum and the radius of the die should be as large as possible. The radius on the punch, although less important, should also be fairly generous in order to avoid shearing the bottom out of a pressing, and a radius of six to eight times the thickness of the sheet should be regarded as the safe minimum. When square-shaped shells have to be made, designers should be persuaded to allow as large a radius as possible at the corners joining the flat sides.

It must not be forgotten that the raised temperature at which press operations are carried out will cause thermal expansion of both tools and pressings which will have to be allowed for. When dimensional accuracy of deep drawn or pressed articles is important it is often necessary to give hot-formed articles a final cold-sizing operation by the usual methods in a press or stamp.

Opinions differ as to the best temperature at which to deep draw and press magnesium alloy sheet of the kind under consideration, although it is agreed that 400° C. is the safe maximum because at about 425° C. " hot shortness " is often evident. This difference of opinion is perhaps explained by the difficulty of measuring accurately the temperature of the surfaces of the tools used and of estimating the temperature at which the metal is actually deformed, and also by the fact that a relatively low temperature may suffice for shallow pressing operations and that the thickness of the sheet, the mass of the tools and the speed of drawing each play a part in determining the best temperature at which to work. For genuine deep drawing operations a temperature of from 280° to 330° C. is probably the best, although lower temperatures may be used for relatively light shaping operations. The use of special tool materials often limits working temperatures; magnesium alloy tools should not be heated to more than 200° C., and when rubber tools are used a considerably lower temperature must be regarded as the maximum unless, as is done sometimes, a thin flexible sheet of asbestos is interposed between the tool and the hot metal.

Even greater diversity of opinion exists regarding speed of drawing. Some users maintain that a speed as low as $\frac{1}{8}$ inch per second is desirable, and it must be admitted that with a given set of tools a very slow speed does sometimes enable shapes to be deep drawn when higher speeds prove unsuccessful. On the other hand, equally good results are being achieved with speeds in the region of 3 feet per second, and it seems that a number of factors, such as heat-transference and the severity of the impact of the punch on the metal, have to be considered. This last item is of particular importance with magnesium alloys, for they behave best when the impact is relatively light and the speed of drawing remains constant during the stroke of the press, conditions which are best fulfilled by the use of fluid-actuated as distinct from crank-actuated presses.

A feature of the hot-shaping procedure used with magnesium-alloy sheet is that a surprising depth of draw can be accomplished at one operation. For example, a plain cylindrical cup having a depth one and a half times the diameter can readily be drawn at one stroke of the press. To those accustomed to the more common metals the absence of "spring back" is a noticeable feature.

Difficulty is sometimes experienced through the sheet "loading" the drawing tools. This can be minimised by careful attention to lubrication, particularly by the use of a lubricant containing graphite, by giving the drawing radius a good polish and by polishing away any signs of "loading" immediately these become apparent.

Tools. It happens that at present the use of deep drawn and pressed parts made from magnesium-alloy sheet is confined very largely to the aircraft industry. This means that the number of pressings made from a set of tools is small and, for this reason, dies are often made of mild steel plate, polished, but not hardened. When large numbers of any article have to be made, ordinary carbon tool-steel, hardened, and tempered at a rather higher temperature than usual, will give excellent service. The tendency, already mentioned, to "foul" during genuine deep-drawing operations can be lessened by the use of nitrided steel dies, which lose little of their original hardness when used at temperatures up to 350° C.

Punches may be made of steel or alloys of zinc, of aluminium or even of magnesium ; but magnesium alloys should not be heated above 200° C. during operation in the press. Rubber, which at first sight would seem to be admirably suited for use with magnesium alloy sheet, is in fact not so because its presence seriously limits the temperature at which the shaping operations can be carried out.

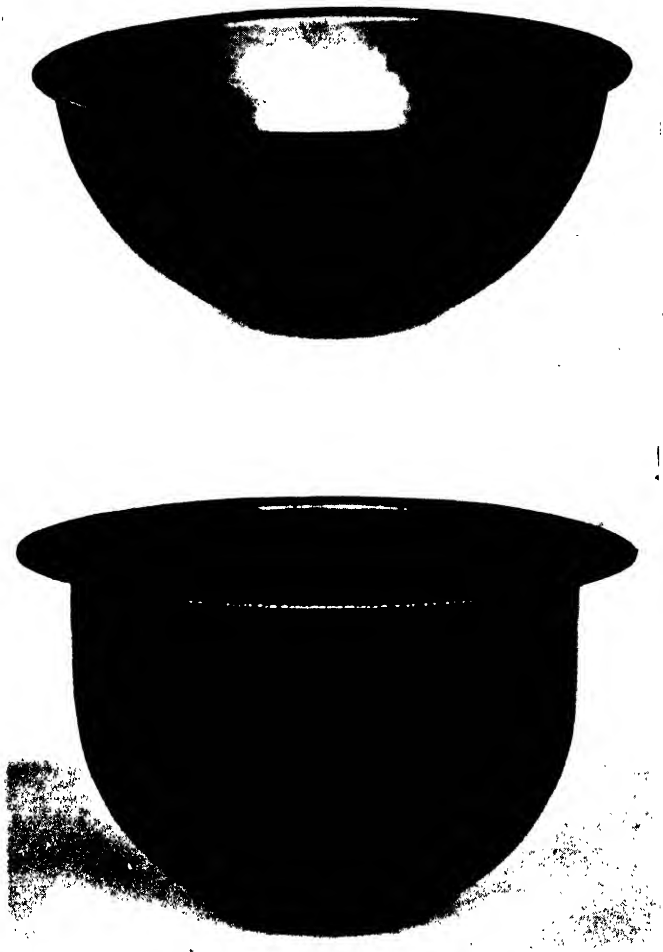
Lubricants. Information concerning lubricants for use with magnesium-alloy sheet is particularly scanty. Either vaseline or lard oil is generally used, although graphited tallow is favoured by some users who remove it immediately after the press operation by means of a hot aqueous solution containing 10 to 20 per cent. of chromic acid.

Methods of Heating. The easiest way to heat magnesium-alloy sheet to the desired working temperature is in an air furnace, but it is desirable that this should have an efficient form of forced circulation in order to ensure that all parts of a charge, and even of a single blank or pressing, reach a uniform temperature.

The caution has already been given that if magnesium is placed in the nitrate salt baths used for solution-treating Duralumin an action will take place which may proceed with explosive violence. When for some reason a salt bath is preferred for solution-treating those alloys which are amenable to this process, a mixture of 75 per cent. sodium dichromate $Na_2Cr_2O_7.2H_2O$ and 25 per cent. potassium dichromate $K_2Cr_2O_7$, which melts at 266° C., is sometimes used, the usual precautions being observed to ensure that the temperature of the bath is uniform and that the pyrometers indicate true temperatures. To retard the reduction of the salts and to prevent the formation of a form of scum on the surface of the molten salt it is advisable to add to the bath about 3 per cent. of potassium chromate K_2CrO_4. Salt baths do not offer a convenient method for heating blanks or pressings for deep drawing and pressing because the adhering salt proves very troublesome.

Copper

It might be thought that, owing to its high ductility and low rate of work-hardening, copper would be one of the easiest of the industrial metals to form into shapes by deep drawing and pressing processes. In practice no marked superiority is found ; indeed, although copper sheet is relatively easy to shape under the press, it will withstand less abuse than sheet of good quality *alpha* brass. This is due primarily to three reasons : relatively low tenacity, which tends to cause the walls of shells to break if the restraint imposed upon the metal beyond the radius of the die is as great as brass will withstand ; greater sensitivity to annealing conditions and, lastly, a greater tendency to "foul" steel tools. On the other hand, its softness and low tensile strength throughout the plastic range make for long tool-life if fouling



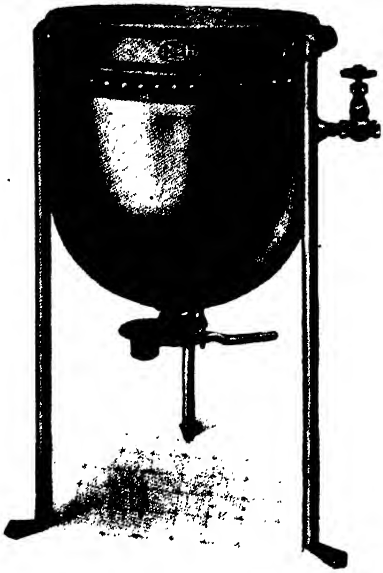
[*By courtesy of the Mint (Birmingham) Ltd.*

FIG. 169. Shells for ball-tap floats pressed from deoxidised copper sheet 0·010 inch thick in one operation.

Top : Hemispherical shell, trimmed, for spherical float.

Bottom : Lower shell, untrimmed, for U-shaped flat-topped float.

[*To face p.* 286.



[*By courtesy of William Brierley, Collier & Hartley Ltd.*

FIG. 170. Steam-jacketed boiling pan. Both the inner and outer shell are pressed from copper sheet.

FIG. 171. Abnormal crystal growth produced during the inter-stage annealing of a copper pressing.
Microsection cut normal to surface of sheet. × 75.

[*To face p.* 287.

can be prevented by adequate lubrication, and its low rate of work-hardening enables a large amount of deformation to be accomplished before annealing becomes necessary. Furthermore, the combined effect of these two characteristics enables very severe deformation to be inflicted in one operation: a benefit which is sometimes exploited beyond reasonable limits.

In spite of its good behaviour under the press, little pressing of copper into shells or containers, as distinct from deep-drawing into tubes or virtually tubular shells, seems to be done; possibly this is because it so happens that other, and sometimes less expensive, metals possess physical properties which, for most purposes, are of greater use from the service aspect: for example, their mechanical strength may be greater, and their resistance to corrosion and tarnishing no less than that of pure copper. This neglect is, in one sense, fortunate; because although copper will withstand very severe deep-drawing and "ironing," its particular combination of physical properties renders it less suitable for those forms of pressing operations in which high tenacity is needed. When such operations have to be carried out, it is often advisable to use sheet which has been given a certain amount of cold-rolling to increase its tenacity, although this naturally entails some reduction in ductility.

The most familiar example of a copper pressing is perhaps the float for the domestic ball-tap, which is made of two pressings, often—but not always—of hemi-spherical shape, soldered or rolled together to form an air-tight vessel. Two typical pressings, each produced in one operation from deoxidised copper sheet, are shown in Fig. 169.

The 14-inch deep shell illustrated in Fig. 288 (p. 601), which is formed from deoxidised copper sheet in three operations with the help of inter-stage annealing, shows that when treated properly copper can be deep-drawn as successfully as any metal. The vessel illustrated in Fig. 170 is a good example of a somewhat heavier pressing, and is typical of many produced for chemical or heating vessels.

Until recently, the copper used for deep drawing and pressing has been mostly of the "tough-pitch" variety. Now, however, the demand for deoxidised copper, in which a controlled degree of deoxidation is given to the molten metal by means of suitable additions such as phosphorus, is increasing rapidly. Deoxidised copper sheet will withstand more severe deep drawing and pressing operations than the ordinary variety; an advantage which needs no comment. A less obvious advantage is that if an article formed in ordinary copper sheet needs one inter-stage annealing operation, the substitution of deoxidised copper sheet may in some instances render this annealing unnecessary and may more than repay the slight extra first-cost of the deoxidised variety.

Very pure copper—for example, the proprietary brand known as

O.F.H.C. (oxygen-free high-conductivity), which contains approximately 99·98 per cent. of copper—is now available for deep drawing and pressing. From curves of physical properties published by Webster, Christie and Pratt.[71] it is evident that the deep drawing and pressing properties of this variety are even better than those of ordinary deoxidised copper. For example, the stated values for percentage reduction in area, which is a useful though incomplete guide to deep drawing and pressing properties, are as follows :—

	Tough-pitch Copper.	Phosphorus-deoxidised Copper.	O.F.H.C. Copper.
Hard-rolled . . .	39	53	70 per cent.
Annealed . . .	58	66	77 „ „

The lower rate of work-hardening of the O.F.H.C. variety is remarkable, and of considerable interest theoretically as an example of the marked influence of small proportions of impurities, both solid and gaseous, upon the work-hardening of a nearly pure metal. When considering these figures it is necessary to bear in mind that the oxygen content of some of the tough-pitch copper used in this country is of the order of 0·08 per cent. and even higher, whereas that of the copper used in the investigation just mentioned was probably considerably lower: a fact which, in some instances, may make the figures just quoted for tough-pitch copper optimistic.

Deoxidised copper owes its industrial advent to its welding properties, more particularly when it is welded autogenously. When any deep drawn or pressed article has subsequently to be welded with the blowpipe it is, therefore, desirable to use deoxidised copper sheet, even when the performance of the ordinary variety under the press is adequate.

Unsatisfactory behaviour of copper sheet during deep drawing and pressing operations can usually be traced to one or more of the following causes : an unsuitable crystal size ; too low an oxygen content in tough-pitch copper or too high an oxygen content in deoxidised copper ; the presence of actual internal discontinuities, often attributable to gas cavities and, occasionally, reduced ductility due to the presence of too high a proportion of impurities. The defects of fouling and of impaired deep-drawing properties caused by seriously incorrect interstage annealing will be discussed later in the appropriate sections.

In addition to the defects just mentioned, the nature and effects of which are too obvious to merit detailed discussion, occasionally a batch of copper sheet is encountered which, although of normal crystal size and hardness, possesses little ductility and opens up in a series of fissures when deformed plastically. This form of embrittlement, which may not show up during rolling in the mill of the supplier, is usually caused by one of three things; heating to too high a temperature, *i.e.* in excess of 900° C., for hot-rolling; too low a percentage of oxygen in tough-pitch copper through over-poling and, lastly, too high a percentage of oxygen in deoxidised copper owing to insufficient deoxidation in the molten condition. Embrittlement produced by any one of these three causes is irremediable.

In comparison with most of the other common metals, a decrease in the crystal size of copper sheet often seems to produce a smaller proportionate decrease in ductility for a given increase in tensile strength. For this reason it is often possible to use sheet having a somewhat smaller "average grain size," say of the order of 0·025 mm., than experience with metals such as brass might suggest as being desirable. In this way it is possible to minimise the natural tendency of copper shapes to tear in the walls, yet still to retain a useful degree of ductility.

The reaction of copper to annealing will be discussed later, but it is appropriate to mention in this general commentary what can only be described as apparent critical-strain crystal growth which is occasionally encountered. An example of this form of growth is illustrated in Fig. 171, which shows part of the wall of a copper pressing after inter-stage annealing; but the rarity of its occurrence must cause some doubt concerning the real nature of this phenomenon, and seems to justify the usual omission in industrial inter-stage annealing of special precautions to avoid it.

This particular form of abnormal crystal growth differs from most kinds of true critical-strain crystal growth in that very large, isolated crystals are usually formed throughout an area in which the degree of cold-work must have varied considerably, and, in the experience of the author, is most likely to occur if annealing has been carried out at an undesirably high temperature. In low-carbon steel, abnormal crystal growth is usually confined to areas which have suffered the so-called range of "critical" stress (see Fig. 137, p. 207), or to areas in which the ferrite crystals are of greatest purity (see Fig. 139, p. 208). This last condition suggests that abnormal crystal growth may take place in copper only in areas in which the crystals happen to be of unusual purity: a tentative explanation which should not be accepted without adequate proof because it is not entirely confirmed by the behaviour of aluminium. It is of interest to record that a similar kind of abnormal crystal growth has been observed in articles pressed from sheet of so-called "aluminium bronze," that is copper containing several per cent. of aluminium.

Cook and Macquarie,[72] investigating the cause of abnormal crystal growth in H.C. copper sheet after cold-rolling and annealing, give certain combinations of percentage reductions and annealing temperature which were found to produce the largest, and entirely abnormal, crystals ; but experience shows that in deep drawn and pressed copper products an entirely abnormal crystal structure can occur after amounts of deformation and annealing temperatures below those stated in the paper just mentioned. An explanation of this discrepancy may lie in the interesting observation of Cook and Macquarie that larger crystals occurred in cross-rolled than in one-way-rolled sheet, for the metal in the walls of most deep drawn and pressed articles has been deformed in a manner far from uni-directional. These investigators record also that no abnormal crystal growth could be produced in phosphorus-deoxidised copper of high purity ; a fact which increases the value of this kind of copper from the viewpoint of the press-shop.

It is a popular belief that copper is immune from season-cracking; but, as was pointed out in Chapter V, evidence exists that season-cracking may occasionally be encountered, particularly when copper contains certain impurities. A stress-relieving anneal is, however, scarcely ever given to deep drawn or pressed copper shapes, and it must be admitted that the extreme rarity of failure due to season-cracking seems to render the extra cost of such a treatment unjustifiable when viewed from the commercial aspect.

Technique. The deep drawing and pressing of copper calls for few, if indeed any, special precautions. Provided that the crystal size, which usually varies from 0·025 to 0·035 mm. " average grain size " according to the nature of the operation, is suitable and that too great a tensile stress is not imposed on the walls of a shell, a surprising amount of maltreatment can be inflicted during most press operations. The metal is relatively insensitive to radii of draw rings and punches, to speed of drawing—within the usual industrial range—and, for draws of normal severity, does not require special lubricants or extremely hard steel tools.

This statement must not be interpreted as meaning that efficient lubricants and properly hardened tools possess no advantages : on the contrary, smoothly polished chromium-plated or nitrided steel tools will enable deeper draws and a better surface to be obtained than would be possible with softer or less smoothly polished tools, and the replacement of ordinary " suds " by a lubricant of higher film strength will usually be of real benefit in severe operations.

It is a well-established belief in most press-shops that copper is very prone to foul steel tools, but there is evidence to suggest that this tendency is due less to the natural properties of the metal than to the fact that its softness and unusually low rate of work-hardening tempt tool designers to impose very large amounts of plastic deformation at one operation. As a result, the task of the lubricant may be as difficult as when much harder metals are given their normal—and lighter—drafts. This fact is not always appreciated, and surprise is expressed when such a relatively inefficient lubricant as dilute suds fails to prevent fouling during heavy draws on copper.

The desired amount of deformation can usually be accomplished by any of the common methods. Copper is specially amenable to "ironing" processes, and it is usual to obtain the required depth of draw by this method from a shell drawn in the preliminary stages to nearly the finished diameter rather than to shape the article in a number of stages each productive of a gradual increase in depth and decrease in diameter, as is of benefit with nickel and copper-nickel alloys.

Tools. Wear on tools, in the usual sense of the phrase, is very low with copper owing to the soft nature of the metal even when the limit of cold-working is being approached. Because of the tendency of copper to "load" steel tools it is, however, desirable to use tools which have been hardened to not less than C63 Rockwell and given a really good polish on the working faces. If these precautions are observed, ordinary plain carbon tool steel will satisfy most demands; but, in view of the softness of copper, case-hardened mild-steel tools give excellent service and, naturally, are less costly than ones made from tool steel of high carbon content. Chromium-plating is a particularly valuable help in preventing fouling. Nitrided steel tools seldom seem to be used for copper, mainly because less costly tools will in most instances give excellent service if the lubrication is adequate.

Lubricants. For deep drawing and pressing operations on copper sheet ordinary "suds," that is soluble oils diluted with water to form an emulsion, is used extensively and is adequate for light draws. For severe draws, a lubricant containing lard oil has proved beneficial, while for exceptionally severe operations castor oil is a valuable addition.

It was pointed out earlier that the problem of lubrication may be more difficult than is suspected because, although copper is so soft, unusually heavy amounts of deformation are often imposed at one operation. For this reason it is usually advisable to use a lubricant containing an "oily" addition such as lard oil or castor oil or, if preferred, one of the newer kinds of lubricant described in Chapter XI. In some shops it is still current practice to use a mineral oil for press operations on copper but, in view of the relatively low efficiency of this lubricant for deep drawing, its use should only be tolerated for light draws: even then a good soluble oil offers practical advantages.

Annealing. It is sometimes erroneously stated that, in comparison with the other industrial metals, copper is relatively insensitive to time and temperature effects during annealing. Although this may be true within limits, the reaction of copper to annealing is influenced in a marked manner by the presence of small traces of impurities; for example, cold-worked pure copper will begin to soften at about 200° C. —and even at 120° C. if held at this temperature for prolonged periods

—whereas copper containing even less than 0·10 per cent. of silver needs to be heated to 300° C. before softening begins. Small percentages of nickel, arsenic and iron—which are often present in industrial copper—have a similar, though less marked, effect.

In addition to the effect of impurities, the degree of cold-work also has a marked influence upon the temperature at which recrystallisation occurs, and it is fortunate that, as a rule, annealing for reasonably short periods at a temperature considerably in excess of that needed to produce recrystallisation will not lead to the formation of undesirably large crystals. Were this not so, it would be more than usually difficult to avoid the occurrence of local areas of excessive crystal growth in the more severely cold-worked portions of a complex shape during inter-stage annealing. The occasional occurrence of abnormal crystal growth of the kind already illustrated in Fig. 171 (p. 287) does not contradict this general statement.

Although severely cold-worked pure copper can be completely annealed at 250° C., and less pure copper at not more than 400° C., industrial annealing is usually carried out at not less than 500° C. and often at higher temperatures when the heating period is brief; furthermore, in industrial practice it is generally unnecessary to vary the temperature or time according to the amount of cold work which the metal has received. In spite of this, trouble is occasionally experienced as a result of excessive crystal growth; as the rate of crystal growth of copper has been computed to be at least one-fifth that of 70/30 brass, it will be obvious that grossly incorrect annealing treatment must be inflicted to produce a really coarse crystal structure. Unless a protective atmosphere is used, it is advisable to anneal at as low a temperature as possible in order to minimise the formation of scale and the associated deterioration of surface which must occur whether scale is removed by quenching the work in water from the annealing temperature, or by subsequent pickling.

As is well known, the essential precaution which must be observed during the annealing of "tough-pitch" copper is the avoidance of an atmosphere containing reducing gases, such as hydrogen or certain hydro-carbons, because these will react with the cuprous oxide in the metal to form steam, producing blisters or, which is even more harmful, a characteristic form of inter-crystalline embrittlement in the surface layers of the annealed metal, as shown in Fig. 172. This embrittlement, which causes the surface of the metal to open up in a series of fissures when stretched or bent, is irremediable, and it is important to observe that embrittlement of this kind sometimes occurs unaccompanied by the visible network of inter-crystalline cracks which can usually be seen under the microscope. Johnston [21] has observed the presence in the inter-crystalline voids of embrittled copper of actual soot or carbon deposit caused by decomposition of hydro-carbon gases which

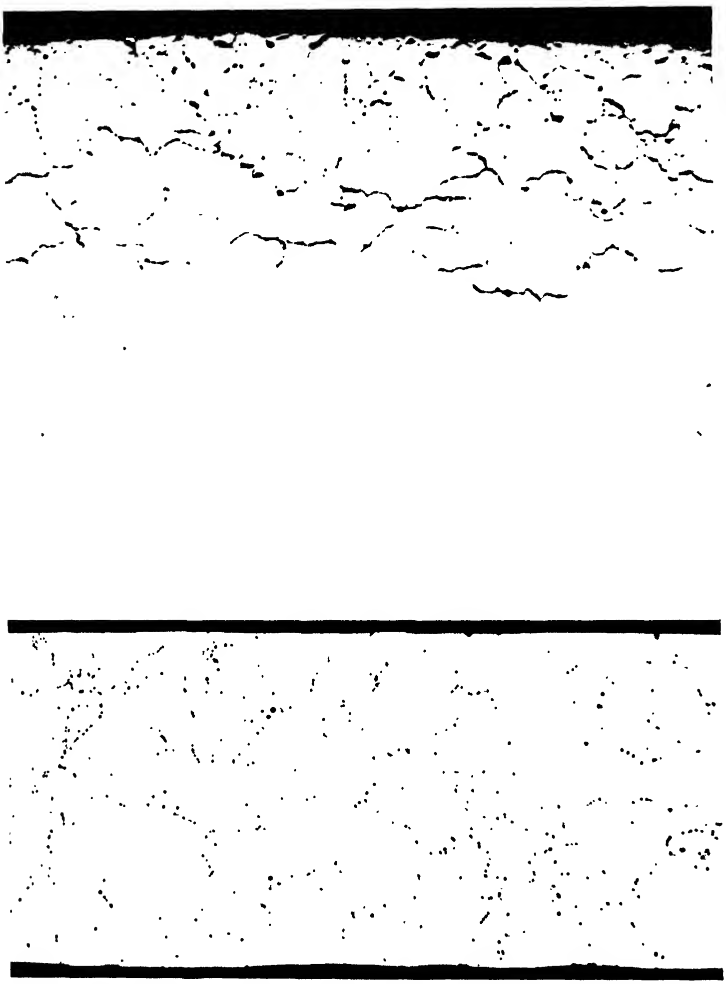


Fig. 172. Photomicrographs showing intercrystalline embrittlement of copper pressings annealed in a reducing atmosphere.

Top : Surface penetration, × 100.

Bottom : Complete penetration, × 60.

Microsections cut normal to surface of sheet.

[*To face p.* 292.

[*By courtesy of Elkington & Co. Ltd.*

FIG. 173. Cooking vessels deep-drawn from pure nickel sheet.

[*By courtesy of Monel-Weir Ltd., and the Mond Nickel Co. Ltd.*

FIG. 174. Pan for chemical processing deep-drawn in Monel metal.

[*To face p.* 293.

have penetrated into the metal, probably along the crystal boundaries. Deoxidised copper, which is finding increasing application for deep drawing and pressing, is usually assumed to be immune from embrittlement when heated in a reducing atmosphere; for most industrial purposes this assumption appears to be justifiable.

Copper is one of the easiest metals to bright-anneal. Before the industrial advent of modern controlled-atmosphere furnaces the formation of scale during annealing was prevented quite effectively by the use of water-sealed furnaces, sometimes with the help of steam introduced into the heating chamber; but the passage of the copper through water seals is liable to cause water-staining, and the surface produced must be described as "clean" rather than truly "bright." Now that modern controlled-atmosphere annealing furnaces which do not need to employ water seals are available, there is no reason why virtually true "bright" annealing methods should not be taken advantage of to restore ductility to deep drawn and pressed copper shapes.

An atmosphere of burnt town's gas is being widely used for the inter-stage bright-annealing of copper, but in order to keep the hydrogen content low, the mixture must be kept richer than that used for many of the other industrial metals, and the sulphur content of the gas must be reduced to a very low value. As low a proportion of hydrogen as possible is naturally desirable, but practical experience indicates that if this does not rise above 5 per cent. it is unlikely that serious embrittlement of the charge will occur with ordinary grades of copper provided, of course, that the time of annealing is not unduly prolonged or the temperature too high.

"Burnt" ammonia is tending to replace burnt town's gas now that the successful industrial application of the principle of recirculation has lowered the cost of annealing in an atmosphere so produced. Considered from the aspect of results rather than cost, burnt ammonia is preferable to burnt town's gas as an atmosphere in which to bright-anneal copper; for this reason, although existing plants will probably continue to use town's gas, it is likely that new plants will be of the ammonia-burner type.

Little can be said by way of summary. Copper is a metal which is easily worked under the press and demands few special precautions except the avoidance of certain harmful annealing atmospheres. Indeed, its general adaptability often proves the cause of trouble, because there is always a tendency to maltreat a willing servant more than one which protests at comparatively slight abuse.

Nickel and Nickel Alloys

Nickel and Monel Metal. Considered from the aspect of deep drawing and pressing, the properties of both pure nickel and Monel metal can only be described as excellent. Cupping tests and the shape of the true stress-strain curves suggest that severe plastic working of these metals can be accomplished before annealing becomes necessary; yet, in the past, these metals have not always proved welcome in the press-shop.

The reason for this seems to be three-fold: nickel and Monel metal quickly lose their ductility if annealed in atmospheres which—for reasons explained later—produce inter-crystalline embrittlement in the surface layers; they are peculiarly prone to fracture under the press owing to the influence of small surface imperfections caused by mechanical means, by very slight inter-crystalline penetration of the kind just mentioned, or even by an adherent and barely-penetrative coating of oxide and, thirdly, they are liable to foul and to cause somewhat rapid wear on tools owing to the relatively high pressures which have to be imposed during deep pressing and drawing.

Given suitable treatment, nickel or Monel metal sheet can be deep drawn and pressed into a large variety of useful and, when desired, genuinely deep shapes such as containers or dishes for industrial and domestic use in which the corrosion resistance and non-tarnishing properties of these metals is most valuable and their bright, silvery appearance attractive. The cooking vessels shown in Fig. 173 provide a good example of drawn articles in pure nickel, while the depth of draw which can be accomplished in Monel metal is well illustrated by ice-cream containers, which are formed in depths up to 24 inches in the same shape as that of the stainless-steel container illustrated in Fig. 178 (p. 314). On a larger scale, sheet of heavy gauge is shaped into pans such as that shown in Fig. 174, both cylindrical and hemispherical, for use in the chemical and food industries.

Nickel sheet destined for deep drawing and pressing is, naturally, of the variety known industrially as "malleable" nickel, a term which usually means that it has been deoxidised with magnesium or manganese shortly prior to casting. Although it is accepted that the ductility of nickel deoxidised with magnesium is greater than that of nickel deoxidised with manganese, deoxidation is often accomplished by adding first manganese and then magnesium; sometimes phosphorus in the form of phosphor-copper is added as a third addition immediately before pouring. It is important that the proportion of non-metallic inclusions and of impurities such as sulphur, arsenic and carbon be very low if the sheet is to possess good ductility. Nickel is very sensitive to the influence of carbon but, although the proportion of this element must be low, a certain amount—usually of the order of 0·05 per cent.—is often retained purposely in order to avoid the occurrence of nickel oxide which, even in traces, is even more detrimental to high ductility than carbon.

The excellent ductility of nickel and of its alloys with copper is indicated by the Erichsen test which, on annealed sheet of moderate thickness, sometimes gives values of from 13·5 to 14·0 mm. and from 12·2 to 12·8 mm. for pure nickel and Monel metal respectively, that for steel sheet of similar thickness being of the order of 11·0 mm.

Monel metal is the trade name given to an impure form of copper-nickel alloy produced by the reduction of a natural ore and, therefore, liable to vary somewhat from the following chemical analysis, which may be regarded as average :—

Nickel	65 to 75 per cent.
Copper	26 to 30 ,, ,,
Iron	up to 3 ,, ,,
Manganese	1·5 ,, ,,
Other impurities	0·5 ,, ,,

Although the presence of the impurities indicated in this typical analysis must be regarded as detrimental to ductility, the deep drawing and pressing properties of Monel metal sheet are appreciably better than those of steel, a fact reflected in the Erichsen values already quoted.

Technique. Monel metal, which is slightly less ductile than pure nickel, closely resembles steel in its behaviour. Indeed, tools designed and used for steel can in some instances be used without alteration for Monel metal ; but, in order to render " fouling " and an undesired reduction in wall thickness less likely, it is advantageous if the radii are made rather larger than those commonly used for steel. Unless " ironing " is being carried out intentionally, the clearance between the punch and the die should be rather greater than for steel, while the pressure-plate loading should be the lowest which will just prevent an objectionable amount of wrinkling : excessive pressure-plate loading will seriously limit the depth of draw which can be obtained.

In the opinion of some authorities it is advisable to arrange successive draws in such a way that at each stage a reduction in the diameter of the shell as well as an increase in depth is produced, a procedure not always adopted with metals which are more amenable to " ironing " processes whereby the wall-thickness of a shell can be reduced and the depth increased without materially altering the diameter.

As far as the author is aware, no information has been published relating to the benefit of " reversed " drawing with nickel and copper-nickel alloys. Their similarity to steel, coupled with their greater work-hardening tendencies, suggests that this method might prove very valuable.

It is desirable to anneal nickel and Monel metal shapes at a somewhat earlier stage than may seem essential because these metals exhibit a tendency to develop small surface fissures during the upper range of work-hardening, and it will be obvious that, once formed, such fissures cannot be removed and will open up during subsequent working even though the apparent ductility of the metal itself has been restored by annealing. A hardness of approximately B92 Rockwell, or 190 V.P.N., has been recommended as the highest value which pressed or deep-drawn Monel metal shapes should be permitted to attain before an inter-stage annealing treatment is given.[73]

Nickel and Monel metal are particularly sensitive to surface condition : the presence of scratches, pits, or similar defects and, in particular, of even a very shallow surface zone of inter-crystalline penetration of oxide—which occurs very readily under unsatisfactory annealing conditions—reduces the ductility of a sheet or a partly-formed shape very markedly. For this reason both the mechanical working and the thermal and chemical treatment accorded to these metals during deep drawing and pressing needs to be watched closely.

In order to give the lubricant the best possible chance to perform its allotted task of preventing metal-to-metal contact, it is desirable to use slower speeds than would normally be employed for comparable draws on steel. It is the practice in some shops to copper-plate copper-nickel alloys before drawing is started. This certainly reduces the inherent tendency of these alloys to " foul " steel tools, and has proved particularly useful in tube-drawing. In spite of the extra processes and expense involved, it may be accepted that copper-plating will facilitate the uninterrupted passage of work through the press-shop and may render the use of special drawing lubricants unnecessary.

Tools. Nickel and Monel metal are liable to " foul " or " gall " the surface of steel tools unless these are really hard and protected by a drawing lubricant of high film-strength. It so happens that articles for which copper-nickel alloys are used—for example kitchen utensils, food containers and sinks—are often of fairly large size, need not be kept with close dimensional tolerances, and are required in relatively small numbers ; for this reason properly hardened tools of expensive steel are not always used, with the result that " loading " takes place.

If the tools are of good quality steel hardened to not less than C62 Rockwell and a good lubricant of high film-strength is used, nickel and copper-nickel alloys can be deep drawn and pressed without difficulty if the pressures are fairly low. For severe draws a steel containing from 1·5 to 2·0 per cent. of carbon with about 6 per cent. of tungsten, which hardens in water to C64–66 Rockwell, gives excellent service. Nitrided steel tools give even better results, but it is essential that the core strength be sufficient to prevent the case from " caving-in " : for this reason ordinary grades of Nitralloy steel are sometimes inadequate, and special steels, such as the high-carbon high-chromium steels mentioned in Chapter X, have to be used.

With any of the varieties of steel tools just mentioned it is most desirable that a really good polish be given to, and maintained on, the working surfaces in order to reduce the likelihood of fouling and also the drag on the metal.

When the expense of perhaps large-size tools in hardened steel cannot be borne and the desired draws are of moderate severity, heat-treated inoculated cast-iron tools will give a useful life if a good lubricant is used. Alternatively, a draw-ring of hard, cast bronze—for example, one containing 80 per cent. of copper and 20 per cent. of tin—set in a cast-iron bolster may be used. These two tool materials are of considerable value for pressing operations on thin sheet, but when the size of the article to be produced is fairly small and a large output is desired it is usually preferable to use hardened steel, although it may be mentioned that dies of sintered tungsten carbide have proved very satisfactory for small deep-drawn articles in both nickel and Monel metal.

Lubricants. It has already been remarked that, unless the operations are light, it is usually necessary to use a lubricant which possesses a high film-strength if fouling is to be avoided. For light operations, a good soluble oil not too heavily diluted, or a solution of good quality soap shavings in water, may suffice ; if to this last solution graphite be added, a much more efficient lubricant is obtained. For severe draws a lime-soap-base lubricant " filled " with chalk is of proved benefit, although pure castor oil and unfilled lubricants containing graphite are sometimes used with success. If some of the new varieties of lubricant are used, steps should be taken to ascertain whether the one selected contains sulphur, for this element must be avoided with nickel or copper-nickel alloys as also must lead, a consideration which prevents the use of that favourite lubricant for severe operations—white lead and castor oil.

Annealing. Many of the difficulties which have been experienced in the deep drawing and pressing of nickel and Monel metal must be attributed to unsatisfactory inter-stage annealing. In general, the faults are one or more of three : the use of too high a temperature, or soaking for too long a period at a suitable temperature ; the formation, and inadequate removal, of surface scale and, lastly, embrittlement resulting from inter-crystalline attack by an injurious furnace atmosphere.

The temperature at which pure cold-worked nickel recrystallises has been a matter of doubt and even controversy for many years due, it now seems, to the varying interpretation which has been placed upon the adjective " pure." In industrial practice a temperature of from 800 to 850° C. is generally used for the annealing of commercially-pure cold-worked nickel, but Fetz [74] has shown that electrolytic nickel of high purity given a 90 per cent. reduction will recrystallise at as low a temperature as 230° C., and wrought carbonyl-nickel at 350° C. In view of the increasing purity of the nickel which is finding its way into the press-shop, it is likely that the annealing temperatures now used can be lowered with advantage in many instances, but the minimum temperatures just quoted must be regarded as of scientific rather than of industrial significance. The most satisfactory annealing temperature for nickel of given purity still needs to be established, and it must be borne in mind that, at present, the industrialist is not always aware of the purity of the nickel sheet he manipulates.

Monel metal is somewhat sensitive to annealing temperature: if it is heated to too high a temperature, or held at an adjudged correct temperature for too long a time, the size of the crystals will increase sufficiently to impair the deep-drawing properties of the metal or, at best, to give a coarse " orange peel " surface after subsequent working. The most suitable annealing temperature will vary with the degree of plastic deformation which has been inflicted on the metal; readers interested in this subject are referred to the investigations of Fetz,[74] Crawford [75] and other workers. As an approximate guide, the following temperatures have been recommended for Monel metal sheet of moderate gauge cold-worked the stated amounts; for very thin sheet rather higher temperatures may be preferable [76] :—

10 to 15 per cent. elongation	870 to 900° C.
20 to 25 ,, ,,	800 to 835° C.
40 to 45 ,, ,,	730 to 750° C.

The work should be heated so that it attains full temperature, and then cooled immediately without any appreciable soaking; the influence of rate of cooling is slight although, curiously, the ductility of sheet which has been either quenched or cooled very slowly is often a little better than that of sheet cooled at intermediate rates.

If nickel or Monel metal is cooled in air from the annealing temperature, which, depending upon the severity of the cold-working inflicted, should lie between 750° and 900° C., it acquires a heavy coating of black oxide. Obviously the most satisfactory plan is to avoid the formation of oxide by heating and cooling in one of the several types of controlled-atmosphere annealing furnace which are now available, thus avoiding any need for the unpleasant operation of pickling.

Apart from preventing surface oxidation, a suitable protective atmosphere also prevents a form of embrittlement which nickel and Monel metal are liable to acquire when annealed in an uncontrolled atmosphere. This embrittlement is caused by inter-crystalline penetration, and experience shows that it can be brought about by an oxidising atmosphere which does *not* contain sulphur, the presence of which element was at one time thought to be essential for its development.

Prior to the industrial advent of controlled-atmosphere annealing furnaces, a popular procedure to avoid oxidation has been to pack partly-formed shapes in containers sealed with sand—and sometimes sodium silicate—containing a little charcoal. Excellent results can be achieved in this way and, as an additional precaution, the charge is often quenched from the full annealing temperature in a bath of water containing about 5 per cent. of methyl alcohol, the bath being, for preference, kept warm. This quench will produce a silvery-white surface on pure nickel, but copper-nickel alloys will acquire a very thin coating of copper, the presence of which is distinctly beneficial during subsequent deep-drawing operations because it lessens the tendency of the metal to foul the tools ; it can easily be removed from the surface of the finished article by a light pickle or even by a light buffing operation. As an alternative to charcoal, sealed containers are sometimes purged with town's gas, but it is essential that this be freed from all traces of sulphur ; in the United States natural gas has been used with success.

Useful as the methods just described for preventing oxidation have been, the use of modern controlled-atmosphere annealing furnaces offers by far the best means for carrying out the inter-stage annealing of nickel and Monel metal shapes, for it enables perfectly clean work, requiring no pickling, to be produced consistently and also removes any danger of inter-crystalline embrittlement caused by the action of oxidising or contaminated atmospheres. Burnt town's gas which, if freed from all traces of sulphur, is a cheap and reasonably satisfactory atmosphere for use in bright-annealing furnaces of either batch or conveyor type, is used in a considerable number of plants. Because of this, the more expensive atmosphere derived from cracked ammonia has not been used to any extent, but the recent development of furnaces employing a protective atmosphere of "regenerated" and recirculated burnt ammonia has made this latter a serious rival to town's gas. Owing to its greater purity, burnt ammonia gives a better surface on annealed work and, although the use of town's gas in existing furnaces is likely to continue, it is likely that a regenerated burnt-ammonia atmosphere will tend to be chosen for new plants in spite of the higher first cost of the necessary plant.

Recently nickel, Monel metal, cupro-nickel and nickel-chromium articles have been annealed in salt baths of a kind similar to that used for the heat-treatment of Duralumin but containing, instead of the usual nitrates, a mixture of equal parts of sodium and potassium chlorides plus about 2 per cent. of calcium chloride. This mixture can be maintained at a temperature of about 820° C. without fuming, and has the special advantage that it cleans and pickles the surface of nickel and nickel alloys, thus eliminating the need for a separate pickling operation after annealing. It is advisable first to treat the molten bath with a little powdered charcoal and borax to remove any sulphur which may be present. When annealed and cleaned, articles should be quenched in water and any salt which remains adhering to their surfaces removed by a quick dip in a solution containing 10 parts of sulphuric and 1 of nitric acid.

If scale is allowed to form during inter-stage annealing it is most important that it be completely removed before further deep drawing or pressing is attempted. When copper-nickel alloy shapes have to be pickled, the ordinary warm sulphuric or nitric acid pickling solutions used for other metals can be employed if an oxidising agent such as iron oxide, or preferably sodium or potassium dichromate, is added to prevent the copper from plating out on to the surface of the pickled metal. When the quantity of work is sufficiently large to enable special baths to be used, hot sulphuric acid solutions containing additions of sodium chloride and potassium nitrate are recommended.[76] It should be observed that nickel cannot be pickled successfully in a solution which has been used previously for copper-nickel alloys.

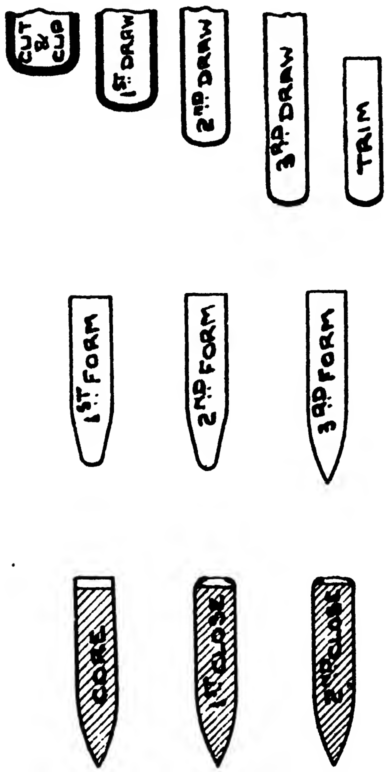


FIG. 175. Diagram showing stages in deep-drawing, forming and closing of cupro-nickel bullet envelopes. No inter-stage annealing is used.

Nickel and nickel alloys are particularly susceptible to surface injury caused, to use press-shop terminology, by the "burning-in" of drawing lubricant or other foreign matter adhering to the surface of work when it is annealed. It is therefore essential that articles be thoroughly cleaned and degreased before they are annealed, and that during annealing they are prevented from coming into contact with silica, scale and particles which fall from the refractory linings of furnaces. If these precautions are not observed stains and even patches of scale will persist through repeated pickling operations. Sulphur is, as has already been mentioned, fatal to nickel and nickel alloys, and it should be borne in mind that the paints used for marking sheets often contain sulphur, for example as zinc sulphide.

Cupro-nickel. A useful and widely-used range of ductile industrial alloys is provided by the addition of nickel to copper. For deep drawing and pressing, the alloy containing 20 per cent. of nickel is used most extensively; but, before examining this alloy in some detail, mention may be made of the cupro-nickel alloys containing, respectively, 70 per cent. of copper and 30 per cent. of nickel, and 85 per cent. of copper and 15 per cent. of nickel. Although possessing nearly equal ductility, the 70/30 alloy is appreciably harder than the 80/20 variety. It is used extensively for condenser tubes. The 85/15 alloy has a ductility equal to, but a tensile strength rather less than, the 80/20 alloy. It is often drawn into tubes but is seldom made into shapes by manipulation of sheet under the press.

The alloy containing approximately 80 per cent. copper and 20 per cent. nickel occupies virtually a unique position by reason of its remarkable ductility, good tenacity and low rate of work-hardening. Because of this, it is often possible to carry out a whole sequence of normally severe or difficult deep drawing or pressing operations without any inter-stage annealing whatever. Some idea of the properties of the alloy can be gathered from Fig. 175, which shows the stages in the manufacture of a bullet envelope from flat, cupro-nickel sheet without any inter-stage annealing: it will be appreciated that, with most metals, it would prove impossible to turn over the severely cold-worked rim of a deep-drawn shell without the help of annealing.

The behaviour of "80/20" under the press is only partially reflected in the values obtained by the common methods of testing. For example, although the Erichsen value obtained on annealed sheet of 0·062 inch thickness may be of the order of 13·0 to 13·5 mm.—that is, no better than 70/30 brass—the reduction in area obtained in the tensile test often exceeds 80 per cent. on a 2-inch gauge length.

It seems likely that this excellent ductility is due largely to the reduction in the actual percentage of impurities which results when industrially-pure nickel, itself possessing excellent ductility, is diluted with approximately four times its weight of industrially-pure copper, which is also a very ductile metal. It is recognised that as the purity of a metal is increased the influence of impurities often tends to become relatively more marked; this tendency is seen in copper, nickel and the alloys of copper and nickel, and affords an interesting illustration of the effect of impurities upon ductility and rate of work-hardening, properties which are of paramount importance from the aspect of deep drawing and pressing.

The rate of work-hardening of both pure nickel and pure copper is low, and the increase in tenacity conferred upon copper by the addition of 20 per cent. of nickel produces an alloy which is admirably suited to conventional methods of deep drawing and pressing. It is rather unfortunate that, unless the service requirements of an article render the special properties of "80/20" of real practical value, the relatively high cost of this alloy usually precludes its use in industry.

One defect sometimes found in cupro-nickel and, in rather less degree, in nickel-silver sheet is unusually pronounced "directionality." In some batches of sheet this may be sufficiently marked to produce not only excessive "earing" but actual failure in articles normally deep-drawn without difficulty, as in the cup illustrated in Fig. 58 (p. 86). As explained elsewhere, this variation in the severity of "directionality" is caused by variation in the sequence of rolling and annealing treatments by which the sheet is produced, a matter which only the supplier can study and control. For this reason it is more than usually necessary to test all deliveries of cupro-nickel sheet for the property of directionality in the manner described in Chapter XII.

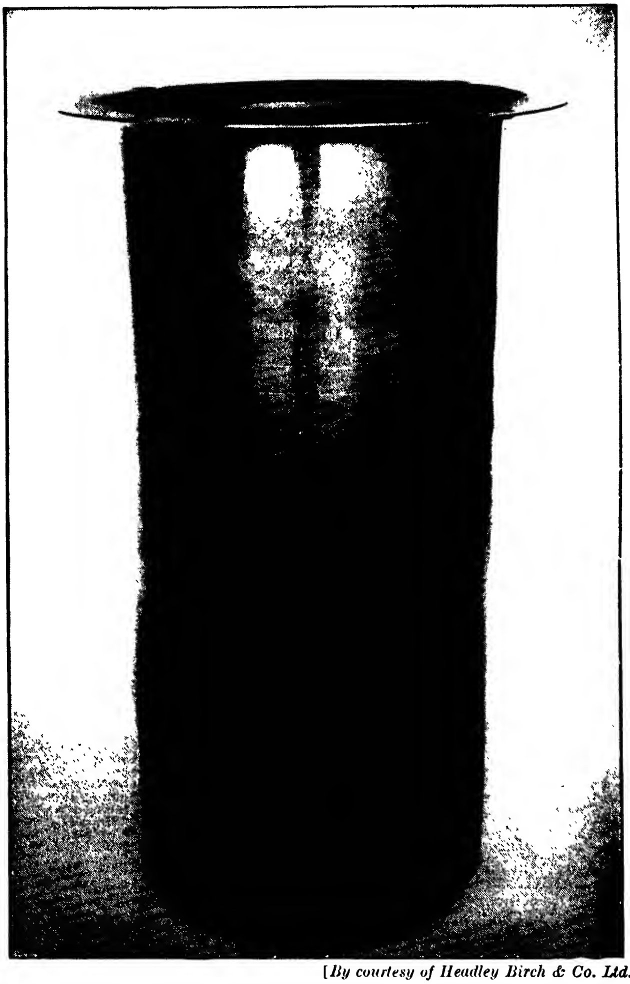
Tools and Lubricants. No useful purpose will be served by describing the tool materials and lubricants used for 80/20 cupro-nickel. The requirements of the metal are more severe than those of copper, but less exacting than those of nickel or Monel metal whose requirements have been discussed in some detail in the respective sections devoted to these metals. Rather severe fouling is sometimes experienced, but it must be allowed that this is often caused by the severity of the operations which the natural properties of the 80/20 alloy render possible. In such instances the use of a lubricant of high film-strength and hard, well-polished tools is, clearly, essential.

Annealing. It has been pointed out that the natural ductility and low rate of work-hardening of the 80/20 alloy renders inter-stage annealing unnecessary in most industrial press-work. When annealing has to be carried out, a temperature of from 600 to 690° C. seems to give best results if the period of heating is not prolonged, although the alloy does not appear to be as sensitive to over-annealing as is *alpha* brass. Above 690° C. there is a tendency for any carbon in cupro-nickel to be precipitated.

The high-copper alloys can be quenched from the annealing temperature to remove adhering scale without detriment to ductility, and the methods adopted to prevent oxidation with nickel and Monel metal (*quod vide*) can be used. It is only natural that the benefits of modern "clean" annealing should be utilised whenever possible; burnt town's gas, well freed from sulphur, is a satisfactory protective atmosphere but, as with other metals, it seems likely that in new plants this may be replaced by a regenerated atmosphere of burnt ammonia.

Nickel-silver. In common with those of other nickel alloys, the excellent deep-drawing properties of nickel-silver are not generally recognised outside the few shops which specialise in the manipulation of this range of alloys. How excellent these properties are can be judged from the 12½ inch-deep container illustrated in Fig. 176, which is drawn in six operations, with inter-stage annealings, from sheet only 0·028 inch thick.

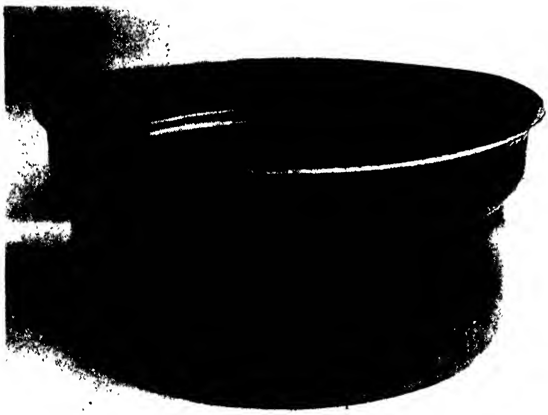
Nickel-silver, and occasionally German silver, is the industrial description applied to alloys consisting of nickel, copper and zinc;



[*By courtesy of Headley Birch & Co. Ltd.*

FIG. 176. Food container 12 inches high deep-drawn from nickel-silver sheet 0·028 inch thick.

[*To face p.* 302.



[By courtesy of the Valor Company Ltd.

FIG. 177. Flanged shell 8 inches diameter deep-drawn from zinc sheet 0·10 inch thick.

[To face p. 303.

"nickel brasses" is a more logical description of these alloys, which may be regarded as *alpha*-brasses in which part of the normal proportion of zinc has been replaced by nickel.

Nickel-silvers are usually graded according to their nickel content, the copper content remaining in the region of 60 to 65 per cent. In Great Britain the following form of grading has persisted :—

Per cent. nickel.	*Grade.*
30	BB
25	B
20	A1 or "Firsts"
18	A
16	"Seconds."
12	"Thirds"
8–10	"Fourths"
5–7	"Fifths"

No fixed connection exists as to the zinc content of each of these grades. Generally, the percentage of zinc is increased as the nickel content is decreased ; common percentages are 15 of zinc with 30 of nickel, 17 of zinc with 20 of nickel, and 22 of zinc with 18 of nickel, increasing to about 35 per cent. zinc in "Fifths," but these values must not be taken as being applicable in all instances.

There is, happily, a growing tendency to refer to the various grades by the percentage of nickel, and this has been helped by the issue of a series of seven compositions in the form of a British Standards Specification (790–1938). This includes 10, 12, 15, 18 and 20 per cent. nickel alloys with 60 to 65 per cent. copper, and 25 and 30 per cent. nickel alloys with 55 to 60 per cent. of copper, a tolerance of $\pm$ 1 per cent. being allowed on the nickel content of each grade.

It would be tedious to examine the properties of each of these grades individually. Considered from the aspect of deep drawing and pressing it can be stated that, in the form of annealed sheet, the alloys are similar to, although somewhat harder than, the straight *alpha*-brasses ; that the high-nickel alloys do not work-harden so rapidly as the low-nickel alloys, and that the behaviour of the metal is influenced to some extent by the zinc content. How far the zinc content does affect the deep-drawing properties of nickel-silvers is a matter of uncertainty. Some users are of the opinion that, provided the casting procedure has been really good, it is unnecessary to match the zinc content to the severity of the draw ; others find it advisable to decrease the zinc content of purchased sheet as the severity of the draw increases. Eighteen per cent. is often held to be the highest proportion of zinc which should be allowed in an 18 per cent. grade of nickel-silver destined for severe deep drawing.

Be this as it may, it is established beyond question that the influence of casting conditions upon the deep-drawing properties of the final sheet is particularly marked in the case of nickel-silver, a fact which consumers having more than one source of supply know full well. The severe draw illustrated in Fig. 176 (p. 302) is carried out in sheet containing 20 per cent. nickel, 20 per cent. zinc and 60 per cent. copper ; no other proof is needed of the excellent deep-drawing properties of nickel-silver sheet of relatively high zinc content when properly cast.

It may be accepted that reducing the zinc content decreases the rate of work-hardening, decreases the tendency of the metal to " foul " the tools during drawing, and makes it easier to anneal the usual range of nickel-silver alloys without inducing in them an undesirably large crystal size. For these reasons it is often desirable to fix the zinc content having some regard to the severity of the attempted draw even in sheet rolled from ingots emanating from first-class foundries.

Nickel-silvers are very sensitive to the presence of impurities. Lead and tin reduce the ductility, and iron and manganese increase the rate at which the metal work-hardens ; the effect of tin is greatly accentuated by the presence of traces of antimony, an impurity which sometimes enters the metal *viâ* scrap. Thompson [77] has shown that nickel-silver alloys are very liable to contain oxygen, sometimes present as zinc oxide, and that the degree of deoxidation has a profound effect upon the size of the crystals produced by annealing after cold work. It is possible that some connection exists between this fact and the rapidly increasing tendency to grow large crystals which occurs as the zinc content is raised, a matter which will be commented upon later. For all ordinary deep-drawing operations an " average grain size " of from 0·025 to 0·035 mm. is desirable, and every effort should be made to preserve this during inter-stage annealing.

Egeberg and Promisel,[12] having observed tiny cracks—each often extending the length of only a single crystal facet—in severely cold-worked yet not embrittled nickel-silvers, have advanced an interesting hypothesis to explain the marked tendency which these alloys exhibit to foul the surfaces of press tools and rolls. These investigators suggest that the formation of cracks at the surface of sheet or the walls of drawn shapes exposes minute areas of chemically-clean metal which are forced into contact with the tools at very high pressure, thus providing ideal conditions for fouling to take place. This ingenious hypothesis deserves close study ; the fact that it postulates complete breakdown of any lubricating film need not condemn it, for there is ample evidence to show that localised and momentary breakdown does actually occur in many industrial deep drawing and pressing operations when ordinary lubricants are used. Indeed, it seems justifiable to consider its possible extension to explain the fouling experienced with other metals in which microscopical examination has not yet revealed the presence of visible internal discontinuities. A fact which at first sight does not seem to fit in with the general application of this hypothesis is that it is often the more ductile metals which show the greatest tendency to foul, and it might be surmised that the more ductile a metal is the less it will be likely to develop internal discontinuities when cold-worked. On the other hand nickel-silver, in which tiny cracks have been observed, is unquestionably a ductile metal; and it may be that cracks are formed in other ductile metals but that they are so small that they have escaped detection.

Tools and Lubricants. It is unnecessary to describe in any detail the tools and lubricants used for deep drawing and pressing nickel silvers, because these are virtually the same as those used for nickel and Monel metal. To avoid fouling during heavy draws, a lubricant of high film strength, very smoothly polished tool surfaces, and very hard steels should be used. Nitrided steels are excellent, while the 1·5 to 2 per cent. carbon, 6 per cent. tungsten steel already described is a cheaper and useful alternative.

Annealing. If the usual precautions are observed, the annealing of the nickel-silvers having a low or moderate zinc content presents no difficulty; but, as the zinc content rises, the danger of producing an undesirably large crystal size during inter-stage annealing becomes acute. For this reason it is often desirable to avoid the high-zinc alloys when inter-stage annealing has to be given.

The most suitable annealing temperature for nickel-silver varies from 380 to 800° C., depending upon both the nickel and the zinc content, and it is to be feared that in the past insufficient attention has been paid in industrial practice to this variation. A useful guide to annealing temperatures is given by Aitchison and Barclay [78]; for the inter-stage annealing of the 18 per cent. nickel alloy, Egeberg and Promisel [12] recommend the following temperatures :—

10 per cent. zinc . . .	550 to 650° C.
17 ,, ,, . . .	650 to 750° C.
25 ,, ,, . . .	750 to 800° C.
30 ,, ,, . . .	815° C. minimum.

Some users are successfully annealing a wide range of nickel-silver alloys at only two standard, and fairly wide, temperature ranges: 700 to 750° C. for alloys containing from 10 to 15 per cent. nickel, and 750 to 800° C. for alloys containing 18 to 30 per cent. nickel.

Nickel-silver alloys can be quenched from the annealing temperature without appreciable detriment to ductility and, prior to the advent of controlled-atmosphere furnaces, the industrial methods adopted to prevent surface oxidation and to remove adherent scale tended to follow those established for nickel and Monel metal already described. As with other metals, modern clean-annealing methods offer many advantages; protective atmospheres derived from either burnt town's gas or burnt ammonia are satisfactory, but their sulphur content must be kept very low.

It is important that cold-worked articles in nickel-silvers, particularly those containing a high percentage of zinc, should not be held at the annealing temperatures for longer than is necessary to secure reasonable ductility. If this precaution is not observed, an undesirably large crystal size is likely to be produced in some regions of a drawn shell. This rapid growth may not be due entirely to genuine "critical strain" phenomena because, although the likelihood of its occurrence is lessened when the original sheet is in a partially cold-worked instead of a fully-annealed condition, the trouble may still occur in a less virulent form. It will be recalled that with aluminium the practice of using cold-rolled sheet effectively prevents the formation of crystals of abnormal size under proper conditions of annealing, and that a comparable form of growth—that is, one not attributable entirely to the effect of critical strain—occurs sometimes in copper (see Fig. 171, p. 287), and aluminium bronze (see Fig. 87, p. 121).

Season-cracking and Stress-cracking in Nickel and Nickel Alloys. To conclude this survey of nickel and nickel alloys, there remains to be considered the defect of season-cracking and stress-cracking in finished articles. As far as the author is aware, no instance of genuine season-cracking in pure nickel has been recorded. A stress-relieving anneal is seldom given even to severely-drawn nickel articles; and cracking, when it does happen, appears to be attributable to stress-cracking and not to season-cracking.

Cupro-nickel alloys, including Monel metal, are more liable to stress-cracking than pure nickel, yet even with these a stress-relieving anneal is rarely given and, it must be admitted, seldom seems genuinely necessary. Instances are on record, however, of severely cold-drawn nickel and Monel metal having cracked under the influence of apparently safe ranges of alternating stresses encountered during service; with some articles it is, therefore, a wise precaution always to give a final stress-relieving anneal to avoid the possibility of failures of this nature. A rather higher temperature than that required by brass is necessary and can be used without fear of producing appreciable softening; 375 to 425° C., maintained for half an hour, proves satisfactory in the majority of instances, but in the opinion of some authorities the temperature should be raised to 500–550° C. if the amount of cold-work has been moderate as distinct from severe. It is worth bearing in mind that a useful increase in the limit of proportionality of cold-worked nickel and some nickel alloys can be obtained by heating for a period of about two hours at 300° C., a temperature which will give some, though by no means a complete, degree of stress relief.

In contrast with cupro-nickel, a certain amount of trouble—which increases considerably as the zinc content of the alloy increases—is experienced with nickel-silver, yet as often as not a final stress-relieving anneal is omitted from the production schedules of articles deep-drawn from this range of alloys. Heating to 250 to 300° C. will remove dangerous internal stresses. Little proper investigation has been made of the cracking of cold-worked nickel-silver, but it seems likely that the failures which occur are true season-cracking and not merely stress-cracking.

Summing up these remarks it can be said that nickel, cupro-nickel and nickel-silver possess excellent deep drawing and pressing properties, but that in many alloys the property of " directionality " is sometimes pronounced and that special precautions need to be observed during inter-stage annealing.

Inconel. Inconel is a proprietary alloy containing approximately 80 per cent. nickel and 12 to 14 per cent. chromium, the balance consisting mainly of iron. Its main features are excellent resistance to oxidation at elevated temperatures and, in view of the ever-extending application of deep drawn and pressed parts, it is an alloy with which those in charge of press-shops must become acquainted.

Little need be said regarding the technique needed for deep drawing and pressing Inconel, because it resembles that needed for steel except that more power is required. For this reason tools of very hard steel or alloy cast iron are needed, and an efficient lubricant is essential.

Annealing. The main peculiarity of Inconel lies in annealing, which is effected by heating to a temperature of approximately 980° C., soaking for about fifteen minutes, cooling in the furnace or—which gives a cleaner surface—quenching in water or alcohol. Alternatively, very brief heating to a temperature of approximately 1,040° C. can be used; but soaking at this temperature produces crystal growth.

As with all nickel alloys, the furnace atmosphere must be free from sulphur, and every effort should be made to avoid undue oxidation because, if a heavy coating of oxide has to be removed by pickling, a rough, spongy surface is produced which is costly to smooth by grinding and polishing. The special caution given regarding the removal of drawing lubricant, the avoidance of contact with particles of refractory linings and the harmful influence of sulphur-bearing paints should be observed even more carefully with Inconel than with nickel and Monel metal. Owing to the formation of a film of chromium oxide, which is readily produced in the presence of carbon dioxide and water vapour, it is not always possible to bright-anneal Inconel in protective atmospheres which prove satisfactory for nickel and Monel metal. Good results can, however, be obtained in pure hydrogen or in cracked ammonia.

Pickling. The following double treatment is recommended, and it is important that the metal should *not* be rinsed between the two baths :—

Solution No. 1—

Sodium hydroxide	18 oz.
Sodium carbonate	18 oz.
Potassium permanganate	7 to 11 oz.
Water	1 gal.

Solution No. 2—

Sulphuric acid, 66° Be	16 oz.
Sodium nitrate	8 ,,
Copper sulphate or copper nitrate . .	1½ ,,
Water	1 gal.

Work is immersed in solution No. 1, maintained at a temperature of approximately 85° C., for about two hours and then transferred to solution No. 2, maintained at a slightly lower temperature, in which it should be kept until all the oxide has been removed, usually from 1 to 2 minutes. Longer immersion will produce a deposit of copper, a defect which will also occur when the second solution becomes depleted in oxidising agents. This can be corrected by small further additions of either nitric acid or ferric chloride.

Stress-relieving. Owing to the heat-resisting properties of Inconel, stress-relieving must be carried out at a relatively high temperature. The bulk of internal stresses can be relieved in deep drawn or pressed articles by heating to 760° C. for 1½ hours, a treatment which produces only slight softening. As with nickel and Monel metal, an increase in the limit of proportionality of cold-worked Inconel can be obtained by heating for some two hours at a temperature of 400° C., but this treatment will give only a limited degree of stress relief.

Zinc

At one time zinc was regarded as a difficult metal to deep draw or press into shapes of any depth. The classic investigation of Mathewson, Trewin and Finkledey,[79] which must rank as one of the first proper metallurgical researches having as its object the discovery of the most satisfactory deep drawing and pressing conditions for a particular metal, showed that, given a certain range of drawing speeds and temperature of the blank, an unexpected degree of plastic deformation could be inflicted upon zinc.

Notwithstanding the work of Mathewson, Trewin and Finkledey, it so happens that the deep drawing and pressing properties of zinc have not been utilised to any great extent in industry. The reasons for this are two, namely, that this metal can be pressure die-cast very readily into shapes similar to—and when desired far more complex than—ones which can be produced in press-tools and, secondly, that for some time the process of impact-extrusion—whereby the equivalent of deep-drawn shapes can be produced in a single operation—has been developed most energetically.

To the scientific student of deep drawing and pressing, zinc is a particularly interesting metal because its behaviour is influenced to such a marked degree by various conditions, such as temperature, speed of deformation and the presence of very small proportions of impurities. It is, for example, interesting to observe that for the impact-extrusion of zinc the best temperature seems to be about 200° C., whereas for deep drawing and pressing a temperature of from 40 to 90° C. is much better because within this range the most useful combination of ductility and tenacity appears to exist. A good measure of tenacity is essential when metal has to transmit tensile stress, as during deep drawing and pressing ; in the process of impact-extrusion, maximum ductility is needed : tenacity being of little significance. Another most interesting property of zinc is its reaction to speed of deformation ; its behaviour suggests that variations of similar nature, if not comparable magnitude, may be associated with other metals and need to be investigated. The sensitivity of zinc of 99·99 per cent. purity to very small traces of impurities is well known, and need not be elaborated here because it has been studied intensively to elucidate the behaviour—sometimes disastrous—of zinc-base die-castings.

The peculiar and—from the scientific if not always the industrial aspect—interesting mechanical properties of zinc when deformed plastically is usually attributed to the fact that its space lattice is of the hexagonal type. Because of this, the planes upon which slip can occur within its crystals are fewer than for most of the other industrial metals, and this may explain in part why its rate of work-hardening is so low and why a zinc shell is unusually liable to break under press tools by localised " necking " instead of extending uniformly.

These properties are reflected in the behaviour of zinc in tensile and bend tests. In tensile tests the percentage elongation is usually very large if measured on a short length which includes the fracture, because most of the extension will have taken place in this zone, but relatively small if measured on a considerably longer gauge length. By means of a simple bend test the unusually low rate of work-hardening of zinc can be demonstrated in a striking manner if strips of copper and zinc are given a number of repeated flexures. The zinc strip will bend backwards and forwards *in the same place* because the deformation produces very little work-hardening, whereas the copper strip will bend *in a fresh place* at each successive flexure owing to the previous flexure having work-hardened the metal quite appreciably in the vicinity of the bend.

Owing to the peculiar properties of zinc it will be evident that, unless certain precautions are observed and special technique adopted, attempts to deep draw or press this metal will almost certainly prove unsuccessful. Proof that, under suitable conditions, zinc sheet can be deep drawn and pressed to fairly deep shapes is given by the 8-inch diameter container shown in Fig. 177 (p. 303), which is formed in two stages from sheet 0·10 inch thick. Experience with this article showed that, had it not been for the step in the wall, it could have been formed in a single operation. Considerably larger ratios of depth to diameter are obtainable without undue difficulty on shells of smaller diameter, but the popularity of the impact-extrusion process for the production of small articles—for example dry-battery cases—in zinc has led to a neglect of the alternative but lengthier process of deep-drawing.

Having dispelled the illusion that zinc cannot be deep drawn or pressed successfully, the question naturally arises as to why so much trouble is experienced when these operations are attempted by those unfamiliar with the peculiarities of the metal. The answer is two-fold. First, the ductility of zinc varies very greatly with temperature, increasing from a relatively low value at room temperature to a maximum at about 150° C. with, however, some decrease in tenacity. For this reason it is usually necessary to deep draw and press this metal at a raised temperature. Secondly, the temperature of recrystallisation of zinc is so low that annealing usually occurs spontaneously soon after—if not actually during—press operations owing to the rise in temperature which these operations produce in the metal. For this reason an undesirably large crystal size is attained very readily; once attained, it cannot be refined, and it will be appreciated that sheet or partly-formed shapes are very easily transformed into scrap metal.

Two specially-prevalent defects need to be watched for when zinc sheet destined for deep drawing or pressing is purchased: too large a crystal size—for reasons which will now be evident—and, secondly, very pronounced directionality. In zinc of ordinary quality, too small a crystal size will engender low ductility and cause the metal to break in the press: in either ordinary or specially-treated varieties of zinc too large a crystal size will engender low tenacity which will also cause the metal to break or, if it does not actually break, to acquire a very rough "orange-peel" surface. "Directionality" is sometimes so marked that a round shell tends to become distorted and the height of the "ears" may be so great that, using blanks of normal size, the intervening troughs will extend below the line to which the top of the shell is trimmed, thus spoiling the product. For this reason thorough testing of purchased sheet is always advisable.

It has been pointed out that one of the difficulties associated with the deep drawing and pressing of zinc is the natural tendency of drawn shapes—and indeed of the sheet prior to drawing—to grow crystals of an undesirably large size. Attempts have been made to overcome this inherent defect by adding small proportions of other elements or by treating the metal in some special way. Of these, the most successful seems to have been that of bubbling boron trichloride through the molten metal. This treatment induces a very fine crystal structure in the cast metal and minimises the natural tendency of zinc sheet to increase the size of its crystals at temperatures only slightly in excess of room temperature. The normal ductility of the sheet is not impaired, and it is curious that more extensive industrial application has not been made of the process just indicated.

Of solid additions, as distinct from treatment by a gas, nickel, copper and, more particularly, manganese are sometimes added to produce so-called "ductile" zinc which can be rolled into thin foil. The exact way in which these additions act seems uncertain: their benefit is unquestionable, but their influence as a restrainer of crystal growth is less marked, and also less permanent, than that of the boron-trichloride treatment.

Technique. In view of the peculiarities just indicated, it will be evident that zinc must be accorded special treatment and that certain conditions must be observed if failure in the press is to be avoided. Apart from minor precautions which will be discussed later, the following three essential conditions must be observed :—

(1) The sheet must be of high purity, such as the well-known 99·99 per cent. variety, and must have a suitable crystal size which will depend on the nature of the article and operation but should never be more than 0·05 mm. adjudged "average grain size."

(2) The sheet must be deep drawn or pressed warm. The temperature, which may be somewhat critical, will vary a little according to the nature of the operation, the speed of the draw and other factors, but will generally lie between 25° and 50° C. It will be observed that this temperature is much lower than that used for impact-extrusion or that corresponding to the range of maximum ductility found by Mathewson, Trewin and Finkledey,[79] but it will be appreciated that the temperature of the metal will rise almost instantaneously during the press operation.

Blanks may be heated conveniently in a bath containing water or dilute "suds"; careless warming over a hot-plate or in an indifferently-controlled air-oven must be strongly deprecated because it is impossible to heat blanks to exactly the desired temperature in this way.

The critical nature of the temperature to which blanks must be heated is well illustrated by the production of the shell shown in Fig. 177, (p. 303). If blanks having a satisfactory crystal size are heated to

20 to 30° C., they break in the press owing to insufficient ductility ; if they are heated to 30 to 40° C., the shell can be formed satisfactorily ; when they are heated to 40 to 50° C., the crystals grow to such a large size during the spontaneous annealing which occurs as a result of the first draw that failure occurs during the second draw. These values are to be regarded merely as illustrative : other values may obtain under different conditions.

(3) The temperature of the tools must be kept reasonably constant in order to avoid a dangerously large variation in the crystal size of the finished product. Using zinc blanks of initially satisfactory crystal size and heated to a constant temperature it will be found that, as the tools get hotter and hotter during a prolonged run, the crystal size of the product may increase to a most undesirably large value. This defect can be minimised to some extent by warming the tools artificially before a run is started and by warming blanks to the temperature found suitable for continued production ; and, sometimes, by judicious cooling of the tools during action.

Leaving these three principal considerations, tools and speed of drawing claim attention. Owing to the relatively low tenacity of zinc, the radius on drawing dies should be generous and the clearance ample, because any added stress imposed by ironing will tend to fracture the walls of a shell. In practice it is often found that an unusually slow speed of drawing enables the deepest draws to be produced owing, probably, to the lower temperature attained by the metal during its passage through the tools. Could this practical difficulty of temperature increase be overcome, there is reason to suppose that a high speed of drawing might prove distinctly advantageous.

Tools. Owing to the soft nature of zinc it might be expected that tool wear would be very slight and that little attention would need to be given to hardening. While this assumption may be true in theory, in practice it is desirable to use steel tools which have been properly hardened and well polished in order to lessen the likelihood of fouling and, of importance, to reduce friction so that both the heat generated in, and the drag on, the metal may be kept as low as possible. It is the experience of a number of users that the extra cost of chromium-plating steel tools is amply justified.

Lubricants. Information regarding drawing lubricants for zinc is very scarce. This is regrettable, because the peculiarities of zinc extend to its behaviour toward various lubricants. Vaseline is used with success, but it is common experience that good lubricants possessing excellent " oily " characteristics give unexpectedly poor results. On the other hand very dilute " suds," which normally are a relatively poor lubricant, seem to give excellent results when applied generously, and reports show that this lubricant is a popular one for the deep drawing and pressing of zinc ; if desired, blanks can actually be heated to drawing temperature in a bath of suds placed beside the press.

Brownsdon [11] states that dilute soap solutions, although satisfactory when only a single press operation has to be carried out, may cause trouble during a second operation due to the action of the alkali upon the zinc. For this reason it seems preferable to use a soluble oil free from alkali.

Annealing. A peculiarity in the manipulation of zinc is that no annealing is necessary, because the pure metal recrystallises readily—and sometimes almost instantaneously—at the temperature attained during most press operations. Indeed, as has been pointed out already, one of the main problems encountered in the pressing of zinc is how to keep crystal growth within safe limits when blanks are warmed to the temperature necessary to ensure good behaviour under the press.

Crystal growth may continue to take place for some time after the metal leaves the tools if cold-worked articles are allowed to cool down in air. For this reason, when an article has to be shaped in more than one stage, it is the practice in some shops to make a point of carrying out successive operations as quickly as possible and not allowing partially-drawn shapes to stand about for more than a few minutes.

To summarise, it can be said that zinc can be deep drawn and pressed successfully, but that special precautions must be strictly observed if breakage and excessive crystal growth are to be avoided.

Stainless Steels

In the past the deep drawing and pressing of the so-called " stainless steels "—although " corrosion resisting " is a more truthful description—has been confined principally to two austenitic varieties containing, respectively, approximately 18 per cent. of chromium and 8 per cent. of nickel (known universally as " 18/8 ") and 12 per cent. each of chromium and nickel (known sometimes as " 12/12 ") ; the carbon content of each variety being approximately 0·1 per cent. or rather less. Of these, the " 18/8 " possesses the best general corrosion resistance, but it is slightly harder and cannot be deep drawn or pressed to quite the same degree as the " 12/12 " variety which has been developed specially for deep drawing, pressing and spinning. During recent years a variety containing from 17 to 25 per cent. of chromium with little or no nickel has been used to an increasing extent. This range of alloys, which is not austenitic but ferritic, needs a different press technique and different annealing treatment from that required by the austenitic range. The essential differences will be indicated later in the appropriate sections.

For the benefit of readers unfamiliar with metallurgical terms it must be explained that "austenitic" is the adjective derived from "austenite," the name given to a solid-solution of iron carbide in *gamma* iron (see the iron-carbon equilibrium diagram, Fig. 134, p. 202). It will be seen from this diagram that plain carbon steels are austenitic only at high temperatures, although it is possible in high-carbon steels to retain a proportion of austenite by very drastic quenching; but the addition of a considerable proportion of nickel or chromium renders the austenitic phase staple at ordinary temperatures even when the rate of cooling is slow, and confers the corrosion-resisting properties which are such a valuable feature of the range of nickel-chromium-iron alloys known popularly as "stainless steels." The adjective "ferritic" implies that the microstructure consists essentially of ferrite, the principal constituent of ordinary low carbon steels; but when approximately 17 to 25 per cent. of chromium is dissolved in ferrite, the resulting solid-solution acquires corrosion-resisting properties comparable to those of the austenitic variety. To secure the highest possible resistance to corrosion, the highest ductility, and to avoid certain practical difficulties it is important that the percentage of carbon should be as low as possible in both the austenitic and the ferritic kinds of stainless steel sheet used for deep drawing and pressing; 0·1 per cent. of carbon should be regarded as the maximum allowable, and a considerably lower percentage is an advantage.

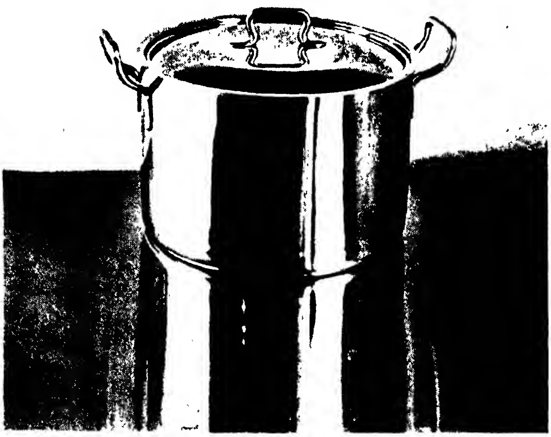
From a consideration of the physical properties of austenitic steels it is clear that, theoretically, these alloys should possess even better deep drawing and pressing properties than the ordinary grades of low carbon deep-drawing quality steel sheet. The fact that austenitic steel can be drawn into the extremely fine tubes used by the medical profession for hypodermic needles gives some idea of its capacity to suffer deformation by true drawing; the ability of sheet to suffer deep drawing and pressing in the ordinary press-shop is well illustrated by the 18-inch deep ice-cream container shown in Fig. 178 and by the many domestic articles—for example those shown in Fig. 287 (p. 600)—with which all readers must be familiar.

To show that the rate of work-hardening of austenitic steel is not, as is believed sometimes, so high as to render inter-stage annealing necessary with even light draws, there may be instanced the saucepan shown in Fig. 179. This saucepan is deep-drawn to its full depth *in one operation*, and aptly demonstrates what can be done with austenitic steel sheet when it is treated properly. As an example of press-work in sheet of heavier gauge, the large pans illustrated in Fig. 180 are of interest.

In spite of the many deep-drawn articles which are produced, the excellence of austenitic steel sheet for deep drawing and pressing is often questioned in no uncertain manner by practical press-shop operators, particularly those of the older school, and it is therefore

[*By courtesy of Joseph Sankey & Sons Ltd.*

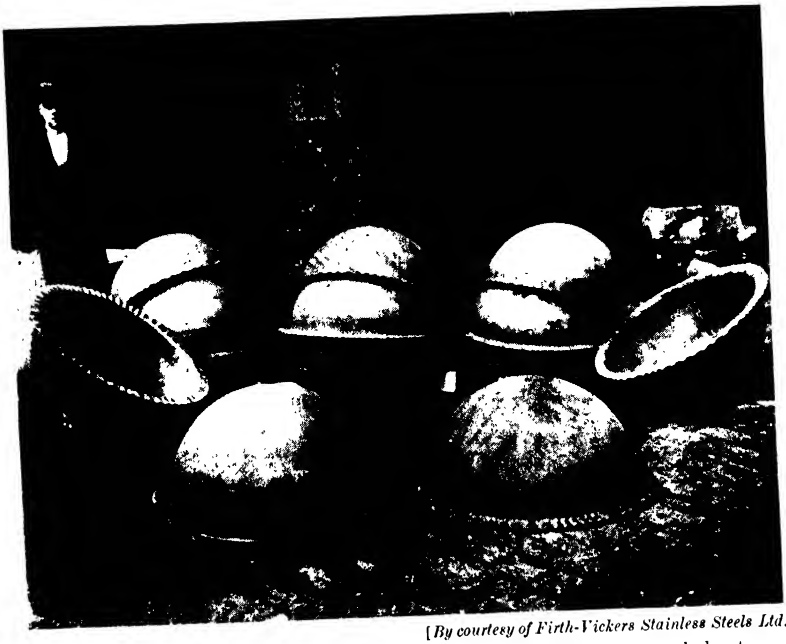
Fig. 178. 18-inch deep ice-cream container deep-drawn in six operations from " 18/8 " austenitic steel 0·048 inch thick.



[*By courtesy of Joseph Sankey & Sons Ltd.*

Fig. 179. Saucepan deep-drawn in one operation from " 18/8 " austenitic steel sheet 0·104 inch thick.

[*To face p.* 314.



[*By courtesy of Firth-Vickers Stainless Steels Ltd.*

FIG. 180. Large pans pressed from "Staybrite" austenitic steel sheet.

FIG. 181. Photomicrograph showing carbide precipitation produced in "18/8" austenitic steel sheet as a result of slow cooling from the annealing temperature. × 300.

[*To face p.* 315.

necessary to examine this apparent discrepancy between theory and practice. It can be stated quite definitely that the theoretical ability of austenitic steels to suffer severe plastic deformation by deep drawing and pressing operations is unquestionable; for example, an Erichsen value of no less than 16 mm. can sometimes be obtained on 20-gauge sheet, while stress-strain curves indicate an unusually large range for cold-working. The practical difficulties—which, it must be admitted, are both genuine and serious—encountered in the press-shop usually arise from the three following causes:

(1). Fouling, scoring and severe wear on tools which occur because of the relatively high pressures which have to be used.

(2). Practical difficulties associated with inter-stage annealing unless this operation is carried out in modern controlled-atmosphere furnaces.

(3). Failure to apportion successive draws in accordance with the true work-hardening behaviour of the alloys under consideration.

Each of these three causes will be examined later but, before passing on to a more detailed consideration of technique, lubricants and annealing, it will be convenient at this stage to examine several causes of trouble which are not embraced by the three just enumerated as needing special attention. As is only natural an unsuitable "average grain size," whether present in purchased sheet or produced by incorrect inter-stage annealing in the works of users, will cause trouble as with other metals; too small a crystal size will engender low ductility, and too large a crystal size will cause an undesirably rough surface to be produced on pressed or drawn work, a fact which is of more than usual significance because—in comparison with brass and steel—austenitic steel is not easy to polish.

Austenitic steels are at least as sensitive to the property of "average crystal size" as the *alpha* brasses. In general, a fairly large crystal size will be found better for pressing provided that polishing is not thereby rendered too difficult and expensive; for true deep drawing, a small crystal size—say of the order of 0·030 to 0·035 mm.—is usually desirable, and this size should not be increased more than can be avoided during inter-stage annealing.

The "average grain size" of brass is often guessed at from the results of an Erichsen test. Although the appearance of the surface of the Erichsen dome remains a useful guide with austenitic steel sheet, it is important to notice that this latter differs markedly from brass and steel in that the depth of the cup is only slightly influenced by the thickness of the sheet being tested. Houdremont [80] records that for austenitic steel sheet of the popular "18/8" variety the depth of the Erichsen cup only increased from 14·4 to 15·5 mm. as the thickness of the sheet increased from 0·020 to 0·080 inches, whereas that of ordinary deep-drawing quality steel sheet increased from 8·3 to 12·1 mm. for a corresponding increase in thickness.

A troublesome defect which is sometimes encountered, particularly when the carbon content is rather high, is that known in the shops as "pimpling." This defect takes the form of clusters of tiny bright spots attributable to the existence of segregated particles of carbides which, being hard and non-ductile, tend to be forced into prominence as the sheet containing them is thinned by stretching.

Defects attributable to under-annealing, over-annealing, precipitation of carbides due to slow cooling from the annealing temperature, inadequate removal of lubricant and incorrect pickling complete the list of the more common causes of trouble encountered during the deep drawing and pressing of austenitic sheet. These defects can be examined most conveniently in the following sections which deal with press-shop technique and annealing; but, to conclude this general survey of the properties of austenitic steel, mention must be made of critical-strain crystal growth and stress-cracking, two defects which often prove troublesome.

Critical-strain crystal growth sometimes occurs in those regions of deep drawn or pressed stainless steel articles which have suffered the "critical" amount of strain. This unwelcome phenomenon is most pronounced in the ferritic as distinct from the austenitic kinds of stainless steel. Houdremont [80] has investigated this tendency and finds that an abnormally large crystal size is quickly developed in the ferritic variety containing approximately 17 per cent. of chromium when the metal is annealed at a temperature near 800° C. after having been strained to an elongation of between 8 and 10 per cent., or at 900° C. after an elongation of between 2 and 10 per cent.; but that at 1,050° to 1,100° C., after the same amount of strain, crystal growth is relatively slight.

The austenitic varieties of stainless steel are not so susceptible to critical-strain crystal growth as the ferritic kinds, but troublesome growth may take place when austenitic steels of the popular "18/8" or "12/12" kinds are annealed at an unnecessarily high temperature. According to Monypenny [134] critical-strain crystal growth is greatest when austenitic steel is annealed at a temperature of 1,200° C. or over after an elongation of about 5 per cent. Fortunately it is markedly less when the annealing temperature is 1,150° C., and usually negligible at 1,050° C.

Austenitic steel, when severely cold-worked, is liable to fail by cracking; but the common assumption that this phenomenon is similar to the season-cracking of brass needs to be proved. The season-cracking of brass, although needing internal strain for its manifestation, is dependent essentially upon the action of some external agent, for example traces of ammonia in the atmosphere; as far as the author is aware, it still remains to be shown that cold-worked austenitic steel will not crack in a very pure atmosphere or when protected by a non-porous electro-deposited coating. Be this as it may, the fact remains that it is always desirable to anneal any severely cold-worked austenitic steel shape within half an hour of its being strained if spontaneous cracking is to be prevented with certainty. Fig. 93 (p. 130) shows a saucepan shell which, owing to the severity of the draw, cracked in the manner shown in less than half an hour after drawing.

Technique. In an earlier chapter attention has been directed to the importance—which is not always appreciated sufficiently—of maintaining sharp edges and suitable clearances on the tools used for blanking, out of sheet or strip, discs or shapes destined to be deep-drawn. It is particularly necessary to observe this precaution with austenitic steel sheet, because its marked work-hardening properties render the influence of a bad burr more than usually detrimental to the free flow of metal.

Owing to their higher tensile strength, austenitic steels need approximately 50 per cent. more power than ordinary dead-mild steels for similar deep drawing and pressing operations. To this fact must be attributed the recognised rapid rate of wear on tools, the tendency to foul and score and, consequently, the need for excellent lubrication; its better appreciation would lead to less invidious comparison of the behaviour of austenitic steel under the press with that of the softer, yet actually not less ductile, metals brass and ordinary steel.

Partly on account of this and partly because of the higher rate of work-hardening of austenitic steel, it is desirable to use a larger radius on drawing dies than is commonly used for brass and steel; indeed, it will usually be found beneficial to have the largest radius which can be used without the formation of objectionable puckers. Clearances should be ample unless "ironing" has to be carried out by design: because the additional drag caused by unnecessary ironing, such as often occurs near the end of the stroke owing to the thickening of the metal near the periphery of a blank, will increase the already considerable power required to complete the draw. The natural physical properties of austenitic steels do not make light loading of the pressure-plate essential but, in order to keep the stress in the metal—and therefore the contact pressure between the tools and work—as low as possible, thus avoiding scoring and fouling, it is usually desirable to work with the pressure-plate loaded relatively lightly unless a fairly shallow shape is being drawn over a draw-ring having a large radius. The process of reversed drawing can be applied to austenitic steels, and facilitates the successful forming of difficult shapes in which straight-forward methods of pressing tend to thin the walls unduly.

Under normal industrial conditions it is found that what, judged by present standards, must be described as a slow speed greatly facilitates deep-drawing. In explanation of this Gordon [81] suggests that the rate of work-hardening of austenitic steels is less with a slow than with a high speed of straining. In the light of present knowledge this explanation must be questioned, because it has been shown that with other metals the reverse may be the case. It seems more likely that the proved benefit of a slow speed of drawing is attributable to the attainment of less high instantaneous temperatures at the surfaces of tools and work during the working stroke, thus reducing the tendency toward fouling, scoring and increased friction through breakdown of the film of lubricant; for, as is now becoming generally recognised, one of the greatest problems encountered in the deep drawing of austenitic steels is the maintenance of a proper film of lubricant which will prevent even momentary metal-to-metal contact between tools and work.

It has already been pointed out that the hardness and tensile strength of fully-annealed austenitic steels is appreciably greater than that of steel, still more so than that of brass. At the other end of the scale the dissimilarity is still more pronounced, for austenitic steels can be cold-worked to give a hardness approaching 500 V.P.N. Although this value may not be attained as a result of ordinary deep drawing and pressing operations, relatively high values will quickly be reached, and it is hardly necessary to point out that as the hardness increases so also will the force needed to draw the metal through the tools; this will increase the contact pressure on the working surfaces and, as a result, there will be an increased likelihood of scoring and fouling taking place. For this reason it is often advisable to anneal shapes before their full capacity to suffer plastic deformation has been exploited, and this precaution will reduce both the wear on the tools and the likelihood of scoring and fouling. When inter-stage annealing had perforce to be carried out in ordinary atmospheres and therefore to be followed by difficult pickling operations—themselves likely to cause failure by severe pitting—there was every excuse to justify the curtailment of annealing to the absolute minimum; now that controlled-atmosphere annealing is becoming the rule rather than the exception, the giving of frequent inter-stage annealings will usually be found well worth while and, if carried out properly, not productive of excessive crystal growth.

It is important to notice that the methods of deep drawing or pressing the austenitic and the ferritic varieties of stainless steel are different; the austenitic alloys should be given the deepest possible draw in the first operation, whereas the ferritic ones should be given a light first draw, after which it will be found that more severe draws can be accomplished without difficulty, a state which is rendered impossible by the imposition of a severe first draw.

Tools. After what has been said it will be obvious that only the most durable tool materials can be expected to give a useful life when called upon to withstand severe deep-draws with austenitic steels.

Carbon steel tools indifferently hardened are of little use ; properly hardened to not less than C64 Rockwell they can give useful service on light draws, but the extra initial expense of nitrided tools will usually be recovered many times over. Because of the high pressures which they often have to withstand, it is most important that nitrided tools destined for use with austenitic steel have a core of relatively high hardness in order to prevent the case "caving-in" and cracking. Lack of appreciation of this point sometimes leads to the early failure of perhaps experimental nitrided tools and, in consequence, to subsequent neglect of the very valuable help which suitable nitrided tools can give in the deep drawing and pressing of austenitic steel.

When fairly heavy draws have to be accomplished with austenitic steel and it is not desired to use nitrided tools, a particularly useful variety of tool steel is one containing from 1·5 to 2 per cent. carbon with about 6 per cent. tungsten. This hardens to C65 Rockwell and is so resistant to abrasion that it proves difficult to grind, and may develop surface cracks if the operation is forced by operators unaware of its special properties.

Opinion seems to be divided concerning the merits of the high-carbon high-chromium class of tool steel when working against austenitic steels ; it may be that, when lubrication is good, such tools will give a better life than ones of plain carbon steel by reason of their recognised greater wear-resisting properties but that, if poor lubrication allows easy metal-to-metal contact between tools and work, the high-chromium steel may possess the greater natural affinity for the austenitic steel and thus actually render the occurrence of "loading" more likely than when plain carbon steel is used. It is not intended that this hypothesis should hinder high-carbon high-chromium tools being experimented with for, though logical, it is based on slender evidence. When nitrided, this type of steel offers a hard core and a fairly hard nitrided skin, and is for this reason particularly useful with austenitic steels. With the ferritic type of stainless steels, high-carbon high-chromium tool steels are of proved value.

Chromium-plated tools have given satisfaction, particularly on light draws, but the plating must be exceptionally good and the underlying steel of ample strength to withstand the high pressures which it has to withstand during service.

Turning to less expensive tool materials, it is refreshing to record that excellent service is being obtained from tools of inoculated cast iron. Without doubt this material, in both the as-cast and the heat-treated condition, will find increasing application for tools used on austenitic steel.

With all tool materials, and particularly with the harder steels, it is most important that the best possible polish be given to the working faces in order to reduce friction as much as possible and to lessen the danger of even highly localised and momentary breakdown of the lubricating film occurring.

Lubricants. It is absolutely essential that a good lubricant be used during the deep drawing and pressing of austenitic steels. If this is not done, severe scoring and fouling is likely to take place and, even should these defects not assume really serious proportions, increased friction may stress the walls of the shape so severely that fracture will occur in them before the full depth of draw has been accomplished.

Although nearly every press-shop seems to have its own special formula for the lubricant to be used on austenitic steel, unanimity of opinion concerning the value of graphite, irrespective of the medium in which it is suspended, is striking. Considering the unique properties of graphite this is not surprising, but quite often its use is restricted by the difficulty attached to its adequate removal from articles after drawing has been accomplished. Although with other metals graphite is invariably suspended in an oily medium, it is interesting to record that good results have been obtained with austenitic steels when a water suspension is used provided that the lubricant is allowed to dry before the metal is pressed or drawn.

In general it may be said that, of the older kinds of lubricants, mixtures of chalk, lithopone and even sulphur with linseed oil are of proved value; that for moderately severe operations the ordinary type of "filled" lubricant used for heavy draws on steel may sometimes be sufficient, and that that true stand-by of the press-shop, castor oil, is as useful as ever. Owing to the necessity for the complete removal of sulphur prior to bright-annealing, it is desirable not to use sulphur-bearing lubricants when inter-stage annealing is carried out in controlled-atmosphere furnaces. Of the new types of lubricant having complex chemical additions to increase their power to form a strongly absorbed film on the surface of the work, none can be singled out for special mention; more time is needed for their proper trial before definite opinions can be expressed.

It is most important that all traces of drawing lubricant be removed from the surface of austenitic steel before it is annealed: failure to do this results in troubles which are often attributed, quite incorrectly, to the annealing or, if one is used, to the pickling operation. De-greasing in a trichlorethylene plant in which only vapour reaches the work may not prove adequate with lubricants of a greasy nature: high-pressure sprays or suitable emulsifying solutions may have to be used. It has been found that carbon tetrachloride removes a higher percentage of grease than trichlorethylene, and this cleanser has proved of considerable benefit in small shops which are not equipped with efficient modern de-greasing plants.

Annealing. Austenitic steels have to be annealed at a higher temperature than any of the commonly-used industrial metals. In the past this has led to much trouble being experienced owing to partly-formed shapes not having been annealed properly and, incidentally, to heavy maintenance costs on furnaces forced to work at temperatures beyond their safe maximum. Annealing at relatively low temperatures will remove internal strain and will restore some measure of ductility; but to ensure proper recrystallisation, which is essential if full ductility is desired, the correct annealing temperature *must* be reached.

In order to anneal cold-worked austenitic steel properly it is necessary to heat it, preferably as quickly as possible, to a temperature of 1,050 to 1,150° C., to hold it at this temperature for only a very short time (say, two or three minutes in the case of thin sheet) and to cool it rapidly. If a longer period of soaking is given, it is likely that an undesirably large crystal size will be produced ; if the cooling rate through the range 900 to 550° C. is not sufficiently rapid, inter-crystalline precipitation of carbides, causing brittleness, will take place unless the steel happens to be one of the special varieties developed to prevent trouble arising from this cause.

In order to prevent carbide precipitation, it is common practice to quench austenitic steel in water from the full annealing temperature, but with thin gauge metal air-cooling is often sufficiently rapid to ensure excellent ductility if quenching is inconvenient or likely to cause serious distortion. For metal of medium thickness, cooling by means of an air-blast is usually adequate, and often more convenient than quenching in water.

In the past one of the difficulties associated with the production of deep drawn or pressed shapes in austenitic steel has been the removal of the very objectionable scale which is formed during annealing at the high temperature, that is in the region of 1,050° C., which is necessary to restore full ductility to the cold-worked metal. Numerous special solutions have been devised to pickle austenitic steels, but the very fact that special baths have to be used is an annoyance in shops having a limited output ; another disadvantage is that, as a rule, even these special solutions leave a grey, slimy sludge on the de-scaled surface of pickled metal which has to be removed by rubbing, an operation which is usually carried out by hand : a messy and objectionable procedure.

Another drawback to the pickling of austenitic steel is that it is very easy to produce a badly pitted surface if the conditions for pickling are not quite right and, in the experience of the author, sometimes even when these appear to be in accordance with the recommendations of the steel supplier.

Whenever possible the inter-stage annealing of austenitic steel shapes should be carried out in modern furnaces having a properly controlled atmosphere, thus avoiding the need for subsequent pickling.

In the early days of so-called bright-annealing, austenitic steels proved to be one of the most difficult of the industrial metals to anneal in a manner which justified the description "bright," and an additional and unexpected difficulty was encountered in that a very thin coating of oxide, consisting mainly of chromium oxide, proved far more difficult to remove by pickling than the thick coating, consisting of a mixture of the oxides of chromium and iron, which was acquired during open-furnace annealing. The advent of controlled-atmosphere muffle furnaces coupled, more recently, with an increase in the purity of the protective atmospheres available industrially (and, incidentally, a reduction in their cost) has removed these difficulties, and it is now possible to carry out genuinely bright inter-stage annealing of austenitic steel pressings at a reasonable cost if certain definite yet not unreasonably exacting precautions are observed.

These essential precautions are three in number. The gas used must be very pure; it must not be allowed to become contaminated while in the furnace and, lastly, the rate at which work cools must be fairly rapid. In the opinion of many authorities "cracked" ammonia, well dried and purified, is the only gas yet available which will enable true bright-annealing to be carried out with safety. The use of a well-sealed muffle furnace is usually necessary because a refractory lining allows traces of moisture to percolate and contaminate the furnace atmosphere. As 0·01 per cent. of moisture is sufficient to cause oxidation, the need for this precaution will be evident; although, if refractory-lined furnaces are not allowed to cool down over a considerable period of operation and are thoroughly purged before a charge is passed through them, good results can be obtained. Experiments with burnt ammonia show that, if well dried, the resulting atmosphere will give adequate protection; so, in view of the low operating costs of a re-circulated burnt-ammonia annealing furnace, it is likely that this type will become popular.

The importance of removing lubricant from the surface of austenitic steel before it enters the furnace must be obvious, yet inadequate cleaning is still the unsuspected cause of much trouble for which the atmosphere is unjustly blamed.

When the inter-stage annealing of varieties of austenitic steel which are not immune from "weld-decay" is being carried out in the popular belt-conveyor type of furnace, such as the one shown in Fig. 312 (p. 680), it is necessary to ensure that the cooling rate is sufficiently rapid to prevent carbide precipitation. By reason of the very short heating time which is necessary, it is usually possible to do this with thin shapes by speeding up the belt of furnaces not specially designed for annealing austenitic steel, yet instances are on record of metal thicker than ⅛ inch having had its ductility impaired by the precipitation of carbides caused by too slow a rate of cooling. Fig. 181 shows a typical example of carbide precipitation at the crystal boundaries of austenitic steel sheet which has cooled too slowly from an annealing temperature of 1,100° C. The steel, which was of the "18/8" variety, contained 0·11 per cent. of carbon with, of course, no inhibitor of "weld-decay." A glance at the photomicrograph will show that considered from the aspect of deep drawing, and indeed from most others, the physical properties of the sheet have been ruined. When new, continuous-type furnaces are being purchased and there is any likelihood of their having to be used for austenitic steel, a special point should, therefore, be made of seeing that a desirably rapid cooling rate can be obtained.

The procedure for inter-stage annealing the ferritic variety of stainless steel differs from that required by the austenitic type. A temperature of 760° C. is sufficient if a moderately short soaking period is allowed, but some users prefer to soak at a higher temperature, say 800 to 820° C., for a period of about two minutes. With either treatment, air cooling is satisfactory. The markedly lower temperature needed by the ferritic steel makes annealing relatively easy, and is a point which may favour the selection of the ferritic rather than the austenitic variety of stainless steel when other conditions allow.

Pickling. It has already been said that, owing to the need for special baths and to the pitting which sometimes occurs on the surface of pickled work, the pickling of stainless steels is an unwelcome operation in many press-shops. Special baths cannot be avoided, but pitting can be greatly reduced by ensuring that the baths used are in good condition and by keeping a close watch on pickling procedure.

One popular bath contains approximately 50 per cent. commercial hydrochloric acid, 5 per cent. nitric acid and about ½ per cent. of one of the proprietary "restrainers." This bath, which should be used at a temperature of from 50° to 60° C., gives a reasonably bright surface but needs to be kept in good condition if pitting is to be avoided. The solution must be kept oxidising by periodical additions of nitric acid, and the percentage of hydrochloric acid must not be allowed to become seriously reduced through the action of the metal or by dilution from steam heating. When, through prolonged use, the percentage of ferric chloride in the solution approaches 20, it is difficult to obtain satisfactory results.

It is a common practice to give austenitic steel a double pickle, first in a warm sulphuric acid solution to loosen the scale and then in a nitric acid solution to brighten the surface, although there is considerable divergence of opinion as to the best strength of both these solutions. Thus the sulphuric acid solution may contain between 5 and 15 per cent. of acid, usually with a "restrainer" and sometimes with an addition of about 5 per cent. of hydrochloric acid or 10 per cent. (by weight) of rock salt to increase the rate of action. The strength of the nitric acid solution seems to vary from 5 to 20 per cent. of acid, and sometimes about ½ per cent. of hydrofluoric acid is added; it is generally used cold.

Another bath, recommended by Monypenny [134] as giving a particularly good surface on austenitic steel, contains from 3 to 5 per cent. of nitric acid with 1 per cent of hydrochloric acid. It is used cold, and is not suitable for removing heavy scale.

Polishing. It is important that polishing compounds used with stainless steels should not contain rouge which, of course, is iron oxide. If they do, traces of rouge will be smeared into the surface of the polished article and this will lead to bad staining if not actual rusting. When for some reason rouge has to be used, it is advisable to dip all polished work into a bath of nitric acid diluted with water to 25 to 30 per cent. strength maintained at a temperature of about 65° C. This dissolves away any surface material not of high-chromium content, and greatly improves the resistance of the polished surface to ordinary atmospheric corrosion.

It is often worth while giving this acid dip even when rouge is not used as a polishing compound, and even when no polishing at all is given, because minute traces of ordinary steel sometimes become smeared on to the surface of stainless steel articles made by machining or pressing. The possibility of surface contamination of stainless steel articles with minute but harmful traces of ordinary iron or steel is one which is often overlooked.

Weld Decay. Many austenitic steels suffer from the defect known as "weld decay," the name given to serious embrittlement attributable to the precipitation of dissolved carbides followed by their migration to the crystal boundaries, as shown in Fig. 181, when the metal is allowed to cool slowly through the range 900° to 500° C. The range 700° to 600° C. is, however, by far the most dangerous, and it is believed that the reason for this is that when the temperature is above the dangerous range the precipitated carbide is relatively mobile and tends to "ball up" instead of segregating in the form of continuous envelopes surrounding the crystal grains; whereas, when it is below this range, movement of the carbide is too sluggish for the dangerous envelope formation to proceed except after prolonged heating.

Opinions differ as to the time of exposure which is necessary to induce a dangerous degree of carbide precipitation. Monypenny [134] states that two minutes at 600° to 700° C. is sufficient to spoil austenitic steel having no special additions to retard such precipitation, yet experience in the annealing of this variety in continuous tunnel type furnaces suggests that longer periods can be tolerated sometimes. However, the carbon content has a marked influence on the tendency of any piece of austenitic steel toward "weld decay," and this may explain seeming discrepancies between the experiences of different workers. Raising the percentage of nickel helps to retard "weld decay," and a steel containing 18 per cent. of chromium with 15 per cent. of nickel is distinctly less susceptible to this defect that the more common, and less expensive, "18/8."

"Weld decay" can be retarded in two ways, namely, by ensuring that the percentage of carbon in the steel is so low that, after precipitation in the form of carbides, it is practically non-injurious; and by the addition of some element which will retard the precipitation of carbide or will render it less harmful after precipitation. The first method is the least efficient, for whereas at one time it was believed that 0·10 was the percentage below which dangerous "weld decay" would not occur after a reasonable period of heating, Bain and Abord [139] have shown that 0·03 per cent. of carbide is retained in solution at temperatures below 800° C. in steels of this kind, and this maximum, which is difficult to achieve under industrial steel-making conditions, is now generally accepted as the only safe one. This method, alone, is therefore not of much industrial value, yet the reduction of carbon to the lowest possible percentage is to be encouraged, first because it does retard "weld decay" and, secondly, because it renders more easy the task of the special elements whose addition constitutes the second preventive method. As already explained these additions act in two ways: from 0·3 to 1·5 per cent. of tungsten may be added to increase the stability of the carbides in solution; or from 0·1 to 2·0 per cent. of titanium, or 0·3 to 2·0 per cent. of vanadium may be added to engender the formation of less harmful carbides. The amount of any of these elements needed to give a useful degree of immunity will depend on the amount of carbide present. Recently Atkinson and Hagon [1] have shown that the addition of about 0·5 per cent. of silicon coupled with a special heat-treatment designed to precipitate the dissolved carbide from solution results in the production of isolated spheroidal carbide particles which are relatively harmless. This method is by far the most efficient of any yet found for the prevention of "weld decay."

Useful as these methods are, it must be emphasised that, with the possible exception of the method of Atkinson and Hagon, they do not give complete immunity from, but merely retard, "weld decay" sufficiently to enable industrial operations such as welding and short-time annealing to be accomplished without impairing the mechanical properties of the metal. For this reason it is most desirable to specify one of the "weld-decay-free" varieties of austenitic steel sheet for the production of deep drawn or pressed articles whenever inter-stage annealing or welding is included in the scheme for fabrication. As a general indication of the behaviour of these "weld-decay-free" austenitic steels, it can be stated that the specially low carbon "18/8" variety possesses deep-drawing properties intermediate between those

[1] British Patent No. 348586, 1931.

of ordinary "18/8," containing about 0·1 per cent. carbon, and those of the "12/12" variety. The presence of tungsten is held by some authorities to reduce the ductility of austenitic steels by a noticeable amount.

Summarising this section, the excellent deep drawing and pressing properties of both the austenitic and ferritic types of "stainless" steel sheet are established beyond question by both theoretical evidence and the achievements of some press-shops. Failure to achieve good results points to ignorance of the special technique demanded by these metals, to unwillingness to adopt special methods, or to a lack of appreciation of their genuine necessity.

Alloy Steels

Information on the deep drawing and pressing of alloy steels is scanty. It appears that best results are obtained if alloy steels—whether of the low-tensile variety, for example ones containing copper or a low proportion of chromium, or the high-tensile variety, such as the nickel-chromium steels used for aircraft spars—are shaped by a technique similar to that established for the ordinary grades of steel sheet used for deep drawing and pressing. As is only natural, less depth of draw can be inflicted as the hardness of the sheet increases, for the essential properties—such as the general form of the strain-hardening curve—remain unchanged unless the alloying elements produce a change to the austenitic phase, in which case the whole behaviour of the metal changes.

An example of a cupping operation in high-tensile nickel-chrome steel 0·020 inch thick is shown in Fig. 286 (p. 600). The tensile strength of the sheet used is approximately 45 tons per square inch and the Erichsen value usually varies from 7·5 to 7·8 mm., although this particular component can be made when the Erichsen value of the sheet falls as low as 6·9 mm. The required tensile strength of this kind of steel sheet is usually obtained partly by alloying and partly by cold-rolling; as the last-named operation tends to give undesirably pronounced "directional" properties, careful examination of purchased sheet is often necessary.

The essential precautions to be observed are the use of very hard and very smoothly polished tools, preferably chromium-plated or nitrided, and of a lubricant of high film strength. Needless to say, a slow speed of drawing will ease the task of the lubricant by keeping the surface temperature lower than would be the case with higher speeds. As an alternative to very hard tools of expensive steel, inoculated cast-iron tools both in the as-cast and the heat-treated condition have given remarkably good service, and are markedly less liable to foul and gall than ordinary steel tools unprotected by nitriding or plating.

With what may be defined as the low-tensile or ductile variety of alloy steels, the process of reverse drawing and pressing has proved of benefit; but this procedure cannot be adopted with non-austenitic steels of high tensile strength, say above 30 to 35 tons per square inch.

Lubricants containing either a filler or some special addition to increase their oiliness and film strength are always desirable, and often essential, for the successful deep drawing and pressing of alloy steels. The question of special lubricants is discussed in Chapter XI and will not be enlarged upon here; in the deep drawing and pressing of high-tensile steel strip into the shapes required for aircraft spars, graphite has proved of considerable value, particularly in prolonging the life of the mandrels which of necessity may have a very small working area, but the problem of removing all traces of graphite from the surface of the finished product often forms a serious drawback to the use of this very efficient lubricant.

It can be said then, by way of summarising this section, that the deep drawing and pressing properties of steel sheet of relatively high-tensile strength, although relatively poor, are sufficiently good to enable shapes of limited yet useful depth to be formed under the press, sometimes in one operation.

An attempt has been made in this chapter to review most of the points of importance relating to the deep drawing and pressing of metals other than brass and steel. Even less published literature exists relating to the working of these other metals than to the working of the more commonly-used metals brass and steel, and readers having specialised knowledge of the manipulation of some particular metal may consider that useful information has been omitted. If by reason of this they feel constrained to publish their own findings for the help of their fellow-workers, this attempted review will have served at least one useful purpose.

In the past the manipulation of the less common metals under the press has been governed almost entirely by the necessarily limited knowledge and experience of individuals. It is to be hoped that dissemination of the very considerable amount of useful knowledge which lies stored in the heads of practical workers will lead to an improvement in the general technique of deep drawing and pressing, and to a more rapid and understanding solution of the many difficulties which are met with. Progress will be still more rapid if, in addition to this badly needed benefit, knowledge gained from theoretical studies is applied. To give but one illustration: the information given by one of the special forms of stress-strain curve described in a later chapter could, if interpreted intelligently by men having both theoretical knowledge and practical experience, provide working data which could only be obtained—and then but qualitatively—by practical workers after many years of experience.

CHAPTER IX

PRESSES

ALTHOUGH consideration of the mechanical design of presses may not seem to fall within the province of the normal metallurgist, it is desirable to include in this essentially metallurgical dissertation some mention of items which are of special significance to him because they exert a profound influence on the behaviour of the metal. This is of importance because presses of orthodox design are sometimes responsible for the failure of perfectly good metal and often prevent its full capacity to suffer plastic deformation being taken advantage of.

In the past, presses have been designed mainly with the object of securing ease, and often speed, of operation rather than with the object of imposing the desired kind and degree of plastic deformation on the metal in the most satisfactory manner. It is therefore encouraging to observe that this last, and to the metallurgist more important, consideration is at last receiving attention and that there is a tendency to choose methods of press operation which enable the metal to be deformed in a manner which approaches more closely to that shown by theory and laboratory experiment to be desirable.

Before commenting upon the trend of press design as indicated by actual practice, several important details claim attention. Readers are reminded that these comments are offered from the viewpoint of the metallurgist, not that of the press manufacturer or production engineer, and to it they are to be regarded as complementary.

METHODS FOR IMPARTING MOTION TO THE PUNCH

Defects Inherent in Crank Actuation.[1] Considered from both the theoretical and the practical aspect, a crank press is a crude and brutal instrument for applying severe stress to thin sheet metal. A blank or partly-formed shape is interposed between a die and a punch positively attached to a crank through a connecting rod and slide, and a clutch engaged. The metal must flow to the full desired extent, and often very rapidly, or else rupture ; for there can be no " coaxing " nor gentle, if nevertheless firm, persuasion. The procedure may at first sight appear to be no more inflexible than that adopted in wire-drawing, but the rapid changes in the velocity of the punch and in the

[1] The verb "to actuate" is used purposely throughout this chapter to imply the giving of mechanical motion. The more common and more pleasant-sounding verb " to operate " sometimes implies " to control," not " to impart movement to."

resistance to deformation offered by the metal as the shape is formed, coupled with the absence of the cushioning effect of a long length of wire between the die and the source of tension, all tend to make conditions more harsh in deep drawing and pressing than in wire-drawing.

Non-uniform Velocity of Punch. The velocity of the punch in a crank-actuated press is changing continually throughout the stroke according to the law of simple harmonic motion, as shown in Fig. 182. This means that as a draw proceeds the metal will be forced to move at a speed which varies very greatly, yet present experimental evidence points wholly to the fact that this rapidly changing velocity prevents

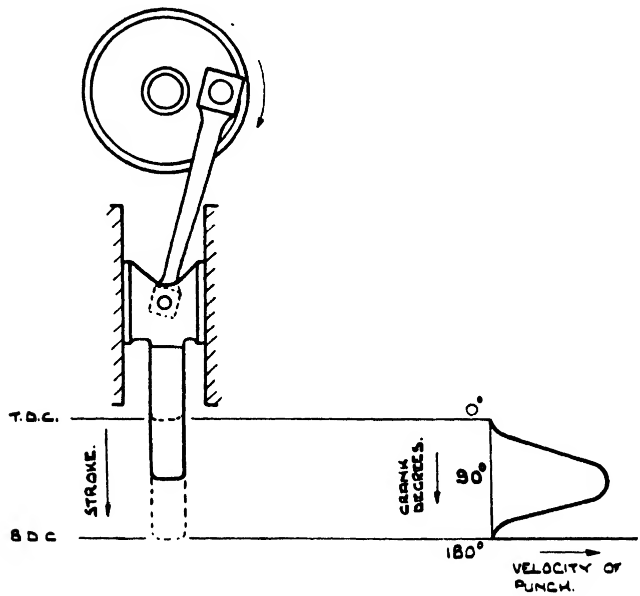


FIG. 182. Graph for simple harmonic motion illustrating the movement of a parallel slide connected to a rotating crank-pin.

advantage being taken of the full capacity of most metals to suffer plastic deformation.

The incorporation of some form of slipping clutch in a crank press of otherwise conventional design, thus—at least in theory—enabling the speed of application and also the severity of the load to be varied at will, might seem to offer some measure of control; but the design of a clutch which, although sufficiently robust and durable to withstand continuous operations is at the same time sensitive and smooth in action, presents a difficult problem. Furthermore, it is doubtful whether any slipping clutch, however carefully manipulated, could transform the movement of the punch from an harmonic to a desirably uniform nature. Friction clutches are installed on many of the larger modern presses, but they are usually regarded purely as a convenience for tool-setting rather than as a useful refinement to be used at each stroke of the press during actual drawing procedure when, as is not always the case, the speed of the draw is sufficiently slow to enable such manipulation to be performed. With the limited use to which they are usually put, clutches give little trouble and have a long useful life; were they to be used in the manner just suggested, considerable modification to design would undoubtedly be necessary.

Neglecting the influence of harmonic motion, the speed of a crank-actuated press and thus the speed of the punch is controlled by the design of the press and the speed of the line-shaft or motor: it is incapable of ready alteration except, and to a limited extent, by alterations made to the gear ratio of the drive and, in presses having an adjustable stroke, to the length of the stroke before a run is started. In other words, the speed of the draw is controlled by a number of factors *entirely unrelated to the most important of all*, which is the requirements of the metal and shape being drawn. Effective adjustment of drawing speed is often impossible under industrial conditions and, even when a useful measure of adjustment is possible, the harmonic motion of the punch renders the chosen "average" speed of relatively small significance.

Impact of Punch on Metal. In addition to the inherent defect of rapidly changing velocity, a crank-actuated punch has another serious, and insufficiently appreciated, fault in that it is usually moving at a high speed when it strikes the metal. This limits the drawing speed which can be used, because the initial impact tends to tear the bottom out of the shape before steady flow of the metal can be attained, thus causing failures which are often attributed, quite wrongly, to faulty metal.

Little vertical clearance space between the punch and the die is needed to allow a flat blank to be introduced; therefore, by using a press of short stroke, it can be arranged—although this is not always done—that in a first operation the velocity of the punch when it strikes the blank is well below its maximum value. Considerable space may be needed to introduce a partly-drawn shell into the tools and, under these conditions, impact of the punch at high speed cannot be avoided unless the punch is lowered gently into contact with the bottom of the shell by careful operation of a slipping clutch. Even when the necessary mechanism is available, gradual lowering of the punch is rarely attempted owing to the resulting very considerable increase in time for the whole cycle of operations needed to produce one article.

An attempt to illustrate these points pictorially has been made in Fig. 183, from which it will be seen that, for a given speed of crank-shaft rotation, the striking velocity of the punch tends to be greater on a partly-drawn shell than on a flat blank owing to the greater length of stroke required to give sufficient clearance space to enable a shell, as distinct from a flat blank, to be placed in the tools.

It is unfortunate that the natural tendency is for the speed of the punch to be higher when it strikes the bottom of a shell than when it strikes a flat blank, because in a shell, and particularly in a flat-bottomed cup, the resulting stresses will be concentrated in certain regions and will therefore be more likely to cause failure.

Cushioning Devices. It is becoming increasingly popular to drive crank-acuated presses through multi-V-belts of rubber. One of the claims advanced for this method is that it gives a cushioning effect, thus rendering the descent of the punch less inflexible. Whether the degree of cushioning obtained is sufficient to be of material benefit is a debatable point; the principal, and certainly valuable, advantage which this form of drive possesses over a connection which is wholly metallic is that in the event of two blanks being introduced by the operator the likelihood of serious damage resulting to press or tools is greatly lessened.

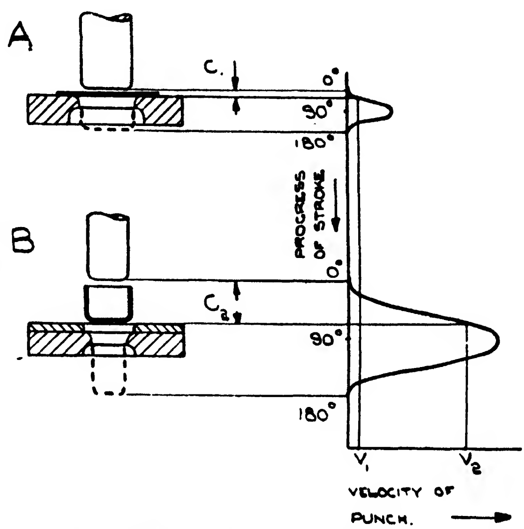


FIG. 183. Effect of harmonic motion due to crank actuation upon velocity of punch at moment of impact with metal.

(A) With a flat bank, needing clearance C_1, the striking velocity V_1 can be made relatively low.

(B) With a shape needing clearance C_2, the striking velocity V_2 is near the maximum for the stroke, unless the punch is lowered gently through the distance C_2. The greater length of the stroke needed in (B) also increases the maximum punch velocity for a given crank-shaft speed.

On large presses pneumatic cushioning devices are occasionally incorporated in the main punch-actuating mechanism. Although such devices certainly minimise the initial impact of the punch on the metal, they are to be found as a rule only on presses of large size; on presses of small size the associated complication of mechanism would certainly be undesirable, and the high working speed would render their efficient functioning problematical. Cushioning devices on toggle mechanism of double-action presses are, of course, fairly common, but these do not ease the shock and inflexibility of the descent of the punch itself.

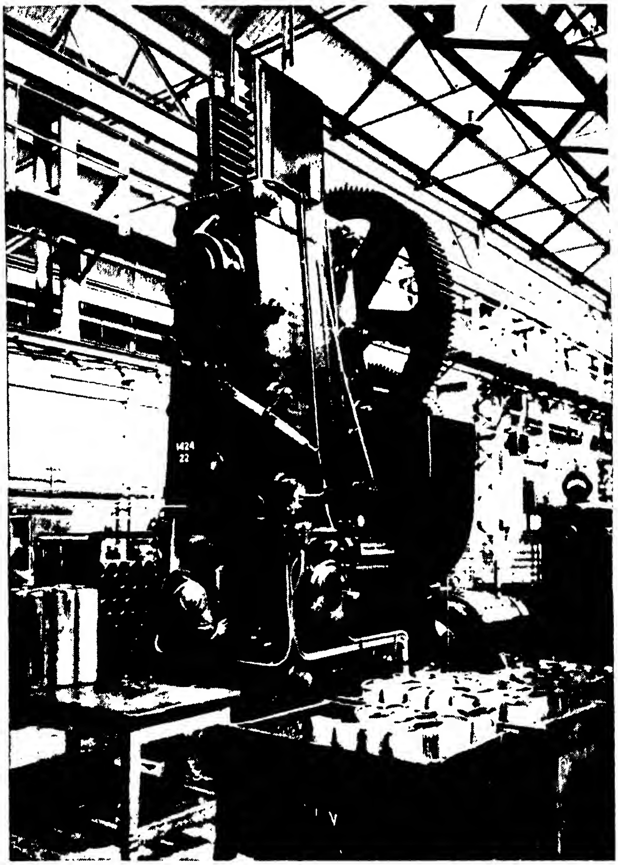
Prevention of Speeding-up. The general replacement of belt drive from line shafting by integral motor drive, whether through rubber belts or gears, lessens the likelihood of serious damage to the press by injudicious speeding-up. In their eagerness to obtain increased output, it is not uncommon for production engineers to increase the speed of presses when this can be done simply by increasing the diameter of a line-shaft pulley; yet, as the momentum of a flywheel increases as the square of the speed, a moderate increase in the speed of rotation will produce a large increase in the power applied to the punch. With integral drive it is not such a simple matter to increase the operating speed of the press without the assistance of the maker, or at least of persons acquainted with the full effect which such an increase will produce, and the likelihood of damage is thus lessened. This consideration applies more particularly when a blanking operation is being performed.

Methods of Actuation other than the Crank. Having regard to the inherent defects of the crank-actuated press, it is certain that considerable benefit would result from the replacement of the crank by some system of actuation which is free from the influence of harmonic motion, and which enables the punch to make contact with the metal without severe impact.

Actuation by Rack and Pinion. There are on the market presses in which movement is imparted to the punch by a rack and pinion, thus giving a uniform velocity instead of the continually changing velocity associated with a crank-actuated punch, although even in this design the punch will strike the metal at drawing velocity unless a friction clutch is available and manipulated properly at every stroke. This type of press has found favour for deep-drawing tubes from circular blanks, mainly by reason of the much greater length of stroke which can be obtained without the mechanical difficulties which are inseparable from a crank-press of very long stroke. It is however significant that, with it, considerably deeper draws can be obtained than with the crank type of press in which the punch moves with harmonic motion. This established fact ought of itself to lead to more serious consideration of this principle of operation for shallower draws than has so far been accorded to it.

A press actuated by means of a rack and pinion, set up for performing an intermediate draw on shells, is shown in Fig. 184. The particular frame illustrated incorporates two punches, arranged so that when one is at the top of its stroke the other is at the bottom, a popular arrangement. Frames containing several punches are often favoured owing to the increased output which is thereby rendered possible, this arrangement being particularly desirable because rack and pinion presses usually work at a slow speed.

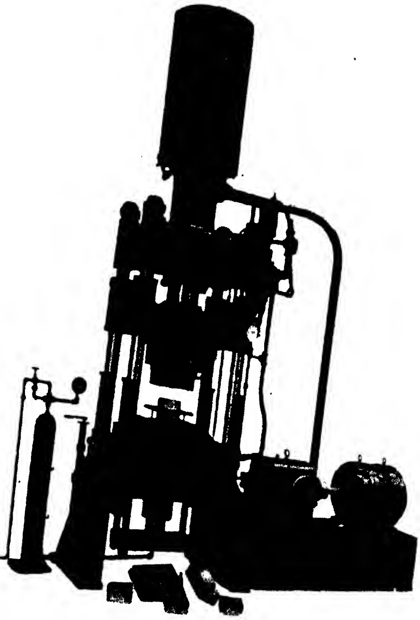
Rack and pinion presses can be obtained in a variety of sizes to give strokes ranging in length from a few inches for drawing shells to as much as 9 feet for drawing tubes ; to shorten the time occupied by the whole operating cycle, the return stroke of these presses is often speeded up by suitable mechanism to several times that of the slow working stroke. It is hardly necessary to add that if a smooth stroke



[*By courtesy of Daniel Smith & Co. Ltd.*

FIG. 184. Press actuated by rack and pinion set up for performing intermediate draw on cylindrical shells.

[*To face p.* 332.



[*By courtesy of Charles F. Elmes Engineering Works.*

FIG. 185. Press employing two separate fluid-pressure systems :—
(1) A motor-driven pump to actuate the main ram.
(2) A hydro-pneumatic accumulator (seen at left) to actuate the pressure-plate, the pressure being controlled by the valve seen on the left of the press.

[*To face p.* 333.

is to be obtained, the accuracy of the teeth on the rack and pinion must be of a high order.

Fluid-pressure Actuation. Rack and pinion actuation, although preferable to crank actuation in that its constant speed lessens the demands made on the metal being shaped, still possesses some of the disadvantages of the crank-press. Some method of actuation in which both the speed and the force of the punch can be controlled, preferably while the stroke is proceeding, seems desirable from the theoretical aspect. The speed of the punch should be uniform throughout the stroke, except when altered purposely, and should be adjustable over a wide range; and in some instances it would be useful if the maximum pressure which could be applied at any stage of the stroke could be limited by automatic, in addition to manual, control. Lastly, it should be possible at each stroke quickly and easily to bring the punch into contact with the metal *gently*, and not allow it to strike the metal at high velocity.

Fluid-pressure or pneumatic actuation, controlled by valves, at once suggests itself as being of possible value; both these mediums have been tried, and fluid-pressure is being utilised on an increasing scale for imparting movement to the punches of deep-drawing presses. How energetically this principle will be applied to presses intended for the ordinary run of drawing and pressing operations will depend largely upon the measure of insistence shown by purchasers upon being offered, at least as an alternative to the usual principle of crank-actuation, one better suited to the requirements of the metal being shaped.

Presses in which oil-pressure is used to actuate and to control both the punch and the pressure-plate can no longer be regarded as a novelty in modern press-shops. The increased depth of draw which can be accomplished with them, once certain differences in operating technique and tool design have been appreciated, demonstrates very clearly the benefit of a drawing speed which does not vary markedly during the stroke, as when crank-actuation is used, of instantaneous and fine regulation of pressure-plate loading during the actual working stroke of the press, and of the other benefits of fluid-pressure actuation already enumerated.

The advantage of hydraulic presses over mechanically-actuated toggle-lever drawing presses for the manufacture of large pressings cannot be over-stated. Size for size, they are cheaper; and, by coupling the two slides together, they can be used as single-action presses giving a total pressure of the combined pressure of the blank holder and the drawing-slide. This is a distinct advantage with deep drawn or pressed parts which have to be finished closely to size, because in some cases the pressure of the drawing-slide alone is insufficient, although sufficient to perform the actual drawing operation. The procedure in such instances would be first to deep draw or press all the articles in the usual way, using the unit as an ordinary double-action press, and then to substitute coining or forming press-tools fitted to the blank-holder and drawing-slide combined as one unit and to operate these for the final " sizing " operation. It is also possible to use coupled rams for heavy work such as blanking large areas.

If the machine is fitted with a pneumatic die-cushion in the table, it is not necessary to provide special control for the compressed air as on mechanical drawing presses, on which—as is well known—the air cushion must be placed out of action by counter-pressure when the drawing-slide rises, as otherwise the drawn part would be damaged under the blank-holder pressure. With the hydraulic press the procedure is that the blank-holder slide rises first and is followed by the drawing-slide. The part cannot therefore be damaged because it is not released by the drawing-slide until the blank-holder slide has reached its highest position. The great loss of air which also occurs with mechanical presses in consequence of the counter-pressure control is avoided, and a relatively small compressor is sufficient to supply the compressed air.

The setting time for the tools is considerably lower on an hydraulic than on a mechanical press, because slide adjustment is completely eliminated. The tools are merely placed in contact with the two slides, the slides are lowered, and the tools are then fixed; whereupon the press is ready for working. With a mechanical press the setting of the two slides has to be determined after the tools have been fixed to them, often a lengthy procedure.

In the aeroplane industry tool-setting times may be a very important item, because quite often only small batches of parts are made at one setting; therefore a reduction in setting times is of much greater importance than a high output when performing the actual deep drawing or pressing operation itself.

As the blank-holder pressure can be very easily regulated by means of a control valve, fine adjustment of the blank-holder is not required. The application of accumulators permits of a very high speed of operation during the return or *idle* stroke of the press, although the speed of the actual pressing or *operating* stroke can be made as slow as the requirements of any particular sheet and article demand. As is well known Duralumin is extremely sensitive to drawing speeds, and if Duralumin sheet is drawn on a mechanical press it is often fractured simply by the speed of contact of the drawing punch. Breakage of this kind can be avoided with hydraulic presses because the actual deep drawing or pressing movement can be started very slowly, and sufficient time allowed for the sheet to flow. In addition, it is possible to stop the drawing process *immediately a certain punch-pressure is exceeded*. For this purpose accurate dial indicators are provided from which the operator can read the exact pressure; and, as the admissible stretching or drawing pressure at which the sheet can be formed without splitting can easily be ascertained by experiment, an intelligent operator having this information can at once stop the press if for any reason this pressure is exceeded during the deep drawing or pressing process. For example, if the sheet is not satisfactorily lubricated, the blank would be scrapped on a mechanical press; but with an hydraulic press the part can be taken out of the press in a semi-drawn condition and again annealed or re-greased, whereupon the drawing process can be continued to a satisfactory completion.

When working with Duralumin the ability to stop the press immediately is of considerable importance because, as explained in Chapter VIII, Duralumin " ages " very quickly and loses much of its ductility within an hour after heat-treatment. With mechanical presses, which cannot be stopped instantly when a certain punch pressure is reached, a great deal of scrap is made if heat-treated sheets are kept too long.

Another advantage associated with the ability to work at low speeds is that the strain on the tools is considerably less than at high speeds. It is, therefore, possible to use wooden punches of low cost when this would be impossible with a mechanical press.

The essential features of a fluid-pressure press can be seen in the small press illustrated in Fig. 185 (p. 333). In this particular press, oil-pressure generated in an attached pump passes to two separate cylinders and rams, one above and one below the tools, which actuate the punch and pressure-plate respectively. In large presses the cylinders and rams are usually mounted at the top of the press; sometimes one ram slides inside the other as shown in Fig. 198 (p. 348), and in some large presses four small rams sometimes actuate the corners of the sliding head, as shown in Fig. 197 (p. 347).

Besides the advantages of fluid-pressure, as distinct from mechanical, operation just mentioned two others, smaller yet of value, must be pointed out. When, as sometimes happens, two blanks are placed together in the tools, serious damage to the press and the tools may occur in an inflexible, mechanically-actuated press; with fluid-pressure actuation the applied pressure cannot rise above a value determined by a release valve, and no serious damage results. Secondly, a crank-actuated punch does not pause even momentarily at the bottom of its stroke; a punch actuated by fluid-pressure can be made to dwell at the limit of its descent, under full pressure, for as long a period as may be desired. In certain instances this " dwell " has been found to be helpful in producing shapes having the desired dimensions and contour, because it prevents, or at least reduces, the " spring back " which follows the immediate release of pressure from a cold-pressed metal shape.

It is only to be expected that fluid-pressure actuation has its own peculiar disadvantages. One of these is that although the inflexible application of load and movement and also the harmonic motion of the crank-press are eliminated, there is a possibility of the movement of the punch being somewhat jerky and erratic due to periodic pulsations in the pressure system or to friction at the packing gland of the ram. The introduction of a mechanical lever system to reduce the magnitude of the fluctuations which reach the metal adds undesirable complication, and it is to be hoped that hydraulic engineers will in due course devise means for moving the punch smoothly.

The full exploitation of fluid-pressure actuation and control is hindered by one serious practical difficulty, namely, that unless the reserve in a common source of pressure is very large, the loading on the pressure-plate varies in an undesired manner due to variation in the main system caused by the changing resistance offered to the main ram. This could be overcome by using two separate pressure systems, one for the main ram and one for the pressure-plate ram; a complication which, though costly, might well be justified in presses of large size.

The development of the fluid-pressure press should be watched with close attention, for it provides the only means yet devised and applied on an industrial scale for giving *all* the following attributes, which are desirable from the metallurgical aspect if not always from the aspect of very rapid production: a working stroke of uniform velocity; lowering of the punch into gradual contact with the metal; control of both the speed and force of the punch—and also the loading of the pressure-plate—during the actual working stroke of the press. It seems likely that, except when a high operating speed is assumed, often erroneously, to keep production costs low, the use of presses actuated by fluid-pressure will enable deeper draws to be obtained in one stage and thus, in some instances, allow articles to be produced in a fewer number of operations and with less risk of failure attributable legitimately to press operation.

Compressed air seems less suitable than oil for imparting movement to the rams of medium and large-size presses, but it is often used to operate accessories and, of course, the pressure-plate itself on mechanically-actuated presses. For small, high-speed presses pneumatic actuation might seem attractive, yet in practice it is usually found that a less resilient form of punch-actuation is needed; the measure of control afforded by air or oil pressure cannot be utilised fully on a press operating at many strokes per minute and, indeed, is seldom required because draws are purposely kept relatively light in order to avoid occasional failures and stoppage of machines, particularly when these are automatic.

Pressing without a Punch. The mechanical, pneumatic and fluid-pressure methods of press actuation considered so far each have as their objective the impartation of true linear movement to a solid punch which in turn makes contact with the metal being shaped. The replacement of this rigid punch by fluid-pressure as the primary operating medium in actual contact with the metal itself—a scheme used on a small scale in the Jovignot cupping-test machine illustrated in Fig. 236 (p. 487)—might, in theory, seem attractive for certain pressing operations as distinct from true deep-drawing operations involving "ironing."

The practical difficulty of making a pressure-tight joint between the blank or the edges of a partly-formed shape and the surface of the die and pressure-plate, a task which proves troublesome even in small fluid-pressure cupping machines of laboratory type, as well as the slowness of the whole operating cycle and the unavoidable messy nature of the procedure, prevents this principle being applied on a large scale industrially. Nevertheless, it is used to a limited extent with either oil or water as the force-transmitting medium, and it proves very useful for giving to a deep-drawn shell some final shape which cannot be imparted by solid tools moving in a straight line. This special technique is described more fully in a later chapter.

A rubber pad is often used to transmit the force of a parallel-sided punch to the sides of a thin shell, thus bulging them into a convex contour; for heavy-gauge metal, complicated expanding tools are better, but it is only the drawbacks just enumerated which prevent the use of fluid-pressure for bulging a large variety of parallel-sided shells.

To summarise this survey of methods for imparting movement to the punches of presses used for deep drawing and pressing, the crank possesses serious fundamental disadvantages from the metallurgical aspect; of the alternative methods yet available, the rack and pinion possesses one advantage—that of constant velocity—while fluid-pressure seems in theory, and has now been proved by practical trial under industrial conditions, to possess many. By reason of its simplicity the crank will undoubtedly remain in favour for many operations, particularly on presses which run at a high speed, but the advantages of other methods which can be used to impart movement to the punch certainly merit more serious consideration than has been given to them in the past.

Miscellaneous Items relating to the Design and Operation of Presses

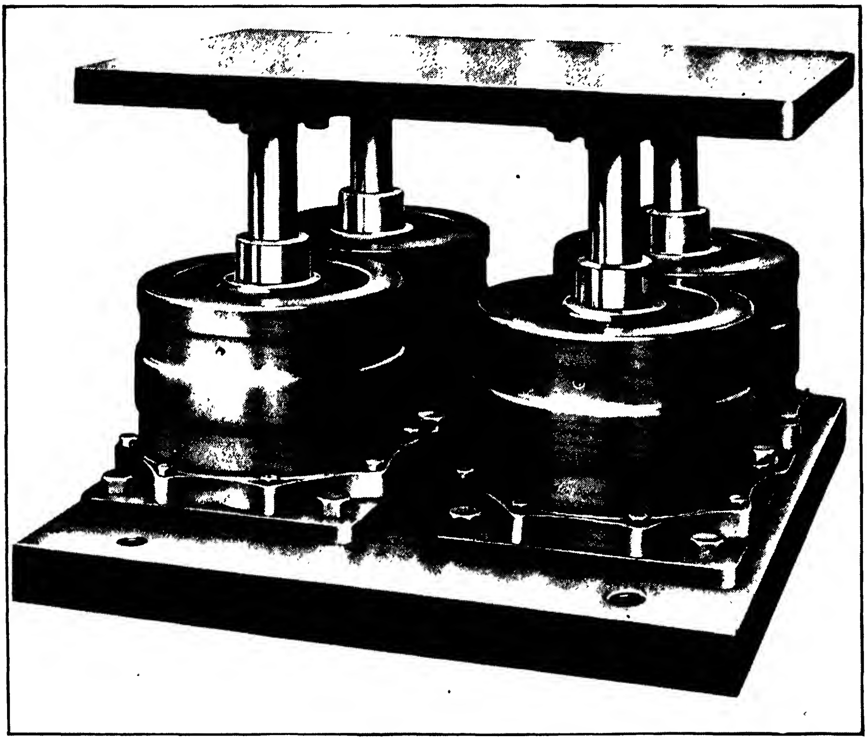
Pressure-plate Control. In the past it has been customary to load pressure-plates, or as they are sometimes termed blank-holders, by springs. During recent years there has been a tendency to replace the old type of spring-loaded pressure-plates by plates loaded by pneumatic rams of the kind illustrated in Fig. 186 and, latterly, by fluid-pressure. The object of this is two-fold : to render a single-action press virtually double-acting so far as pressure-plate actuation is concerned because, before the punch descends, air-pressure closes and loads the pressure-plate quite independently of the mechanical movements of the press itself ; and, secondly, to provide, with the aid of adjustable valves, means for reducing automatically the pressure-plate loading as the stroke of the press progresses—a refinement which is not always utilised. A useful measure of success has been achieved with the first if not with the second of these objectives, but a practical difficulty often arises in that if large presses are mounted on floors other than the ground, the necessary ram and cylinder may protrude through the ceiling of the shop below the press floor ; an expensive and awkward location.

Another useful refinement is now being developed, and it is interesting and significant to observe that the most modern presses for the production of large pressings are equipped with *several* pneumatic or fluid-pressure cylinders whose rams control the pressure at different parts of the pressure-plate; and, of importance, that the pressure in these cylinders can be controlled during the stroke of the punch, whereas in units of earlier design the valves had to be set in a definite position before the start of a run and could not be altered during each stroke.

A logical extension of this principle would seem to be the use of a multi-piece pressure-plate with independently-controlled loading on its various portions. This refinement, used properly, should prove most helpful in the pressing of large panels of irregular shape and, in addition, would render the setting of large tools and the adjustment of local clearances less tedious. At present it is often sought to obtain the effect which this refinement would give by placing lubricant only on those regions of a blank which it is desired shall flow most readily : a crude, though useful, procedure.

It will be appreciated that the provision of the measure of control which is, or could be, obtained with full, controllable, fluid-pressure or pneumatic operation of both punch and pressure-plate will shift much of the onus for successful drawing on to the shoulders of the operator, an aspect which will be enlarged upon later.

It has always seemed to the author that the present practice of pressure-plate control through the medium of an applied load is entirely wrong from the theoretical aspect : the very name for the holder or plate used to restrict the flow of the blank is, indeed, misleading. It is true that pressure must be applied to impose the necessary restriction and to prevent wrinkling; yet, in many operations, the essential factor is the clearance *space* in which the blank must move,



[*By courtesy of Joseph Rhodes & Sons Ltd.*

FIG. 186. Assembly of pneumatic cylinders intended to be mounted below main bolster-plate for controlling the loading applied to the pressure-plate.

[*To face p.* 338.

not the actual pressure applied : a pressure which is sufficiently great to prevent the formation of wrinkles may be far greater than that which is needed merely to restrain the flow of metal over the radius of the die. Once wrinkles are formed, an extremely high pressure may be needed to prevent their continued growth, while they may cause marks on the finished article and, in any case, will hinder the flow of the metal.

To render the formation of wrinkles impossible without imposing an excessive pressure on the metal, entirely non-resilient loading of the pressure-plate is needed, for when force is applied through springs or pneumatic rams the plate will move against it to increase the clearance space if, as may happen, the force exerted by the wrinkles in any area exceeds the force exerted by the controlling medium upon that area.

A perfectly rigid plate is, however, highly undesirable because

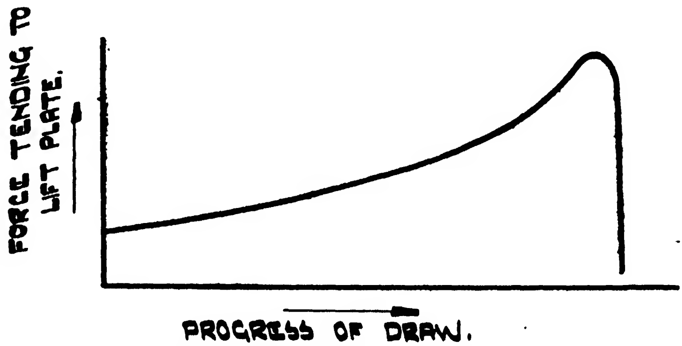


FIG. 187. Curve showing how the force tending to lift the pressure-plate changes during the progress of the stroke when a circular cup is being drawn from a flat blank.

the clearance space should increase to accommodate the ever-increasing thickness of metal which results from the reduction in the peripheral measurement of the blank as the draw proceeds : this is indicated very clearly by the shape of the curve obtained when a recording manometer is attached to the pressure-plate to operate during the stroke of a draw, as shown in Fig. 187. It is surely logical to suggest that the pressure-plate ought, on theoretical grounds, to be controlled in a precise way, *i.e.*, one which is non-resilient and therefore not influenced by the force exerted by the blank itself as drawing proceeds, the movement being so arranged that the clearance space conforms at any stage of the draw to that indicated by the theoretical curve for the particular shape being drawn ; that for a cup drawn from a circular blank having already been illustrated in Fig. 187. By cam operation, with or without the intervention of a fluid-pressure operating medium, this should be possible ; the idea is offered to the makers of press equipment for consideration.

It should be observed particularly that with a method of rigid control devoid of resilient pressure, the formation of wrinkles is rendered impossible yet the metal is not gripped tightly to hinder its flow. When definite restriction is desired, this could be obtained by the action of grooves and corresponding lands such as are already used with ordinary pressure-plate actuation, or else by the action of light auxiliary springs arranged to exercise only a limited degree of control.

Reverting to orthodox practice, pneumatic or fluid-pressure rams are sometimes used on mechanically-actuated presses to equalise the distribution of mechanically-applied force over the whole area of a large pressure-plate or, when inserted in the punch-actuating mechanism, for a similar purpose and, if suitable automatic release valves are incorporated, to ease the shock of application of the punch and even to limit to a predetermined value the force which it can exert. The extra complication of such devices, although useful when added to existing mechanically-actuated presses, seems undesirable when it is possible to use direct fluid-pressure actuation. They do, however, possess the advantage of being free from periodic pulsations or from jerkiness which sometimes is associated with direct fluid-pressure actuation, and possess the advantage that they can be added to existing mechanically-actuated presses.

Turning from principles for exerting force to methods of attachment, it is becoming standard practice to build a pneumatic or fluid-pressure cylinder into the lower portion of the frame as an integral part of the design; this results in a far more rigid and less cramped assembly, and for this reason alone is welcome. When purchasing new presses it is advisable to see that, if no cylinder is incorporated in the original design, there is sufficient room for one to be added, as there is little doubt that pressure-plate control by one of the methods just mentioned will be used to an increased extent in the future.

A typical pneumatically-operated pressure-plate installation, or as it is sometimes termed, "pneumatic cushion bed," is shown in Fig. 188. The pneumatic cylinder itself is mounted beneath the main frame of the press and connected to a reservoir, seen on the right of the press, to enable a reasonably constant pressure to be maintained. Usually this reservoir is connected to a pneumatic pipe-line; but, when no such supply is available, a small motor-driven compressor forms part of the press auxiliary equipment.

Drawing Devices. Many ingenious devices have been conceived to operate the pressure-plate and also to facilitate the actual drawing operation itself. One of the best known of these is the "Simplex" (patented) drawing attachment illustrated in Fig. 189 which, by imparting an upward movement to the die as the punch descends, provides an extra movement which can be utilised in many different

[*By courtesy of E. W. Bliss & Co*

FIG. 188. Single-action drawing press fitted with pneumatic cushion bed. Observe pneumatic cylinder beneath press frame and pneumatic reservoir on right.

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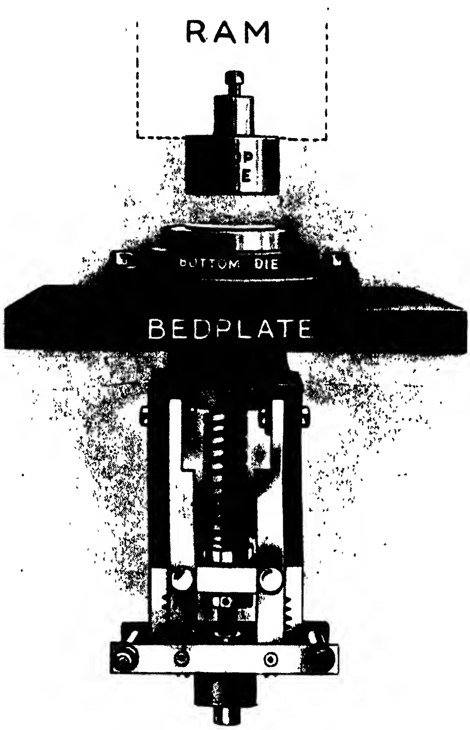


[*By courtesy of Joseph Rhodes & Sons Ltd.*

Fig. 189. "Simplex" drawing device (patented) for attachment to press bed-plate.

[*To face p.* 341.

ways to increase the range and complexity of the products obtainable from a single-action press.

The attachment consists of a rod which, sliding in a tube attached to the bed-plate of the press, carries the die on its upper end and actuates a rack and lever motion at its lower end. The effect of this arrangement is that pressure exerted by the descending punch on the pressure-plate is transmitted, *viâ* pins, to the levers and rack to move the central rod, and hence the die, upwards. In Fig. 190 (p. 342) a "Simplex" drawing attachment is shown fitted to a fairly small single-action press.

From many aspects the attachment of a device of this type transforms a single-action press into one having virtually a double action; the same end is achieved with a pneumatic cushion bed, but without the inflexible upward movement of the die which doubles the depth of draw obtainable on a press of given stroke.

Misalignment and "chatter." It is certain that inaccurate alignment of the punch with respect to the die, perhaps for only a part of its stroke, and also the development by the punch of a slight wobble or "chatter" is the cause of a far higher percentage of failures than is commonly imagined. Whenever persistent breakage of good-quality metal is encountered, yet no obvious tool faults can be detected, these two possible causes—misalignment and "chatter"—should always be investigated. It follows naturally that every effort should be made to reduce these purely mechanical defects to a minimum before actual trouble develops suddenly to upset production. The harmful effects exercised by inaccurate setting or insecure mounting of tools will be so obvious that comment is hardly called for; it is to less evident and less easily remediable causes attributable to the mechanism of the press itself that it is desired to direct attention.

Unless special means of the kind already suggested are adopted for equalising the loading on very large pressure-plates, the contacting surface may not bed down quite uniformly on the sheet being pressed; this will lead to certain areas of the sheet being gripped too tightly, a condition conducive to fracture. In presses of very large size it is difficult to maintain perfect alignment of punch and die, a difficulty which is increased by the natural tendency exhibited by large tools of unsymmetrical shape to tilt when the axis of pressure is not parallel to the guides in which the slide moves.

Makers of presses will be quick to point out that, not infrequently, the cause of both misalignment and chatter is wear in the working parts of the press, and that it behoves users to keep their presses in good condition and adjustment and not to set up excellent and expensive tools in a press having insufficient precision of movement for satisfactory results to be obtained.

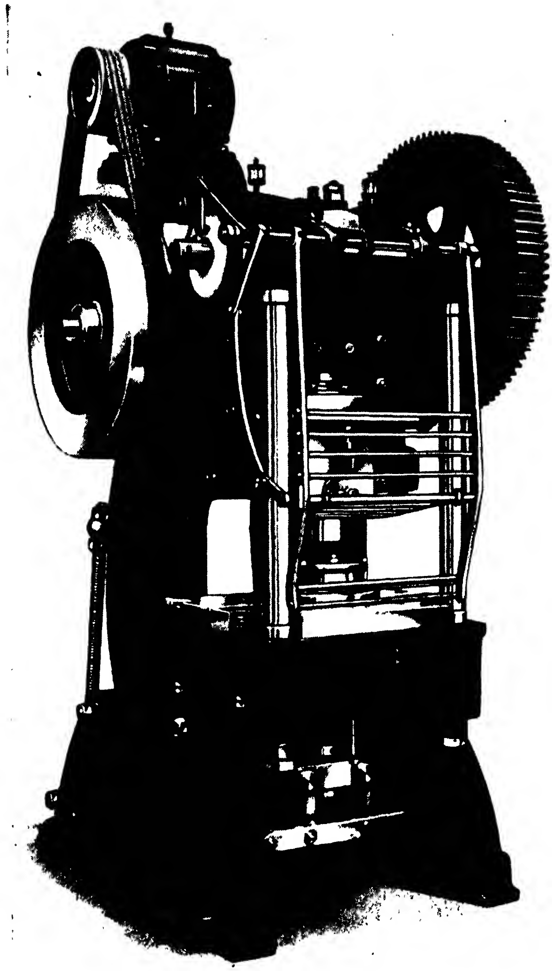
A somewhat different form of "chatter," not attributable to worn parts, is that due to vibration transmitted from inaccurately cut or improperly meshing gear wheels. In rare instances this effect is so severe that a series of wave-like markings can be observed if the surface of drawn work is examined carefully. When fluid-pressure actuation is used, undue friction in the stuffing box of the ram and, in some systems, actual pulsations from the pump may cause the punch to move, respectively, in a spasmodic or a vibratory manner.

Sub-frame Assemblies. The popularity of self-contained assemblies, comprising punch, die and sometimes pressure-plate, working upon guide posts and capable of insertion in any suitable press is increasing. The reason for this is threefold : the tools do not need to be " set " each time they are placed in a press, and the time taken to change a set of tools is for this reason reduced very greatly ; the alignment cannot alter during a long run through a slight shifting of either punch or die, and, thirdly, slackness in the guides of the press cannot affect the alignment of the tools. Guide posts of adequate rigidity are of great use in combating uneven settling of the pressure-plate and tilting of non-symmetrical or non-axially loaded tools in large presses, defects which have already been cited as a source of trouble.

Hitherto users have usually made and fitted their own sub-frame assemblies, yet the advantages associated with standard sub-frame assemblies designed by the makers of a press are several. For example, a number of standard assembly frames can be purchased and additional ones obtained quickly from stock ; proper and convenient attachment can be provided ; rails can be provided to facilitate the easy removal and insertion of heavy assemblies, as shown in Fig. 199 (p. 349). Furthermore, it often happens that the size of the frame of a press not designed to accommodate a sub-press assembly seriously limits the size of the assembly which can be added ; this difficulty does not arise when a standard sub-frame forms part of the original design of the press.

The principal offset to the many advantages of a sub-frame is its extra first cost, but it must be conceded that this item will be repaid many times over during the life of a new press by the saving in the cost of tool-setting ; for the same reason the addition of a sub-frame to an existing press when space allows is often well worth while.

Automatic Lubrication of Work. Modern automatic presses, examples of which will be illustrated later, are often equipped with devices to apply drawing lubricant, usually to both sides of the blank, before the first drawing operation. Provided that these devices are capable of applying lubricant of desirable consistency and efficiency in a satisfactory manner, this development is most welcome and may well be encouraged in presses of simpler construction. It is true that blanks are sometimes lubricated by being dipped in a bath—a very efficient method—or by being passed through rollers either of metal or absorbent material, but this practice is far from general and manual



[*By courtesy of Joseph Rhodes & Sons Ltd.*

FIG. 190. " Simplex " drawing attachment fitted beneath the table of a medium-size single-action crank press incorporating swivelling tie-bars and inclinable frame.

[*To face p.* **342.**

application by disinterested operators often results in inadequate lubrication, particularly when payment is by piece-work. Satisfactory application of some of the thick lubricants used for heavy draws on steel is, however, difficult by automatic methods.

Two methods of automatic lubrication are now in use. In one, either blanks or strip pass through rolls which apply the lubricant, only a limited amount being applied and no recovery attempted. In the other, tools and blanks are flood-lubricated by means of a pump, excess lubricant falling to a tray and reservoir for filtration and recirculation ; this method is applicable only to thin lubricants.

One minor advantage of entirely automatic application is that it renders possible the use of lubricants which are physically injurious or psychologically distasteful to human operators, a matter discussed in Chapter XI.

Safety Devices. Here, again, automatic presses have taken the lead in providing devices in the feeding mechanism which, either by weighing each blank or by means of a thickness gauge, reject excessively thick blanks and thus render it impossible for two blanks to enter the tools at the same time. The value of such devices will be appreciated by those who have had production delayed through damage to tools caused by the insertion of more than one blank at a time by careless operators, and constitutes one reason why mechanical insertion of blanks, for example by a slide or a turntable, is sometimes desirable even on non-automatic presses.

Safety devices having for their objective the prevention of injury to press operators as distinct from damage to metal, tools or presses hardly fall within the normal province of the metallurgist, but it will be apparent that the use of the mechanical feeding devices advocated for other reasons greatly reduces the likelihood of operators having their hands injured by the descent of the punch at an undesired instant.

Operators. In a preceding section there has been recommended the adoption, particularly on large presses, of fluid-pressure actuation by means of which the operator can control the speed and pressure of the punch, and also the pressure-plate loading at different parts of a large plate, during the actual stroke of the press. Presses giving this full measure of control are already available, and it is interesting to ponder the fact that here, in this age when the tendency toward complete mechanisation is often carried to extremes, is a striking—yet by no means unique—example of a reversion to at least partial manual control demanding a very high degree of skill and experience on the part of the operator. It has already been said that the shaping of sheet metal by deep drawing and pressing is essentially an art or craft in which, even when the actual drawing operation itself is inflexible, human skill and judgment plays a large part. Is it not possible that in deep drawing—and perhaps in other processes, such as welding—successful progress will lie in the intelligent wedding of the skill of the craftsman, as the modern operator has perforce become, to the most modern, yet sensitive and at least partially controllable, machinery ?

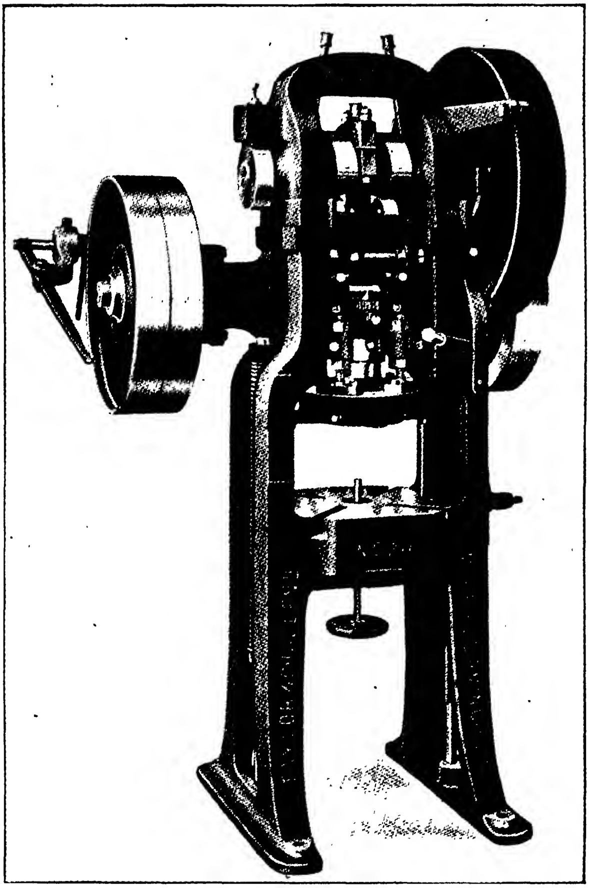
For heavy draws on large articles, particularly when only one main shaping operation is given, the provision of control in the manner just suggested certainly seems desirable from the metallurgical aspect, although the training—and continuous retention of the services—of skilled operators may present problems not recorded in accounts of the crafts of olden times.

Types and Design of Presses

Turning from what may be classed as accessories to a consideration of the actual construction of presses, the item which interests the metallurgist most is the method by which movement is imparted to the punch. It will be recalled that the metallurgical significance of this item has been discussed earlier in this chapter, and it only remains to illustrate how the various systems already discussed are incorporated in press design.

From the metallurgical aspect it is desirable that a useful measure of control should be available, particularly in large presses, for regulating the speed of drawing and also the force applied to both the punch and the pressure-plate during the working stroke of the press ; that the speed of the punch should be constant throughout its stroke unless it is altered purposely, and that the punch can be lowered gently into contact with the metal instead of striking it at considerable velocity. These requirements may not seem essential to some press manufacturers, and even to some users ; yet their genuine value in easing the demands made upon the metal, and thus rendering possible the regular attainment of draws of as yet unattempted depth in one operation, will hardly be denied by unbiased persons possessed of metallurgical knowledge. It will, therefore, be to the ultimate benefit of the industry if all enthusiasts use whatever influence they possess to hasten the development and installation of presses which treat sheet metal in a manner less brutal than that now tolerated as accepted practice.

With presses working at high speed, and to a less extent with slow-speed multi-punch process, the possibility of exercising control of speed and pressure during the working stroke seems more remote. For relatively slow-speed operation in which it is desired to obtain the maximum possible depth of draw in one operation, a full measure of control can be obtained at the present time if, and seemingly only if, full fluid-pressure actuation is employed : increasing application of



[*By courtesy of Taylor and Challen Ltd.*

FIG. 191. Small double-action drawing press with outer slides spring-balanced and cam-actuated.

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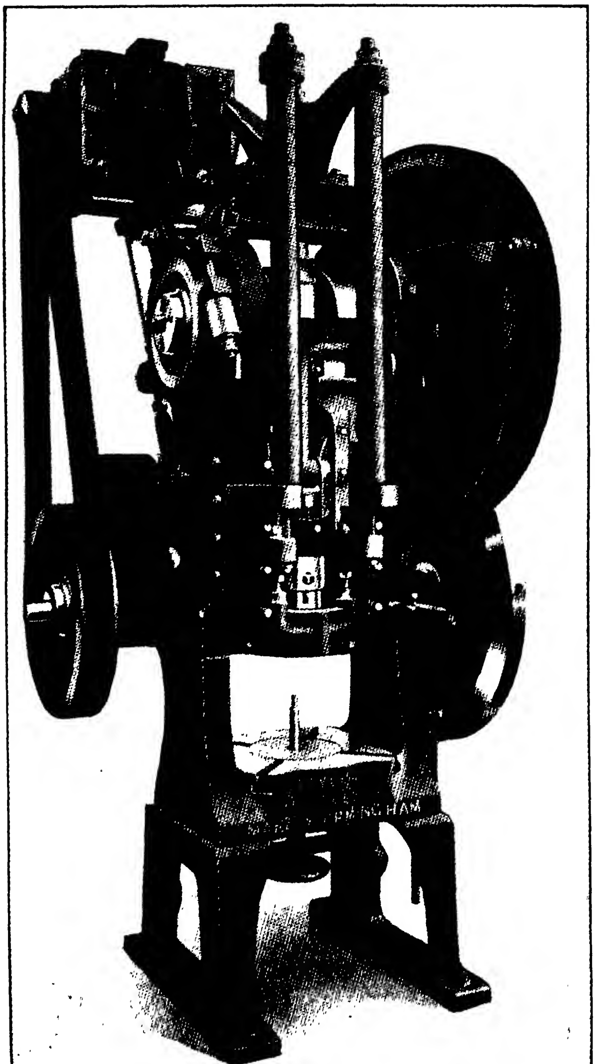


[*By courtesy of Taylor and Challen Ltd.*

FIG. 192. Medium-sized double-action drawing press with self-contained motor drive and cam-actuated spring-balanced outer slides.

[*To face p.* 345.

this principle of operation to the deep drawing and pressing of articles of medium and large size may therefore be looked for and encouraged.

Single-punch Presses. *Crank-actuated Presses.* It seems unlikely that any revolutionary change in crank-actuated presses will take place. During recent years the introduction of tie-bar frame construction, slides balanced with springs or dead weights, cushioning cylinders on toggle actions and sometimes on punches, self-contained drive by electric motor, and automatic lubrication have increased the efficiency of this type of press but have not removed the fundamental disadvantages of crank-actuation. Owing largely to the demands of the automobile industry—and, more recently, the aircraft industry—the size of presses has increased tremendously, a fact which has hastened the application of cushioning devices and separate small electric motors to operate the various adjustments, and has necessitated the use of more than one crank on the primary shaft. It is regrettable that there seems to be a tendency not to include on presses of small size many useful refinements which have been developed and applied successfully to large machines; for example, more frequent use of self-contained sub-press frames working on guide posts would ensure better—and maintained—alignment of tools, and would lessen the time taken to change tools. With tools of small size, the use of guide posts without the elaboration of a complete sub-frame would often be adequate, yet this arrangement is seldom adopted unless a blanking operation is being performed.

Fig. 191 illustrates a small double-action drawing press which is typical of the modern version of this class of tool. The single-stage gearing is designed to be driven by belt from line shafting, the frame is not reinforced by tie-bars, and the outer slides, which are spring-balanced, are actuated by cams which exert their pressure through the medium of rollers running in oil baths. The nominal operating speed is 40 strokes per minute, which is as fast as hand-feeding will allow whatever may be the speed of the actual working stroke.

Fig. 192 shows a somewhat larger version of this type of press; the drive in this instance is from a motor, attached to the top of the frame, operating through multi-V-belts and a double train of gears. The outer slide is actuated as before by means of cams and rollers, but it is balanced by four springs instead of two.

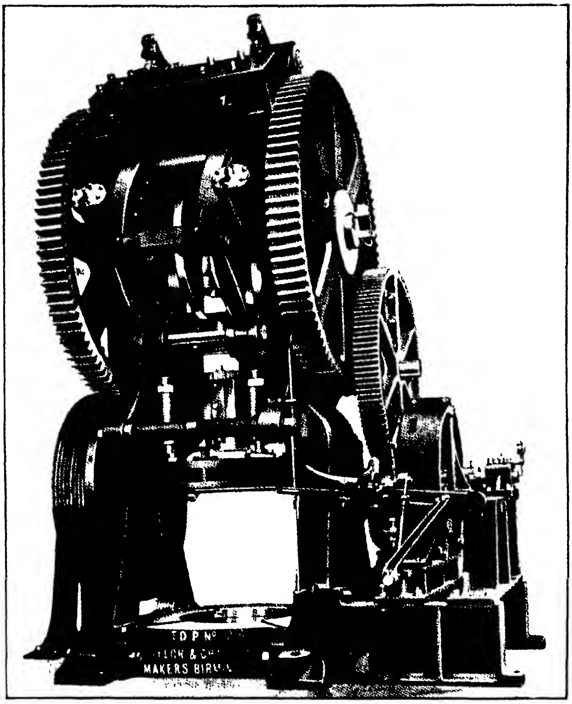
A single-action press employing a special drawing device fitted to the bed-plate has already been illustrated in Fig. 190 (p. 342). The photograph shows the frame swung into the vertical position and fitted with a swinging-action hand-guard of conventional design. It is interesting to compare the general design of this press with that of the one shown in Fig. 192, for both can be regarded as being typical of modern British practice. It should be observed that the tie-bars of the open-frame press can be swung outwards and upwards to leave an unobstructed operating space when desired and if the operation being performed is not sufficiently severe to render the aid of the tie-bars desirable. A useful refinement is the provision of distance-pieces so that the tie-bars cannot be screwed up unevenly or the press frame strained and the tools thereby thrown out of alignment.

A somewhat similar but larger and non-inclinable single-action press fitted with a pneumatic air-cushion has already been illustrated (Fig. 188, p. 340), this embodies tie-bar frame construction, very long guides to the slide, and the usual self-contained motor and multi-V-belt drive.

The considerably larger press shown in Fig. 193 is typical of British practice. Drive is taken from a motor, mounted at the rear of the frame, through multi-V-belts, a double train of gearing and a multi-plate friction clutch. As is usual in large presses, the outer slides are actuated by toggle action instead of cams, are balanced by dead weights —seen at the very top of the illustration—instead of by springs, and are provided with buffers. A press of this size is frequently built over a pit to give ready access to a pneumatic cushion mounted under the main frame. Fig. 194 shows such an arrangement, but in this instance two pneumatic cushions, worked from a compressor attached to the press itself, have been mounted under a special bed, 9 feet long, to enable automobile mud-wings to be produced on the press illustrated in Fig. 193. Large shells, motor-car wheels and body parts are often produced on presses of this type; they are also suitable for heavier work on brake-drums and lorry wheels in steel up to ¼ inch thick, although it will be noticed that tie-bar reinforcement is omitted from the main frame of the particular press illustrated.

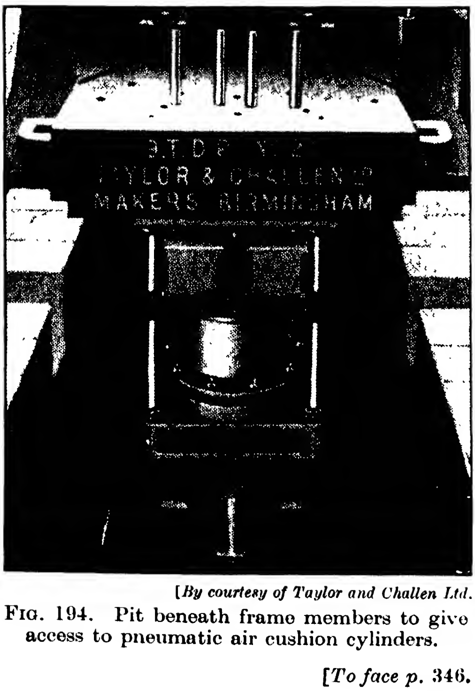
On presses of large size it is usual to employ two cranks instead of one. A typical double crank press of 350-tons capacity is illustrated in Fig. 195, which also shows the separate motor adjustment to the slide mechanism which has become standard practice on presses of really large size. It will be seen that tie-bar reinforcement is incorporated in the construction of the frame. In the illustration a solid T-slotted bottom plate is shown; this is usually drilled with a number of holes through which pins transmit pressure to the blank-holder from pneumatic cylinders mounted beneath it, in the manner already illustrated in Fig. 194. Automobile panels of fair size can be produced in the press actually illustrated, but much larger ones of both single and double action design are already in operation for shaping whole sections of automobile saloon bodies; although the cost of these huge presses can only be borne when very large numbers of bodies have to be produced. In presses of very large size remote control by either electric or pneumatic devices is usually installed, and cushioning and load-equalising cylinders are often incorporated in the action.

The difficulty of ensuring even settling of the pressure-plate and of



[*By courtesy of Taylor and Challen Ltd.*

FIG. 193. Heavy-duty double-action toggle press. Observe balance weights and buffers on toggle mechanism.



[*By courtesy of Taylor and Challen Ltd.*

FIG. 194. Pit beneath frame members to give access to pneumatic air cushion cylinders.

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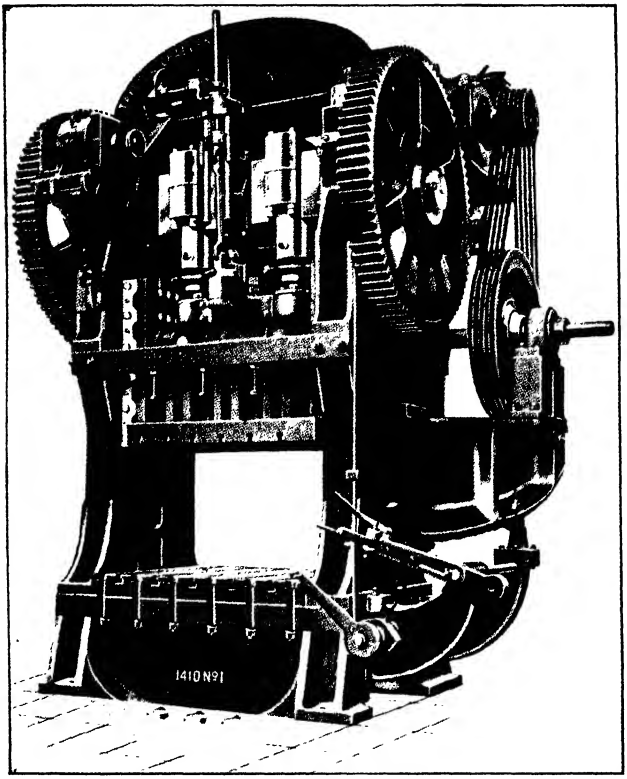
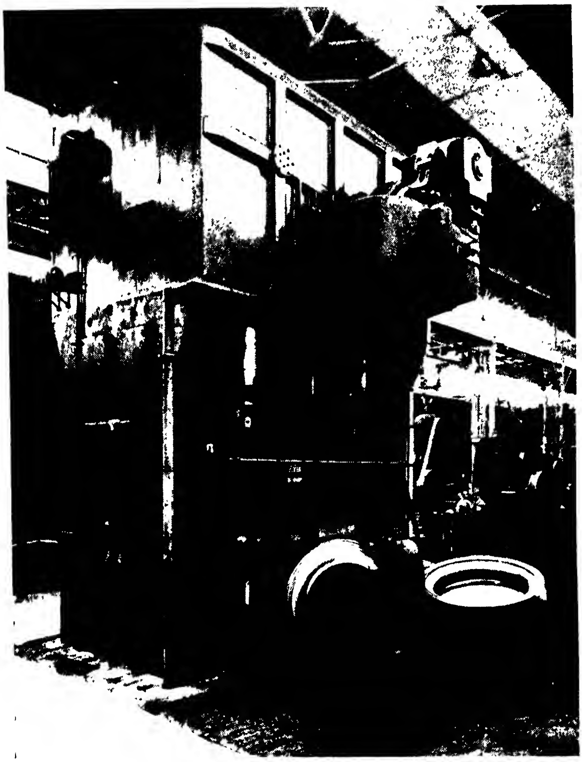


[*By courtesy of Taylor and Challen Ltd.*

Fig. 195. 350-ton double-crank press with multiple rubber belt drive and motor adjustment.

[*To face Fig.* 196.



[*By courtesy of the Austin Motor Co. Ltd.*

FIG. 196. 1,000-ton press with four-point actuation to slide.

[*By courtesy of Schuler and A. C. Wickman Ltd.*

FIG. 197. 750-ton double-action press actuated by oil-pressure generated in the pump seen on the right.

[*To face p.* 347.

avoiding tilting of non-symmetrical tools in presses of very large size has already been pointed out. Attempts to overcome these two defects are made, respectively, by using pressure-plates loaded by pins controlled by a number of separate pneumatic or fluid-pressure rams and, in crank-actuated presses, by imparting movement—and pressure—to the slide by four separate cranks attached to the four corners of the slide, sometimes through the agency of two parallel crankshafts geared together. Fig. 196 shows a modern 1,000-ton press having a slide loaded at four points. This press is also interesting because it illustrates the clean lines which are given by the modern tendency to use welded construction for secondary, and sometimes for primary, members and to make the whole unit as compact as possible.

Tie-bar frame reinforcement is gaining in popularity for small and large presses alike, not so much to enable a lighter frame to be used but to lessen the likelihood of frame breakage in the event of maltreatment through a mishap such as the insertion of two blanks together. An attempt is being made to introduce all-steel welded plate frames; apart from their greater tensile strength, the saving in space which can be effected with this method of construction is often considerable when motor, drive and gearing are positioned with this object in view. Owing to the thin section of the members, very careful design is, however, necessary if adequate rigidity is to be attained with frames of this type.

Mechanical Presses (Non-crank). Of mechanical methods of actuation other than the crank there may be mentioned the rack and pinion already illustrated in Fig. 184 (p. 332), the cam, and the screw. Each of these principles is used to a very limited extent and, although they do not permit the full measure of control given by fluid-pressure, the fact that they give a working stroke having a uniform velocity may well lead to their use on a much larger scale than hitherto.

Attention may also be drawn to systems of levers or link motions whereby the natural harmonic movement of a slide actuated by a crankpin is modified. These have not found favour for the operation of presses and, being only partially effective, it can hardly be claimed that they are superior to the other mechanical methods of actuation just enumerated.

Presses operated by Fluid-pressure. The advantages which can be obtained from the actuation of the punch by fluid-pressure instead of by a crank and slide have already been described, and an illustration of a small press of this kind has been given in Fig. 185 (p. 333). Fig. 197 shows a much larger press of 750 tons nominal capacity. It will be seen that instead of the punch and pressure-plate being actuated by two separate rams one working within the other, as is often arranged, the slide is actuated by four separate rams disposed near its corners, an arrangement which gives more even loading and less tendency to tilt on a slide of large size. Presses of this kind can be arranged for manipulation either by hand-operated valves or push-button control.

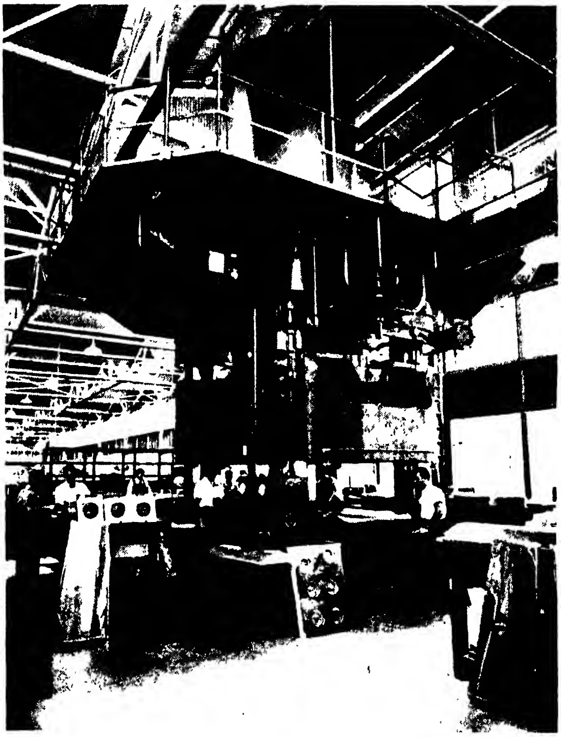
During recent years both the size of fluid-pressure presses and their speed of operation has increased rapidly, and it may be accepted that the speed of operation of fluid-pressure presses of modern design is equal to that of crank-actuated presses of comparable size. Fig. 198 shows a large press of 5,000 tons nominal capacity designed for pressing aircraft parts in Duralumin sheet.

Multi-punch Presses. There is, undoubtedly, a growing tendency to perform several stages of shaping at one stroke in multi-punch presses ; this, to the layman, increases still more the enormous size which presses seem to bear in relation to the articles produced in them. Small multi-punch presses have, of course, been in use for many years ; but Fig. 199 illustrates in a striking manner the size now obtainable from stock and, moreover, the size relative to that of the article produced, which in this instance is a comparatively small brake-drum formed in five successive operations.

This particular 5-punch press is capable of exerting a drawing pressure of 600 tons and an end pressure of 900 tons. Frames containing up to 10 punches are available.

It will be observed that the tools slide on guide posts and are mounted in a self-contained sub-assembly which can be run out on the rails seen protruding from the frame of the press, thereby enabling tools to be changed quickly, ensuring good alignment during service and eliminating the need for skilled and lengthy setting when assembled in the press. The punch is balanced by pneumatic cushioning cylinders and its movement is controlled by the long horizontal bar, seen extending across the whole length of the press, which operates a friction clutch through the medium of air valves. Blanks are fed to the tools by means of a rotary turntable seen on the left side of the frame, after which they pass through a weighing device which ejects over-weight blanks and thus prevents two blanks entering the tools together ; transference between stages is effected by reciprocating gripping-slides. A circulating pump located in the base supplies drawing lubricant to the tools and work, while the automatic lubrication to all working parts of the press mechanism, tie-bar reinforcement to the frame and the other refinements visible in the photograph make this an excellent example of the trend of modern practice.

A similar design of press is available with toggle-arms to give a double action, and with separately adjustable pneumatic cushions built into the base of the press beneath each punch : it will be observed that pneumatic cylinders so located are above floor level and do not need a pit to enable ready access to be gained to them, a convenience not always found even in presses of modern design. Most pneumatic cylinders still give the impression that they have been added as the



[*By courtesy of the Hydraulic Press Mfg. Co.*

FIG. 198. 5,000-ton hydraulic press shaping aircraft parts in light-alloy sheets.

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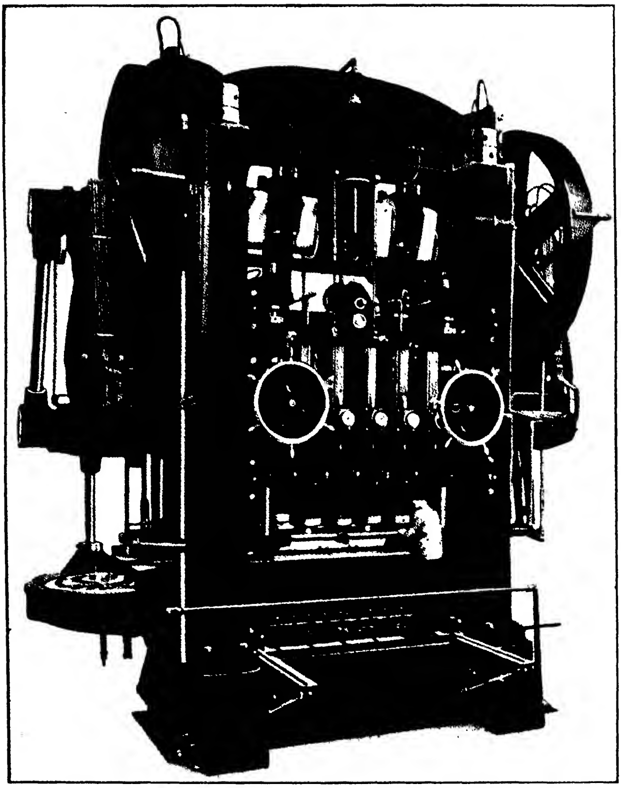


[*By courtesy of Hiltmann and Lorenz, A.G.*

FIG. 199. 900-ton, pneumatically-controlled, double-crank, automatic multiple-punch press with sub-frame. In the illustration this is set up, without a pressure-plate, for forming brake drums from 0·197 inch steel strip in five operations.

[*To face p.* 349.

result of an afterthought, and have not been designed as an integral part of the press.

Apart from any economies in floor space, cost of plant and operating time which may accrue from the use of multi-punch-presses, this type of press may encourage the use of a large number of light draws in place of a small number of more severe ones ; a procedure to be desired in some instances if for no other reason than that it tends to prolong the life of tools and lessens the likelihood of fouling and scoring of the work when lubrication is imperfect.

In addition to the more usual crank-actuated presses, multi-punch designs of rack and pinion types of presses are available and are used to a limited extent, usually for tube drawing. In this type, which usually operates at slow speed, a greatly increased output can be obtained by the use of a number of punches operating simultaneously, because the time occupied by the actual working stroke is large in relation to that occupied by the whole stroke and not, as is usually the case with crank presses, relatively short. In tube-drawing on rack-operated presses it is not uncommon for each punch to perform similar operations and not, as in multi-punch crank presses, different operations through which the metal passes from one side of the frame to the other. The advantages of rack-actuation as compared with crank-actuation have already been pointed out.

There is no reason why a number of punches should not be actuated by a single fluid-pressure cylinder, although one of the main advantages of this method of actuation—that is, its capacity for nice regulation during the actual drawing stroke—cannot be utilised fully when a number of articles are being drawn simultaneously. For this reason rack actuation, which is far cheaper, should form a serious rival in this particular field, especially as it possesses the advantage that the punches can be arranged to move in sequence so that a slow-speed press need not be stopped to enable blanks or shells to be inserted in the tools, an operation which cannot be performed if all the punches in a multi-punch press are arranged to rise and fall together.

Automatic Presses. There will probably be an increasing application of automatic feeding and transferring devices of the roll, vacuum, turn-table, pusher, reciprocating gripping-slide and mechanical-finger types, sometimes assisted by conveyor belts, gravity, or compressed air, to all kinds of presses.

Fig. 200 shows a typical small high-speed press of modern design in which both the inner and outer slides are balanced by springs ; when running at its normal speed of 300 r.p.m. the four punches, actuated by a single crank and slide, blank and shape a total of 1,200 cups of the kind shown in Fig. 201 per minute. Feed is accomplished by two sets of rolls, one set of which operates on the unblanked strip as it uncoils from the integral stand seen on the left of the frame, and the other on the perforated residue, which is then wound up on a scrap-winding device visible on the extreme right of the frame. Scrap-winding devices are a great convenience as they enable the vicinity of presses to be kept clear—a difficult problem with closely grouped high-speed presses—and scrap to be handled easily, safely and to be stored in a small space; they can, however, only be used for strip of thin gauge: when thick strip has to be dealt with an automatic shearing device can be substituted. An air blast is usually used to blow away the cups as they are ejected from the tools, but on presses operating at a comparatively slow speed the whole frame is sometimes inclined at an angle so that cups slide off the table into a container by gravity.

A useful refinement in presses of this type is the provision of separate chutes for the ejection of cups from each punch. By this means the operator is enabled to examine the cups and tell, without stopping the machine, how each punch is performing its task and which of them is responsible for any defect which becomes apparent.

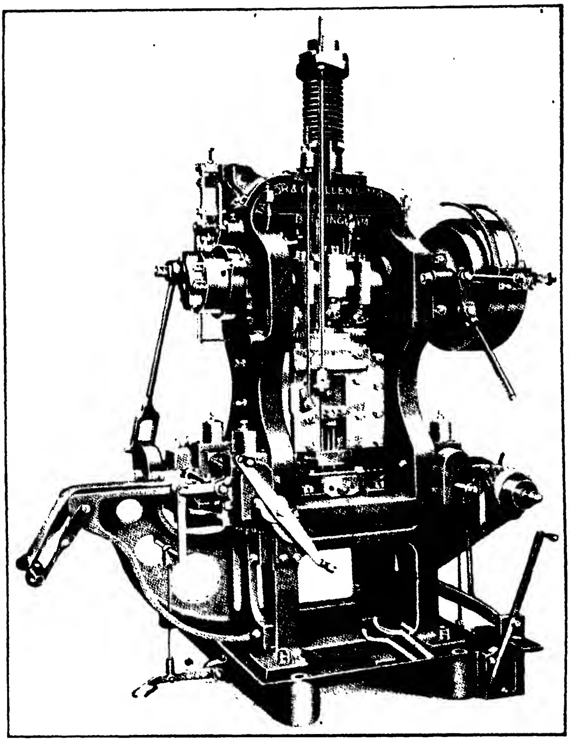
High-speed presses for re-drawing operations are usually of single-action type and are fed from hoppers by means of reciprocating slides or rotating tables as used on other types of automatic machines.

Automatic feed is certainly no novelty for small high-speed presses of the type just illustrated, but except in isolated instances it is only recently that its use seems to have been extended to large presses; an entirely automatic multi-punch press of what may be classed as a very large size has already been illustrated (Fig. 199, p. 349).

A similar fully-automatic press, rather smaller than the one just mentioned yet far removed from the familiar small high-speed automatic press, is shown in Fig. 202. This press, which has eight punches, incorporates many of the refinements fitted to the larger model, and the illustration shows how pneumatic cylinders, one for each operation, are built into the lower part of the main framework. In the large press (Fig. 199) a rotary turn-table is employed to feed circular blanks; in the smaller press (Fig. 202) blanks are raised from a stack and fed by means of a slide and pusher. Either of these arrangements can be replaced by a device, mounted not at the end but at the front or rear of the press, to uncoil, level and feed coiled strip to the first punch, under which it is blanked, thus reducing by one the available number of actual drawing stages.

The provision of a levelling device in the feeding mechanism is a most useful refinement and one which, it can be envisaged, could be elaborated actually to roller-level steel strip immediately prior to its entry into the tools, thus eliminating stretcher-strain markings in strip which has not been temper-rolled.

It will readily be appreciated how greatly the output of multi-punch, and in less degree single-punch, presses can be increased if efficient automatic feed and transferring mechanism is fitted for



[*By courtesy of Taylor and Challen Ltd.*

FIG. 200. High-speed automatic blanking and cupping press to produce 1,200 cups per minute from coiled strip. Observe double-feed rolls and scrap winder.

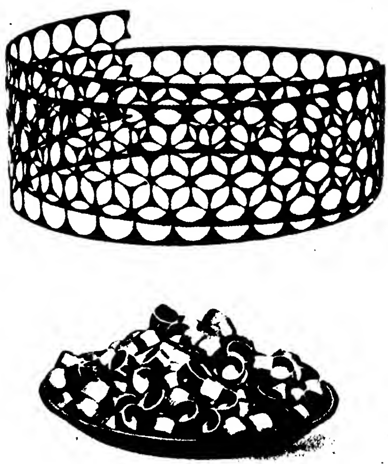


FIG. 201. Example of cups and residue from high-speed automatic blanking and cupping press illustrated in Fig. 189.

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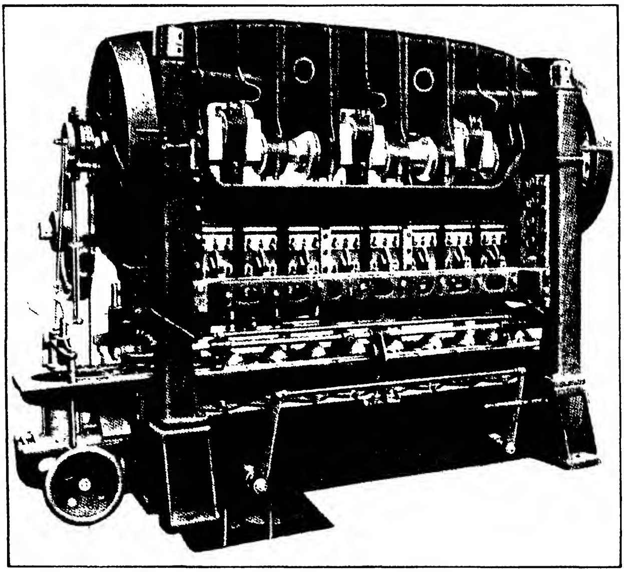


[*By courtesy of Hiltmann and Lorenz, A.G.*

FIG. 202. Eight-punch, automatic-feed, triple-crank press set up for producing reflectors in the stages shown. Each punch and pneumatic cushion can be adjusted separately.

[*To face p.* 351.

without it, the working stroke of the press occupies only a small proportion of the total time cycle, a fact of increasing significance as the number of the punches is increased.

The drawback to all high-speed drawing and pressing operations, whether carried out in single or multi-punch presses, is that no " coaxing " of the metal is possible : tools, lubricant and metal must all be maintained at a proper standard if failures are to be avoided ; and, as every production engineer knows, frequent interruption in the running of a high-speed automatic machine is usually a serious matter when production schedules have to be maintained.

An attempt has been made to review the current trend of development in presses used for deep drawing and pressing, to criticise certain points in design and methods of actuation, and to indicate several alterations which would be beneficial. This has been done from the viewpoint of the metallurgist, not from the more usual one of the press manufacturer or production engineer : the very fact that an expression of this viewpoint is unusual is to be deplored and regarded as a lamentable example of lack of co-operation between engineers and metallurgists.

The design of the conventional press was established long before the finer points which govern the plastic deformation of sheet metal became recognised generally ; this statement is not intended to suggest that all points are now understood fully : on the contrary, attention has been drawn more than once in these pages to the incompleteness of the knowledge which even now is available upon this subject. Much valuable knowledge has been gained almost intuitively by practical craftsmen of long experience, and it is unfortunate that their ideas have not always been translated into actual modifications to presses and general drawing procedure.

The time has certainly arrived when the metallurgist should be allowed to have a say in the design of the presses to which he has to submit the metal for the quality and performance of which he is being held responsible to an ever increasing extent. The press is the essential, indeed often the only, tool used for shaping deep drawn and pressed products : it is therefore only logical that it should be designed to give, as far as may be possible having proper—but not entirely subservient—regard to the desires of press manufacturers and production engineers, the kind of action and the measure of control which will enable the metal to give of its best.

CHAPTER X

TOOLS

To examine in any detail the composition, treatment and properties of the materials which are used, or seem suitable for use, in press tools would need a book rather than one single chapter. For this reason only salient points can be discussed, and attention will be directed to less obvious yet important aspects and details rather than to ones generally recognised though not always made full use of.

At the present time the choice of tool material, like many other decisions which have to be made concerning deep-drawing procedure, is usually based upon results of past experience or, sometimes, upon fallacious conceptions as to the relative importance of first cost. Serious consideration is seldom given to the fundamental properties which are desired, or which the chosen material can or cannot offer. For this reason, some examination of these properties is desirable before critical discussion of actual tool materials is attempted.

The ideal tool material should be of reasonable cost, easily shaped (a condition which includes casting, forging, machining and polishing), easily hardened and unlikely to crack or even distort during hardening when this treatment is necessary. During service it should be highly resistant to plastic deformation, abrasion, scoring and fouling; last but not least, it should possess as high as possible a degree of unctuousness, *i.e.*, natural "slipperiness," in combination with the metal it is desired to draw and the lubricant used to hinder direct metal-to-metal contact. Truly an apt illustration of the word as defined in the dictionary: "Ideal . . . existing in fancy only; a standard of perfection to be aimed at; the perfect as opposed to the real"!

In order that their true significance may be appreciated, these properties require to be considered in somewhat greater detail; for the sake of convenience the order in which they have just been enumerated will be retained, but it must be understood that this is not one of special importance.

Desirable Properties of Tool Materials

Cost. The price of available tool materials varies greatly. Starting with wood, which is used in some instances, it increases through a range of cast irons from plain grey iron to alloy irons, continues through the range of steels from plain carbon steel to steel alloyed with expensive elements, and ends with special materials such as sintered carbide aggregates and complex alloys such as the well-known "Stellite" proprietary product containing as its principal constituents cobalt, chromium and tungsten.

It is safe to say that in small tools the cost of the actual material forms only a small proportion of the total cost of the tool. For this reason the use of a relatively costly material, or the giving of an expensive surface treatment, may prove highly economical if the useful life of the tool is thereby lengthened. Again, if practical experience has shown that a certain relatively expensive steel is less liable to crack or distort during hardening than others of less cost, the use of this steel in tools which, through their inherent design, are likely to crack or distort may prove a highly profitable form of insurance. It is hardly necessary to emphasise the fact that, tools of very large bulk again excepted, by far the greatest proportion of the cost lies in the machining of the tools to shape and the polishing of the working surfaces, all of which labour and overhead charges are lost when a tool is spoilt during heat-treatment.

In the experience of the author this aspect is often not appreciated. In large organisations the final choice of a tool material is too often made by persons who, through short-sightedness, disregard the advice of practical men and base their selection upon the isolated item of first cost of material without giving due regard to the influence of this factor upon subsequent, and actually more important, items.

In the case of large tools, such as those used for forming automobile panels, the use of an expensive material for the whole tool is not usually justifiable. Even so, an appreciable increase in cost of material, such as would result from the replacement of an ordinary cast iron by a special or low-alloy iron, may prove economical when large outputs are desired. Again, the cost of insertion of blocks of more durable nature at certain places may be recovered many times over as a result of the increased life of the whole tool.

As distinct from inserted blocks, it is sometimes convenient to make the whole working face of special material. A good example of this practice is seen in the 6-foot diameter tools shown in Fig. 203, which are both made of ordinary cast iron faced with inoculated cast iron, a variety more expensive but much more durable. In tools of large size and suitable shape the use of complete cast facings of this kind often makes it possible to use a durable material for the whole working face when the cost of a relatively expensive material for the whole tool could not be borne. Needless to say, the use of castings or forgings gives a large saving in machining costs, particularly with tools of large size.

These remarks are necessarily general rather than specific; the tooling for a series of drawing operations must always remain a matter for careful and fresh consideration in the light of past experience and of the peculiarities of any particular article and production conditions.

The point it is desired to emphasise is that when large outputs have to be provided for it is false economy to pay undue attention to the cost of the actual tool material and treatment when the tools are small, and that with large tools a cost appreciably greater than that of the cheapest may be amply justified.

Ease of Shaping. The importance of this factor will vary with the size and the intricacy of shape of any tool. Two aspects will be considered, that of general "machinability" and that relating to the most economical methods for shaping and finishing individual tools as influenced by their size and shape.

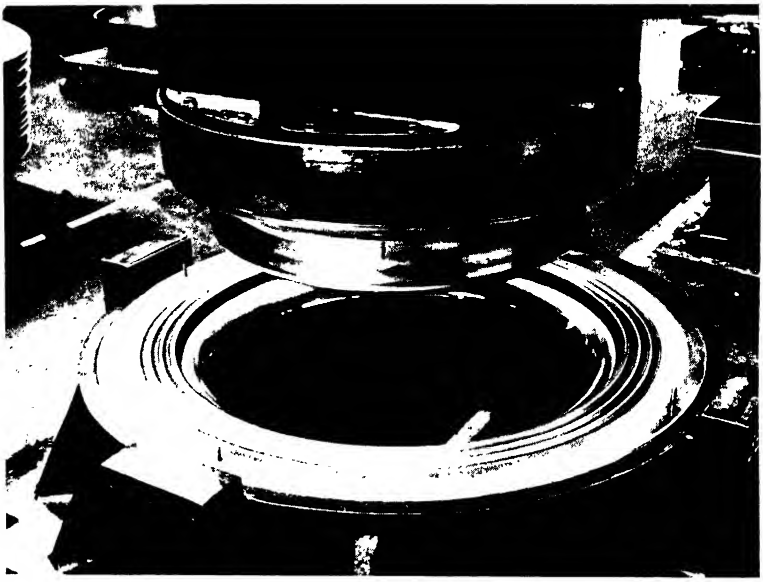
Machinability. Although modern machine tools and cutting materials have greatly facilitated the machining of all classes of steel, ease of machinability still remains a factor of some importance when a considerable bulk has to be removed in the shaping of large tools. The machinability of metals is such a vast subject that only brief mention of a few points especially important in relation to dies for deep drawing and pressing can be made here.

The machining properties of an annealed tool steel are determined primarily by its chemical composition and microstructure ; hardness, as such, is often of secondary importance. The ease with which plain carbon steels can be cut decreases with increasing carbon content up to the wholly pearlitic condition ; the range used for drawing dies usually lies at or above this limiting composition, and there is actually a negligible difference in the machining properties of a 0·8 and a 1·1 or 1·2 per cent. carbon steel. The machinability of alloy steels, on the other hand, is influenced to a considerable extent by the toughness of the matrix as determined by the alloy content and microstructural condition and, in lesser degree, by the quantity and form of the free carbides.

An advantage associated with low-carbon case-hardening steels, whether plain or alloy, is their relative easy machinability, a feature which may favour their selection when the light character of the drawing operation for which they are intended renders the use of case-hardened tools having a relatively low core strength permissible.

Die steels are nearly always machined in the annealed condition. The supplier is relied upon to deliver bars or forgings in the fully annealed condition; yet as it is not unknown for imperfectly annealed steel to find its way into the tool room, it behoves the user at least to check the hardness of his blanks before starting machining. Hardness tests are very far from a complete and reliable guide to machinability but, as when used to test drawing-quality sheet itself, they do give a useful indication of the *probability* of conformity to standards which experience and other more informative tests have shown to be desirable.

Attention must be drawn to the fact that the fully-annealed



[*By courtesy of the Austin Motor Co. Ltd.*

FIG. 203. Six-foot diameter punch and die made of ordinary cast iron with Meehanite inoculated cast iron facings.

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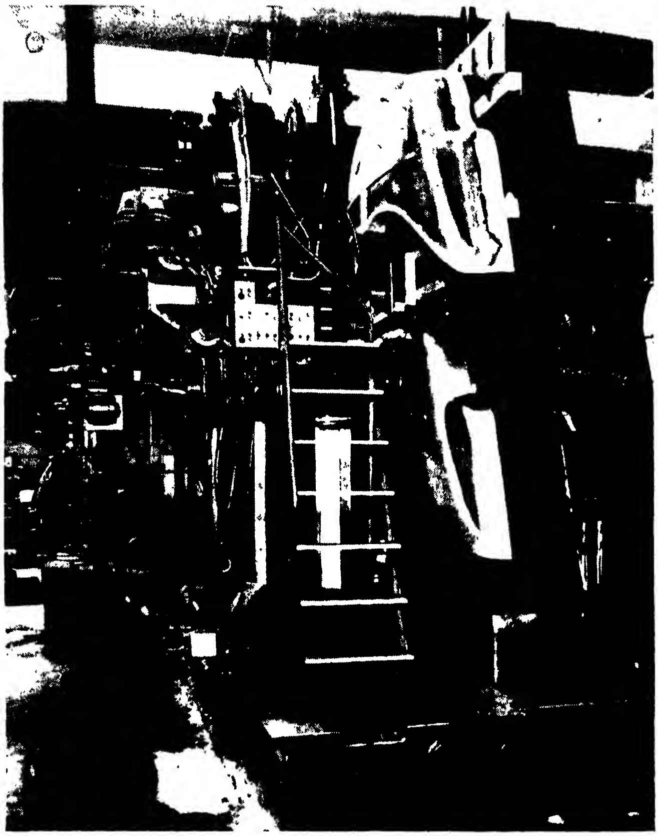


[By courtesy of Vauxhall Motors Ltd.

FIG. 204. Keller automatic profiling machine cutting press-tool for automobile body panel. The master pattern is mounted above the tool being cut.

[To face p. 355.

condition may not always provide the best machining properties with all steels. Much depends upon the chemical composition, but those responsible for the machining of die steels may well bear in mind the potential advantages obtainable from special heat-treatment of the kind sometimes given to engineering alloy steels—usually of relatively low carbon content—to facilitate machining. The fact that treatment of this kind does not always leave the steel in its softest condition still occasions surprise to those unfamiliar with such sparse knowledge as is yet available upon the influence of microstructure upon machinability. Needless to say, a small increase in hardness—above that proper to any steel in its fully-annealed condition—imparted purposely by special heat-treatment must not be confused with an increase of the same numerical order which may arise from improper annealing.

In the case of plain cast iron, machinability is determined principally by the fineness of the microstructure—in particular, of the graphite particles—and by the absence of hard spots and local chilling, average hardness being, as usual, of relatively minor importance. This is clearly demonstrated by the "inoculated" irons, which machine far more readily than ordinary irons of similar hardness. In alloy, as distinct from plain, cast irons the alloy content naturally influences the toughness of the pearlitic matrix.

Cast-iron tools are always rough-machined, if not always finished, in the pearlitic condition and are not amenable to heat-treatment given specially to increase machinability, which property is usually relatively good; the main precaution to be observed is the avoidance of chilled or semi-chilled areas by careful control of chemical composition and casting conditions.

The machining properties of tool materials other than steel and cast iron will not be discussed, because their use is at present very limited and, in general, their shaping presents no great difficulty. Specially hard materials, as used for facings, can only be ground. Suitable grades of grit and bonds have been developed by the makers of abrasive wheels, whose recommendations should always be sought and adopted if the most economical grinding and the best finish is to be obtained.

Methods and Stages of Shaping. Three stages need to be considered: rough-shaping (either by casting, forging, or machining from the solid); finish-machining or filing, and, lastly, polishing.

Rough Shaping. Small tools can be machined from solid bar or forged blocks without much trouble even from those steels whose machining properties are wont to be described on paper as "difficult," although more picturesque words are sometimes used by operators whose task it is to carry out the actual work. With this class of tool, machining costs do not usually call for serious consideration except with special alloys or surface deposits which cannot be cut and have to be shaped entirely by grinding. Even so, the advantage of a material—such as cast iron—which can be cast closely to finished dimensions is always worth serious consideration.

The usual procedure adopted when tools are to be cast closely to shape is to make an accurate pattern of either the punch or the die and to coat the working surfaces of this with a thickness of wax, which may be conveniently applied in the form of thin sheet, the exact thickness of the sheet required to be drawn. Plaster or other suitable material is then poured over the waxed surface in a frame, allowed to set, frame and plaster removed and the wax removed from the first pattern. There are then available accurately fitting patterns for both punch and die which, assuming good foundry technique, will require only very slight dressing—in addition to polishing—to make them ready for use. The amount of careful machining and fitting saved by this method can be very great indeed, and may cut down the time required to make a pair of medium-sized tools by many days.

With medium-size tools, cost of shaping is of more importance, and the value of a material which can be cast closely to shape and finished by light machining, or even by filing only, may be considerable. With difficult-machining steels, it may pay to have forgings made when the shape of the tool lends itself to this procedure rather than to machine entirely from the solid.

Large tools, whether solid or composite, are nearly always made from castings or forgings, although small inserts of specially durable material may be conveniently and cheaply machined from the solid and attached to castings or built-up bases of soft, easily-machinable material.

Ease and cost of machining will, naturally, be dependent to some extent upon the equipment used. Time of machining may be reduced many hundred per cent. when, to supplement the usual machine-tools, there are available machines such as the Keller die-sinker illustrated in Fig. 204 which, by means of electrical control operated by the light pressure of a mechanical finger sliding over the surface of a replica of the desired shape, cut this shape (in three dimensions) from a block or forging. The illustration is of a die-sinker, controlled in three dimensions; the same principle, applied to movement in two dimensions only, is also utilised on the Keller lathe on which the profiles of wholly-circular drawing dies and punches can be machined.

Whatever type of machine is used, it may be accepted that the cost of rough machining will be cut down enormously by the use of castings and that forgings, although they cannot equal castings for closeness of limits and intricacy of shape, will show a useful saving. The saving will usually vary proportionately with the size of the tool being made.

FINISH MACHINING. As with rough machining, the cost of this will vary with the equipment which is available and with the nature and intricacy of shape of the tool; but another factor must be considered, namely, the ease with which a good surface can be imparted to the working faces of the tools. Although this factor assumes greatest importance in the final, or polish, stage of tool manufacture, the ease with which polishing can be carried out is influenced to a considerable extent by the finish imparted during the final machining operations.

To mention two extreme instances, certain special cast irons machine very easily and readily take an excellent surface; whereas hard, fused-on facings cannot be machined at all, and have to be ground. Naturally, the area of the surface to be smoothly finished is an important factor in determining whether it will be economic to use material which is difficult to finish-machine.

More care and time spent on finish-machining would frequently enable a better polish to be obtained with less labour than is usually expended on the final operation, and would show a saving in the total cost of manufacture of the tool.

POLISHING. In spite of the considerable variation shown by various materials in both the degree of polish obtainable and the time taken to produce an adjudged satisfactory finish—itself too seldom the best, or even a desirably good one—little attention seems to be given to these two factors. In a later section attention will be drawn to the benefits derivable from a much better polish than that usually given. Ease of polishing, and degree of polish obtainable, are two factors which ought always to be borne in mind when a tool material is being selected.

Cast irons must, by reason of their natural properties, be placed in a class by themselves as regards ease of polishing and the facility with which they acquire an increasingly good polish during use (when not overloaded). As may be expected, the ease of polishing decreases with increasing hardness imparted by means of heat-treatment.

Steels, on the other hand, are invariably difficult to polish in the hardened condition, particularly when the hardness rises above C60–62 Rockwell or thereabouts. Chemical composition seems to exert little influence upon the readiness with which steels can be polished and, assuming an absence of abnormal inclusions or unusual structural characteristics, hardness seems to be the only important variable relating to the material itself.

The value of machining the surface as smooth as possible before polishing is started has already been stressed. When tools have to be hardened, polishing costs can be greatly reduced by taking every possible precaution to avoid scaling of the roughly polished surface during heat-treatment.

Readers may think that some of the factors relative to ease of shaping which have been enumerated are too obvious to justify consideration. This enumeration has, however, been attempted mainly for the purpose of emphasising the fact that all of them must be borne in mind, and their relative importance assessed, before a really sound decision can be made regarding the suitability of any material for use in a given tool. Serious consideration is, unhappily, not always attempted; "same as usual" or "whatever is in the stores" are phrases which often prevent the use of the most suitable steel and sometimes hinder experiment leading to better tools.

Ease of Heat-treatment. This defines the ease and certainty with which a tool material, after having been machined to shape, can be hardened and tempered or otherwise treated to produce the desired surface condition without cracking, distorting or behaving in an erratic manner.

One of the advantages of cast iron as a tool material is that quite often it can be used in an unquenched condition, thereby saving the cost of heat-treatment and avoiding all risk of distortion and cracking. This advantage will be appreciated fully only by those who have to take the blame when an expensive tool cracks during heat-treatment, often due not to incorrect manipulation but to some defect in the metal or to the use of an unsuitable variety of steel.

In selecting a steel which will give a very hard surface, too great a risk of cracking is frequently run. For example, for a die of considerable mass, or containing sharp fillets and narrow sections, it is better to sacrifice a few points in hardness by choosing a plain steel of 0·7 to 0·8 per cent. carbon rather than one of 1·1 to 1·2 per cent. carbon which is more likely to crack. If the extra hardness is deemed essential, it may be a profitable form of insurance to select a somewhat more expensive steel containing the lower range of carbon plus about 1½ per cent. tungsten. Again, when the design of the tool is conducive to cracking or distortion it may be better, and indeed sometimes essential, to select a so-called expensive alloy steel which can be oil-quenched.

A common cause of cracking in all types of tool steels is marked residual "ingotism" or dendritic structure resulting from the bar or forged block having received insufficient mechanical treatment in the works of the steel-maker. A typical example of this structure, which caused a high-carbon high-chromium steel die of simple shape to crack during quenching, is shown in Fig. 205. Residual dendritic structure is more prevalent in large-diameter bars than in small bars and forgings, as less work is put upon the cast metal in reducing it to the size in which it is purchased by the user, who is entirely in the hands of the steel-maker and receives no hint of the unsatisfactory nature of the steel he is using until he has spent a very considerable sum of money upon shaping and polishing a tool.

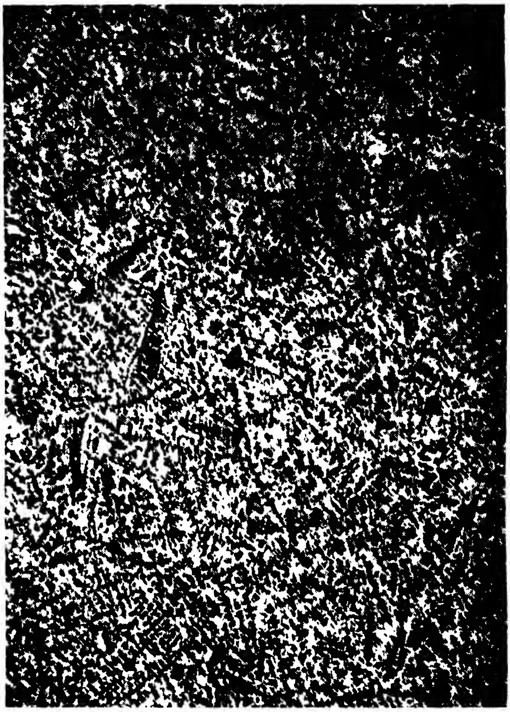


Fig. 205. Photomicrograph showing dendritic structure in tool made from high-carbon high-chromium steel which cracked during hardening. × 12.

[*To face p.* 358.

Experience seems to suggest that there is risk of appreciable residual ingotism in bars having a diameter greater than one-quarter that of the cast ingot.

Examination of suitable macro- and micro-specimens cut from a large bar can sometimes prevent the use of unsatisfactory steel when a metallurgist is available, although with separate forgings it is usually possible to detach a specimen only from the surface layers, a form of examination which may not always be adequate because the micro-structure of the surface layers may be very different from that of the core.

In addition to structural defects or conditions, the presence of internal stresses due to inadequate normalising after forging constitutes a potent source of cracking even when normalising has, as it should, formed part of the schedule of shaping operations prior to hardening proper.

Distinct from influences arising out of residual stresses or visible structural conditions, there exists the very important property which practical hardeners describe as "sharpness." This property, which may be defined as the intrinsic proneness of any particular steel to crack during quenching, is most important, and one which is aggravated by super-imposed conditions of structure and stress to a markedly varying extent in steels of different type.

It must be admitted that the real cause of variation in "sharpness" is still obscure. It is, of course, dependent largely upon chemical composition, mechanical and thermal history; yet the indisputable fact remains that steels of the same chemical composition produced by different steel-makers will vary very markedly in behaviour during heat-treatment. For example, three brands of 1 per cent. plain carbon steel with which the author has been familiar for some years exhibit such widely different, yet surprisingly constant, degrees of "sharpness" that they have come to be regarded as virtually different steels. As such, they are allocated to tools of different shape and, what is more, given different manipulative treatment during hardening.

"Sharpness" is probably related to the property descriptively termed "hardenability," to which increasing attention is being paid. It is likely that the "inherent grain size" of steel, as distinct from the microstructure revealed by normal methods of examination, will in the future be recognised as a partial, if not a complete, guide to behaviour during hardening. Interesting advances in this study are being made but, for the immediate present, the experience of practical hardeners with steels of different types and brands seems to be the surest guide to "sharpness," and many cracked tools could be avoided if the advice of such men was sought before the steel for any given tool was decided upon.

One means of minimising the risk of cracking with steel tools of thick section is the use of low-carbon steels case-hardened; but as a core possessed of a very high resistance to crushing is often necessary, this practice is of less value than might at first sight be imagined. For light draws, cast iron may prove cheaper and equally, if not more, satisfactory as regards performance.

Distortion is a defect which, although less dramatic than cracking (and a large tool can crack with explosive violence), can be equally effective in spoiling an expensive die or punch. Distortion is influenced by three principal factors: residual stresses in the steel remaining from forging, machining or previous heat-treatment; stresses produced during quenching by reason of the shape of the tool itself and, lastly, the inherent tendency exhibited by various types of steel to distort, a factor which for the purpose of this classification is intended to include the necessary method of cooling, *i.e.*, by means of water, oil or air. Although less definite than in the case of "sharpness," there is ample evidence to show that steels of similar chemical composition made by different steel-makers may exhibit varying proneness to distort under similar conditions: for instance, the difference in distortion normally exhibited by two popular brands of high-carbon high-chrome steel is so marked that whereas no trouble is experienced with one, the distortion assumed by the other is so great that tool output is seriously hampered. As in the case of "sharpness" and "hardenability," the true nature of the factors which control the magnitude of distortion are not really known; in addition to obvious causes such as residual stresses, both the nature and disposition of the free carbides and the "inherent" grain size may be of importance.

The temptation to pass a slightly distorted and urgently needed tool is seldom resisted by those responsible for releasing finished tools for use. The resulting locally incorrect clearances between die and punch certainly account for the failure of much good quality sheet.

Although detailed consideration of those causes which govern the tendency of steel to crack and distort fall outside the province of this chapter, this brief mention of proneness to crack and distort has been necessary in order to draw attention to the need for proper consideration being given to this property when the steel for any tool is being chosen. For the very good reason that a cracked or badly distorted tool is useless, "sharpness" and proneness to distort must be regarded as two very important properties of a tool steel. It is, surely, foolish to select for a given tool a steel which, although its properties with respect to service performance may be most excellent, is likely to crack or, alternatively, almost certain to distort; yet such selection is frequently made and the hardening-shop blamed for the resulting failure and delay. In some instances some sacrifice of hardness and durability may be advisable in order to minimise the likelihood of an expensive tool cracking or distorting during heat-treatment. In this respect the claims of cast iron must not be overlooked, for this material can often be used in an unquenched condition and when hardening has to be done there is, on the whole, considerably less likelihood of cracking or distortion occurring than with steel.

Resistance to Plastic Deformation, Abrasion, Scoring and Fouling. These four properties are the ones which, often to the exclusion of others, may seem of paramount importance to those concerned with actual deep drawing and pressing operations. It is true that these four properties determine both the useful life of the tools and, to a considerable extent, the quality of the surface imparted to the drawn product. For this reason it will be profitable to examine them closely and to attempt to ascertain their true nature as far as present knowledge will allow.

Resistance to Plastic Deformation. This is by far the most readily understood and also the most easily attainable of the four properties enumerated. It is clear that very high pressures can be imposed upon the surface of tools during the deep-drawing of, for example, steel sheet of thick gauge, and even of moderate gauge when " ironing " is being performed. The practice of dividing the maximum force exerted by a certain press, or even the estimated force required to deform a given section of sheet, by the estimated working surface of the die in order to compute the maximum pressure per unit area to which its surface can be subjected is wholly unreliable. Practical proof of this is sometimes found in tools which suffer plastic deformation in spite of the fact that their surface-loading per unit area, estimated on casual examination, is well below the known limit of proportionality of the material from which they are made. The severity of the draw is not, therefore, the sole factor in determining the pressure to which tools will be subjected ; the shape of the working regions of the die exercises an important influence on the pressure borne per unit area of surface.

The remedy for plastic deformation lies, obviously, in the use of a tool material possessing a sufficiently high limit of proportionality, but this apparently simple cure is not always effected easily owing to the very high pressures which occur locally in tools of somewhat empirical design. For example, the author has handled a number of intrided tools made from an ordinary aluminium-chromium variety of nitriding steel possessing a core strength of some 70 to 80 tons per square inch which have collapsed very quickly when drawing a certain shape in 0·060 inch thick steel sheet. Only the substitution of a high-carbon high-chromium steel having a core strength in the region of 140 tons per square inch enabled the benefits of a nitrided surface to be secured on these (and other) tools. But for the visible evidence provided by the deformed 70-ton tools their designers would never have imagined, or admitted, that such high surface-pressures were being borne by them. For the same reason ordinary case-hardened tools, which for cheapness, ease of machining and also nature and condition of surface have much to commend them, often prove inadequate.

Misconception of the term " crushing strength " sometimes arises. This is particularly so with respect to cast iron due to the habit of certain suppliers of including values described as " crushing strength " in tables of physical properties. Under the action of comprehensive stresses a metal fails by shear, the maximum stress occurring along planes situate at 45 degrees to the direction of compression; the limiting stress which a metal will withstand without suffering plastic deformation is, therefore, related directly to the limit of proportionality. In steel both the limit of proportionality and the theoretical ultimate strength are virtually the same in tension and compression. In cast iron, due to the extreme weakness of its graphite flakes in tension, the ultimate strength is considerably greater in compression than in tension; but it must not be assumed that a similar difference exists for the limit of proportionality, a value which is rarely measured or quoted for cast iron. The tool designer has, for this reason, little data upon which to work when dealing with cast iron, but he can be tolerably certain that the safe loading in compression is certainly less, and sometimes markedly so, than the figure claimed as " crushing strength," particularly in irons containing coarse graphite.

Although from first principles it would seem that such a fundamental property as the limit of proportionality of a mass of metal cannot be changed by purely elastic stressing, it is an established fact that in dies used for the heading of wire a steel of given physical properties is more resistant to deformation if kept, by means of a shrunk-on holder, under a high stress which opposes that applied during use. This method of construction might offer advantages for severely stressed deep-drawing dies, particularly for those made in cast iron; it would certainly enable thinner sections to be used in the die proper, and would thereby enable a greater depth of its section to be fully hardened.

Consideration of what, without any implied sole reference to case-hardened tools, may be termed core strength, provides another illustration of the necessity for bearing in mind a large number of factors when decisions regarding tool materials are being made. Taking a broad view, it may be found that it is more economical to use a number of fairly light draws which can be satisfactorily performed with a die material possessed of a relatively low core strength than to use one or two severe draws which demand the highest core strength obtainable, a finding which it is often difficult to prove, except by actual trial, to those responsible for drawing up production schedules. As a general indication it may be pointed out that in certain instances the cost of tools may be reduced and the surface of the product improved by substituting, say, four draws in cast iron or case-hardened steel dies for two draws in high-alloy steel dies. It will be shown later that procedure of this nature often confers benefits other than a saving in the cost of tools.

Resistance to Abrasion and Scoring. This means resistance to attrition in the sense of cutting, and not that form of scoring produced by "fouling," that is, seizure between tool and work. "Macro-attrition" seems a convenient description of this particular kind of wear.

It seems reasonable to assume that macro-attrition, in the form of abrasion and scoring, is produced wholly by the action of foreign matter which finds its way between the tools and the work. This foreign matter consists of two main types: extraneous particles of a miscellaneous nature which unaccountably find their way into unwanted places *viâ* the air, floor, bins, and even lubricant—the author has discovered steel swarf, carborundum, silica sand and chilled-iron shot on metal offered to the tools—and, secondly, oxide adhering to the surface of annealed sheet or partially-drawn shapes.

The resistance of a tool to abrasion by macro-attrition increases with increasing hardness; nitrided steel, for example, seems to possess the maximum resistance of the more commonly used tool materials. In particularly "dirty" shops the use of nitrided tools may, therefore, be specially advantageous in order to resist scoring, apart from other benefits associated with a nitrided surface. There is, however, another aspect which has to be considered. The harder the tool the more difficult it becomes to polish out or even minimise scores once these have been formed; hence men having shop experience sometimes express a preference for relatively soft tools from which scores can be removed or minimised with comparative ease. It is difficult to reconcile such conflicting opinions: unless unusual shop conditions exist it seems better when choosing tool materials not to pay undue attention to the special property of resistance to macro-attrition, but to exercise all possible care to exclude foreign particles from the tools and work during use.

The second cause of abrasion, namely, that produced by oxide scale, is one which has to be met when those in authority deem it economical to use "black" sheet for the production of an article, or when poor inter-stage annealing conditions have to be endured. It is surprising what havoc oxide can cause to ordinary hardened steel tools, and even to nitrided steel; indeed, it is questionable whether it is worth while producing a really good polish on new tools destined to be used with oxide-coated metal. "Stellite" and, in lesser degree, nitrided steels suffer less than fully-hardened carbon or alloy steels, but even with these it is virtually impossible to maintain a polished surface. This being so, the use of cheap material—even unhardened cast iron—which can be readily dressed is often preferable when its core strength is adequate. An illustration of the damage caused by severe draws on oxide-coated steel, even with hardened tools, has already been given (see Fig. 72, p. 100).

Here, again, the necessity for due consideration of all factors is apparent; the fact that oxide-coated work has to be drawn is not always taken into account (and in large organisations is not always known) by those who decide what tool materials are to be used. With most materials, whether hard or soft, light draws cause far less damage than severe ones.

In addition to what has been classified as "macro-attrition," there remains that very important form of wear which, extending the simile, can be called "micro-attrition." This may be defined as the normal or legitimate wear produced by the passage of clean sheet over the die, although the term "legitimate" needs qualification for, under ideal conditions, a film of lubricant would prevent direct metal-to-metal contact at all stages and attrition of the die surface would, for all practical purposes, not occur.

Regarding micro-attrition, experience points for once wholly in one direction. With steels, the harder and more smoothly polished the surface is, the less will be the wear. Although it is doubtful if any direct relationship exists, the increase in tool life which often results from an increase in hardness of from about C60–62 to C64–66 Rockwell is rather surprising, and not altogether what would be expected from extrapolation of the relationship existing above, and particularly below, the small range just mentioned.

To resist micro-attrition steel should, then, be in its hardest possible condition; but practical considerations, some of which have already been discussed, often limit the degree of hardness which is both obtainable and desirable from the one aspect of longevity of life. By the use of chromium-plating or by nitriding steels of suitable chemical composition it is possible to produce a surface considerably harder, and consequently more resistant to attrition, than that obtainable even from fully-hardened plain carbon or carbon-tungsten steel. In this way a relatively soft steel, unlikely to crack during hardening, can be used for the base metal, although the term "relatively" may often mean a decrease of only a few Rockwell points because it is most important that both chromium-plating and nitrided skins be adequately supported, or they will crack and "cave in."

With cast iron, on the other hand, hardness and even state of initial polish do not seem to constitute the only, or sometimes even the principal, criterion of micro-attrition; microstructure, alloy additions and, in particular, the form and dispersion of the graphite appear to be the most important factors. Here, again, experience leads to one conclusion: resistance to micro-attrition increases with the hardness of the ferrite constituent as determined by the alloy content and, more markedly, with the fineness and uniformity of distribution of the graphite particles. The remarkable properties of cast iron when used as a tool material are often attributed to the lubricating properties of the free graphite contained in it, although other reasons will be suggested later; and direct comparison of its resistance to wear with that of steel is, for this reason, not justifiable. Bearing in mind the importance of extreme hardness with steel tools, the length of life of soft cast iron of suitable nature is truly remarkable, and illustrative of the amazing power of a film of lubricant probably of molecular thickness.

Resistance to Fouling. Because under the conditions obtaining during deep-drawing operations it is seldom possible, by maintaining an unbroken film of lubricant, to prevent at least momentary localised metal-to-metal contact between tools and sheet, the property of resistance to fouling assumes considerable practical importance.

Fouling, which is of course actual welding together or "seizing" of the tool and the sheet, produces scores and general damage to the surface of the drawn product and, frequently, damage to the surface of the tool from which the "loaded" metal has to be removed by stoning and polishing. Once started, such loading is cumulative, because the affinity between the loaded deposit and its parent sheet will be greater than that between the sheet and the clean tool. For this reason the most thorough possible cleaning of loaded areas is desirable, and a wise insurance even though the consequent delay in production may cause annoyance to those unfamiliar with all aspects of the stoppage. Fig. 83 (p. 114) shows typical "loaded" areas on a "fouled" hardened steel die used to deep-draw a circular cup from sheet steel at, what experience proved to be, a rather high speed. It should be noticed that the loaded areas are situated near the lower edge of the bore of the die where the contact pressure is high and *conditions of lubrication are worst.*

Perhaps the most serious result of fouling is the time taken to recondition the loaded tools, assuming that reconditioning is possible, with consequent loss of working time and upset to production schedules. For this reason working is often continued with untouched or imperfectly rectified tools, to the detriment of the drawn product unless greatly increased polishing costs can be tolerated.

Dealing with steel, the most commonly used tool material, the greatest possible difference in hardness between the tool and the sheet seems to be the best and indeed the only available remedy with respect to the tool material itself. Freedom from surface irregularities is of the utmost importance, for these will easily penetrate the film of lubricant and, furthermore, will rapidly attain a very high temperature, a condition most conducive to seizure. Smoothness of surface cannot, however, be classed as a property of a material, and consideration of this attribute will be postponed.

Hardness, then, is the main factor to be borne in mind, and it is logical to expect that the hardest condition of all, namely, that produced by nitriding, will offer the greatest resistance to fouling. Practical experience shows that this assumption is correct, and that the resistance of a nitrided surface to fouling is markedly greater than that of the hardest obtainable quenched steel. When it is not possible by a change in lubricant, in tool design or in speed of drawing to overcome persistent fouling on ordinary steel tools, the substitution of nitrided steel offers a most valuable, and often entirely effective, remedy.

Proneness to seizure is determined by the natural affinity of the molecules of the tool material for those of the sheet being drawn. Considered from the fundamental aspect it would seem logical, therefore, to use a non-ferrous tool for shaping a ferrous sheet. Unfortunately, the very high core strength demanded by many deep-drawing operations in which steel tools are used renders the use of steel essential and, if surface pressures are reduced, a good lubricant or the substitution of cast iron may effectively prevent serious fouling without resort to unusual, and probably expensive, tool materials.

A notable exception to this generalisation with respect to non-ferrous materials arises when these can be deposited on to the surface of hardened steel. The most familiar example of this is electro-deposited chromium, which combines great hardness, a non-ferrous nature and, in addition, a high degree of natural "slipperiness," a property which will be examined later. The resistance to fouling offered by well-polished and properly chromium-plated tools is at least equal to, and sometimes greater than, that offered by nitrided steel; but, in the experience of the author, the qualifications just mentioned render it less trustworthy, because it is not uncommon for the polish and the deposition to be mediocre.

Turning to cast iron, the high resistance to seizure, even to ferrous sheet, exhibited by this material is believed to be due to the peculiar self-lubricating properties which it possesses. It is probable that a soft cast iron containing ferrite but no graphite, if such a material can be visualised, would foul badly under normal conditions of service. In resistance to fouling, as in other properties, cast iron must be regarded as unique. Many instances are on record in which, under identical conditions, cast iron tools have shown no tendency to foul when persistent and serious difficulty due to this defect has been experienced with steel tools. When conditions allow cast iron to be used its cost will be far less than, and its resistance to fouling will often be at least equal to, that of nitrided or chromium-plated stel.

It will have been apparent that in the majority of these remarks it has been assumed that the metal being deep drawn or pressed has been steel. It is hardly necessary to say that serious fouling may occur with non-ferrous metals when contact pressures are high, but most of what has been said applies to tools used for non-ferrous metals. As with steel sheet, the use of tools having the highest possible hardness seems to be the best remedy, with the possible exception of chromium-plating.

The tendency to foul evinced by any given sheet and tool is influenced by the load, the speed of drawing, the nature and efficiency of the lubrication as well as by the chemical composition of the two materials themselves. Prior to the work of Brownsdon,[10] who investigated the fouling and wear produced by pressing a revolving disc of hard steel into the smooth surface of various metals under controlled conditions of speed, load, lubrication and time, no precise observations of the influence of these various factors seem to have been published. It may be argued that the conditions of this test, particularly as regards time, bear little semblance to conditions obtaining in most deep-drawing operations. Nevertheless the definite indications and differences revealed by it suggest that, although not ideal, it is likely to lead to a useful increase in knowledge.

Using a steel disc of 775 V.P.N.—*i.e.*, about C60 Rockwell—hardness, but unstated chemical composition, Brownsdon found that zinc-bearing alloys—*e.g.*, brass and nickel-silver—were most prone to foul ; aluminium-bronze less, and copper, tin-bronze and cupro-nickel least of all. The benefit of a smooth surface on the disc and of a lubricant having " oily " characteristics were clearly demonstrated.

To summarise, fouling of steel tools can best be combated by using the hardest possible surface, nitriding offering valuable assistance. Cast iron is unique by reason of its self-lubricating properties, but direct comparison with steel is not justifiable when working pressures are different. A fruitful field for experiment lies open with non-ferrous tool materials, chromium in the form of a thin electro-deposited coating offering a notable, though possibly an exceptional, example.

Slipperiness. This, the last property enumerated in our list of specially important properties of tool materials, may at first sight appear akin to that of resistance to fouling, the property just examined. Although it is true that a slippery material will not foul readily and, again, that true slipperiness is of importance only when actual metal-to-metal contact occurs between tool and work, separate consideration seems desirable in order to distinguish between certain fine yet essential differences, mainly because a surface resistant to fouling may not necessarily be slippery. Expressed more precisely, two sliding solids which do not readily " seize " may yet possess a relatively high coefficient of friction. Resistance to fouling postulates lack of natural affinity between the molecules of tool and work ; slipperness is a condition arising from the nature of the molecules of the tool material itself and its study is closely akin to that of lubrication, a subject which is dealt with at some length in the next chapter.

The property of slipperiness exhibited by smooth solids, termed by Archbutt and Deeley [82] "unctuousness," is determined—apart from mechanical considerations arising from the degree of smoothness of the surface—by the nature and properties of the surface molecules. In a non-slippery solid it is believed that unsatisfied atomic linkages exist ready to be attracted, if not always to unite in mass to cause the effect known as seizure, to those belonging to an adjacent surface. In chromium, the surface of which has a recognised "slippery" or "greasy" nature, it is envisaged that the surface energy, which is high, causes the unsatisfied atomic linkages to bend over and unite with surrounding linkages leaving none, or only a relatively small proportion, free to attract, or attach themselves to, those of an adjacent surface. Expressed pictorially, the surface of a non-slippery metal may be likened to a field of stubble, the stubble representing unsatisfied atomic linkages; whereas a slippery surface may be likened to the same field after industrious fairies have been over the upstanding sticks and pushed the free ends into the ground.

It is instructive to bear this simile in mind when observing plain steel and chromium-plated tools working under similar conditions, particularly if steel sheet is being drawn. When these conditions are such that with the plain tools seizure is being approached, the draw will proceed with an audible "*scree—ee—ee—eech,*" which can be visualised as the upstanding sticks (atomic linkages) scraping unwillingly past one another. With chromium-plated tools the audible result of the draw may be an almost limpid-sounding "*plonk,*" suggestive of an absence of upstanding ends and the presence, continuing the simile, of rounded, smoothly sliding sticks or excresences.

With steel tools it seems that the harder the steel the more slippery —in a purely relative sense—they become. Best of all are nitrided tools, and it may be that variation in surface energy explains observed differences in behaviour. It might be thought from theoretical considerations that steels which exhibit what is virtually a "bearing-metal" type of structure, such as the high-carbon high-chromium varieties which consist of carbide globules embedded in a matrix of martensite, would exhibit a higher degree of slipperiness than plain carbon steels of uniform microstructure; yet there seems no definite evidence that this is so.

In order of increasing slipperiness there must be placed moderately hard steel, hard steel and, by far the best, nitrided steel. Markedly superior even to this last is chromium-plated steel of adequate core strength. Cast iron, by reason of its special self-lubricating properties, possesses a fairly high degree of slipperiness, but this is attributable to the action of its graphite molecules which constitute only a small proportion of the total.

Whatever the nature of the metal, as smooth a surface as possible is a great asset to apparent slipperiness. For practical purposes, therefore, slipperiness is related to ease of polishing, a property already discussed.

There is little need to emphasise the value of a high degree of slipperiness in a tool material. Clearly, this property will lessen the resistance to flow of the sheet over the tool radius, an effect which is highly desirable not so much from the aspect of a reduction in the power required to produce a given draw, but because the less the friction between die and sheet the lower will be the stresses set up in the walls of the drawn portion of the shape (and consequently the less the danger of rupture) and the lower the temperature attained. From a practical aspect slipperiness can, as suggested previously, be regarded largely as lubrication under limiting conditions.

During discussion of resistance to fouling mention was made of the possible value of materials other than steel and cast iron for the construction of drawing tools, or at least the working surfaces thereof. It will now be clear that this field of exploration is of equal potential value in the quest for materials possessing enhanced slipperiness with respect to true unctuousness and also to the properties of adsorbed films of lubricants formed upon them.

Another aspect, distinct from behaviour during metal-to-metal contact, must however be noticed. It will be explained in the next chapter that the properties of an adsorbed film of lubricant formed upon a metal surface will be influenced to some extent by the nature of the molecules which compose the metal surface as well as by that of the lubricant itself. It follows, therefore, that any study of that property or condition here termed slipperiness extends beyond that of pure unctuousness, or friction between the dry surfaces of various metals, to include the behaviour of adsorbed films of various lubricants upon those surfaces.

Viewed thus, the choice of a tool material to give the best possible performance with a certain sheet and lubricant becomes a decidedly abstruse problem dealing, as it does, with the limits of available knowledge. Should the value of such academic considerations be questioned, as it certainly will by practical workers, the proved and outstanding value of chromium-plating may be instanced. The fact that this valuable adjunct was discovered by accident, and is widely used without thought of the underlying principles involved, does not detract from the potential value of such considerations in indicating other valuable combinations.

Hardness. Readers may well have wondered why hardness, a property of tools and tool steel which is doubtless mentioned more often than all the ones which have just been examined put together, has not been given place of priority. It has been left till the end in order that better distinction might be made between other properties which, through false assumptions, it is often held to embrace. For example, longevity is not necessarily a function of hardness, a fact demonstrated by tools made of cast iron; again, although resistance to fouling is apparently related to hardness in the case of steels, other factors such as chemical composition and degree of surface polish need always to be considered.

The unique position occupied by hardness as a property of tools is due to the fact that it is the only one of many important properties which can be measured accurately and quickly. Because of this, hardness measurements provide a most welcome and valuable method for rapidly checking whether a tool has received proper heat-treatment, although even when used in this way hardness measurements really indicate nothing more than the *probability* of correct material and heat-treatment; an incorrectly heat-treated tool of specified material or a properly heat-treated tool of incorrect material may give the same indicated hardness value as a properly heat-treated tool of specified material, as the unwary or over-trustful may discover to their cost.

In spite of this drawback, which to the practical man may seem of no more than academic importance, it must be conceded that hardness is a most valuable guide to those who have to handle or discuss tools, although the difficulty of measuring or even defining true "hardness" as a fundamental property is very great. For the purpose of this review, "hardness" will be defined as a numerical reading correctly indicated on a suitable machine and used for the purpose of comparison with other readings obtained in a similar manner.

At this stage it becomes necessary to mention the several types of machine which are in common use for testing the hardness of tools in both the soft and the hardened condition, and to indicate the significance of, and relationship between, the respective scales belonging to these machines.

Types of Hardness Test. Vickers Pyramid Numerals, Rockwell C-scale readings, scleroscope so-called "degrees" and Brinell Numerals are the units of the four commonly used scales; the respective methods of test are described later in Chapter XII.

The Vickers test is undoubtedly the most accurate and reliable for hard materials, and the small size of the impression enables tests to be made on working surfaces even when these are polished. The comparative slowness of this test may perhaps explain why it is less popular outside the laboratory than is the Rockwell test. Vickers Pyramid Numerals are the only units which can be converted into Brinell numbers, by reference to tables or graphs, with any degree of certainty and without modification according to the nature and condition of the material being tested. Until such time as the Vickers scale may come to be regarded as a standard in preference to the Brinell scale, this ease and reliability of conversion is a very useful, if not fundamentally important, benefit.

The Firth hardometer, used with the diamond indentor, can under certain conditions prove equal in reliability and accuracy to the Vickers machine, but the smaller range of standard loads tends to limit its field of safe application.

The Rockwell test, which is used more than any other for the routine testing of hardened tools, will give consistent and reliable readings *provided that care is taken to see that the tool being tested is supported quite rigidly*, a precaution which it is not easy to ensure with tools of awkward shape unless special supporting or clamping fixtures are made for attachment to the machine. An advantage of this test is that the preliminary, unindicated load and the greater depth of the impression render unnecessary the same degree of preparatory polish which is required for an accurate Vickers reading, unless a heavy load is used in this latter test. For shop use, the Rockwell test is probably the best of any.

The Brinell test ceases to give truly proportional readings on hard metals by reason of the deformation suffered by the indentor ball, which itself is made of hardened steel. Owing to the much greater area of the impression it is, however, more reliable for soft metals of non-homogeneous structure, such as grey cast iron, than any test employing a very small indentor. Obviously, a tiny, pointed indentor will indicate only the hardness of the immediately surrounding mass, which may not be the same as a true general or average hardness of a matrix containing either harder or softer particles.

It is conceded by most impartial authorities that scleroscope readings tend to be erratic. The main advantage of this device is that the tube can be detached from its stand and placed upon selected surfaces of tools which are too large to be tested on Rockwell or Vickers machines. Used thus, a fair indication of hardness can be obtained by a practised operator from the average of a number of readings if the surface being tested is smooth and the material homogeneous.

It is scarcely necessary to point out that if a true hardness value is to be obtained on hardened steel, any decarburised surface skin must be removed before a small indentation hardness test is made, or a low reading will be forthcoming. On the other hand, proof of the existence of the desired hardness in the underlying metal must not lead to dismissal of a decarburised surface as unimportant when the working surface of the tool is not to be ground before it is ready for service. For the reasons indicated when the properties of tool materials were being discussed, the presence of a decarburised skin is conducive to fouling besides the more obvious defect of rapid wear until the hard core is reached.

In addition to the mechanical testing machines which have just been mentioned, and other less popular machines which cannot be included in this brief review, there exists the oldest of all commonly used hardness tests, namely, the file test. This, in the opinion of some, is often of greater value than any precision measuring instrument. Although this opinion may well be challenged, it must be conceded that in skilled hands a file can quickly reveal properties and conditions which are not indicated by any testing machine except the Vickers, and then only if a large number of careful readings are taken under different load settings and over a wide area. For example, the chances of the detection of soft spots are vastly greater when a file is used than when testing is carried out with the aid of a machine.

The greatest advantage of the file test is, however, that it can instantly reveal the existence, and to some extent the severity and even the depth, of any surface decarburisation which may exist. Surface decarburisation can easily be mistaken for general softness if the file is not used to supplement shallow indentation tests; as a result tools may be spoilt still more by repeated heat-treatment, and the primary cause of the defect remain unremedied.

It is unwise to place too much reliance on the "feel" of a file on steel as an indication of true hardness, for the feel of steels of different chemical composition varies appreciably; some measure of comparison can, however, be made by a skilled man between different pieces of steel of similar type *provided that one file is used*. Files vary appreciably in hardness, and a hard file may cut where a softer one would slide. A fine-cut file will make a piece of steel seem harder than a relatively coarse-cut file.

To overcome errors due to differences in cut, a "file scratch" test is preferred by some workers to the more usual method. In the scratch test the end of a small square or triangular file is ground to a point with which an attempt to scratch the surface of the specimen is made. An elaboration of the test revived by Hamilton [83] is the use of a series of files tempered to cover a range of about C25 to C65 Rockwell, the hardness of the surface under test being assumed to lie between that of the two files which will and will not produce a scratch.

Notwithstanding its limitations the file can be of real use, but it should be employed to supplement, and not to replace, orthodox hardness tests.

A suggested Scheme for the Testing of Tools. Having regard to the peculiarities of the four hardness testing machines just mentioned, the following scheme for the recording of reliable hardness values on various tool materials is offered.

GREY CAST IRON. For cast iron the Brinell test employing a 10-mm.

ball is the most reliable, although if the iron is of fine texture a 5-mm. ball will be equally satisfactory. The 30 to 1 load/ball-diameter-squared ratio should, of course, always be employed.

HEAT-TREATED CAST IRON. The same method may be followed for grey cast iron up to hardness values of about 450 Brinell. Above this it is informative to make both Brinell and Rockwell C-scale impressions. With irons of very fine texture, the average of several Rockwell C-scale impressions may prove fairly reliable.

ANNEALED STEEL. Either the Brinell or the Vickers test may be used. Readings obtained at the lower end of the Rockwell C-scale and at the upper end of the Rockwell B-scale tend to be unreliable.

DIRECT-HARDENED STEEL. Whenever possible either the Vickers or the Rockwell C-scale test should be used; the Brinell test should be avoided as being likely to give misleading information. When tools cannot be brought to a Vickers or a Rockwell machine, a scleroscope can give useful information when used carefully.

CASE-HARDENED STEEL. For cases of greater depth than 0·025 inch Rockwell C-scale readings (150 kg. load) are reliable; for cases of a depth from 0·025 to 0·012 inch Rockwell A-scale (60 kg. load) should always be used, as with the 150 kg. load the indentor tends to pierce the case. A special Rockwell machine, known as the "Superficial" model, which employs still lighter loads is available for measuring the hardness of very thin cases. The Vickers test can be adapted to cases of any thickness and, in the opinion of many authorities, is the most reliable of any.

The criticism may be made that this scheme is complicated and unnecessary, and that one hardness test ought to be applicable to all materials. Adequate reasons why such a welcome simplification is not possible have been given: the use of one general test cannot fail to give misleading results in some instances. Throughout this chapter the scheme just outlined will be followed with the modification that when either the Vickers or the Rockwell tests could have been used the Rockwell has been chosen as being the one more adapted to shop, as distinct from laboratory, usage. Scleroscope readings, being the least reliable of any, have not been given.

Conversion of Hardness Readings. It is regrettable that the practice of converting hardness readings from one scale to another by reference to published tables has become so common. In particular, free conversion of Rockwell C-scale readings to Brinell numerals, or scleroscope degrees to either Brinell numerals or Rockwell readings, is likely to lead to untrue statements if not to serious errors in practical application. Vickers Pyramid Numerals, Rockwell values, Brinell numbers and scleroscope degrees have each obtained practically universal recognition; conversion from one scale to another is unnecessary and should be avoided.

Smoothness of Surface. There have now been considered those properties of materials which determine more than others their suitability for tools used for deep drawing and pressing operations. Before examining in what degree these properties are procurable in certain commonly used tool materials it is necessary to discuss another, and most important, item not legitimately classifiable as a natural property of a material, namely, smoothness of surface.

It is a firm conviction of the author that the benefits derivable from a really smooth and well-polished surface on the working regions of deep-drawing tools is insufficiently appreciated. The production of a very smooth polish is, admittedly, a difficult and lengthy task, particularly on hardened steel: it is not surprising, therefore, that those responsible for making tools, particularly under the exigencies of modern factory conditions, are loath to be convinced of these potential benefits. Furthermore, the excuse that a very smoothly polished surface will soon get spoilt in use is, unhappily, only too well founded in view of the lack of cleanliness and often lack of lubrication under which it has to perform.

Apparently insuperable difficulties can, however, sometimes be overcome. Because no radical change in practice is necessary for its attainment, the idea of smooth, well-swept floors, white tiles, clean presses, filtered lubricant, scrupulously clean blanks and partly-drawn shapes, even an absence of bins to house dirt is, surely, less fantastic than was that of a clean steel-melting shop prior to the advent of electric induction furnaces. Under such improved conditions an initial smoothly-polished surface could be maintained on tools provided that attrition due to excessive pressure was avoided, as it could and ought to be, by proper design of tools and apportionment of draughts.

Leaving realms which it is hoped may not be entirely fanciful for the world of hard facts, the following reasons are offered to show why a very smooth and highly polished surface is so desirable in spite of the argument that conditions in deep-drawing tools are comparable to those obtaining in a bearing, and that it is held by the old if not by the new school of thought that a bearing-metal should consist of hard, upstanding excrescences in a soft matrix, *i.e.*, that a perfect polish on drawing dies is unnecessary and even undesirable. The answer to this argument lies in the fact that in deep-drawing practice the pressure per unit area is markedly, and often immensely, higher than in bearings.

It is envisaged that the essential function of the hill-and-valley contour of a bearing is to retain oil in the valleys and thereby increase the likelihood of the immediate restoration of a rupture in the oil film separating the sliding metal surfaces. But, when pressure between these surfaces is very high, projections will readily penetrate the oil film, which will be far thinner than under the conditions of (relatively) light load and consequent "fluid" lubrication obtaining in a bearing.

At this point it is interesting to digress slightly and visualise a surface devoid of excresences but containing depressions, serving as oil reservoirs, having a total area small compared with that of the rest of the remaining (and postulated smooth) surface. Contrasting this surface with that of a bearing metal, there exists a smooth hard surface, having an effective load-carrying area nearly equal to that of its superficial measurement and containing minute sunken oil pockets, instead of large reservoirs from which protrude isolated load-carrying peaks having an effective area which is very small indeed compared with that of the superficial area of the surface.

Is not the first picture that of a smoothly polished surface of cast iron, and may not this explain the really remarkable properties of this material when used in drawing dies ? The fact that a cast-iron die will suffer tens of thousands of very severe draws has always seemed to the author to demand an explanation other than, or at least supplementary to, the accepted theory of natural graphite lubrication; for the store of graphite, being so small, must surely tend to become depleted if, as is postulated, even minute traces are continually being transferred to the surface of the work, and it is an ascertained fact that the efficiency of cast-iron dies does not diminish during service. If the graphite pockets are regarded as reservoirs continuously filled with lubricant by capillary action—and it is conceivable that under pressure they may even act as *resilient* reservoirs—an explanation more satisfying than that which postulates nothing more than graphite lubrication is provided. An obvious corollary is that any material having, in addition to certain necessary properties, pores of a suitable nature—*i.e.* of a suitable size and number, and discontinuous so that lubricant cannot escape through the mass—might prove highly efficient as a lubricated die material.

Returning from this digression to the study of smoothly polished tool surfaces, an absence of excrescences is desirable for two reasons : to prevent rupture of the lubricant film by these excrescences, leading to scoring of the work, and to prevent the attainment of a very high temperature at these peaks productive of seizing when the lubricant film is ruptured. Clearly, the more nearly the height of the higher upstanding peaks approaches molecular dimensions the greater will be the effective load-carrying area per unit area of superficial measurement, and the less will be the actual loading per unit area. Moreover, the effective area will increase very rapidly as the height of the higher peaks decreases by reason of the markedly greater number of peaks which will carry the load.

From theoretical grounds then, as smooth a surface as possible is desirable in order to reduce the actual loading per unit of area and to reduce the likelihood of rupture of the lubricant film by projecting peaks ; minute, well-distributed cavities, having a total area small in comparison with that of a unit area of surface, may act as lubricant reservoirs and may for this reason be highly beneficial. Practical experience shows that steel, chromium and such-like hard metals demand the best possible polish; that cast iron, being relatively soft, more readily assumes a polished surface during service and that, in all instances, the surface condition of the drawn product improves, and the loading of the die and the power required to draw decreases, as the polish on the die becomes higher.

In the face of theoretical considerations and of definite, if limited, practical experience it is surely idle to contend that the smoothest possible surface on the working regions of tools is other than highly desirable from every aspect; "smooth" here meaning an absence of excresences but not, for the reasons described, a necessary absence of *small* cavities in an otherwise smooth surface.

For the very good reason that it is much easier to polish the majority of dies and pressure-plates, particularly circular ones, circumferentially, this direction is usually chosen. The result is that the surfaces of the drawing radii present a series of minute ridges over and at right angles to which the sheet must flow. Experience shows that when polishing is effected by strokes given *parallel to the direction in which the sheet moves* over the radii a better surface may be obtained on the drawn product and, of greater importance, the difficulty of maintaining a continuous film of lubricant is appreciably lessened. In many instances the extra cost involved in polishing radii in the proper direction is well worth while.

Tool Materials

Having examined some of the properties which determine the suitability of a material for use in deep-drawing tools, it is now possible to distinguish the principal characteristics of a number of common tool materials more clearly. Too frequently a tool material is described merely as "good" or "poor"; more precise description would be far more valuable both for immediate consideration and for the purpose of record for future reference. In particular, mention is seldom made of working pressure which, after all, is the principal factor in determining the magnitude of the effects it is hoped to obtain or avoid by the use of certain tool materials. Hardness, lubrication and speed of drawing are other factors which influence in a profound manner the behaviour of deep-drawing tools; proper comparison of different tool materials is not possible unless conditions are similar or varying factors taken into consideration.

In the preceding consideration of general properties of tool materials it has been necessary to mention special attributes of certain materials by way of illustration. As repetition will be avoided as far as possible, readers who may turn to this particular section for information are warned that additional facts may be found in the preceding portion of this chapter.

Steel. Prior to the development of special cast irons, steel was the generally accepted material for use in deep-drawing dies unless the size of the tools made it desirable to use cast iron in the interests of economy. Although the position of steel is now challenged even in the realm of small tools, it is still widely used as it remains and will continue to remain pre-eminent as regards both its resistance to crushing and the degree of surface hardness obtainable; attributes which will always render it a most valuable tool material for certain purposes.

Judged from the usual distinguishing property of chemical composition, the number of steels which can or could be used for the construction of deep-drawing tools is great, but the purpose of this review will be served if five general types are examined. These are :—

(1) Plain carbon steels with or without small proportions (*i.e.*, up to 0·25 per cent.) of alloying elements such as chromium, tungsten, molybdenum and vanadium;

(2) Medium-carbon alloy steels (usually with from 1 to 3 per cent. of alloying element);

(3) High-carbon alloy steels (sometimes with a high percentage of alloying element);

(4) Case-hardening steels, either plain-carbon or alloyed;

(5) Chromium-plated steels (usually of types 1, 2 or 3).

Steel-makers who chance to peruse this chapter may feel that many special and even popular compositions have been omitted. It is asked that failure to mention such varieties be accepted as a necessary sacrifice in so brief an examination rather than as an implied disbelief in the claims made for them.

Plain Carbon Steels. Considered as a material for the construction of deep-drawing tools, two subdivisions of this general class may be made :—

0·7 TO 0·9 PER CENT. CARBON STEEL. This variety will harden in water to about C62 to 63 Rockwell when heated in the open furnace, and up to C65 Rockwell when pack-hardened in spent charcoal. It should always be selected for large tools in preference to the higher-carbon variety as the difference in hardness is almost negligible and the risk of cracking is appreciably reduced; even so, it is always advisable to temper tools of any size while they are still warm. A tempering temperature of 200° C., or sometimes 220° C., may be used without fear of reducing the hardness.

As an example of the lesser degree of "sharpness" exhibited by this steel compared with a 1·1 or 1·2 per cent. carbon steel, certain punches of the type shown in the frontispiece may be instanced. Numerous failures during hardening were experienced when these punches were made in 1·1 to 1·2 per cent. carbon steel, as used for the die : a change to steel of 0·8 per cent. carbon entirely overcame breakages due to this cause without the least observable difference in the life or performance of the tool.

1·0 TO 1·2 PER CENT. CARBON STEEL. This is a very popular type of steel for use in dies in spite of its marked " sharpness " or tendency to crack during hardening. When pack-hardened, values up to C66 Rockwell can be attained with proper manipulation even in tools of large bulk, but considerable skill and experience is needed if loud, disastrous and expensive reports are not to be heard from the tempering bath to which, needless to say, tools should be transferred from the quenching tank while still warm. A tempering temperature of from 200 to 220° C. may be used if no diminution in hardness is desired.

Adequate forging is of great help in reducing the likelihood of cracking. Tools made from solid bar which has been reduced by forging to perhaps only one half the diameter of the cast ingot are particularly prone to crack during quenching.

The main, and it might even be said the only, virtue of high-carbon water-hardening steels is the very high surface hardness which can be attained after suitable manipulation during heat-treatment. This degree of hardness engenders fairly high resistance to attrition, scoring and fouling ; these attributes, in conjunction with moderate cost, no doubt explain the undoubted popularity which this type of steel has achieved in many press-shops (but not in hardening-shops) for tools of small and medium size. Their chief disadvantage, it will already have been gathered, lies in a high hardening-hazard. It is desirable that a high surface polish be given but, with hardness values in the region of C63 to 64 Rockwell, polishing—and of course dressing and reconditioning—is a matter of considerable difficulty.

In brief, it can be said that for draws of reasonable severity on brass, plain carbon steel tools often give satisfaction ; for severe draws on steel, scoring and fouling is likely to occur unless both the lubrication and the polish on the tools is unusually good.

Medium-carbon Alloy Steels. This class of steel does not seem to find extensive use for the construction of dies except, perhaps, for light draws such as are often used in the jewellery industry. For use in punches, which have to suffer much less rubbing action than dies, and in pressure-plates when the loading is not particularly severe, this type merits more attention than is usually given to it.

The most suitable range of composition would seem to be from 0·3 to 0·5 per cent. carbon with one or both of 1 to 3 per cent. nickel and 0·5 to 1·5 per cent. chromium, preferably with about 0·25 per cent. molybdenum.

The hardness obtainable from this type of steel by a normal quench is, in general, less than that obtainable from plain high-carbon steel : the main claim of steels of this class as an alternative is that, being oil hardening, they distort less and are less liable to crack. Durability and liability to score and foul are comparable to those of plain carbon steel of similar hardness, but inferior to that of carbon steels of high hardness. The value of this type of steel as a base for chromium-plating will be discussed later.

Pack-hardening is generally advisable to ensure cleanliness and freedom from surface decarburisation, while a light carburising treatment can produce an increase in surface hardness which is sometimes useful.

High-Carbon High-alloy Steels. The most popular of this class are the tungsten (usually with chromium) and the high-carbon high-chromium varieties.

TUNGSTEN STEELS. Of the first-mentioned variety, a steel containing approximately 0·7 per cent. carbon with 0·5 to 0·8 per cent. tungsten is a most useful and little more expensive alternative to plain carbon steels. Hardness readings equal to those obtainable with a 1·2 per cent. carbon steel can be obtained; yet, although the steel is water-quenching, the likelihood of cracking is considerably less. Its use in place of plain carbon steel is often well worth the slight extra cost.

A steel containing about 1·1 per cent. carbon, 1·2 per cent. chromium and 1·2 per cent. tungsten possesses the valuable property of attaining a hardness of C62, and occasionally higher readings, when quenched *in oil.* It forms a most useful material for the construction of heavily loaded, highly stressed small tools, particularly when some pressing operation becomes akin to coining. Some steel-makers increase the manganese range of this type of steel from the usual value of about 0·4 or 0·6 to as much as 1·2 per cent., with excellent results.

For severe duty the percentage of tungsten may be increased to as much as 10 per cent., the resulting steel being very fine grained and attaining a higher surface hardness after oil-quenching.

HIGH-CARBON HIGH-CHROMIUM STEELS. This variety of steel has achieved considerable popularity for use in drawing dies. Apart from the fact that it can be nitrided, an aspect which will be discussed later, its principal claim to superiority over steels of lower carbon content is that a higher core strength and somewhat greater surface hardness is obtainable and, over plain carbon steel, that it is oil-hardening and therefore more immune from the danger of cracking. It is less liable to crack than the high-tungsten variety, and is therefore more suitable for use in tools of relatively large size.

Its main disadvantages are its high cost, the need for proper dispersion of the free carbides during forging and, in some instances, a tendency to distort during hardening. Furthermore, unless the carbon is kept high, difficulty is usually experienced in producing the desired hardness of approximately C64 Rockwell by a normal quench, yet the tendency to crack during hardening increases markedly between the limits of 2 and 2·4 per cent. carbon.

It is difficult to make helpful comment on the vexed subject of soaking time for high-carbon high-chromium steels. If maximum hardness is desired it is necessary to soak at the hardening temperature, which is usually in the region of 920 to 950° C., for a time considerably longer than that required by plain high-carbon or low-carbon alloy steel owing to the sluggishness of the complex carbides. When, however, the long soak necessary to ensure full hardening is given, distortion is usually markedly greater than when only a relatively short soaking period is allowed. Whether maximum hardness or minimum movement is the more desirable property must be decided upon the requirements of any particular tool; hardeners familiar with the vagaries of this type of steel can obtain a useful measure of compromise through knowing just how long a tool of given section can be soaked before severe distortion, which seems to increase suddenly as the soaking time is increased, occurs. It is advisable to heat tools of high-carbon high-chromium steels more slowly than similar sections of plain high-carbon steel. A small but useful increase in surface hardness can be obtained by packing in charcoal.

Although steels of this type are giving satisfactory service in drawing dies by virtue of the properties already enumerated, it is questionable whether their use in the normal, quenched condition is always justifiable. When the permissible outlay allows them to be chosen, the slight additional cost of nitriding may double or treble their useful life.

MISCELLANEOUS ALLOY-STEELS. In addition to the tungsten and high-chromium types of steel just considered, at least two others deserve mention, namely, low-chromium and high-speed steels. Plain carbon-chrome steels containing approximately 1 per cent. of each of these elements are seldom used for drawing tools, perhaps on account of their proneness to distort; yet this type of steel would seem to offer a useful base for chromium-plating when tools can be ground after hardening.

High-speed steel is seldom used owing to its high cost, difficulty of hardening in large masses, and liability to distort. In spite of these drawbacks its ability to withstand better than other steels the high surface temperatures which are attained at the surface of dies when lubrication fails would seem, in theory, to constitute a property of considerable value when severe draws have to be undertaken. Although useful results have been obtained with it, experience shows that it is more likely to score and foul than the other types of high-alloy steel already discussed, owing, probably, to the action of retained austenite.

By virtue of its well-known work-hardening properties, a high-manganese steel would seem to be of possible value for drawing dies. Difficulty of initial shaping would, however, be so great that only tools of very simple shape could be made at reasonable cost.

It is very difficult to summarise usefully the particular merits of the alloy steels mentioned in this section, the approximate chemical analyses of which are set out in Table III.

TABLE III

Approximate Chemical Compositions of Alloy Steels suitable for Dies

	C	Ni	Cr	W	Co	V	
A	0·7	—	—	1	—	—	See note 1
B	1·2	—	1·2	1·2	—	—	
C	1·6	—	0·5	6	—	—	
D	1·0	—	3	10	—	—	
E	2·3	—	14	—	—	—	
F	2·2	1	12	—	—	—	
G	1·1	0·5	14	—	16	—	See note 2
H	0·6	—	4	14	—	0·5	
I	0·7	—	3	18	—	1	

NOTE 1.—Manganese may vary from 0·4 to 1·2 per cent., giving appreciably different hardening properties.

NOTE 2.—Molybdenum 1·2 per cent. In all these steels small amounts of molybdenum or vanadium may be present.

The high-tungsten type certainly seems to give satisfaction in small, very heavily stressed tools, and the high-carbon high-chromium type under slightly less severe conditions of service. The high cost of these high-alloy steels precludes their use in large tools; with the notable exception of high-carbon high-chromium steels when nitrided, it is by no means certain that their use is always justified even in small tools. Far cheaper steels chromium-plated would appear to offer equal service performance under good conditions, but their resistance to abuse is less and this fact may account in part for the continued popularity of tungsten steel and, in part, high-carbon high-chromium steels.

It is worth bearing in mind that with all these steels a slightly higher hardness can be attained when tools are pack-hardened in spent charcoal than when they are heated in the open furnace.

Case-hardening Steels. This class must be divided into two distinct and widely differing varieties: carburising and nitrogen-hardening steels.

CARBURISING STEELS. The whole range of engineering case-hardening steels may be used for dies and punches. Extending as it does from mild steels of 30 to 40 tons to nickel-chrome steels of 70 to 80 tons ultimate tensile strength, this range is of considerable value for use in both dies and punches. It provides a surface equal to that of a plain or low-alloy high-carbon steel at less cost and with far less danger of cracking; the principal limitation is, naturally, resistance to crushing, and it is this factor which governs the choice of chemical composition and, hence, the cost. Machinability is markedly easier, more particularly in the low core-strength steels than with high-carbon or medium and high-carbon alloy steels. When the conditions of loading permit, the use of case-hardened steel tools has much to commend it, although such tools are naturally subject to the same tendency to foul as the ordinary high-carbon variety.

It is worth mentioning that the case-hardened surface of a nickel steel is noticeably more " slippery " than that of a corresponding steel free from nickel, this being more apparent with the 5 per cent. nickel variety than with the 3 per cent. The phenomenon resembles that associated with a surface of pure chromium in nature but not in magnitude; curiously, the addition of chromium in the proportions normally added to case-hardening steels does not induce any noticeable increase in slipperiness of surface. Whether the small increase in slipperiness given by a nickel case-hardening steel will justify its extra cost in comparison with a plain carbon case-hardening steel must remain a matter for decision after careful consideration of all facts relating to any particular tool.

The author has achieved most useful results from carburising and oil-quenching a popular alloy steel containing approximately 0·3 carbon, 1·5 nickel, 1 chromium and 0·25 per cent. molybdenum. The strength of the fully-hardened core is of the order of 120 tons/square inch, and a hardness of C64 Rockwell can be obtained on the carburised surface. For punches this steel and treatment has proved invaluable, as it combines the core strength, immunity from cracking and—relatively—slight distortion of an oil-hardening alloy steel with the surface hardness of a plain carbon steel. The practice is commended with every confidence to other users.

Nitriding Steels. When steels of suitable chemical composition are heated in an atmosphere of atomic nitrogen for a fairly lengthy period—ninety hours is commonly given—at a temperature closely approximating to 500° C., they gain a very thin surface case which has a hardness appreciably in excess of that obtainable by quenching carburised steel.

This extreme hardness, which may rise to 1,150 Vickers Pyramid Numerals, although 1,050 is a more usual figure, is the principal and indeed a most valuable attribute of nitriding steels. (950 V.P.N. corresponds roughly to C64 Rockwell, the maximum hardness normally attainable from quenched steel tools of any mass.) Another advantage is that although distortion during the preliminary heat-treatment, which consists of an oil quench followed by a temper at some temperature above 520° C., is of the order to be expected from steels and treatment of the type under consideration, distortion during the actual nitriding process is usually negligible. If, therefore, tools are finished to size after the preliminary heat-treatment, no distortion occurs during the main hardening or nitriding treatment: a most valuable attribute.

In the original form of "Nitralloy" there is a range of steels having carbon contents of from 0·2 to 0·55 per cent. together with 0·9 to 1·5 per cent. chromium and 0·5 to 1·4 per cent. aluminium. These two alloying elements were at first deemed essential for the nitriding treatment to be carried out, but subsequently other grades of "Nitralloy" steel have been marketed which take on a case of rather less hardness, *i.e.*, about 900 V.P.N., which is adequate for many purposes and is appreciably less brittle than that of the original type of steel. In this connection it may be remarked that the addition of small amounts of nickel to the aluminium nitriding steels reduces the hardness but increases both the toughness of the case and the hardness of the core; too high a proportion of this element, however, renders a steel unsuitable for nitriding.

It is now common practice to nitride non-aluminium steels of many types. The author has tried experiments with, among other varieties, the four high-carbon high-chromium steels listed in Table III. Results were highly satisfactory: a case of 950 to 1,050 V.P.N. was obtained together with a core strength considerably higher than that obtainable with the highest carbon-content grade of the Nitralloy range. Certain tools of a type which had previously failed owing to inadequate core-strength now proved entirely satisfactory and gave outputs in the drawing, for example, of the steel cup illustrated in Fig. 59 (p. 86), which were remarkable in both number of articles drawn and in freedom from surface scores.

Homerberg [84] has published a most valuable review of experiments on the nitriding of steels of many types. Some of the steels therein described, such as those used with great success in thread-rolling dies, appear to be very suitable for use in deep-drawing tools; readers who are interested in this subject should consult the original work, which cannot be usefully summarised in a short space. However, in general it seems that steels containing chromium, cobalt and tungsten, usually with molybdenum, offer the greatest possibilities for nitrided tools in which the properties of a nitrided case cannot be utilised without a core of high hardness. The nickel content must be low.

As an indication of the widely varying varieties of steel which can be nitrided, those given in Table IV. have all been used with success.

Experience shows that the readiness and uniformity with which some of the high-chromium steels take on a nitrided surface is greatly increased if the surface is etched immediately prior to the nitriding operation, a 50 per cent. solution of hydrochloric acid being suitable for this purpose. Curiously, the electro-deposition of a very thin coating of copper facilitates the nitriding of some steels, more par-

TABLE IV

Approximate Chemical Compositions of Nitriding Steels suitable for Dies

	C	Al	Cr	Ni	Co	W	Mo	V
A	0·2–0·5	0·5–1·4	0·9–1·5	—	—	—	0·25	—
B	0·5	—	3·5	—	—	—	0·5	0·7
C	1·5	—	13	—	—	—	0·9	0·9
D	1·4	—	13	0·5	3	—	—	—
E	1·3	—	1	—	—	5	—	0·25
F	1	—	3	—	—	10	—	0·25
G	1·1	—	14	0·5	16	—	1·3	—
H	2·3	—	13·5	—	—	—	0·25	—
I	2·2	—	12	1	—	—	—	—
J	2·3	—	14	—	—	—	0·25	—

ticularly those of an austenitic nature, and at the same time appears to induce uniformity of case.

If it is desired to protect certain areas on tools this can be done by "tinning" the surface with pure tin or a tin-lead solder or, alternatively, by painting with a paste made of tin oxide and glycerine or of finely powdered lead oxide and chromium oxide. Tinning is a more reliable protection than painting, but it is often a difficult operation to carry out on small areas of tools of large bulk. Small tapped holes can be conveniently protected by screwing in plugs of pure aluminium.

With the possible exception of chromium-plated tools (in which it is not the steel itself which functions as a working surface) it can safely be said that, of all the available steels, those which can be nitrided are the most valuable from the aspect of deep-drawing. When a very high core strength is essential, nitrided steel of suitable type is usually by far the most useful of any tool material; even when working pressures are of an order which allows other tool materials to be considered as alternatives, the merits of nitrided steel are often still worth close attention.

The outstanding advantages of nitrided steel tools are their freedom from fouling and scoring and also their long life. All these attributes are due to the extreme hardness of the nitrided surface: freedom from fouling because the largest possible dissimilarity in hardness is one of the best preventives of seizure between surfaces having a natural tendency to unite in this way; freedom from scoring because resistance to abrasion increases with increasing hardness; long life due to the two attributes just mentioned and, also, to a high resistance to what has been defined earlier as "micro-attrition."

In addition to these advantages two others of a less obvious nature must be pointed out. One is the recognised capacity of a nitrided steel surface to withstand without structural alteration a fairly high temperature: the attainment, at least momentarily, of high local surface temperatures at the contacting surfaces of work and tools has been demonstrated very clearly by Bowden and Ridler.[7] This capacity to resist the effect of heat will in itself greatly minimise any tendency to seize.

Secondly, if the surface is initially good, the high resistance to fouling and scoring conferred by nitriding will help to preserve the original smoothness and so make it easier to maintain an unbroken film of lubricant, which itself greatly reduces the danger of fouling and scoring. Once formed, scores and surface irregularities will tend to rupture the film of lubricant, and a vicious circle is established.

The smoothest possible surface polish must be given to the working regions of nitrided steel tools if the full advantages of the process are to be obtained. This is a most important condition, to which sufficient attention is seldom given. During the nitriding process only a light "bloom" is produced on a polished surface; the procedure should be, therefore: rough polish, harden and temper, polish as perfectly as possible, nitride, re-polish. It need hardly be said that the extreme hardness of the nitrided surface renders the removal of any surface imperfections which have not been removed prior to nitriding a matter of very great difficulty. Whenever possible it is desirable to avoid grinding a nitrided surface; when grinding is unavoidable, the special grades of wheels recommended by the proprietors of the process should be used, the lightest of cuts taken, and the least possible total amount removed because with many of the non-aluminium varieties of steel the depth of case may be no more than from 0·012 to 0·015 inch, and the greatest hardness will occur for only a small proportion of this depth.

So far only the merits of nitrided tools have been discussed. It is only natural that certain disadvantages exist; of these the most serious is, perhaps, that very little "dressing" or reconditioning of damaged or worn tools is possible by reason of their extreme hardness and the thinness of the useful portion of the case. Indeed, it is seldom worth while to attempt the removal of serious blemishes and, as the normal life of nitrided tools is very great, every precaution should be taken to avoid harm produced by abuse or neglect.

High cost is often advanced as a disadvantage. This is not always justifiable; if an expensive alloy steel is already in use, or contemplated, the extra cost of nitriding will be relatively small and may make one set of tools outlive several un-nitrided sets. The time occupied by the nitriding process, which may amount to a week, ought surely to be regarded as a shortcoming of factory organisation rather than of the steel and process. Again, the excellence of surface demanded ought not to be held up as a disadvantage peculiar to nitrided steel: the inadequacy of the polish often given to ordinary hardened steel tools has already been stressed.

In brief, the merits of a nitrided surface are quite outstanding; when, owing perhaps to the high core strength demanded in a particular deep-drawing operation, steel tools are essential, and sometimes when tool materials other than steel are admissible, the use of nitrided steel should always be considered when long life and freedom from scoring is desired, particularly when steel sheet is being drawn. An essential condition which must be observed is the provision of the smoothest possible surface polish on the working regions of the tools in the first instance.

Graphitic Steel. Although graphitic steel cannot yet be classed as a commonly used tool material, any survey of tool steels would be incomplete without some reference to this recent addition. Steels containing free graphite are, of course, no novelty to laboratory investigators; but it is only recently that genuine graphitic steel has been produced and made into drawing dies on what may be regarded as an industrial scale.

At present this type of steel is made in an electric furnace and contains about 1·5 per cent. carbon with 1 per cent. silicon added to render the carbide unstaple and capable of being partially decomposed into graphite and ferrite by suitable annealing. If sufficiently close control of casting conditions has been exercised, the microstructure of the cast steel will consist of a finely pearlitic matrix containing free cementite with possibly a number of small particles of graphite; in this condition it can be forged and rolled without difficulty. After forging or rolling has been accomplished, a proportion of the free cementite can be broken down by heat-treatment to give very finely divided, isolated particles of graphite, the matrix still remaining pearlitic. In this condition the machining properties of the steel are comparable to those of a grey iron, from which material it differs in appearance only in the nature of the graphite particles. By heating to a temperature in the region of 850° C. and quenching in oil or water, hardness values up to C60 Rockwell can be obtained. When maximum hardness is desired it is advisable to temper drawing dies at not less than 150° C.; in some instances a hardness appreciably lower than the maximum obtainable seems to be adequate, and for some purposes preferable.

As graphitic steel closely resembles the better varieties of inoculated cast iron, no separate examination of its properties and heat-treatment will be made; readers are asked to consider graphitic steel to be included in the subsequent discussion of inoculated iron.

It must on no account be thought that the brevity of this discussion of graphitic steel implies that this material is of small importance for drawing dies; on the contrary, it may become a formidable rival to inoculated cast iron, the benefits of which very valuable tool material will be described later. Comparing these two materials it can be said that the cost of graphitic steel is higher than that of inoculated iron. On the other hand, graphitic steel can be forged and rolled, whereas cast iron cannot be worked in this way. Graphitic steel possesses a higher impact strength, and can be hardened with safety up to C60 Rockwell, a value which cannot be allowed with cast iron.

From theoretical considerations there is reason to believe that graphitic steel may prove superior to inoculated cast iron owing to its greater strength, finer texture, and to the more uniform size and finer dispersion of its graphite particles. Although casting will undoubtedly present greater difficulty, the fact that forging can be successfully carried out may counterbalance this drawback. As a die material for severe duty in the deep drawing of all kinds of sheet, graphitic steel may have a big future ; its development can safely be encouraged, particularly for small tools because the cost of metal is of less importance than in tools of large mass.

Chromium-plated Steel. As the steel serves only as a base or core to carry the chromium deposit, discussion of chromium-plated tools does not legitimately fall within the province of this section. The properties of the electro-deposited coating will be examined later, and it is proposed here only to offer a few comments upon the steels which are, or could be, used as a base.

In spite of the recognised value of chromium-plated steel tools it often happens that little consideration is given to the steel base. As a result of this neglect a needlessly expensive steel may be used or, on the other hand, the condition of the steel may be such that a base of inadequate strength is provided.

In the case of existing tools the only useful alteration which can be made is in the hardness which, if very high, may be reduced—by a suitable tempering treatment—to minimise the likelihood of cracking due to the action of hydrogen evolved during the plating operation. Even when new tools are chromium-plated before service, not as an afterthought or when they have been reconditioned, the same steel which would be used if the tools were not to be chromium-plated is often selected. There is no necessity for this : it has already been pointed out that a very high degree of hardness is actually undesirable in the steel base of chromium-plated tools, so the expense of high-alloy steels and the risk of cracking associated with unalloyed high-carbon steels (when water-quenched) is unnecessary and unjustifiable.

It is here that the ordinary medium-carbon alloy steels can often be used to provide an adequate and relatively cheap base, although it may often be advisable to select a variety and brand of steel which experience has shown to suffer least from distortion, a property which varies considerably. Opinions differ as to the maximum hardness at which it is safe to chromium-plate steel, but a range of hardness valuesof from C48, which is considered by some to be the safe maximum, up to C55 Rockwell is easily obtainable in simple alloy oil-hardening steels of low price. When an even stronger base is desired and the risk of cracking appreciated but accepted, alloy steels of somewhat higher cost are obtainable which will harden in oil up to C62 Rockwell.

The knowledge that a hard core is essential to support chromium-plating is now fairly general, but in the past many tools have been ruined, and the efficacy of chromium-plating questioned, through chromium having been deposited on unhardened steel. In such instances, unless the draw happened to be very light, the plating would crack and "cave-in," thus completely spoiling the tool.

Attention has been drawn in an earlier section to the necessity for the smoothest possible polish being given to the working surfaces of tools prior to their being chromium-plated. This point is so important that no apology is made for mentioning it again. When the maximum benefits, which can be very great, are desired from chromium-plating, time and care spent in polishing will be well repaid. A really good polish, devoid of scores, should be attained before the tools are hardened; every precaution should be taken during heat-treatment to avoid scaling or "crazing" and, after heat-treatment, the final polish should be the very best which the nature of the steel and permissible tool-room expenditure will allow. Needless to say a "dirty" steel containing non-metallic inclusions of appreciable size cannot be made into a really good base for chromium-plating; here, again, prolonged experience with various brands of steel can be a useful aid in the selection of a suitable steel for use as a base for chromium-plating. The partial avoidance of inclusions constitutes the one and only claim to superiority of bar over forged blanks for small drawing dies as, in the majority of instances, the centre of a disc cut from a solid bar will be bored out and, with it, the inclusions which are usually segregated in the centre of a bar. In a forging the central segregation may be spread out to the regions of the working surfaces of the die.

Cast Iron. In the opinion of many users cast iron is now the most valuable of any commonly used tool material, particularly for use with steel sheet. The qualification "now" is necessary because this popularity has been achieved only since comparatively recent developments have led to the availability on a commercial scale (and at a low price) of what may still be termed "special" cast irons.

From the aspect of the deep drawing and pressing industries cast iron for tools may be divided into three broad classes: unalloyed, alloyed, and inoculated (which may be either plain or alloyed) iron. The best idea of the outstanding characteristics of each class will be obtained by individual examination rather than by a comprehensive survey.

Unalloyed Cast Iron. Although overshadowed by the recently developed varieties, the importance of plain grey cast iron as a tool material must not be overlooked. At the present time it is likely that as regards actual tonnage in use this grade easily heads the list of all tool materials, as many of the larger tools are still made of it, *e.g.*, those for automobile body-work ; however, local inserts of special iron are already popular, and there is a growing tendency to cast even the largest tools in low-alloy or inoculated iron when large outputs are guaranteed.

The advantage of cast iron for tools of any size is that it possesses unique self-lubricating properties which render it remarkably immune from fouling and scoring, is easily machined, easily polished, and that it quickly assumes and maintains a high degree of polish during service. For large tools the advantage that it is by far the cheapest tool material possessing a useful measure of durability, *and that it can be cast closely to shape* thus greatly reducing shaping costs, is of very great importance. Furthermore, large tools can be hand-finished and punch and die " spotted in " or " fitted " in a manner which would be impossible with a hard material, and any small surface defects which may be produced during use can easily be polished out.

Its main disadvantage is that if loaded heavily it wears sufficiently rapidly to prevent really large outputs being obtained unless, as is sometimes the case with large pressings, the article being produced has not to be held to close dimensional tolerances and tool clearances need not be maintained constant (as when " ironing " forms no part of the drawing operation). Another disadvantage is that in large castings it is not unusual for areas of unsoundness to occur even when the finished working surface of the tool is not far below the original cast surface, while both the quality and texture of the iron and the soundness of the castings may vary considerably unless unusually good foundry control and technique have been exercised.

Plain cast iron as used for press tools usually contains about 3·1 to 3·3 per cent. carbon and 1·7 to 2·0 per cent. silicon. Its Brinell hardness will range from about 170–200 and its tensile strength from 10 to 15 tons square inch, although, as already hinted, its properties may vary appreciably throughout one casting when markedly different sections exist, and local chilling causing considerable hardness may occur in thin sections.

Chilled iron constitutes a rather special variety which under certain conditions has proved of value for small tools which have to withstand a decided abrasive action. Chilled-iron tools tend to be somewhat erratic in quality, and their use seems to have been confined to a few unusual drawing operations.

Alloy Cast Iron. Nickel and chromium, added in various proportions either separately or together, are the two elements which are most commonly used to improve the properties of cast iron. The principal object of these additions is to increase the soundness of castings, to give a closer grain and greater uniformity of properties throughout sections of varying thickness, to minimise the likelihood of occurrence of hard spots and, sometimes, to facilitate hardening and tempering. In addition to these effects, alloy additions will increase the hardness of the matrix in the as-cast condition, although it should be noticed that an alloy iron of, say, 240 Brinell may machine as readily as a plain iron of 180 Brinell.

These objects are usually achieved if a reasonable standard of foundry control is available, and it is a pity that in the past the substitution of alloy for plain cast-iron tools has not always been an unqualified success; it is but small consolation to those responsible for tool production and maintenance to know that the blame lies with the foundry rather than with the true qualities of the iron.

In the as-cast condition, suitable alloy cast iron is considerably more durable than plain cast iron; the closer texture, greater hardness and—assuming proper foundry technique—greater soundness all contribute to improved properties as a tool material. This is particularly noticeable on narrow upstanding ridges, such as often occur on the working surfaces of large press-tools for automobile body parts.

One most important feature of alloy cast-iron tools is that when the chemical composition is suitable they can be easily hardened and tempered to give hardness values up to 450 Brinell, a procedure which, as is to be expected, greatly increases their durability and provides a most useful range of tool materials. The substitution of heat-treated for as-cast cast iron in large press-tools will nearly always give an increased useful life; in genuine deep-drawing operations in which hardened steel tools are normally used, replacement by heat-treated cast iron will nearly always decrease scoring and fouling tendencies, and will often be found to give greater outputs than the far harder steel tools.

With suitable alloy additions a hard, martensitic iron can be produced in the as-cast condition, hardness values up to 450 Brinell being obtainable. For small dies which can be cast closely to shape and ground to size such iron may be useful; for larger tools it will usually be preferable to select an iron which can be cast in a soft condition and hardened after shaping has been carried out. In a chilled alloy iron of suitable composition the disadvantages of chilled plain iron, *i.e.*, brittleness, non-uniformity and a general tendency toward erratic behaviour, are distinctly lessened. If the nickel content is increased to 5 per cent. and sufficient chromium added to counteract the graphitising action of the nickel, a hardness as high as 800 Brinell may be obtained in the chilled condition. Such an iron should be useful for small, heavily loaded tools; for example, those used to deep-draw bullet cases for small arms ammunition.

Owing to the individual requirements of any given tool and to the almost continuous range of alloy additions which are made, it is somewhat difficult to divide alloy irons into distinct classes with respect to chemical composition. The division made in Table V, which is partly

TABLE V

Types of Alloy Cast Iron suitable for Dies

	Ordinary Grey Iron.	Hard Grey Iron.	Heat-treatable Iron.	Martensitic Iron.
Chemical composition				
Total carbon, per cent.	3·0–3·3	2·9–3·2	2·9–3·2	3·0–3·4
Silicon ,,	0·8–1·6	1·0–1·5	1·2–1·6	1·0–1·5
Manganese ,,	0·5–1·0	0·7–1·0	0·7–1·0	0·7–1·0
Nickel ,,	1·25–1·75	2·5–3·5	2·5–4·0	5·0–6·0
Chromium ,,	0·4–0·8	0·6–1·0	0·5–1·0	1·0–1·5
Sulphur ,,	0·12 max.	0·12 max.	0·12 max.	0·12 max.
Phosphorus ,,	0·30 max.	0·30 max.	0·30 max.	0·30 max.
Brinell hardness				
As cast	200–220	250–280	—	380–420
Heat-treated	—	—	300–350	—
Tensile strength				
As cast, tons sq. in.	16–19	18–20	—	24–26
Heat-treated ,,	—	—	24–26	—

based on recommendations made by the Bureau of Information on Nickel,[85], [86] attempts some measure of classification to serve as a general guide; but the ranges of chemical composition therein given must not be taken as working specifications. Recognised adjustment of values for the principal elements must be made when drawing up actual specifications. It is, for example, better to keep to the higher limits for carbon, silicon and nickel for castings of light section, and *vice versâ*, whilst a high nickel content should usually be balanced by a low chromium content.

Besides the principal alloying elements nickel and chromium, an addition of 0·25 to 0·50 per cent. molybdenum is sometimes made with distinct benefit.

It is possible to nitride cast irons of suitable chemical composition, *e.g.*, one containing approximately 2·6 per cent. carbon, 1·5 per cent. chromium and 1·5 per cent. aluminium, as developed for the " Nitrihard " proprietary cast iron used in cylinder liners which, after being hardened at 850° C. and tempered at 600° C., can be nitrided to give a surface hardness of about 900–950 V.P.N. The use of nitrided cast iron for drawing dies seems well worth investigation, if only for the reason that it may enable a nitrided surface to be obtained on large tools for which the use of forgings in special steel would be too costly to be considered.

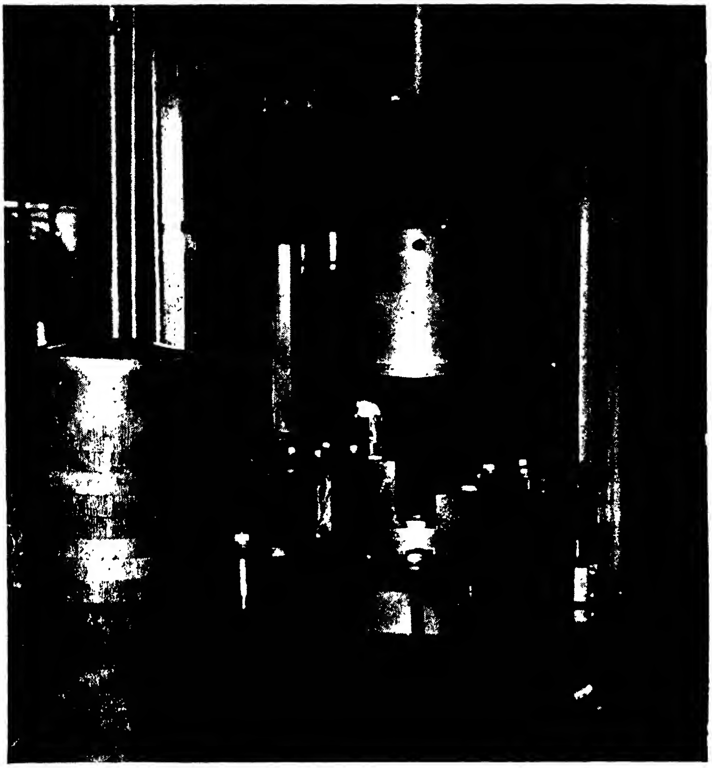
Heat-treatment of Cast Iron. Hardening is usually accomplished by heating the tool fairly slowly to a temperature of about 600 to 650° C., then more rapidly to about 850 to 870° C., soaking for no longer than is necessary for the tool to attain a uniform temperature, and quenching in oil. Tempering should be carried out immediately after quenching; a temperature of about 250° C. is sometimes adequate and should not be exceeded when maximum hardness is desired, but a range of 300 to 350° C. is often preferable owing to the resulting increase in tensile strength and toughness. It is important that the tools should not be soaked for a long period at or near the hardening temperature; operators accustomed to hardening steel tools, particular ones of large bulk, need to be warned of this difference.

Whether castings are to be hardened or not it is always desirable, and sometimes essential, to give a "normalising" treatment to relieve casting stresses. Opinions differ as to the best temperature and time of soaking for such normalising; as a general indication, soaking for a period of one hour per inch thickness of section at a temperature of 500 to 550° C., followed by moderately slow cooling, will generally be found adequate. The widespread use of the term "normalising" when "stress-relieving anneal" is meant is to be deplored: the true meaning of the metallurgical term "normalising" has already been explained (see p. 202).

Fig. 206 shows some nickel-chromium-iron tools which drew 200,000 steel beer kegs with a very much better surface than was obtained previously with plain cast-iron tools from which an output of only 20,000 was obtained. Fig. 207 illustrates typical heat-treated iron tools used for pressing steel radiator shells. These tools have a Brinell hardness of 350, and maintained a very fine polish during a long period of service.

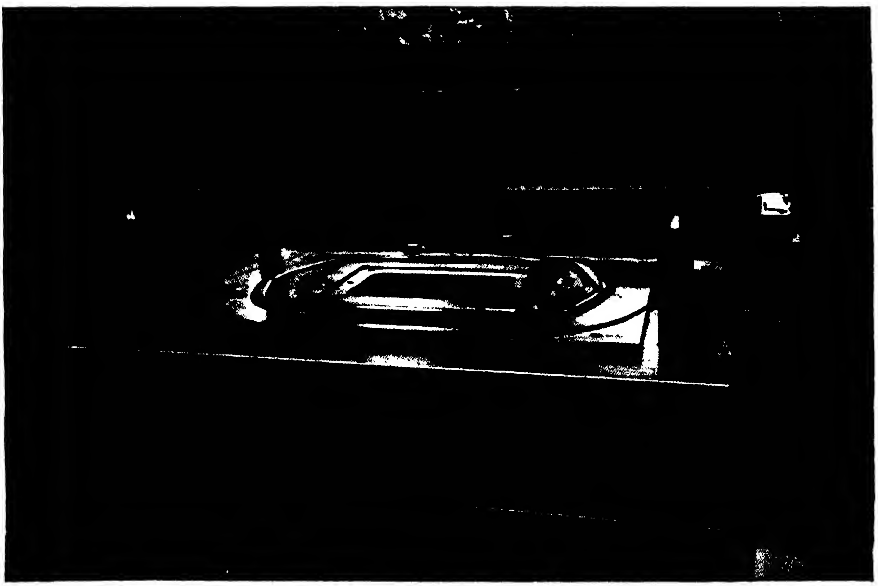
Inoculated Cast Iron. The process of inoculation has raised plain cast iron from a position of mediocrity to one of top rank as a material for deep drawing and pressing tools even when conditions would allow hardened steel to be used as an alternative. With alloy irons the improvement, although less marked, is nevertheless valuable, and in many instances inoculated alloy irons of suitable type have proved markedly superior to expensive alloy steels costing many times as much. This apparent eulogy of inoculated cast iron is not intended to minimise the usefulness of uninoculated cast iron, both plain and alloyed, as a tool material; but the superiority of the inoculated varieties for heavy duty has been amply demonstrated by numerous unbiased comparisons of performance under similar conditions of service.

The distinguishing feature of an inoculated iron is the very fine nature and uniform dispersion of the graphite flakes contained in it, a refinement which extends to the microstructure of the matrix which is, or should be, wholly pearlitic. The practical effect of this graphite refinement is to increase the strength of the iron appreciably and the toughness very considerably, to increase the soundness and uniformity



[By courtesy of the Pressed Steel Tank Co. and the Mond Nickel Co. Ltd.

FIG. 206. Alloy cast iron tools, unhardened, used to deep-draw beer kegs from steel sheet.



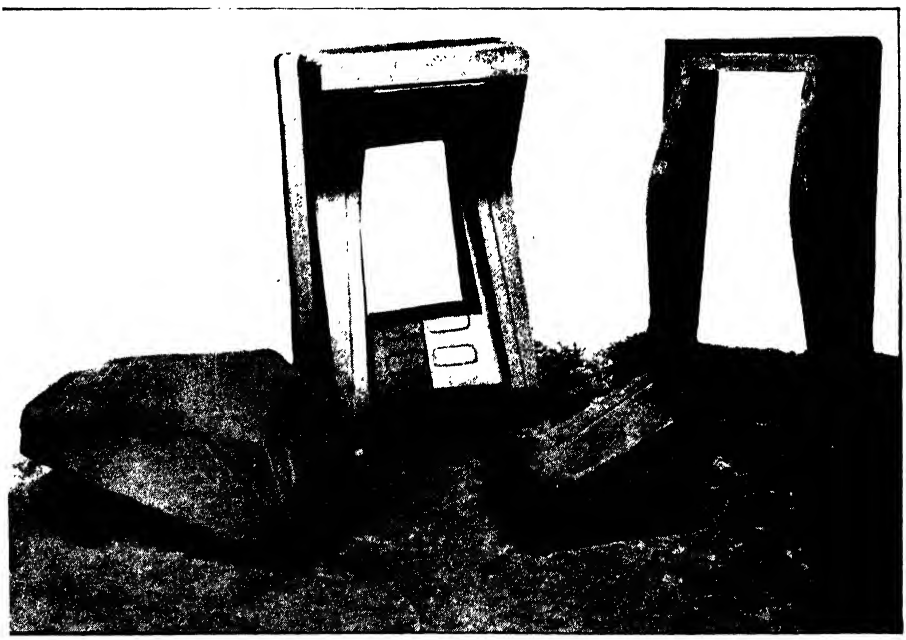
[By courtesy of the Ford Motor Co. Ltd., U.S.A., and the Mond Nickel Co. Ltd.

FIG. 207. Hardened and tempered alloy cast iron tools used for forming automobile radiator shell.

[To face p. 392.

[*By courtesy of the Austin Motor Co. Ltd.*

FIG. 208. Punch and die in heat-treated inoculated iron.



[*By courtesy of the Ealing Park Foundry Ltd.*

FIG. 209. Set of tools in inoculated cast iron (not heat-treated) for forming panel from steel sheet.

[*To face p.* 393.

throughout varying sections, and to render the effect of hardening by quenching more beneficial. A punch and die of inoculated cast iron, used for pressing steel sheet of fairly heavy gauge, is shown in Fig. 208. The size of these tools is 24 by 18 inches, approximately, and it is easily understood how the use of castings such as those illustrated reduces machining costs to a very low figure indeed. The tools shown are finish-machined ; but quite often only light hand-finishing is all that is needed, as with the set of tools shown in Fig. 209.

The essential principle underlying the usual methods for the production of inoculated iron is that metal of suitable chemical composition be super-heated in order to dissolve all the graphite and any other possible nuclei—it is believed that complete solution does not always occur during ordinary cupola melting practice—and that the iron be prevented from solidifying " white," as it normally would do under the imposed conditions, by the addition of some inoculating material which will cause precipitation of graphite in a very fine flake form. Graphite produced in this manner usually assumes the form of small, uniformly distributed and often curved flakes set in a wholly pearlitic matrix, and therefore differs from the extremely fine variety of *delta*-graphite eutectic which is precipitated under certain conditions of solidification when an inoculant is not used. There is a tendency for so-called *delta*-graphite to be associated with free ferrite (of which " *delta* " is one allotropic form) a constituent which is undesirable for some purposes, and to form in clusters outside which coarser flakes often occur. The effect of inoculation upon the microstructure of a typical cast iron is illustrated in Fig. 210 (p. 394).

The inoculating material most commonly used is powdered calcium silicide, but powdered silicon, nickel shot and certain ferro-silicon alloys are also used. The term " inoculation " is, in the light of present knowledge, not altogether appropriate, for the original conception of the nucleus or genuine inoculation method of functioning of the added material has been discarded. One important discovery which led to the abandonment of this theory is that it is possible to produce fine precipitation of graphite in irons containing titanium by bubbling carbon dioxide gas through a ladle of the molten metal, a procedure in which solid nuclei are certainly not added from outside the melt.

By reason of patent rights, the only inoculated irons available on a commercial scale in Great Britain at the present time (as far as the author is aware) are those marketed under the trade names of " Meehanite " and " Ni-Tensyl," the first being of American and the second of British origin. Meehanite is produced in a number of varieties which differ not so much in chemical composition as in the percentage of steel scrap incorporated in the charge and in the degree of inoculation given, the grades being aptly designated by a " process " and not a " grade " letter. For press-work and deep-drawing tools the most suitable varieties are, in general, those known as "Process A" Meehanite, which should always be used when heat-treatment is to be carried out, and "Process B" Meehanite, which may be used when the duty is less severe and no heat-treatment is contemplated.

The chemical composition and physical properties of these two varieties are indicated in Table VI, but it must be understood that as

TABLE VI

Types of Inoculated Cast Iron suitable for Dies

	"Process B Meehanite," as Cast.	"Process A Meehanite," as Cast.	"Process A Meehanite," Heat-treated.	"Ni-Tensyl," as Cast.	"Ni-Tensyl," Heat-treated.
Chemical composition					
Total carbon, per cent. .	2·8–3·0	2·7–2·9	2·8–3·0	2·7–2·9	2·7–2·9
Silicon ,, .	1·4–1·6	1·3–1·5	1·3–1·5	1·25–1·5	1·25–1·5
Manganese ,, .	0·6–0·8	0·7–0·9	0·8–1·0	0·5–1·0	0·5–1·0
Nickel ,, .	0·0–1·0	0·0–1·0	0·0–1·0	1·25–1·75	2·5–3·5
Chromium ,, .	0·3–0·5	0·3–0·5	0·3–0·5	nil	nil
Sulphur ,, .	0·1 max.	0·1 max.	0·1 max.	0·12 max.	0·12 max.
Phosphorus ,, .	0·15 max.	0·15 max.	0·15 max.	0·3 max.	0·3 max.
Brinell hardness					
As cast . . .	220–240	220–250	—	220–240	—
Heat-treated . .	—	—	350–500	—	350–500
Tensile strength					
As cast, tons/sq. in. .	22–24	24–26	—	24–26	—
Heat-treated ,, . .	—	—	30–35	—	28–32

the composition can with advantage be adjusted to the requirements of each casting the advice of experienced foundries should always be sought if the best results are to be obtained. The fact that heat-treatment is to be given should always be indicated in order that the manganese may be kept on the upper limit of the range and certain other adjustments made.

The approximate chemical composition of "Ni-Tensyl," the second type of inoculated iron, is also shown in Table VI. It will be seen that the alloy content is considerably higher than in "Meehanite"; yet, by reason of the overshadowing primary effect attributable to inoculation, the difference in physical properties and service behaviour of the low and more highly alloyed irons does not seem to be of the order which might be imagined from that which occurs in uninoculated irons.

As with uninoculated alloy irons, the durability of inoculated irons can be increased very markedly by heat-treatment. The danger of cracking during hardening is almost negligible, and very large dies can be quenched without undue apprehension when the estimated output justifies heat-treatment. Distortion, although influenced markedly by the shape and section of the tool, is far less than with plain

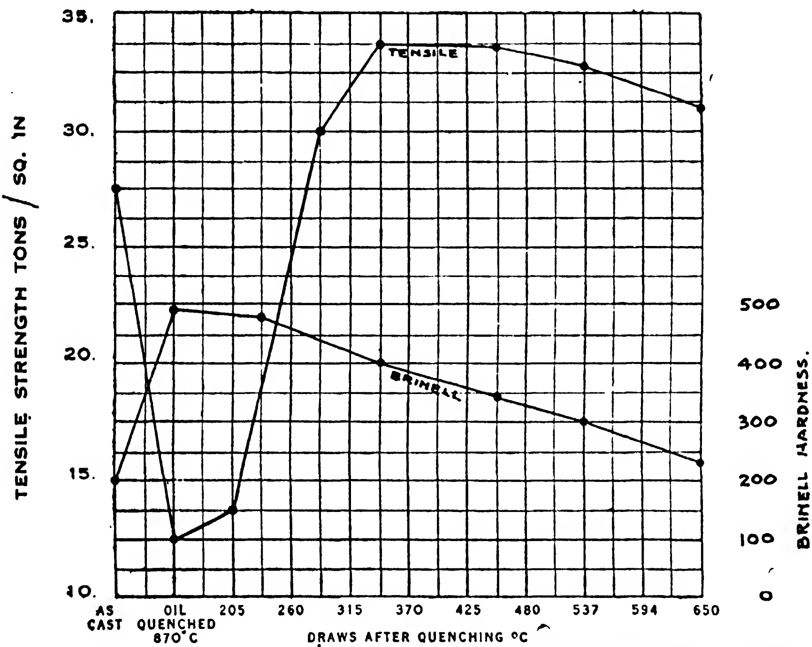
Fig. 210. Photomicrographs illustrating effect of inoculation upon the graphite separation in cast iron.

Top : ordinary engineering-quality cast iron, × 100, unetched.

Bottom : inoculated cast iron, × 100, unetched.

carbon steel and often less than with the so-called non-distorting varieties of alloy steel.

For medium-sized tools required in the hardest possible condition it is usually safe to machine to within $\frac{1}{32}$ inch of the finished size prior to hardening, the final finishing being of necessity carried out by grinding. Those accustomed to seek the maximum obtainable hardness in steel tools must not lose sight of the fact that in many instances a hardness of, say, 300–350 Brinell may be quite adequate with special cast iron, at which hardness finish machining can just be carried out.



[*By courtesy of the Meehanite Corporation.*

FIG. 211. Curve showing effect of heat-treatment upon the ultimate strength and hardness of a 2-inch section cast in "Process A Meehanite" iron.

The heat-treatment of inoculated iron is carried out in exactly the same manner as that already described for uninoculated alloy iron, the essential operations being an oil quench from 850 to 870° C., no soaking being given at the hardening temperature, followed immediately by a temper at whatever temperature is necessary to give the desired hardness. A somewhat lower tempering temperature can safely be used with inoculated than with uninoculated cast iron, 200° C. being adequate for small tools which are required to be as hard as possible. Fig. 211 shows the effect of heat-treatment upon the hardness and tensile strength of "Process A" Meehanite. As with uninoculated alloy cast irons, a stress-relieving treatment is recommended for all castings.

Summarising the advantages of cast iron as a tool material, and comparing its performance with that of hardened steel, it can be said that its low cost together with its extreme ease of shaping and polishing render its value unapproachable for tools of large size; that its resistance to fouling and scoring, particularly when in contact with steel sheet, is markedly superior; that in its special, and particularly its inoculated, forms its durability may be surprisingly greater; that its ease of heat-treatment and immunity from cracking and distortion is superior, and render hardening a safe and useful operation available at will; and that a single casting may replace a built-up steel tool containing many separately-hardened pieces, thereby giving greater rigidity and greater accuracy.

Another advantage which is sometimes claimed for cast-iron tools is that with them no lubricant need be used, the sheets being drawn dry; a procedure impossible with steel tools. It will be recalled that when the subject of lubrication was being considered attention was drawn to the marked influence upon puckering exerted by the nature and the quantity of lubricant applied to a blank; the fact that no lubricant is applied to blanks by the press operator contributes, therefore, towards more constant working conditions, a very desirable feature in many instances. The phrase "drawn dry" is seldom true literally: although no lubricant is placed on the surface of blanks during actual drawing operations, steel sheet usually bears a thin coating of protective grease applied by the supplier, while brass, which is often delivered in a more truly dry condition, is not infrequently drawn in tools which are periodically wiped with a rag dipped in lubricant. Until more experience is obtained and made available all that can safely be said is that, in many instances, a much *smaller* quantity of lubricant does seem to be necessary with cast iron than with steel tools. A point upon which more knowledge is needed is whether the self-lubricating, as distinct from other, properties of cast iron in the hardened state are equal to those in the as-cast condition.

As regards disadvantages, one which, though insuperable, is less marked with soft than with hardened cast iron is that if sheet splits during drawing the danger of serious damage to the polished surface of the tool is much greater than with hardened steel. It must be admitted that this disadvantage may be serious when continuous production is desired and no reserve tools are kept, a condition by no means rare in industry.

Another disadvantage is that a suitable composition, proper foundry control and good foundry technique are essential if satisfactorily sound castings are to be produced. That the desired conditions can be attained without undue difficulty is demonstrated by the fact that it is now common practice to keep in stock solid blocks of special iron from which small tools may be shaped or pieces cut for use as inserts in large tools of softer iron. This illustration in no way weakens the fact that to obtain the very best properties on working surfaces it is desirable, and sometimes essential, to make shaped patterns for large tools of which the working surfaces would be near the centre of a thick section were they machined from the solid. Ordinary foundry precautions must still be observed even though their need is less urgent.

Notwithstanding the degree of soundness obtainable in the main portions of castings there is always a danger, particularly if foundry technique is not of the best, for some unsoundness to occur in the immediate vicinity of gates and feeding heads. The foundry-man should, therefore, always be informed—preferably by suitable indication on a blueprint—which are the working surfaces of any tool cast to shape from a pattern. This precaution may seem almost too obvious to merit special mention, yet many good tools have had to be scrapped after rough machining because a riser or gate has inadvertently been placed over an important area of the working surface.

Great though the potential advantages of special irons may be, it must be clearly understood that the addition of alloying elements or the use of inoculation will not remedy poor melting and casting conditions. Indeed, the more special the iron, the more strict must be the control at all stages of foundry procedure and the more care will be necessary in the selection of a suitable composition and treatment for any given casting. As the user of press and deep-drawing tools is seldom familiar with foundry technique, and not always with even the elementary metallurgy of cast iron, his only recourse is to obtain his tools from foundries of repute who have had prolonged experience in the production of the particular type of iron desired. The specification of a certain analysis is no guarantee of the suitability of any casting for use in tools: foundry control and technique is of greater importance than chemical composition alone.

Chromium. Chromium, in the form of an electro-deposited coating, is one of the most valuable known materials for use in dies for deep drawing due to its peculiar "slippery" nature and marked resistance to attrition and fouling; three properties which have already been discussed with special reference to this metal.

In spite of glowing accounts of its merits from users—and also platers to the trade—who, by plating steel tools, have overcome persistent scoring and fouling difficulties, a considerable number of bad reports from less satisfied users have to be considered. It can be said without violation of truth that, unless working conditions are quite unreasonable, unsatisfactory performance of chromium-plated steel tools is due to one or more of three causes: unsatisfactory deposition, unsatisfactory surface-polish on the steel base, or inadequate hardness (or "core strength") of its base.

The electro-deposition of chromium upon steel for engineering, as distinct from decorative, purposes requires a special technique which until recently was not always known by persons or concerns who undertook the deposition and, even now, is not always carried out effectively. A show of secrecy is often maintained by those who specialise in the electro-deposition of wear-resisting chromium, but it seems that the essential stages for successful deposition are perfect cleaning, a roughening of the surface—preferably finished, if not produced entirely, by anodic etching—and, of course, suitable conditions of solution, temperature and current density in the actual plating vat. An initial reversal of current in the plating vat, giving a final anodic etch, is sometimes recommended, but there is a danger that this practice may cause a film of carbon to be left on the anodically-etched surface of high-carbon steels thus preventing proper adhesion of the chromium when plating is started. For this reason it is often better to give the desired anodic etch in a separate bath. Should electro-deposited chromium flake off the working surface of drawing dies even under the most arduous duty, it is a sign that either the preparation or else the electro-deposition itself has not been carried out properly.

It seems hardly necessary to say that no under-coat of copper must be deposited beneath wear-resisting chromium-plate, yet the author has seen a number of tools which have failed through this cause. Obviously, an intermediate layer of soft copper between the steel base and the chromium coating will deform plastically under pressure and allow the brittle chromium coating to collapse and crack.

The second possible cause of unsatisfactory performance from chromium-plated tools is an insufficiently good polish on the underlying steel tool. The plated coating will follow, and may accentuate, any uneven contours of the steel base and, as the hardness of the deposited chromium will be higher than that of hardened steel, effects produced by surface irregularities will also be accentuated. These effects have already been discussed earlier in this chapter.

Chromium-plating is too often regarded as a panacea for all ills; it is quite definite and quite logical that it will *not* overcome defects caused by inadequate smoothness of tool surfaces. Surface excresences which cause scoring before being plated will still cause scoring after they have been plated; yet the fact that this is so has often resulted in the condemnation of chromium-plating as being of no use.

The third and last cause of unsatisfactory behaviour ought, like the second, to be obvious. The thickness of coating normally given is very small, and it is therefore essential that the hardness of the base upon which it is deposited should be sufficiently high to resist plastic deformation under the pressure imposed during operations. Through lack of appreciation of this fact unhardened steel tools are sometimes sent to be chromium-plated and, if their condition is not noticed by those responsible for plating, failure will soon occur if—as is usual when chromium-plating is resorted to—working pressures are high.

The best hardness for the steel base underlying a wear-resisting chromium deposit is a somewhat controversial point. Some authorities maintain that it is courting disaster to chromium-plate tools in the region of C60 Rockwell hardness owing to the likelihood of the steel cracking due to the influence of hydrogen, and one large firm of chromium-plated gauge makers has standardised a hardness of approximately C46–48, and never more than C50, Rockwell as the highest safe value. On the other hand, tools of C60 and even C62–64 Rockwell have upon occasion been plated without failure; this is fortunate for, when very high working pressures have from force of circumstances to be endured, a hardness of C46 Rockwell would often provide a quite inadequate support. It is, of course, likely that the conditions under which electro-deposition is carried out have an appreciable influence upon the tendency of hardened steel to crack; yet, in spite of the fact that much useful data must have been accumulated, little information upon this important point has been published. Whatever the hardness of the tool, the giving of a low-temperature annealing at about 150 to 180° C. immediately after electro-deposition seems to be a simple and useful precaution rapidly to relieve possible hydrogen-embrittlement.

The best thickness of chromium-plating is another controversial point. Quite thick deposits formed on the worn parts of old tools often give remarkably good service, but present experience seems to indicate that, with new tools, a deposit approximately 0·001 inch thick gives a satisfactory combination of robustness and longevity, provided that the surface of the steel base is really smooth and that the tools are not subjected to abuse during service, two conditions which are not always satisfied.

The hardness of an electro-deposited coating of chromium varies very markedly according to the chemical composition and temperature of the bath and the current density. By varying these factors Cymboliste [87] has obtained a range of hardness values, measured on Vickers and Eugène machines, equivalent to 400–1,200 Brinell. For this reason more complete theoretical knowledge than is needed for merely decorative plating, assisted by the exercise of close control, is necessary for the successful electro-deposition of wear-resisting chromium. It is likely that the highest hardness consistent with reasonable freedom from cracking will give the best performance, although definite experimental proof of this assumption seems lacking.

Wood. Considered as a tool material, wood possesses several useful and even unique properties. It is the cheapest, lightest and most easily shaped of any of the commonly used materials; it is incapable of "fouling" or "loading," and unless—as happens somewhat readily

—foreign particles become embedded in its surface it will not score even soft sheet.

Owing to its softness wood can, unfortunately, be used only when a set of tools is required to produce a relatively small number of pieces from thin, soft sheet. In spite of this limitation it proves of real value in certain industries, such as those engaged in the production of aircraft or in body building, in which limited numbers of some particular panel, cowl or fairing have to be produced in light-alloy, and even in thin austenitic steel, sheet by pressing or stretching processes.

When wooden tools have to withstand genuine deep drawing as distinct from bending and pressing operations, both their life and range of application can be increased very greatly by facing the working surfaces with cold-rolled steel sheet of about $\frac{1}{8}$ or $\frac{3}{16}$ inch thickness which, of course, then becomes the true tool material. Fig. 212 shows a steel-faced wooden tool and it will be evident that this method of construction, which adds little to the cost of plain wooden tools, can be used for tools of all sizes. Utilising wood construction, both plain and steel-faced tools can be made in quite large sizes very cheaply and quickly. Indeed, were this method of construction not available, both the cost of production and the delivery period for shapes of the kind now made by means of wooden tools would be so high that they would often be prohibitive.

One important advantage of wood is its light weight. This enables two men to lift large-sized tools which, were they made in metal, might weigh more than a ton, and is a real help when short runs on different pressings necessitate frequent changing and transportation of tools from press to stores.

Little published data relating to the merits of various kinds of wood for drawing and pressing tools is available, and still less regarding the lubricants suitable for use with them. Hard woods such as box-wood, teak and lignum vitæ are used for small tools not protected by steel facings. For larger tools maple and yellow or red birch are popular in the United States by virtue of their high compressive strength parallel to the grain ; white birch is considered to be less satisfactory. In Europe glued slabs of either ash or red beech are popular for building up the wooden tools used for pressing, rather than deep drawing, large panels. Ash is the less likely to split and warp during storage.

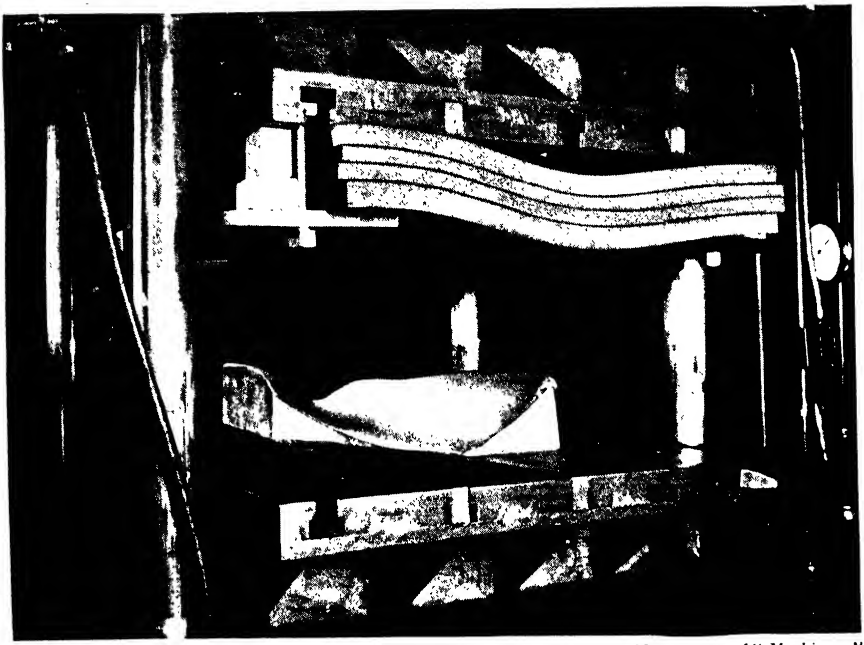
It is most important that no aqueous-base lubricants be used with wooden tools ; vaseline is relatively harmless toward wood, yet it is a good lubricant for light-alloy sheet.

Rubber. Considered as a tool material rubber is no newcomer to the press-shop, for it has long been used as an elastic punch when a shape having a restricted orifice has to be formed from one having parallel sides, familiar instances being the final shaping of watch cases and convex-sided hollow-ware from deep-drawn shells. This applica-

[By courtesy of "Machinery."

FIG. 212. A typical application of steel-faced wooden tools to form a raised panel.

[To face p. 400.



[*By courtesy of "Machinery."*

Fig. 213. Assembly illustrating the use of rubber pads to force light alloy-sheet into a cast zinc mould mounted on an hydraulic press.

[*By courtesy of General Aircraft Ltd.*

Fig. 214. Pair of tools cast in zinc for producing pressing in aluminium sheet under a drop stamp.

[*To face p.* 401.

tion, although important, has yet been on a small scale and confined to specialised trades ; but the quantity-production of all-metal aircraft has opened up a very wide field for the utilisation of rubber as a press-tool material, and as a result it is likely that its use will extend to other fields in which hitherto its use has not been considered.

As a tool material rubber is, of course, unique owing to its remarkable elastic properties which enable pressure exerted at one face of a block to be transmitted and distributed uniformly to other faces no matter whether these are plane or, within limits, of irregular shape. To most people rubber is simply rubber, but its ever increasing use makes it essential for those who use it in the press-shop to recognise that a considerable range of grades, having different physical properties, is available for intelligent selection.

Rubber differs essentially from metals in that its stress-strain curve is not a straight line within the elastic range, although up to about 25 per cent. compression the departure is not large ; but this value is often exceeded in press-shop practice. For this reason no true modulus of elasticity can be given except as an approximation for the lower ranges of compression. Hardness, a somewhat ambiguous term when applied to metals, is even less precise when applied to rubber. However, it is generally accepted that the term signifies indentation hardness, even though no permanent indentation is made during the test, and this property is usually measured on the Schore Durometer instrument and taken as an indication of rigidity or "stiffness," an assumption which, if indefensible on theoretical grounds, is useful at least as a rough guide to users who do not wish to make tests of a more scientific nature.

The "stiffness" of rubber varies considerably according to the method used for curing it, and it is useful to hold stocks having "hardness" values of 30, 50 and 70 on the Schore Durometer scale from which selection can be made to meet the demands of any particular press operation.

Proper compression tests give much more informative information than so-called hardness tests, but it must always be remembered that special methods have to be adopted when testing rubber in compression, and that a simple compression test made on a cylinder or block of rubber in the manner adopted for metal specimens will give incomplete and probably misleading information. For example, both the shape and the ratio of the height to the cross-sectional area of the test piece influence the results obtained. The kind of contact made between the rubber specimen and the faces of the testing machine is also of profound importance, for very different results will be obtained on similar specimens according as to whether these surfaces are rough or smooth and, when smooth, according as to whether they are clean or lubricated.

Turning to the practical application of rubber as a press-tool material, its use in small punches is explained in the section headed "Bulging" on p. 612, and a typical article produced by it is illustrated in Fig. 294 (p. 612). The application of rubber to both large and small tools making aircraft or similar parts from sheet usually involves the use of one metal tool, often cast to shape in one of the "soft" metals described in the next section, in conjunction with a rubber pad. This pad is built up from sheets which are sometimes cut so that the assembled pieces conform roughly to the contour of the shape to be formed and are sometimes reinforced locally by separate pieces of rubber or by hard blocks inserted at suitable positions under the pad proper. The rubber may be held loosely and the metal tool left free to move, as in the set-up illustrated in Fig. 213, or its side movement may be restricted in places by plates. For some purposes it is helpful to house a thick rubber pad in a strong four-sided steel box so that it cannot expand laterally at all, an arrangement which forms the basis of the Guerin process (described on p. 617) for pressing and, when a sharp-edged metal die forms the opposite member, for blanking. It will be obvious that rubber may be used for either the male or the female tool, and only experience can decide which is the better arrangement for any particular shape.

The use of rubber as a tool material is not confined to shaping light-alloy sheet. It has proved quite capable of giving accurate impressions in steel and even stainless steel sheet of relatively thin gauge if good ductility is maintained by inter-stage annealing, although when the thickness rises higher than about 0·040 inch it becomes difficult to fill sharp contours. The life of the pads will depend entirely on the severity of the deformation and loading imposed on them ; in extreme instances it may be possible to produce only a few articles, in others several months of continuous operation can be obtained.

Lubrication is of importance. Blanks should be coated with oil on the side placed in contact with the metal tool and, when in position in the press, dusted on the other side with powdered talc, graphite, French chalk or other suitable dry lubricant. Oil should not be allowed to come in contact with the rubber pads or their life will be shortened and the even flow of the metal hindered.

"Soft Metals." Applied to tools used in the press-shop the description "soft metal" usually implies zinc either in the pure state or alloyed to give greater hardness, although lead, nearly always hardened by the addition of antimony, is used sometimes. Occasionally complex alloys containing bismuth find favour because, although they are undesirably soft and very expensive, their negative coefficient of expansion facilitates the making of tools by the special casting methods described later.

"Soft metal" tools are particularly useful for shaping sheet by the drop-stamp method and also as the opposite member to a rubber pad as in the Guerin process, two new methods described in Chapter XV. At first they were used only for soft sheet of aluminium and aluminium alloy, but they are now being used on an ever increasing scale both for steel and for such relatively hard metals as austenitic stainless steel and Inconel, an employment in which they often show a surprisingly long life. Fig. 214 (p. 401) shows a pair of cast zinc tools used to form an aluminium article by the drop-stamp method.

The principal advantage of " soft metal " tools is that they can be produced in a fraction of the time and at a fraction of the cost of steel—and even of cast iron—tools, particularly when the size of the tools is large. As explained later both the male and the female tool can often be cast from one pattern, and both can be cast so closely to shape and with such a good surface that as a rule only a little polishing is needed. Moreover, casting can be done in the works of the user—often indeed in the actual press-shop itself—without the aid of skilled moulders and the usual foundry plant and trained workers, thus showing a further saving in time and money. Although the metals themselves are relatively expensive, old tools can be melted down and the metal used over and over again. The principal disadvantage of these tools is, of course, that they are not so durable as steel or cast iron tools when long production runs and high, localised loading are demanded.

Although choice must be guided by the special requirements of every job, it is usual to make the movable member of a pair of " soft metal " tools in lead, zinc or rubber whether this be the male or the female tool, and to arrange for the lower tool to be of zinc and the upper tool of lead or rubber. Owing to its softness and low tenacity lead is, as a rule, used only for punches, and sometimes zinc dies are reinforced by steel inserts in zones specially liable to wear.

Screwed studs are sometimes cast into the reverse faces of " soft metal " tools for the purpose of securing these to the tables of the press ; and it is important that an adequate number of studs be used to ensure even support of a large mass of metal, and that the reverse surface be smooth and flat. Special precautions must be taken when lifting large lead tools because these often distort under their own weight, and it is helpful to arrange for steel joists to be screwed to them, and sometimes to zinc tools as well, to prevent deformation during handling and, with the harder alloyed metals, to lessen the danger of breakage. When, as happens sometimes, zinc tools crack, a repair made by soldering will often enable a cracked tool to be used till the end of its allotted run, provided that it is attached firmly to the press table by a sufficient number of studs.

Considering, first, lead punches, the question whether pure lead or a lead alloy is to be used will depend upon the kind of sheet it has to shape and upon the nature of the shaping operation. Sometimes pure lead is best because it is so soft that it flows slightly under stress thus enabling a relatively uniform pressure to be exerted over the whole surface of the punch. When a harder and more rigid tool is needed an alloying element must be added, and for this purpose antimony, in amounts varying from 4 to 12 per cent., is nearly always used. When more than 12 per cent. of antimony is added there is a tendency for tools to crack. Hardness values vary considerably with the purity of the lead used, but the following values are fairly typical :—

Pure lead	3–4	Brinell	(10/100/15)
Lead plus 2 per cent. antimony .	6–8	,,	,,
,, 6 ,, ,, .	8–12	,,	,,
,, 12 ,, ,, .	12–16	,,	,,

Lead is one of the easiest metals to melt and cast, and the only precaution that need be observed is that of stirring the melt before pouring because antimony, being lighter than lead, tends to rise toward the top of the pot. The pouring temperature is not at all critical, and is often governed primarily by the amount of contraction which the punch must undergo in order to give the desired working clearance between the punch and the die—a zinc die usually being used as the mould into which the lead is cast to form the punch member of a pair of tools. This clearance can be varied when desired by warming the zinc die to a predetermined temperature before pouring the lead into it.

Although lead punches have a useful field of application, particularly with soft aluminium sheet, their softness is often a serious disadvantage. One reason for this is that the wrinkles and puckers which are usually formed when sheet is shaped by the drop-stamp technique produce indentations in the punch surface which mark subsequent pressings. With the harder varieties of sheet it is therefore often preferable to use punches of zinc or zinc alloy.

Zinc, whether for dies or punches, may be either pure or alloyed depending upon the kind of sheet it has to shape, the severity of the shaping operation and the number of pressings to be made. Two kinds of zinc alloy have proved satisfactory and are in general use. One is a binary alloy containing about 5 per cent. of copper ; the other, a harder and more durable though more expensive alloy, contains aluminium, copper and a little magnesium. Users can prepare the binary alloy themselves by adding copper to zinc of only moderate purity, such as debased " electro " zinc. Owing to the great difference between the melting points of zinc and copper it is best to purchase a " hardener " alloy of zinc containing a relatively high percentage of copper and to add this in the proportion needed to give the desired percentage of copper in the final alloy. The other alloy, which resembles one of a number used to make pressure die-castings, has to be made from zinc of very high purity ; and, as the alloys of most satisfactory chemical composition are covered by patents, it is usual to buy metal in ingot form ready to melt and cast. In the United States a suitable zinc alloy is sold under the trade name of " Kirksite " ; in this country " Mazak 3 " or "Durak " (which is the same alloy made with slightly less pure metals) are avilable. The tensile strength of pure zinc is a little over 2 tons/square inch ; whereas that of " Kirksite A " and " Durak " often approaches 17 tons/square inch. The hardness of these alloys varies considerably, but the following values apply in most instances. The values for both tensile strength (above) and hardness relate to the sand-cast condition.

Pure zinc	35–45 Brinell
Moderately pure zinc plus 5 per cent. of copper	55–65 ,,
" Kirksite A " and " Durak " . . .	80–100 ,,

When melting zinc and zinc alloys it is important to avoid contamination of the melt by unwanted metals introduced with old tools—*e.g.*, from solder used to repair cracked tools or from fragments or " smears " of the metal against which they have been used—or by the solution of an excessive amount of iron from the pot used for melting, because this renders the tools more likely to crack. In this connection it is interesting to record that when nominally pure zinc is used, press-shop operators often prefer metal which has been re-melted several times. This is explained by the fact that the impurities picked up—particularly iron—harden the tools somewhat, but as too much iron causes embrittlement the use of proper alloys of controlled composition kept as free from impurities as possible is to be preferred.

The low melting point of zinc and the ease with which it can be melted and cast must not be made an excuse for the abandonment of normal foundry precautions. Conditions of reasonable cleanliness must be observed, overheating must be avoided, the pouring temperature must be controlled with reasonable accuracy and moulds must be dry if sound castings are to be produced. As a general rule it is best not to heat zinc or zinc alloys above the lowest temperature which will give sufficient fluidity for castings to be made without difficulty, because a high temperature increases the rate of solution of iron from the pot, increases the crystal size of the cast tool (thus increasing its brittleness), and makes it more difficult to obtain a smooth surface on the cast tool. The casting temperature for tools made of nominally pure zinc will vary according to the proportion and nature of impurities present. For a first cast a temperature of about 430° C. may suffice, but after the metal has been re-melted a number of times it may be necessary to increase this to 510° C. The best casting temperature for the straight 5 per cent. copper alloy is approximately 500° C., and alloys of " Kirksite A " and " Durak " type should be cast at a temperature of from 400° to 425° C. Above 470° C. the rate of iron pick-up from the pot increases markedly and the impact strength of the cast metal falls rapidly.

Care must be taken to avoid local " hot spots " in the steel or cast iron pots used to melt zinc because these will lead to localised attack, giving a short pot-life, and to excessive contamination of the zinc by iron dissolved from the overheated zones. A useful method which gives long pot-life coupled with a uniform and easily controlled temperature is to make the zinc pot the inner member of a double-walled vessel, with molten lead in the space separating the inner and the outer (externally heated) pot.

Approximate values for the melting points and coefficients of expansion of some of the metals which have been mentioned are :—

	Melting point, °C.	Coefficient of linear expansion.
Lead, industrial purity	325	27×10^{-6}
Lead plus 6 per cent. antimony	300	26 ,,
Lead plus 12 per cent. antimony	265	25 ,,
Zinc, industrial purity	420	30 ,,
Zinc plus 5 per cent. copper	510	27 ,,
" Kirksite A "	380	27·5 ,,

The procedure to be adopted for casting a pair of " soft metal " tools varies somewhat according to the metals used, the size of the tools and the preferred practice of any particular press-shop ; but an important feature is that it is seldom necessary to make more than one mould. One method is to make a wood pattern, or a replica of the article fabricated by hand from sheet metal, and from this to make a mould either in sand or in plaster of Paris strengthened with shredded asbestos. This is used to cast the die in zinc or zinc alloy. The die is then surrounded by sand or by a built-up frame of asbestos-covered wood, and used as a mould in which the punch is cast in either the same metal, or perhaps in antimonial lead. To prevent local melting and to facilitate separation after casting it is advisable to spray the surface of the die with a thin coat of a refractory wash, such as one of those described in the next paragraph.

By warming the die it is usually possible in tools of fairly small size to control the shrinkage of the punch to give the correct working clearance between the cold punch and die for the gauge of sheet they have to shape. With large tools, however, the shrinkage of the punch often gives too large a working clearance, and other methods have to be adopted. One is to make a mould for the punch, instead of for the die, after having built up the working surface of the punch to the desired extent by some means such as spraying on to the warmed surface successive coats of a heat-resisting wash, for example of colloidal graphite and alundum cement, or a water suspension of iron oxide, graphite and sodium silicate containing a binder and an anti-settling agent. The built-up punch is then placed in a suitable flask of sand and the die cast over it.

One of the important advantages of " soft metal " tools is that very little finishing of the cast surfaces is needed, and it is therefore important that the casting procedure for any pair of tools should be carefully planned to give the correct working clearance without having recourse to lengthy and expensive machining or hand-trimming in order to get this clearance.

It is safe to predict that " soft metal " tools will be used to an increasing extent both in existing and in many fresh fields of application. Those who use them are alive to both their virtues and their limitations; many who do not yet use them might with advantage consider their adoption when conditions allow, and, in some instances, might find it worth while to modify their normal press-shop procedure so that they might be used.

Apart from their primary use in production, " soft metal " tools might well be used experimentally to try out a new pressing, for example an automobile mudguard pressing. Such tools could be quickly made and, owing to their softness, easily altered to obtain the desired shape by cutting and scraping, by building up, by soldering or by " burning-on " operations. Even the scrapping and recasting of large tools would be a relatively inexpensive, and rapid, undertaking. Once a satisfactory shape was arrived at, patterns could be made and the proper production tools cast so closely to shape in cast iron that but little finishing and bedding-in—both lengthy and expensive operations—would be needed, and the necessity for a long and difficult production run on tools which are not quite " right," yet are too expensive to scrap, would not arise.

Miscellaneous Materials. Besides the common tool materials steel and cast iron, and the less common though fairly widely used materials wood, rubber and " soft metals," mention must be made of certain others which, although used on a limited scale, are of special value under certain circumstances.

Cast Elektron has been used for large tools employed for pressing light-alloy sheet. This rather surprising practice originated in Germany through efforts to use the plentiful supply of magnesium which is available in that country, but it was soon found that Elektron gave excellent service in the tools used for many pressing operations. Its extreme lightness and the fact that it can be cast to shape and re-melted when the tools are no longer needed have helped to increase its popularity for relatively light operations. Cast aluminium alloy tools, which can be made at a relatively low cost by melting accumulated stocks of blank-surrounds and sheet clippings, have been used for the same purpose and even for actual dies for drawing aluminium and solution-treated Duralumin sheet. Although not so light as magnesium-alloy tools, they are very much more easily handled than are ones in steel or cast iron. In the aircraft industry, owing to the small numbers of parts which have to be produced at a time off a set of tools, weight becomes an important factor and quite large tools of magnesium or aluminium alloys can be changed easily and quickly; whereas cast iron tools of equal size would need heavy tackle and lengthy manipulation at every change of set-up.

Ordinary cast bronze is used with excellent results for deep-drawing aluminium and, for draws of moderate severity, austenitic steel; it can be cast closely to shape and is, of course, easily machined and hand-finished. Special bronzes having a hardness of 300 Brinell or more are sometimes used for drawing austenitic steel when pressures are relatively low, and seem, from some reports, to give a better surface on the drawn product than that obtainable with steel tools. The special bronzes offer a fruitful field for experiment in the search for new tool materials which can be cast to shape, easily finished, are reasonably durable and possess a low coefficient of friction. If the hypothesis advanced earlier (p. 375) as to the value of small sunken oil reservoirs is correct, a fine duplex structure would seem preferable to one containing relatively few hard particles.

A recent departure is the use of special nickel-chromium alloys which can be cast to shape and then heat-treated. One proprietary brand of these alloys containing nickel, chromium and molybdenum can be heat-treated to a hardness of approximately C55 to 60 Rockwell. The chief drawback to this class of tool material is its high cost, although against this must be balanced a relatively high scrap value, the usual benefits attached to a tool cast closely to shape and, according to reports, excellent durability.

Hard facings, such as Stellite and other synthetic products, are seldom used by design unless specially severe conditions have to be endured, *e.g.*, as are imposed by the bending or pressing of thick, oxide-coated steel. Their cost is high as regards material, deposition by welding, shaping—grinding being imperative—and polishing. The use of such materials should be avoided whenever possible, although their specially high resistance to abrasion may prove useful in special instances when a certain operation forming part of an established production sequence has to be carried through at any cost.

The success in heavily loaded bearings, *e.g.*, those used in rolling mills, of substances such as resin-impregnated fabrics, suggests that for light draws a die made of some such material might show useful properties if it could be moulded to the desired shape without first making expensive dies. For heavy draws its strength would be inadequate, but it is reported to give good service in dies of simple shape used for light-alloy sheet.

In so short a space it has been impossible to give more than an outline of the materials which can be used for the tools in which sheet metal of all kinds is deep drawn or pressed. The main classes of steel and cast iron, together with various heat-treatments which can be given to them, have been considered, and brief mention has been made of less popular, yet for some purposes important materials—for example, wood, rubber and the so-called "soft metals." Bearing in mind the various essential properties discussed in the first part of this chapter, an attempt has been made to indicate as far as possible in what degree these properties are exhibited by the various tool materials described. Later, a more detailed consideration of the choice of a tool material to meet certain conditions will be given.

The Heat-treatment of Tools

It is not possible in this volume to deal in any adequate manner with the heat-treatment of tool steels, upon which subject many useful treatises have been written. Yet as heat-treatment, and particularly hardening, is such an important and often dangerous stage in the production of deep-drawing tools, a few brief observations on matters of special importance cannot be omitted.

Co-operation between Designers and Hardeners. Attention has already been directed to the value of consultation between tool designer and hardener in the matter of selection of tool material in order to avoid as far as may be possible unnecessary hazards, either by cracking or distortion, during heat-treatment. Such co-operation can further reduce these hazards in another direction, namely, in the location of shoulders, sharp fillets, holes into which are screwed eye-bolts for lifting or studs for securing the tool in position, and even letter-punch markings. When the position of these stress-raisers is considered at an early stage in the lay-out of a tool, it is usually possible to arrange for them to be situated in positions of far less potential harm than when they are located without thought or purely to suit mechanical requirements. In the majority of instances shoulders and stepped sections are not used for purposes of location, and a radius can be substituted for a sharp fillet without any inconvenience whatever.

Even in the shape of the outside of the tool, particularly when the bore is unsymmetrical in shape, the experience of the hardener can be of use if only to avoid localised dangerously weak sections, although the dimensions of the available press and bolster may impose serious limits on the most favourable shape.

In addition to minimising the risk of cracking during hardening, careful design will sometimes permit the safe use of a tool material more suitable from the service aspect than that which would have perforce been used had severe stress-raisers been present.

Normalising. In its true metallurgical meaning "normalising" implies heating to above the critical temperature and cooling in still air. Steel tools ought always to be thoroughly normalised before being hardened. . Users often assume that bars and forgings are delivered in a properly normalised condition by steel-makers; this assumption may or may not be correct, and a firm rule that all tools must be normalised before being hardened will undoubtedly reduce hardening hazards and result in better hardening. If the rate of cooling is not too rapid, a normalising operation can be utilised as a stress-relieving treatment when introduced at an appropriate stage in the machining of a tool.

The procedure is to heat tools slowly and carefully to slightly above the critical temperature of the particular steel being treated, soak for no longer than is necessary to ensure all sections reaching the temperature, and cool moderately slowly, usually in still air. Prolonged soaking or very slow cooling may produce an undesirable coarsening of the structure; but too rapid cooling may set up internal stresses and also render the steel harder than is desired for machining. As cooling in air is usually necessary to produce the desired refinement of structure, it is advisable to normalise tools at an early stage in machining operations, when a scaled surface can be roughed off with a single heavy cut, packing being used for subsequent heat-treatments. It is interesting to note that a distinct increase in the output obtained from heavily-loaded steel tools has been recorded by a number of users when a double normalising, instead of the usual single normalising, has been given prior to hardening.

Stress-relieving. The value of this operation, sometimes misleadingly termed "normalising" in tool-room parlance, cannot be emphasised too strongly. One or more stress-relieving treatments is a cheap and effective insurance against undue distortion, and even against cracking, no matter whether tools are made from castings, forgings or solid bar. Although this form of treatment is still deemed unnecessary in some shops, it is significant that once it has been given a fair trial it is seldom discarded in spite of protests occasioned by the extra time involved in tool production.

It is, without question, good practice to give a stress-relieving treatment to castings either before or after rough machining. The need may seem less with forgings and bar; yet, even with these, treatment is always desirable. With nearly all shapes and sizes of tool a stress-relieving anneal prior to finish-machining to size ought never to be omitted; when heavy machining has to be carried out on thick sections a third or intermediate treatment is often beneficial.

The temperature and time of soaking employed for stress-relieving annealing varies widely, being determined to some extent by the material and the section of the tool being treated and also influenced by the favourite practice of different shops. For steel, temperatures ranging from 200 to 720° C. are recommended by various authorities; at the lower temperatures a long time of soak will, obviously, be desirable, but an open furnace can be used because no severe surface oxidation will occur; at temperatures of the order of 600° C. packing may be needed to prevent surface deterioration. In the absence of special circumstances it is better to pack-anneal at a temperature of 680 to 720° C., as this treatment will ensure an adequate release of internal stresses in a reasonably short time.

Cast-iron tools should not be treated above 650° C.; heating to 550 to 650° C. without prolonged soaking will usually remove stresses without changing the microstructure of the iron. With both steel and cast iron the rate of heating and cooling should be sufficiently slow to prevent the formation in the tool of steep temperature gradients. For this reason it is often advisable to cool packed tools in their containers.

Rate of Heating. Both distortion and cracking may occur as a result of too rapid heating up through the lower temperature ranges, particularly in tools of medium and large size. It is a wise precaution always to heat up to at least 650° C. at a rate such that a steep temperature gradient does not occur throughout any section. Above this temperature steel—and also cast iron—seems to have softened sufficiently to enable thermal stresses to be relieved by plastic deformation fairly readily, and the rate of heating can be increased appreciably without risk of cracking. With cast iron reasonably rapid heating from 650° C. to the quenching temperature is desirable; with steels this increase in rate need not be so great, but some increase is desirable to avoid surface deterioration, unnecessary waste of fuel and undue coarsening of the structure.

Time of Soaking. The time during which the tool is maintained at the hardening temperature before it is quenched is of considerable importance; it varies with cast iron, which should never be soaked, and with different varieties of steel. It is the practice in some shops to soak a little below the actual temperature used for quenching, only raising the tool to this temperature immediately prior to this operation. The merits of this procedure are not established, but it does seem that in certain instances some advantages are forthcoming.

Prolonged practical experience seems to be the only safe guide to the choice of soaking time for any given steel and section; some indication of the peculiarities of certain materials has already been given, and it would be unsafe to elaborate these into more definite instructions which might not be applicable in all instances.

Hardening Temperature. The temperature from which quenching is carried out is a most important factor in determining the success or failure of the hardening operation. It has become customary—except among practical hardeners—to assume that the best quenching temperature of any steel is fixed by its chemical composition to within a few degrees, and that the hardening temperature for any tool can be written on the blue-print beneath the chemical analysis of the steel to be used. Although this may seem possible in theory, practical experience shows very clearly that the theories upon which this assumption is based are as yet incomplete. Investigations such as those of Herty, McBride and Hollenback [88] concerning the influence of "inherent grain size" may lead to a more complete understanding of those properties of steel which influence what has been termed "hardenability."

It appears probable that the reason for the recognised variation in "hardenability"—and other properties—in steels of similar chemical composition may be largely due to the grain size of the steel at the instant of quenching. It is important to bear in mind that this "inherent grain size" may not be the same as that revealed by tests made at other temperatures, for example, by the well-known McQuaid-Ehn test, in which the size of the austenite crystal grains *at* 925° *C.* is inferred from the appearance of the cementite network produced in the surface layers of specimens carburised for eight hours at this temperature and cooled slowly.

Turning from theory to practice, it is well established that steels of almost identical chemical composition may behave quite differently when quenched from the same temperature after having been soaked for the same length of time. This is observed repeatedly with steels made to the same analysis by different steel-makers, and experience with their respective products is at present the only way in which the best quenching temperature can be ascertained. Differences as great as 20° C. may be necessary with plain high-carbon steels, and as much as 50° C. for steels of complex composition. Cast iron seems to be far less critical; little difference can usually be observed over a quenching range of 50° C.

Other more readily understandable factors which need to be taken into consideration when deciding to what temperature any tool is to be heated prior to being quenched are the size of the tool, the time which is likely to elapse and the facilities for surface heat loss between cessation of heat-input and quenching, the effectiveness of the quenching bath and, sometimes, whether hardness or freedom from distortion is of greater importance in the particular tool which has to be hardened. The manner in which each of these factors can influence the hardening temperature will be evident without explanation.

Quenching. Of all stages in heat-treatment, quenching is the one in which the manipulative skill, ingenuity and experience of the hardener is needed most. The more closely any procedure approaches to an art, the more difficult it becomes to describe it in precise language; at best only broad generalisation can be attempted, for the essence of such an art is the interpretation by the artist of sets of conditions which may never be exactly the same. Attention will therefore be drawn only to one or two details which are known to cause trouble, such as the use of quenching tanks of inadequate size when large tools have to be quenched. This occurrence is not uncommon as, in many hardening-shops, deep drawing and pressing tools are the bulkiest pieces which have to be handled. Agitation of the liquid or article, although of great assistance, is not always a complete remedy. When water quenching is used, and also with some of the oil-quenching steels which attain a high hardness, it is desirable even in large tanks to arrange for powerful submerged jets to impinge upon the important surfaces of the tool, and many are the ingenious arrangements contrived for this purpose.

Soft Spots. Soft spots or areas are a common defect for which quenching procedure invariably seems to be blamed. Adhering scale or packing material, and also adhering bubbles of steam or oil vapour formed in the quenching tank, are frequently offered as a sufficient reason for observed effects, but it must be admitted that many puzzling happenings seem to require at least supplementary explanation.

Pursuing this subject, a theory has been advanced that the property of "hardenability" of a steel, as determined by its grain size at the instant of quenching, has an important influence upon the likelihood of occurrence and severity of soft spots produced under reasonably constant conditions of quenching. It is postulated that the ability or failure of protected areas on a steel surface to harden will depend upon the "critical cooling rate" of the steel, a property known to be profoundly influenced by inherent grain size and one which varies also with chemical composition.

A quick brush can be given to the important surfaces of large tools to remove the larger masses of adhering packing compound, but if appreciable oxidation has occurred as a result of heating in an open furnace it is usually impossible to remove all dangerous scale. Protection by packing or control of furnace atmosphere is, clearly, most desirable to minimise both surface damage and the likelihood of adhering scale causing soft spots when the tool is quenched.

Apart from the influence of substances which adhere to and protect the surface of the tool, soft spots are less likely to occur if de-aerated water is used in place of water which has not recently been boiled. This is attributed to the tendency of dissolved gases to come out of solution and to adhere to the surface being quenched. Brine is far less likely to cause soft spots than de-aerated water by reason of the lower solubility of gases in it and, more particularly, of the curious and very fortunate action whereby steam bubbles which are formed upon the quenched surface are instantaneously destroyed by the explosion of minute particles of salt which crystallise out within them on the surface of the steel. The discovery of the true action of brine and other quenching mediums by the aid of the ultra-rapid cinematographic camera has disproved many hypotheses concerning the way in which these solutions function, and has paved the way to a more intelligent selection and use of them in the hardening of steel.

The old belief that brine is a more drastic quenching medium than water is no longer tenable. In comparison with water, brine of suitable strength may produce a more rapid quench, and therefore a harder surface, by reason of its inability to form a lingering protective envelope of steam, but the far greater uniformity of the quench thereby obtained actually *lessens* the danger of cracking due to uneven cooling of a hot surface. In the opinion of many hardeners, brine is always preferable to water for a still bath.

A solution containing about $\frac{1}{2}$ to $\frac{3}{4}$ lb. of rock salt per gallon, *i.e.*, about 5 to 8 per cent., is probably the best for general use. A stronger solution will certainly dissolve less air on standing, but its quenching action will be slower—although more uniform—than that of water.

A 5 to 10 per cent. solution of caustic soda gives a more rapid quench than brine, but this solution is rather objectionable to use and, for the type of tools under consideration, is rarely necessary.

Temperature of Quenching Medium. The temperature of the quenching medium is of importance. In general, it is not advisable to use either water or brine below a temperature of 15° or 20° C.; and 35° C. and 65° C., respectively, are accepted as the upper limits above which a full quenching action will not take place in these two mediums. With oil the useful range usually extends to the region of 200° C., at which temperature factors appertaining to the steel itself become of equal importance to the latent heat of evaporation of the oil.

Manipulation. With tools of considerable section, such as large punches, it is usual to submerge only the working surfaces in the quenching medium and to withdraw the tool, sometimes intermittently, when it is judged that the internal heat will not cause the skin to soften. In this way the danger of bursting can be minimised, but it is a practice which calls for experience on the part of the hardener and also for familiarity with the particular brand of steel which he is handling.

Easily controlled quick-action lifting gear is of very great help when tools of any weight have to be dealt with. Electrically-operated hoists running on conveniently arranged overhead run-ways are probably the most effective aid to rapid transfer and also to manipulation in the tanks themselves. When hand-operated tackle is used the angle at which the chains will function should be tested ; if this angle does not extend well away from the vertical the operator may be faced with the unenviable task of pulling on chains with his knuckles only a few inches removed from a mass of red-hot metal on which the chains will rest when allowed to hang loose and from which they will absorb heat with surprising rapidity !

The ease and swiftness with which work can be transferred from furnace to quenching tank will depend, apart from the lifting tackle available, on the general lay-out of the shop ; both the proximity of the furnace to the tank, the relative heights of each, and the heights to floor level if tools have to be unpacked, are of importance.

Tempering. It is a safe rule always to transfer tools from the quenching tank to a tempering bath maintained at a temperature of 150 to 180° C. before they are cold, and often when the surface is at a temperature no lower than 150° C., leaving them in this bath for several hours at least, perhaps over-night when convenient. The practice of delaying tempering even for a few hours may result in cracking which could have been prevented by immediate tempering.

When subsequent tempering at a higher temperature is required, large tools should be heated up very gradually, especially if the long post-hardening low-temperature soaking just described has not been given : to utilise the rapid heating capacity of modern devices such as forced-circulation air tempering furnaces, useful as these are for some purposes, is to invite disaster.

Tools should not be cooled too rapidly from the tempering temperature ; quenching in cold water from a temperature no higher than 150° C. is likely to cause a hard tool to crack, as many a novice entrusted with the final stages of manipulation has discovered to his cost.

Surface Decarburitsaion. A tool which has been subjected to a perfectly satisfactory thermal cycle may yet be quite unsuitable for service if this treatment has produced decarburisation of its working surfaces. A soft, decarburised surface will wear rapidly, will score readily and, particularly when steel is being deep-drawn, will prove very liable to " foul." For this reason every precaution should be taken to prevent surface decarburisation, and hardened tools should be examined carefully for the presence of this defect.

A decarburised skin of normal depth will usually be removed when the working surfaces of the tool have to be ground after hardening, but the completeness of its removal will depend naturally upon the depth of the decarburisation and the amount removed by grinding ; when surfaces are only polished, it is unlikely that the whole of the unsatisfactory outer layer will be removed.

It is common practice to pack tools of small and medium size in containers filled with some suitable non-active medium, the resulting increase in time of heating for the greater mass being far outweighed by the cleanliness of surface and freedom from decarburisation imparted to tools heated in this way. The two most commonly used packing mediums are cast-iron swarf and charcoal; but with both these certain precautions must be observed. For example, cast-iron swarf should be clean, as the presence of oil will make the surface of the tools dirty and may cause local carburisation.

Charcoal should be of the wood, not the animal, variety and should be sieved to remove the smaller particles and dust. Whether fresh or spent charcoal should be used is a somewhat controversial problem, for the satisfactory elucidation of which clear thinking and a proper regard to the conditions appertaining to any one job are necessary. It may be accepted that there is a general tendency for fresh charcoal to carburise at high temperatures even though the susceptibility of various tool steels to suffer carburisation differs considerably. With spent charcoal the tendency to carburise at high temperatures is certainly less, but at low temperatures there may be a possibility of *decarburisation* taking place, although here again the susceptibility of steels of different chemical composition varies. Palmer [89] states that decarburisation is likely to occur in tools packed in charcoal at temperatures below 870° C., but it must be allowed that large numbers of tools are pack-hardened in charcoal at temperatures considerably below this without suffering appreciable surface decarburisation. The experience of the author does not confirm that of Palmer.

The use of spent carburising compound instead of wood charcoal as a packing medium is to be avoided, as its action tends to be erratic and it is not uncommon for small isolated areas of severe carburisation to result from its use. Thorough sieving is not a reliable cure for this uncertainty in action.

It is usual to use cast-iron swarf instead of charcoal when packing for annealing because it is cheaper, produces a satisfactorily clean surface at the usual annealing temperatures, and does not exercise the decarburising action which is sometimes attributed to charcoal at these relatively low temperatures. For higher temperatures, as used for hardening, charcoal is nearly always chosen in preference to cast-iron swarf because it gives a cleaner surface, is less prone to clog and adhere, and because it definitely counteracts any tendency of the steel to decarburise.

When tools have to be heated to hardening temperature in an open furnace, a useful expedient is to cover them with a paste made of boracic acid (not borax) powder and methylated spirit. This always hinders the formation of scale and quite often gives a reasonably clean or only slightly mottled surface.

"Controlled—or protective—atmosphere" types of furnace are used occasionally for quite small tools; but, as a rule, tools for deep

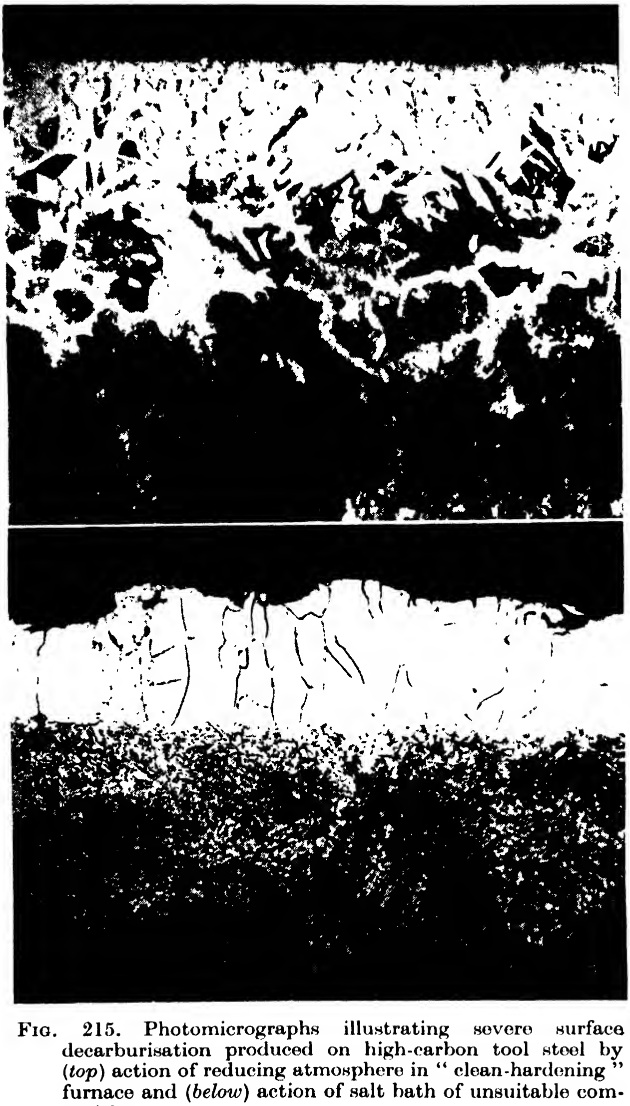


FIG. 215. Photomicrographs illustrating severe surface decarburisation produced on high-carbon tool steel by (*top*) action of reducing atmosphere in " clean-hardening " furnace and (*below*) action of salt bath of unsuitable composition.

Microsections cut normal to decarburised surface. × 200.

[*To face p.* 417.

drawing and pressing are too bulky to be heated in furnaces installed for the "bright" hardening of small tools and components. Useful as these furnaces are, they need careful supervision by persons alive to their shortcomings if surface decarburisation is always to be kept within tolerable limits. This caution is very necessary because press tools of relatively large bulk may be kept in the furnace atmosphere much longer than the small tools usually treated, and the likelihood of surface decarburisation is therefore greater.

A tool which emerges from the hardening treatment in a really clean, silvery-grey condition should always be regarded with suspicion, no matter how proud the hardener may be of the cleanliness of his product. A very clean condition is usually an indication that the furnace atmosphere has had a definitely "reducing" action, and this will certainly produce marked surface decarburisation—perhaps of the severity illustrated in Fig. 215. A dull appearance, indicative of a very thin coat of scale, is far safer, though less pleasing to look at. Some hardeners actually dip tools in oil before placing them in a controlled-atmosphere hardening furnace. Although it destroys all chance of really "bright" hardening, this practice has much to commend it, for the likelihood of decarburisation is lessened and the black coating which is formed can easily be removed by light polishing.

"Clean" hardening furnaces, for example those using a protective atmosphere of charcoal gas, tend to be more reliable than "bright" hardening furnaces employing an atmosphere which has to be regulated very carefully. The hardened product will be dull, or even slightly scaled, but the deposit can be removed very readily and the danger of surface decarburisation is small.

Salt bath furnaces, which are used occasionally for small tools, have the merit that really "bright" hardening can be obtained without decarburisation if the bath is suitable *and in proper condition.* Unfortunately, there is a tendency for the composition of salt baths to be left unchecked for long periods; when this happens, quite severe surface decarburisation sometimes takes place, as illustrated in Fig. 215.

Defects attributable to Packing. Notwithstanding the great value of packing tools in charcoal in order to avoid scaling and decarburisation, this procedure has its drawbacks. One obvious disadvantage is the extra furnace space, fuel and time needed to heat a packed tool to the desired temperature, but this failing is fully compensated by the excellence of the surface of the packed tool. Another disadvantage is the tendency of the packing medium to adhere to the surface of the tool after its removal from the container, particularly if a high temperature has been reached. This may lead to the occurrence of soft spots after quenching; fortunately it is usually possible quickly to brush off adhering particles prior to immersion of the tool in the quenching bath.

A more serious defect, for which no remedy seems to have been discovered, is that known appositely as "crazing" or "worming." This defect, as its name implies, takes the form of curious surface markings—like the tracks of moth caterpillars under the bark of elm trees—which are always most pronounced, and also most injurious, on regions which have been polished prior to heating. These markings add very greatly to the cost of the final polishing of a hardened tool, and invariably bring down invectives upon the hardening-shop. Some similarity may be observed with markings occasionally seen on high-speed steel heated to hardening temperature in barium-chloride baths, and also occasionally on case-hardened surfaces carburised in some carburising mixtures. Beyond the fact that this defect seems less prone to occur with high-carbon high-alloy steels than with ones of plain carbon variety, little knowledge of the conditions which produce it seems to exist. The use of best quality well-sieved wood charcoal is not always a guarantee that it will not occur; conversely the use, perhaps in an emergency, of powdery, contaminated charcoal does not always produce it.

General Precautions. Heat-treatment comes very near the end of a sequence of operations which in the case of a large tool made to close dimensional limits may represent a considerable expenditure of time and money; it is, furthermore, an essential operation, for on proper hardening will depend the satisfactory functioning and life of the tool. Again, modern factory procedure often leads to tools being urgently required so that production can be started or continued: destruction during hardening may mean a delay of days or even weeks, with perhaps serious consequences.

This being so, it is curious that the hardening-shop is sometimes far below the standard of other, and often less essential, sections of a factory. Too frequently the equipment is out of date, the lay-out poor and amazingly cramped, for to those unappreciative of its proper significance "hardening" is simply an operation such as boring or turning. Even so, this lack of appreciation is to the metallurgist still incomprehensible when a shed, within a few feet of some mechanical marvel so delicate that a glass partition is built round it, may house obsolete furnaces and improvised equipment from which perspiring hardeners coax results for which they receive blame instead of praise.

On the other hand, a well laid-out shop equipped with modern furnaces and pyrometric apparatus may easily fail to justify expectations because, with tools, there can as yet be no "button-control" hardening. The hardener of the old school, whose eye (although subject to human variation such as psychologists have at infinite pains traced to causes like the day of the week and the football calendar) can judge the *condition* if not the actual temperature of a piece of steel more accurately than any pyrometer, is fast disappearing and will not be replaced. The new school, brought up to rely on pyrometer readings but equipped with some knowledge of theory, still encounter failures and unexpected happenings. Pending the attainment of new discoveries which will render hardening far more automatic than it is at present, the modern hardener must utilise all the help his modern equipment can give him, but he must at all times be keenly observant, possess a retentive memory, and apply his theoretical knowledge intelligently, being ready to modify theories when these are proved incomplete by careful and repeated practical findings. Manipulative skill and the intuitive sense born of long experience are still as necessary as ever.

Automatic control, the term just used, is intended to embrace the so-called automatic devices which depend upon loss of magnetism, upon a hump traced in a continuously recorded chart or sometimes upon the varying rate of expansion of steel in the region of its critical temperature. As an indication of the attainment of this temperature such devices are useful ; their danger lies in the fact that this temperature, or one " safely " above it—to quote the rather naïve instructions often given—is not always the most suitable one from which to quench. Some alloy steels, in particular, need to be heated to within a fairly small range of temperature *which may vary from* 20 *to* 100° *C. above the indicated critical point*, and a definite period of soak, varying with different steels, is often necessary. The wide variety of steels, bulks and sections encountered in a tool-hardening shop effectually precludes the laying down of set rules in the manner possible for the large-scale production of a single article made always from the same steel. Although these automatic devices are of indisputable value, their use does not lessen the necessity for the exercise of skill and knowledge born of experience, perhaps gained without their aid.

No apology is offered for this somewhat philosophical digression. It is likely that this decade may come to be regarded as the end of the swing from the old to newer hardening technique, but attempts to extend to the realm of tool-hardening the mechanised and wholly automatic control which in some instances has been successfully adapted to the production-hardening of large numbers of similar pieces will usually entail disaster.

The Choice of a Tool Material

The nature of certain desired properties, a number of commonly-used tool materials, and the heat-treatment of tools having been examined, it remains to be seen how these various considerations should influence the choice of a material for any given tool. The main object of the preceding portion of this chapter has been to separate and draw attention to the various properties and attributes which ought to be, but are not always, considered when choice is being made. If this object has been achieved, little useful purpose will be served by recapitulating much that has already been said. The requirements of deep drawing and pressing tools vary widely and, having attempted to indicate the factors to be considered, it seems better to leave selection of materials to the judgment of those fully conversant with their own special needs. A few general principles may, however, be suggested to give some order to the many factors which have to be considered. A process of elimination is often the most useful.

First and foremost the size of the tool will usually determine whether cheap material, which is invariably some form of cast iron, or expensive material is to be used. If cast iron, the next item is estimated output and, closely associated with this, severity of draw. For small outputs, or moderate outputs with light draws, an ordinary iron may be adequate; for moderately severe loading, or for large outputs with light draws, an alloy iron or an inoculated iron should be chosen; for heavy duty, heated-treated inoculated iron is unquestionably the best form of cast iron to use. It should be remembered that heat-treated cast iron is just machinable up to about 320 Brinell: when this hardness is adjudged adequate for service requirements, tools can be finished by machining instead of by grinding, a procedure which will cut down their cost of production appreciably.

For small tools in which cost of material does not entirely preclude the use of expensive alloy steels, choice usually lies between plain carbon steels, alloy steels, case-hardened steels, chromium-plated steels, and cast iron: at first sight a field of bewildering size and complexity. Here, in addition to magnitude of output, essential factors are the core strength demanded and the cost of rectification of distortion produced during heat-treatment.

For brass, plain carbon steels are often adequate as regards durability, but a better surface on the drawn product coupled with less danger of fouling is obtainable with nitrided or chromium-plated steel, and the shape of the tool may render the use of an oil-hardening preferable to a water-hardening steel in order to reduce distortion during hardening. On the other hand, tools made in cast iron, particularly the inoculated varieties, often give complete satisfaction with brass, and are considerably cheaper to make than steel tools. Unless severe "ironing" is to be performed, in which case the resistance to crushing may not be adequate, non-heat-treated inoculated iron is often worthy of trial.

For the deep drawing of steel, the special merits of cast iron, especially inoculated cast iron, may render it a first choice when its resistance to crushing is adequate. Greater outputs and a better surface on the drawn product have frequently resulted from the substitution of cast iron for far more expensive alloy steel even in tools used for relatively severe draws.

When greater resistance to crushing is required, attention must be directed to plain carbon and alloy steels, but the very marked advantages offered by chromium-plating and nitriding must be kept in mind for, without these aids, steel tools drawing steel sheet are very prone to score and foul. Apart from their beneficial influence on the surface of the drawn product, nitriding or chromium-plating will usually pay for themselves many times over through prolonging the useful life of the tool.

Cast iron is by far the cheapest, and nitrided alloy steels of high core strength the most expensive, of the more commonly used tool materials ; yet, when steel sheet is to be drawn, it often seems justifiable to choose one or the other of these materials to the exclusion of steels of intermediate cost. On account of distortion during hardening, the relatively cheap plain-carbon steels, chromium-plated, may not offer a particularly useful intermediary ; when " ironing " is performed nitriding seems preferable to chromium-plating, although the unique "slippery " nature of chromium is a great asset when loading is not extremely severe.

In all instances the finish of the sheet purchased and the finish desired on the deep-drawn article must influence the choice of material, as also must the size and shape of the tool considered in relation to its heat-treatment hazards and the likelihood and detriment of distortion during heat-treatment. It must also be borne in mind that the difficulty and cost of producing a really smooth polish on a very hard surface is far greater than it is on a relatively soft surface : an important point in favour of soft materials when these can be used.

The very great saving in cost and time associated with a tool cast closely to shape as compared with that of one machined from the solid hardly needs further emphasis. The product of a good foundry is usually so accurate that no machining is required on many types of tool—*e.g.*, ones used for the production of household utensils and toys—and, when the operation is one more akin to pressing than deep-drawing, proper polishing may be unnecessary. When smoothing is the only operation to be carried out, the time required for production has, in certain instances, actually been reduced from several days to less than an hour for small unhardened tools of fairly simple shape.

The particular and limited application of special materials such as wood, zinc and bronze have already been indicated and will not be elaborated. The field of application of " soft-metal " dies and punches has increased rapidly during recent years owing to the increasing use made of press-tools in the forming of light-alloy sheet for aircraft. For short runs, however, their use for harder metals, particularly if the sheet is of thin gauge, justifies serious consideration in view of their speed of manufacture. Indeed, it often happens that a limited number of parts can be produced easily, quickly and cheaply in a press using soft-metal tools *made in the works* when the cost and the delay of steel tools would be prohibitive, and even cast-iron tools would necessitate calling upon the resources of an outside foundry, with consequent delay and expense.

It must be pointed out that it is often quite satisfactory to use a cheaper material for a punch than for a die. When cast iron is insufficiently resistant to crushing, the cheaper varieties of steel may be used here with advantage. The excellent behaviour, low heat-treatment hazard in large bulk, and relatively low cost of a carburised nickel-chrome steel of about 0·3 per cent. carbon has already been commented upon.

In conclusion a plea is advanced for the more intelligent selection of tool materials. Too often the material is specified by tool designers or draughtsmen who, though efficient in their own vocation, have but scant metallurgical knowledge. In consequence, the material chosen may be unsuitable or, sometimes, needlessly expensive; also, when tools have to be hardened, both the design of the tool and the material chosen may make the hardening hazard needlessly high. Both these errors could be avoided, or at least a helpful compromise made, if the advice of the metallurgist and the practical hardener were sought while the tool was still on the drawing board.

CHAPTER XI

LUBRICANTS

It may be argued that lubrication hardly falls within the province covered by the title of this book. While admitting this, the author offers no apology for devoting a whole chapter to a consideration of this subject because existing literature is very sparse and scrappy and because the metallurgist, and indeed everyone concerned with the practical production of shapes by deep drawing, is continually meeting with problems which resolve themselves very largely, and often entirely, into ones of lubrication. It can be said without hesitation that in many instances much trouble attributed in ignorance to metal, and even to tools, has its origin in inadequate or unsuitable lubrication; more widespread recognition of this fact is needed throughout the industry.

To any student of deep-drawing practice this neglect of the study of lubrication must seem remarkable for at least two reasons. As a lubricant is essential for the successful carrying out of most deep-drawing operations, it must be considered to be a primary factor in the process and, for this reason alone, surely worthy of serious study. Again, the established fact that different lubricants vary very markedly in their efficiency under various pressures and, of greater significance, in contact with different metals, in itself indicates the potential value of more definite knowledge concerning both the theoretical and practical aspects of such observed variations in behaviour. As far as the author is aware, not even a bare list showing the suitability or unsuitability of a number of useful lubricants for use with the more common deep-drawing metals has been published. The selection of a lubricant is, for this reason, at the present time usually governed by the necessarily limited experience of individuals, a state of affairs which in these days can only be described as foolish.

The reason for this neglect appears to be two-fold. Firstly, it is only comparatively recently that the application of scientific knowledge, and even logical study, to the very old-established practice of deep drawing has been seriously attempted. Secondly, the study of lubrication is itself in its infancy, and the application of existing knowledge to the very specialised conditions encountered in the lubrication of drawing tools has as yet hardly been attempted. This application is not facilitated by the fact that the conditions of lubrication to be studied in connection with deep-drawing practice are those known as "boundary" conditions, by which is meant the stage at which the film of lubricant separating two surfaces is of only a few molecules thickness and possesses very special, and fortunately highly useful, properties by virtue of this fact. Except in very light drawing operations, considerations relating to thick-film or viscous-flow lubrication, an aspect about which more precise knowledge is available, do not apply.

In addition to these two primary reasons for the dearth of useful data concerning the lubrication of tools for deep drawing and pressing, there is the very real difficulty of expressing, in a form sufficiently precise to enable it to be fully understood and correlated by other workers, such knowledge as has been obtained through practical experience. Unless some simple, empirical, experimentally-determinable values are devised and standardised, it will remain difficult to express the efficiency of any particular lubricant in such a manner that its value for certain combinations of pressure, temperature and metals can be assessed in useful measure.

The Theory of Lubrication

Before proceeding to a consideration of the many and varied aspects of lubrication in relation to deep-drawing operations, it will be desirable to review very briefly some of the theoretical knowledge and hypotheses which at the present time are accepted as explaining the phenomenon of lubrication in general. This is necessary in order to obtain some idea of the fundamental principles involved, and also to define certain terms which will be used freely in subsequent discussion of the various desirable properties of deep-drawing lubricants.

Friction between two solid surfaces may be of two distinct kinds: *solid* friction, when the surfaces are in actual contact, and *fluid* friction, when they are entirely separated by a viscous film of lubricant. Although the primary object of practical lubrication is to reduce the sum total of friction, it is necessary clearly to distinguish between these two kinds particularly when, as in drawing operations, an initial state of fluid friction usually breaks down to give place to one in which both fluid and solid friction and, very frequently, purely solid friction exist.

Fluid Friction. When perfectly smooth surfaces of sliding solids are completely separated by a relatively thick and wholly viscous film of lubricant, a condition desired but not always completely attained in the bearings of machinery in motion, both the coefficient of friction and the load which the oil film will stand are determined solely by the viscosity of the particular oil at the temperature attained by the oil film which separates the surfaces. The viscosity of an oil varies very markedly with temperature and, what is of importance, in a different manner with different oils.

Under conditions of practical lubrication a viscous film very frequently breaks down, if only locally and momentarily, due to the attainment of very high pressure, and probably temperature, produced by the influence of local peaks in the sliding surfaces which, when judged by molecular dimensions, are enormously rough even in the instance of polished metals. When and where such localised breakdown of the viscous film occurs, considerations appertaining to fluid friction are no longer applicable, and the state of solid friction has to be considered.

Solid Friction. Although perhaps incapable of definite division from the fundamental aspect, solid friction may be conveniently considered under two headings, namely, friction of clean surfaces, and friction of surfaces bearing what is known as an "adsorbed" film of lubricant. By adsorbed film is meant a film only one or at most a few molecules thick in which the molecules are attached to the metal surface by inter-molecular adhesive forces of the same nature, if not always of the same magnitude, as those productive of the highest attainable degree of attachment known as actual chemical combination. These adhesive forces are produced by what are termed electronic bonds or atomic linkages, which are the manifestation of electro-magnetic forces exhibited by the atoms composing matter.

Clean Surfaces. The coefficient of friction between two clean surfaces is dependent upon the inherent nature of the two substances, excluding for the moment the purely mechanical yet very important influence exerted by their degree of smoothness. The slipperiness of solids is termed by Archbutt and Deeley, in their text-book on lubrication and lubricants,[82] "unctuousness." Like the viscosity of a viscous film, this property is influenced by temperature, because temperature affects both the mobility of the molecules forming solid matter and also the activity and strength of the atomic linkages.

Degree of unctuousness is dependent upon the structure and arrangement of the molecules forming any given substance, and also upon the surface energy of the substance. By surface energy is meant the magnitude, activity and arrangement of the atomic linkages at the free surface of the metal; chromium, for example, owes its well-recognised peculiarly "slippery" nature to its high degree of surface energy. This, it is envisaged, produces a curving over and re-entrance of the incompletely satisfied atomic linkages to unite with linkages offered by adjacent atoms in its own surface instead, as in metals of less unctuousness, of remaining relatively free to attach themselves to linkages exhibited by those of a closely adjacent metal surface to produce the phenomenon termed "seizing."

Surfaces bearing an Adsorbed Film. The "slippery" property of a film of lubricant adsorbed upon a solid surface is termed "oiliness." The coefficient of friction between surfaces bearing an adsorbed film of lubricant, a precise measurement at least indicative of degree of oiliness, is dependent partly upon the unctuousness of the solid surfaces and partly upon the oiliness of the adsorbed layer of lubricant which behaves in many ways as if it were a solid.

The slipperiness of an adsorbed layer is thought to be due to, and to be dependent upon, the regularity of the orientation of the molecules forming the layer.. A degree of flexibility of the adsorbed complex oil molecules, comparable in character with that of the pile of velvet, is commonly postulated ; in view of this the supreme importance of regular orientation, together with the strongest possible attachment of the base or tail of the adsorbed molecule to the surface of adsorption, will be clearly evident.

The forces which produce and maintain an adsorbed layer are believed to be divisible into two classes : those termed co-ordinated bonds, exhibited by the unsaturated hydrocarbon molecules of animal and vegetable oils, and those termed polar bonds exhibited by certain atoms in the complex molecules of some of the recently developed extreme-pressure types of lubricant. These latter may be legitimately described as chemically active toward the metal surface upon which they form an adsorbed film, and can be far stronger than those of the co-ordinated variety.

Theoretical Terms Summarised. To summarise, conditions of lubrication between sliding metal surfaces are termed *viscous* when a relatively thick film of lubricant exists and *boundary* when no such film is present. Under boundary conditions the attribute of slipperiness is termed *oiliness ;* oiliness is believed to be due to properties exhibited by an *adsorbed film* formed by the lubricant upon the surface of the metal. An adsorbed film is believed to be formed and attached to a surface by the action of incompletely unsatisfied *atomic linkages* which may be of a relatively weak type, termed *co-ordinated bonds,* or sometimes of a stronger and more active type, termed *polar* bonds, depending upon the particular lubricant used. The oiliness of an adsorbed layer is probably due to the molecules of this layer being oriented in a regular manner and to an extent flexible about their fixed point of attachment, which is believed to be an atom possessed of partially unsatisfied valencies.

Theory Applied to Lubrication in Actual Drawing Operations. Distinction has been drawn between viscous lubrication, in which sliding surfaces are separated by a relatively thick film of lubricant, and boundary lubrication in which surfaces are so tightly pressed together that the liquid film is squeezed out and only a very thin adsorbed film, believed to be no more than a few molecules thick, remains. In the lubrication of machinery, in which viscous lubrication is always aimed at, the viscosity of the lubricant becomes a primary factor in determining the degree of friction between sliding surfaces :

oiliness, the term used to denote good lubricating efficiency after breakdown of the relatively thick viscous film of lubricant has occurred, *i.e.*, under boundary conditions, is of importance only during temporary breakdown. In the lubrication of tools for deep drawing and pressing, conditions are different ; because, except in the instance of light draws on very smooth metal, it seems fairly certain that the conditions of viscous lubrication are always exceeded locally, if not generally, and that boundary conditions are attained and even themselves transcended. For this reason, the viscosity of the lubricant, in so far as its influence on sliding friction is concerned, is usually of small importance : thick greases, possessed of a high measure of oiliness yet having a viscosity which would offer serious friction in machinery bearings, are admissible and sometimes preferable to light-bodied lubricating oils of low viscosity, always provided that they possess adequate spreading power, an attribute which will be discussed later.

It may therefore be postulated that, in general, the lubricating value of a deep-drawing lubricant is dependent upon its ability to form on the surface of the particular metal being drawn an adsorbed film possessed of adequate strength and slipperiness to prevent, as far as may be possible, metal-to-metal contact under the conditions of temperature and pressure produced in any given deep drawing or pressing operation. In addition to this primary property, the adsorbed film should possess as high a degree of slipperiness as possible in order to reduce friction, for friction is productive of heat and heat greatly decreases the load value under which a lubricating film will break down.

Literature. Very little work dealing specifically with the lubrication of tools used in deep drawing or pressing operations appears to have been published.

Archbutt and Deeley [82] in their classic text-book on lubrication and lubricants make no mention of this particular application, a statement that solid graphite is used as a lubricant in the drawing of tungsten filament wire through diamond dies being the only reference to the use of lubricants in metal-working, as distinct from metal-cutting, operations.

With a view to obtaining knowledge whereby the fouling of drawing tools could be minimised, Brownsdon [10] has endeavoured to determine the relative efficiency of various lubricants under controlled, albeit empirical, conditions by measuring the size of the impression made by a revolving steel wheel pressed against the surface of flat plates of various metals kept flooded with the particular lubricant under test. By this method, various lubricants can at least be placed in order of relative merit for the fixed conditions of the test ; and, with this same reservation, the effect of surface finish, speed, load and other factors can be studied.

It is to be hoped that a continuation of this work will yield much useful information; but, although as a noteworthy step toward the attainment of useful data this method is worthy of close attention, Brownsdon's own warning against any general application of such results as he has obtained must be borne in mind. It is obvious that the conditions of this test are in many ways not strictly comparable with those met with at the surfaces of deep-drawing tools. Important points of variation would appear to be the cooling effect produced by a copious supply of lubricant, prolonged as distinct from short and sudden application of load, and other effects arising out of the totally different circumstances under which metal-to-metal contact is brought about in this test and in deep-drawing practice.

Several papers, for example those by Reswick [90] and Montgomery,[91] have summarised the desirable properties of an ideal drawing lubricant and have given somewhat indefinite hints as to the function of various substances in compounded lubricants in producing certain desired, but often incompatible, properties. Useful as papers of this kind are, it is certain that a proper study of boundary lubrication necessitates, in addition to the more obvious curriculum of the oil technician, a thoroughly up-to-date knowledge of atomic physics and the structure of complex molecules.

Some metallurgists have long suspected that very high temperatures are attained at the surface of metal when it is being drawn. The work of Bowden and Ridler [7] confirms beyond doubt this effect, at one time disputed, and is of very great interest from many aspects. These two investigators have shown by mathematical calculation that, theoretically, a very high temperature should be reached at the surfaces of smooth, sliding pieces of metal and have then proved, by very pretty experimental work, that such temperatures are actually attained under conditions which produce no observable increase in temperature in the main body of the two sliding pieces.

By measuring the E.M.F. between the flat bottoms of weighted, stationary rods of various metals and a polished, rotating disc of mild steel, it has been shown that the average temperature at the junction reaches and remains constant at the melting point of metals such as gallium, lead and Wood's metal. For rods of higher melting point, surface temperatures as high as 1,000° C. have been recorded. Definite "fouling" of the surfaces was shown to occur before this could be observed visually.

Kehl and Siebel [92] have used a similar mechanical arrangement to investigate effects other than surface temperature produced at both dry and lubricated sliding metal surfaces. The conclusion of these two investigators is that very important information can be obtained by this simple experimental method; it is to be hoped that their published results may lead to more extensive work on similar lines. This form of apparatus is capable of demonstrating in a simple and convincing manner the value of a smooth polish on the surface of drawing dies to those who doubt the practical value of the best possible finish on tools.

Turning from the theoretical to the essentially practical field, no really comprehensive literature appears to be available. There is no doubt that a large volume of first-hand information concerning the merits of very many lubricants for various metals and operations lies stored in the heads of press operators and supervisors in many countries. Could even a part of this stock be collected, sifted and correlated, the resulting data would be of very great value to practical operators engaged in the industry and to investigators attempting the study and development of the craft of deep drawing and pressing from both the practical and the theoretical aspect.

Here the practical worker, even as the more precise scientific investigator, is seriously hampered by the absence of any standard by which to designate and compare the performance of different lubricants on similar metals even on similar operations, still less on the infinite variety of shapes which can be produced by infinitely variable stages. As every press operator knows, a lubricant of a certain composition which may be recommended in all good faith by an operator from another factory as being of especial merit for a particularly difficult draw on, say, steel, may prove the reverse of beneficial when tried by him on his own particular set of tools, even though these, too, are handling steel. The necessity for comparison on a more scientific basis is evident.

Properties Desired in a Drawing Lubricant

After this brief review of available literature, an attempt may be made to group and discuss certain known facts in order to clarify existing conceptions concerning the nature and function of lubricants for use in deep-drawing operations and to ascertain, if possible, in what directions further study and experiment appear most likely to yield useful results.

In any list enumerating the desirable properties of a drawing lubricant, for example, in the ones given in the reviews mentioned earlier,[90, 91] the descriptive terms employed and the order of priority are, naturally, influenced by the outlook of the compiler. It is certain that no fewer than ten principal properties or attributes, which are at least recognisable from the terminology used in the following list, merit close consideration.

1. **Slipperiness.** The ability of a lubricant to reduce the coefficient of friction between sliding surfaces under stated conditions. The most important property of any, yet one dependent upon the second here enumerated.

2. **Film Strength.** Ability to prevent metal-to-metal contact under

increasing pressure; ability to maintain some or all of such slippery qualities as a lubricant may possess initially. Dependent on both (1) and (3).

3. **Heat Resistance.** Ability to resist both mechanical and physico-chemical breakdown with rise of temperature. The importance of this property of drawing lubricants, in common with the attainment of really high temperatures by metal surfaces during drawing operations, is not always appreciated.

4. **Cost.** Cost price of lubricant can be wholly misleading unless considered in conjunction with other factors which will be discussed later.

5. **Ease of Removal.** A most important property, lack of which may render lubricants of very high efficiency useless in drawing operations.

6. **Spreading Power.** Ability to spread and cover with great ease the surface of an article passing through drawing tools in order that a protective film may be formed ahead of and over the whole of the rapidly moving critical area of high pressure.

7. **Adhesiveness.** The ability of a lubricant to adhere to a metal surface from the time of its application until after the tools have performed their task, whereupon it changes from a beneficial to a deleterious attribute.

8. **Stability.** The ability of a lubricant to maintain its useful properties without detriment arising from chemical change or mechanical separation of its constituents during storage.

9. **Corrosiveness.** The degree of chemical attack exerted by a lubricant upon the tools and work with which it comes in contact.

10. **Psychological and Physical Effect on Users.** This includes such attributes as appearance, smell, touch; also adhesiveness and effect, if any, upon the human skin.

The foregoing list enumerates very briefly the more important of the properties which have to be studied in connection with a lubricant intended for use in deep-drawing processes. These properties will now be discussed in somewhat greater detail.

1. **Slipperiness.** Since the primary function of a lubricant is to reduce the coefficient of friction between two surfaces, it follows that the quality of slipperiness is equalled in importance only by that of film strength, or ability to maintain this slipperiness under severe conditions of temperature and pressure. The very words lubricant and lubrication are derived from the Latin *lubricus*, slippery; a strangely intuitive appreciation by our forefathers of the importance of boundary, as distinct from viscous, lubrication!

The term "slipperiness" has been chosen as a heading for this section because it can be used with greater aptness than "oiliness" to describe the apparent effect produced by viscous lubrication, oiliness, and unctuousness, each of which distinct states have to be considered in deep-drawing operations. Oiliness, the term commonly employed by oil technologists in discussion of lubricants, is, as has already been stated, strictly applicable only to adsorbed films.

It is known that under conditions of viscous lubrication, that is, so long as a relatively thick film of suitable lubricant is maintained between two surfaces, the ease with which they will slide one over the other is immensely greater than when no suitable lubricant is interposed. It is known also that, in the assumed absence of localised areas of film breakdown, the ease of sliding is dependent upon the viscosity of any particular lubricant at the temperature which it attains between two sliding surfaces, and not upon the quality termed oiliness.

This certainly suggests that, under conditions of truly viscous lubrication, the particular quality of slipperiness or oiliness is of no practical value. Universal appreciation of its actual supreme importance in drawing, or for that matter in all, lubricants can only be construed as an implied, if not always a conscious, recognition of the breakdown, if only temporary, of the viscous lubricating film under most normal operating conditions.

Slipperiness may, therefore, be defined as ability to reduce the coefficient of friction between sliding surfaces after the breakdown, or in the entire absence, of a viscous film. This definition applies also to the " filler " type of lubricant, but consideration of this special type would, at the moment, cloud this attempted examination of fundamental qualities.

Oiliness. Practical experience and experiment have shown that, notwithstanding the postulated primary importance of viscosity under conditions of assumed viscous lubrication, certain oils possessing the same viscosity will exhibit markedly different lubricating values under similar conditions of service or test. For example, long before the advancement of any attempted scientific explanation of the fact, it was known that when a machine bearing lubricated with a thin mineral oil ran hot the addition of a proportion of castor oil sufficient to increase very considerably the viscosity of the compounded lubricant would make the bearing run cool notwithstanding the *increase* in fluid friction. It was shown later, by precise experiment, that such an addition actually reduced the co-efficient of friction in spite of the attendant increase in viscosity.

Clearly, some property other than viscosity was of primary importance in determining the value of a lubricant. To this property the term " oiliness " was given and, notwithstanding its indefinite nature, machines have been devised which, by measuring the coefficient of friction between lubricated surfaces, will indicate at least a relative degree of oiliness for various lubricants.

Archbutt and Deeley [82] define oiliness, or what in this review is termed slipperiness, of liquids, greases or solid bodies as :

$$\text{Oiliness} = 100 - (\mu \times 100)$$

in which equation μ represents the static coefficient of friction between the lubricant and the surface under consideration. During comparatively recent years the real nature of oiliness, as outlined earlier in this review, has been established as being due to the formation and peculiar properties of an adsorbed film which is formed by oily lubricants on surfaces upon which they are placed.

It is known that the unctuousness or, expressed more precisely, the coefficient of friction exhibited by the contacting surfaces of clean solids is different for each element, and it is thought that the change is a periodic one with increasing atomic weight. The degree of slipperiness exhibited by a surface on which is present an adsorbed film has a value which is dependent partly on the chemical nature of the solid surface and partly upon the chemical nature of the lubricant ; the effect of these two is believed to be cumulative.

This explains why a lubricant which possesses valuable properties when used with one substance may be practically useless when used with another. For example, water exhibits a useful measure of slipperiness when used as a lubricant for glass upon ebonite but not when it is used for glass upon wood, the inference being that the orientation of the molecules which constitute the adsorbed layer of water on ebonite differs markedly from that of the molecules which constitute the adsorbed layer on wood.

Similarly it will be recalled that aluminium cannot be drawn successfully with some of the lubricants commonly employed for the drawing of steel, and that brass and cupro-nickel alloys behave differently toward certain commonly used lubricants.

Measurement of Slipperiness. The precise measurement of the property here termed slipperiness is difficult. Many laboratory machines have been devised and marketed for measuring the coefficient of friction between sliding surfaces under conditions which are controlled as closely as may be possible ; the worth of such machines for determining the slipperiness of lubricants intended for use on deep-drawing tools is doubtful owing to the impossibility of reproducing the very sudden application of pressure and rise in temperature which must occur in actual drawing practice.

It is of interest to observe that a mechanical testing device termed an "adheroscope," invented to measure the adhesive power of a lubricant,[83] seems to give a clear indication of the presence or absence of a truly adsorbed film of lubricant on a metal surface. As a marked degree of adsorption is considered to be essential for the exhibition of oiliness, this test may be of some value in the assessment of the latter property, although actual slipperiness is not indicated by it as by machines which measure the coefficient of friction between lubricated surfaces. The adheroscope is described in a subsequent section in which the property of adhesiveness is considered.

Attainment of Slipperiness. Recognition of the existence of the property termed oiliness has come mainly from the very marked variation in this valuable property which practical experience has shown to be exhibited by different lubricants. For instance, it has long been established that, in comparison with animal and vegetable base oils, straight mineral oils possess a poor measure of oiliness; and it has been found as a result of practical experience in the lubrication of machinery—notably of internal combustion engines—as well as of drawing tools that castor oil is particularly useful in producing a high degree of slipperiness on most metals. It has been found that the addition to a mineral oil of even a very small proportion of animal or vegetable oil increases the oiliness of the resulting " compounded " oil very markedly; such additions are widely used to produce from relatively cheap mineral oils lubricants possessing some of the advantages of the more expensive, and often high-viscosity, animal and vegetable products.

It is now known that the essential practical difference between mineral and animal or vegetable oils lies in the ability of the two latter to form an adsorbed film on a contacting metal surface. Mineral oils are termed by chemists " saturated " hydrocarbons; this implies that their molecules have no incompletely satisfied atomic linkages which can be utilised for the attachment of these molecules to those forming a metal surface. Animal and vegetable oils on the other hand possess, in a degree which varies with different oils, incompletely satisfied atomic linkages; these, by uniting with the contacting surface, attach the oil molecules to it to form an adsorbed layer.

In the rather special lubricants which have been developed specifically for deep-drawing operations, some distinction needs to be made between the property of true " oiliness " and the wider attribute here termed " slipperiness." Oiliness is attained by the addition to the lubricant of a suitable oily substance, either free or in a combined state; slipperiness is attained by the addition of solids ranging from graphite, a substance held by some to possess truly oily characteristics, to substances such as chalk, which, although not oily in the accepted sense of the word, yet produce a measure of apparent " slipperiness " in drawing lubricants containing them.

(*a*) Substances Productive of Oiliness. Slipperiness engendered by true oiliness is usually attained by the incorporation in a drawing lubricant of oils or fats such as castor oil, palm oil, tallow or lard either free or in a combined state. Mineral oils, unless treated with some activating element such as chlorine or sulphur, are not oily in the true meaning of the term and are used mainly as carriers or diluents.

Mention has been made of the fact that the slipperiness, or ability to reduce friction, of an adsorbed film is known to be dependent in part upon the orientation of the molecules of lubricant which form it. It is believed that the unusually good lubricating properties of chlorinated oils are attributable to the regularity of orientation exhibited by the molecules of the adsorbed films which they form upon many metals. As it is the chlorine atom which attaches itself, and hence its parent oil molecule, to the metal surface, and as the chlorine atoms will occupy the same relative positions in each complex oil molecule, it follows that a higher degree of regularity than that exhibited by unsaturated hydro-carbon molecules *not* possessed of a specially active atom may be expected to exist in the resulting adsorbed layer of such molecules. It is believed that a layer such as this exhibits a distinct degree of flexibility, which, it will be recalled, has been likened to that of the pile on velvet; visualisation of this effect enables the value of perfect orientation of molecules, coupled with strongly adherent bases or fixed points of attachment, to be appreciated.

(*b*) NON-OILY SUBSTANCES PRODUCTIVE OF SLIPPERINESS. Solid additions, which produce apparent slipperiness by virtue not of inherent oily characteristics but by purely solid or mechanical prevention of metal-to-metal contact, will be considered in the section which deals with film strength; the following substances are used: soapstone, chalk, borax, fireclay, potter's clay, rosin, and mica. Lead oxide, although very efficient under severe conditions, is rarely used on account of certain inherent disadvantages which will be discussed later. Graphite and zinc oxide, although solid additions, possess particularly beneficial properties which place them in a class of their own.

(*c*) SOLIDS POSSESSING SPECIAL PROPERTIES. Between these two distinct classes of oily and non-oily ingredients lies a third class of solids which, although offering definite solid or mechanical separation between sliding surfaces, possess, in addition, oily characteristics by reason of the fact that they form an adsorbed layer upon metal surfaces. Zinc oxide, for instance, gives definite solid or mechanical separation between sliding surfaces; yet it is also chemically active toward many metals, upon the surfaces of which it forms a strongly adherent film.

Graphite must be placed in a class of its own by reason of its apparent, and possibly true, oily properties coupled with its crystallographic planes of "easy slip"; mica also possesses gliding planes, but no natural oiliness or chemical activity. Planes of easy slip are exhibited by certain substances, *e.g.*, mica, graphite and ice, which crystallise in a manner such that on parallel planes bearing a certain orientation to the crystallographic axis portions or blocks of crystals can slide one over another with relative ease yet, on planes normal to the ones first mentioned, resistance to such slip is relatively very great. The practical effect of this is well illustrated by mica which, as is well known, can very easily be split on certain planes into thin flat plates by the application of a force many hundred times less than that required to rupture a section of similar area on a plane normal to that of easy split. This peculiar property of extremely easy slip upon certain crystallographic planes in the solid suspension particles of a drawing lubricant will produce apparent slipperiness, while the associated high strength on other crystallographic planes will produce high film strength, a property discussed later.

Graphite possesses another very marked and highly valuable property, namely, great unctuousness, or "solid slipperiness," in combination with most metals. Whether or not a truly oily or adsorbed film of graphite molecules is formed on metals as with oily liquids does not appear to be known definitely. In short, graphite is unique in its ability to act as a lubricant for metal under severe conditions of very high temperature and pressure, and it is unfortunate that the difficulty associated with its removal from drawn work often detracts seriously from its usefulness under practical conditions in the press-shop.

Practical Value of Slipperiness. The practical value of a high degree of slipperiness in a deep-drawing lubricant is well recognised, although difficult to define in precise terms. Clearly, any attribute which reduces the friction between the work and the tools is of very great benefit, not so much because it decreases the power, as such, which is required to perform a given press operation, but because it enables the metal to slide over and be shaped by the tools with a minimum amount of energy, thus reducing the tendency toward the attainment of very high local pressures leading to high temperatures and complete breakdown of the lubricating film productive of scoring of work and fouling of tools. Apart from the prevention of complete breakdown of lubricant, it does seem that a better surface is produced on drawn work when a high degree of oiliness and slipperiness is manifested by the particular lubricant used. Lack of oiliness can of itself aggravate to a serious degree any tendency toward local thinning in the walls of thin articles due to the increased friction set up on certain areas; in severe draws on heavy gauge sheet the slipperiness of the "filler" type of lubricant rather than the oiliness of a simple oil usually becomes the important factor.

To summarise. Assuming the breakdown or absence of a viscous film, slippery properties are given to a drawing lubricant by the incorporation in it of substances which produce an adsorbed layer of a desirable nature upon the metal being drawn or which, being solids, offer solid separation associated with a certain degree of unctuousness.

The property of slipperiness is of primary importance, yet of equal importance is the ability to maintain this property under working conditions. This ability will now be considered under the heading of "film strength."

2. Film Strength. In the brief list of desirable properties already given, film strength has been defined as ability to prevent metal-to-metal contact under severe conditions of pressure and, probably, temperature. As film strength is sometimes interpreted as applying only to a liquid, it must be emphasised that, as applied to deep-drawing lubricants, the term may signify the resistance to breakdown of an adsorbed layer, which usually behaves more like a solid than a liquid, or even the strength of a film containing solid particles suspended in a viscous medium. Interpreted in this sense, film strength is not a precise, easily definable and determinable property as is the surface tension of a liquid, with which it is sometimes confused.

The film strength of any particular lubricant is determined by the intrinsic nature of the latter; but it is important to remember that this value is influenced by the nature of the metal upon which it rests, and, very markedly, by temperature, an aspect which is dealt with in a subsequent section.

When no suspended solid matter or filler is present in a lubricant, its film strength or breakdown point is determined fundamentally by the magnitude of the inter-molecular forces functioning, firstly, between its own molecules and, secondly, between its own molecules and those of the metal surface upon which it rests. The marked difference which is observable in the behaviour of any particular lubricant when used on different metals is due to the different degree of molecular affinity possessed by it for these several metals. It is this same affinity, the manifestation of exactly the same fundamental forces of atomic attraction and cohesion, which, when sufficiently strong, produces not merely adsorption but the actual union termed chemical combination.

Langmuir, in his researches on the nature of surface tension and thin films,[94] formed the opinion in 1917 that the so-called physical forces or "surface energy" responsible for the formation and maintenance of adsorbed films were identically the same as those productive of chemical union. The very great increase which has been made since that time in our knowledge of atomic physics continues to support this theory; indeed, certain of the recently developed extreme-pressure lubricants have provided unexpected confirmation in that appreciable chemical attack, in the form of a clearly visible surface etch comparable with that resulting from attack by acid, is produced on metallic surfaces by certain lubricants known to form upon them a specially strong adsorbed layer. It becomes easier to understand the extraordinary power of resistance to rupture and detachment shown by the adsorbed films of certain lubricants when it is appreciated that they are attached to their parent surface by forces of a similar nature, and sometimes comparable magnitude, to those which hold matter in chemical combination.

In deep-drawing operations boundary lubrication, dependent upon the formation and maintenance of an adsorbed layer, is probably of far greater importance than viscous lubrication, the kind which usually obtains in moving machinery. This explains why the all-too-freely used term "film strength" is dependent not only upon the intrinsic properties of the lubricant itself, and of the effect upon them of temperature, but also upon the nature of the metal surface upon which it is placed and with which it reacts "chemically" to some varying degree determined by the nature of the available and functioning atomic linkages, *i.e.*, whether co-ordinated or polar.

When the lubricant contains solid particles in suspension, the nature and meaning of the term "film strength" becomes even less definite than when a homogeneous film has to be considered. Clearly, the strength of the viscous base will be artificially raised, owing to the reasons discussed in the preceding section dealing with the property of slipperiness. In addition, bearing in mind that for the purpose of this review the term film strength implies ability to prevent metal-to-metal contact, it is evident that the compressive strength of the solid particles, and also the degree of fineness to which they can be reduced by mechanical means, will exert an influence upon the apparent film strength of the lubricant as a whole. Furthermore, the shape of the drawing tools and also the effect of temperature upon the viscosity of the base will influence the readiness with which the lubricant can be squeezed out and, hence, its apparent film strength.

These considerations show that the property commonly known as film strength cannot easily be defined in the precise manner which its frequent use during discussions on drawing lubricants may seem to suggest; in many instances "breakdown point" would be a more accurate and descriptive term. Whatever nomenclature is used, the fundamental property implied is the ability of a lubricant to maintain its slippery properties, no matter how these are produced, under conditions of extreme pressure and, quite often, high temperature.

Attainment of Film Strength. It is convenient to divide lubricants into two categories, namely, those known to produce a strong adsorbed film, in which instance the property of film strength is due to the magnitude of the inter-molecular affinity exhibited, and those which, being solids, behave in the more complicated manner already indicated. Justification for such division is provided by practical experience, which shows that the substances usually added to produce a high film strength fall naturally into these two distinct classes. In the first class can be grouped many fats, such as tallow and lard, and oils such as palm oil and also the newly-developed chlorinated oils; in the second fall substances such as chalk, fireclay, borax, rosin, mica and graphite.

OILY SUBSTANCES PRODUCTIVE OF HIGH FILM STRENGTH. In the first, or oily, type of lubricant, an oil or fat possessing a high degree of oiliness may be added directly to the base, either as a simple miscible addition or as an emulsion depending upon its reaction to the base; as, for example, when a small proportion of vegetable oil is added to a mineral oil. Very often the desired addition substance is introduced in a combined state to facilitate its admixture and, of importance, its subsequent removal from metal surfaces. In this class there may be instanced tallow, an animal fat of proved merit, which is usually added in the combined state with calcium, sodium, potassium, lead or aluminium soap. Lard, palm oil and many other fats behave in a manner similar to that of tallow. It is established that, in general, oiliness is engendered by fatty acids and triglycerides; but glycerine is known to destroy this attribute. Oleic acid is particularly useful owing to the slipperiness and strength of the adsorbed layer which it forms on many metals, as also are the chlorinated and sulphurised lubricants to which increasing attention is being paid.

The specially valuable nature of chlorinated oils seems to be due, apart from the regular molecular orientation already mentioned, to the very strongly adherent nature of the molecules forming the adsorbed film. This adhesion is usually attributed to some of the atomic linkages of the chlorine atoms in the oil molecules being markedly unsatisfied, and therefore free to unite with linkages on the metal surface. Sulphurised lubricants probably act in a similar but somewhat less active manner. The exact nature of the atomic linkage in these types of lubricant is discussed more fully in section 9, which deals with the corrosion of metals by drawing lubricants.

Montgomery [91] instances certain organic sulphates as being of great value in producing a high film strength, meaning a highly adhesive adsorbed layer, but states that the degree of chemical attack may be sufficient to spoil the surface of tools and drawn work. In such instances the affinity between the molecules of the lubricant and metal is so great that chemical combination may occur upon normal contact and not, as is thought to be the case with chlorinated and sulphurised lubricants, only when the activity of the chlorine atom is increased by rise in temperature and perhaps liberation following the breakdown of the lubricant molecule.

NON-OILY SUBSTANCES PRODUCTIVE OF HIGH FILM STRENGTH. To the second, or solid-addition, type of lubricant a proportion of very finely divided solid is added to produce a measure of slipperiness. The behaviour of such "fillers," as they are called, is not entirely clear, although recent confirmation of the attainment of very high temperatures by sliding metal surfaces [7] suggests that a primary function is to prevent metal-to-metal contact when both the viscous film and the adsorbed film of the main " carrier " lubricant have broken down. This suggestion is strengthened by the proved merit of such heat-resisting substances as mica and graphite, although the latter is known to possess other peculiar and valuable properties. Chalk, fireclay, potter's clay, soapstone, borax and even flour, to mention a few commonly used fillers, are definitely *not* oily. These substances probably owe their usefulness to the fact that, by comparison with their viscous carrying medium, they are very difficult completely to squeeze out even under very high pressure, and remain to provide a means of definite mechanical separation between the work and the die. Under these conditions, although the coefficient of friction will be higher than when a continuous, oily, adsorbed film exists, definite seizing and " fouling " of the two metal surfaces is prevented and the ease of sliding remains, for this reason, relatively great. Another probable function of fillers is the prevention, or at least hindrance, by them of the complete squeezing out of the real or truly oily lubricant. This is effected by purely mechanical entrapment of the lubricant between the particles of the suspension solid, in addition to the more obvious hindrance attributable to the increased viscosity of the lubricant as a mixture. Reswick [90] draws attention to the fact that soapstone and chalk may be added to a drawing lubricant in combined form with other ingredients.

Sulphur is sometimes added to drawing lubricants. When this element exists as a finely divided solid held in suspension, and not in a combined form, it falls within the category of additions considered in this section. The precise action of suspended sulphur does not appear to be known. It is certain that part of its usefulness lies in the ability of its particles to prevent metal-to-metal contact as do those of the other solid additions already mentioned, but there is reason to suppose that this mechanical action is supplemented by some chemical action of a kind not yet understood fully. In spite of its value as a lubricant, sulphur is often objectionable, and it is best not to bring it into contact with many non-ferrous metals, particularly when bright-annealing is to be carried out.

Two highly beneficial solid additions commonly made to lubricants intended for use during severe drawing operations on steel and stainless steel, *i.e.*, when the most severe practical conditions have to be contended with, are mica and graphite. The peculiar properties of these two substances—for example, their great resistance to heat and their inherent slipperiness attributable to crystallographic planes of easy slip—have already been commented upon ; as a means of engendering a high film strength their addition to very many drawing lubricants is of great value.

The property of slipperiness in drawing lubricants and also the property of film strength, meaning ability to maintain a full or partial measure of slipperiness under operating conditions, have now been examined. Both these properties are strongly influenced by temperature, an aspect which will be considered next.

3. Resistance to Temperature. The behaviour of different lubricants as their temperature is altered varies immensely, and the value of any lubricant at one temperature gives no indication whatever of its value at an appreciably different temperature. The practical effect of this is, of course, that a lubricant which, at a certain temperature, may be of equal efficiency to that of another at the same temperature, may break down completely at a temperature far below that at which the other ceases to lubricate satisfactorily.

Mention has already been made of the probable attainment of very high temperatures by the surface of metal during its passage through drawing tools. By sliding constantan on mild steel, Bowden and Ridler [7] obtained surface temperatures of the following order under similar conditions of speed and loading :—

Lubricant.	*Surface Temperature.*
Oleic acid	320° C.
Castrol XL oil	610° C.
None	1,000° C.

As these values are average ones it is certain that, locally, very high temperatures indeed are attained, and it becomes clear why it is so important that a lubricant intended for use in severe drawing operations should be able to maintain at least a proportion of its slippery properties at as high a temperature as possible.

Assuming that the viscous stage of lubrication has been exceeded, the heat-resisting qualities of a lubricant are determined by two principal factors, namely, the nature and properties of the adsorbed film and the nature and properties of any solid filler which may be present in the lubricant.

Considering the first, it is natural to expect marked differences in the behaviour of the adsorbed films produced by different lubricants by reason of the difference in both the strength, and the rate of change of strength with temperature, of the forces which hold the adsorbed molecules to the parent surface. Nevertheless, it should be borne in mind that the actual temperature which is attained will be influenced to a considerable degree by the film strength and slipperiness of the particular lubricant employed. In other words if, due to the use of a very slippery lubricant of high film strength, the coefficient of friction between two sliding surfaces is low, there will be less heat generated and hence less tendency for the lubricating film to break down than if, due to the use of a less efficient lubricant, the coefficient of friction were higher. The apparent resistance of a lubricant to temperature is, for this reason, closely bound up with the two other essential properties of slipperiness and film strength. This is indicated by the results of Bowden and Ridler already cited.

When a solid filler is added to a drawing lubricant, the practical or apparent resistance of the lubricant to breakdown with rise of temperature may increase markedly. The action of fillers has already been considered; in this section attention need be drawn only to the markedly beneficial influence, in severe deep-drawing operations, of additions of mica and talc—both substances of remarkable heat-resisting power—and, in a lesser degree, chalk, fireclay and other solid additions. Graphite is even more beneficial but it will be recalled that, in addition to its recognised heat-resisting powers, this substance possesses peculiar slippery qualities which are not exhibited by the other fillers just mentioned.

To summarise, it is to be expected from theoretical considerations that a high temperature will be attained by metal surfaces during deep-drawing operations; the proved value of additions of recognised heat-resisting substances in a fine state of division confirms theoretical expectations, and indicates that one of the essential qualities of a lubricant for severe drawing operations is, without doubt, a very high degree of heat-resistance. Because the temperature attained is influenced by the slipperiness and film strength of the lubricant, these three essential properties—namely slipperiness, film strength and heat-resistance—are closely associated, and to some extent interdependent; a fact which will have been apparent throughout the sections in which these three properties have been considered. Although under extreme conditions solid heat-resisting additions to a drawing lubricant appear to be necessary, breakdown of an adsorbed film through rise of temperature can be prevented by increasing the slipperiness of this film and, hence, reducing the temperature which it will attain.

4. Cost. Although it is desirable, and sometimes essential, that a lubricant intended for use in deep drawing and pressing processes shall be cheap, it is necessary to study most carefully the purchase cost of a lubricant in relation to the influence of this factor upon the total cost of the various press operations used in the formation of a given article. Leaving aside instances in which, either by design or unexpected necessity, a very special lubricant—for example, white lead and castor oil—*has* to be used in order to allow a certain operation to be performed at all, it may be found that the use of a relatively expensive lubricant will enable a given article to be produced with fewer press operations than are necessary when a somewhat cheaper but less efficient lubricant is employed. An increase in the life of tools, and the attainment of a better surface on drawn work with consequent reduction in polishing costs, constitute other advantages which although real are difficult to assess.

In addition to effects such as the ones just mentioned, which are produced by the action of the lubricant, certain others relating to its handling require to be borne in mind. Among these may be instanced necessity for thorough mixing before use; ease of application, *i.e.*, whether or not careful spreading over the whole surface is needed; also, a matter discussed later in the section dealing with spreading power, the amount required on each blank or article. Last, but by no means least, the cost of removing the lubricant from drawn work must always be taken into consideration.

It is perhaps necessary to add a warning that the price of a proprietary lubricant may not always be a reliable guide to its true merit. Although the incorporation of substances such as finely divided graphite, sulphur or the addition of chlorinated oils must bring about some increase in cost, users should be on their guard against paying an exorbitant price which the composition of a lubricant clearly fails to justify. The chemical analysis of oils and greases is not simple, and many users of deep-drawing lubricants do not themselves possess the facilities for analysis or even determinations of physical values; these users may find that the cost of a fairly full examination by a reliable laboratory accustomed to dealing with oils will be amply justified.

These few observations will show that a true assessment of the relative merits of lubricants of different first cost is by no means a simple matter. Indeed, it would be hard to find a better or more illuminating exercise for the student of factory costing.

5. Ease of Removal. Whether it is unnecessary, desirable or essential carefully to remove the lubricant used in press operations will depend primarily upon the nature of the lubricant used and, to a lesser extent, upon the succeeding operation, *i.e.*, whether this is another draw, an anneal, a polish or a painting operation.

A lubricant which actually attacks the drawn metal must, obviously, be removed before serious damage is done; but, apart from such straightforward instances, it is certain that in future much closer attention will have to be given to this matter of lubricant removal. Even with the older types of annealing plant and relatively non-corrosive drawing lubricants trouble has been, and still is, caused through inadequate removal of lubricant. This is particularly so when, as is quite usual if thoroughly well organised continuous "line" processing is not in use, bins of partly- or finish-drawn articles are allowed to stand for days and even weeks with lubricant upon them. That this should be permitted may seem strange to those unaccustomed to factory procedure; those familiar with the conditions which are to be found in many press-shops will appreciate how hard it may be to ensure that work is not allowed to stand for considerable periods between draws.

Causes of difficulty in Removal. It would appear that the difficulty of removal of a lubricant may be attributable to one or more of three causes: firstly, to non-miscibility or non-emulsifiability of the lubricant with the washing medium, as when one containing a high proportion of uncombined mineral oil is washed off with water; secondly, to mechanical entrapment of the lubricant in the pores of the metal, as with those containing graphite and other solids in a fine state of division, and, thirdly, to molecular affinity as shown by those lubricants which form a strong adsorbed layer.

It is clear that ease of removal of a drawing lubricant can be engendered only by omitting chemically-tenacious substances which may be essential for the production of the desired properties, by adding these substances when possible in such a form that they can be removed by solvents or emulsifying carriers, or by choosing substances for which a cheap and effective solvent can be readily obtained and used. The practical adoption of this apparently simple scheme is very difficult, and the problem of removal of many really efficient lubricants is a very real one.

Factors controlling Ease of Removal. If free from certain of the commonly used suspended solids and from too large a proportion of mineral oil, light lubricants can usually be removed to a satisfactory extent by washing work in hot, weakly alkaline solutions such as sodium carbonate or sodium meta-silicate. The latter possesses several advantages over caustic soda solution, one being that it is itself removed more easily by washing in water.

One very good reason for the incorporation in the form of soaps of such fatty acids as may be necessary to produce the desired degree of oiliness in a compounded lubricant, instead of admixture in the free state, is that in the combined form they are more easily removed by water or weak alkali washes. If the mineral oil is not combined with a soda-base (as distinct from a lime-base) soap or other emulsifying substance, or if it is present in too high a proportion, these simple washing mediums may not be adequate, and solvents such as naphtha or benzene must be used. The use of these more expensive mediu ms can sometimes be avoided if baths or swills of weak alkali solution are replaced by hot, high-pressure sprays of the same solutions.

It is, unfortunately, with lubricants possessing the highest degree of slipperiness and film strength that the problem of removal often becomes acute. This is perfectly natural because, as has already been shown, the practical value of an adsorbed film of lubricant is attributable in a large measure to the strength of the atomic linkages which hold its molecules to the parent surface, and these linkages have to be broken when the film is removed either by mechanical action or by the action of a chemical solvent. It may be remarked that lubricants containing lead oleate, a highly beneficial constituent, which are not normally removable by a hot water wash can be so removed if the metal surface is hand-wiped during the washing process.

Of the solid-suspension or filler type of lubricant those containing soapstone or chalk are easily washed off, but mica and graphite are very difficult indeed to dislodge, the latter being especially hard to remove from the pores of the metal in which it tends to remain to cause trouble if and when the finish-drawn articles have to be plated. Lead and zinc oxide, two other useful suspension additions, are very hard to remove.

In view of the popularity of degreasing apparatus employing ethylene trichloride or similar liquids, it may be well to stress the fact that the type of appliance in which only vapour reaches the work will not remove adherent solids or, without prolonged exposure, thick greases. Appliances in which articles are actually swilled or sprayed with the cleansing liquid are more efficient in this respect; indeed, the value of high-pressure sprays for the removal of solid or viscous lubricants no matter what cleansing medium is employed cannot be stressed too highly. The usefulness of hand-wiping in certain instances has already been commented upon.

Possible Deleterious Effect of Non-removal. Apart from any action which the lubricant itself may have on the particular metal upon which it is allowed to remain, there is the additional and very serious danger that any residual film or drops may collect dirt, soot, or other sulphur-bearing matter, and even gases and vapours in works' atmospheres. The contaminatory substances, which may or may not enter into solution in the lubricant, often produce severe local staining or actual corrosive attack even when the lubricant itself is without appreciable action upon the metal in question. With steel there is always the added danger of rusting when water is present in the lubricant itself or when a water-free lubricant does not form a completely protective film over the whole surface of drawn articles. Another well-proven advantage in the prompt cleaning of drawn work is that the presence of some lubricants greatly aggravates the tendency for severely drawn articles to crack before a stress-relieving anneal can be given to them.

With the advent of controlled-atmosphere furnaces capable of producing really " clean-annealed " work, it becomes virtually essential that most drawing lubricants be removed prior to annealing if the full capabilities of the furnace are to be utilised. If the lubricant contains an oil which oxidises on exposure to air, articles which can be cleaned fairly easily immediately after drawing may present increased difficulty if they are allowed to stand about for several days before cleaning is attempted. Pure mineral oils have no tendency to oxidise on exposure to air ; vegetable oils, on the other hand, possess this tendency in varying degrees. This factor should be borne in mind when a lubricant is being chosen, as should the fact that most mineral oils, with the possible exception of the sulphurised or chlorine-treated varieties, usually contain a proportion of added vegetable oil to increase their "oiliness."

It will thus be seen that the ease with which a lubricant can be removed from drawn work constitutes a very important property and one which, for the reason just stated and also because of the advent of the extreme-pressure type of lubricant with its inherent chemically-tenacious nature, will become of increasing importance.

6. Spreading Power. It is desirable that a lubricant shall be capable of spreading with great ease over the whole surface of an article passing through drawing tools in order that a protective film may be built up ahead of the actual area of high pressure. The property of spreading power is dependent upon the combined influence of others such as viscosity, surface tension and actual chemical affinity, all of which depend fundamentally upon the nature and strength of the inter-molecular forces functioning between the molecules of the lubricant, its adsorbed film on the metal surface, and the metal itself.

It is frequently assumed that a liquid possessed of a surface tension lower than that of any particular solid will spread over, or "wet," a clean surface of that solid. This assumption, although apparently true if judged by many specific instances, is not correct. The spreading of a liquid upon a surface is influenced to a profound degree by the action of active atomic linkages of the co-ordinated or secondary valency kind : whether or not a liquid will spread over a certain surface depends, therefore, not only upon its viscosity and the relative surface tensions of the two substances, but also upon the degree of chemical affinity existent between the two.

Attainment. The attainment of good spreading power in a drawing lubricant is, it will now be clear, facilitated by a low viscosity and by a suitable degree of secondary-nature chemical affinity between any particular lubricant and metal surface. The first attribute is attainable by suitable dilution of essential, but perhaps high-viscosity, primary ingredients ; the second can be engendered only by the incorporation in the lubricant of substances which exhibit the desired active atomic linkages. Fortunately, substances which produce an adsorbed film often wet fairly well by virtue of the fact that both phenomena are produced by definite inter-molecular affinity. Tallow, lard, palm oil and other fixed fats, all productive of a useful measure of slipperiness, assist a lubricant to spread well. Lubricants such as chlorinated oils, in which the degree of inter-molecular affinity is probably more nearly polar than co-ordinated atomic linkage, spread readily if the viscosity permits. With lubricants containing colloidal graphite the fact must always be borne in mind that a trace of free acid, such as is frequently present in compounded oils, is liable to cause agglomeration of the graphite with consequent diminution in mobility of this particular ingredient.

Lubricants containing an appreciable proportion of solid fillers do not spread nearly so readily as do the more fluid varieties unless the viscosity and wetting power of their suspension medium is relatively low, and the state of division of the suspended solid very fine.

Practical Value of Spreading Power. The practical effect of the property here termed spreading power as it interests the student of deep drawing is that, expressed as simply as possible, when a drop of lubricant is applied to a metal surface, this drop—or possibly certain constituents in it—may " ball up " and refuse to spread, may flatten out and spread in a relatively thick and frequently visible film to a certain size, or may spread in an invisible film of an adsorbed nature only a very few molecules thick. Obviously, the first or " balling up " method of behaviour is not conducive to the attainment by the blank or article of a uniform film of lubricant even when the shape of the die assists the spreading and intimate contact of lubricant adhering to the surface of the work. The second and third methods of behaviour will vary in accordance with the characteristics of the lubricant and its behaviour toward the particular metal with which it happens to be in contact. Considered again from the wholly practical aspect, if the metal, as it enters the region of high pressure in the tools, bears a continuous film of lubricant upon the whole of its surface about that region, the *introduction* of lubricant can probably be considered to be satisfactory. Its subsequent behaviour is, of course, an altogether different and unrelated matter.

It may be supposed that, immediately prior to the entry of the metal surface into this critical region of high pressure, the adhering film of lubricant need not necessarily be of more than adsorbed thickness. Nevertheless, since the coefficient of friction under conditions of viscous lubrication is always, and often markedly, less than that under boundary conditions, it seems desirable that sufficient lubricant be present to form a continuous film of appreciable thickness over the whole of the area of the work as it enters the initial low-pressure region of the tools. By reducing the friction in this region, both work and lubricant will become less heated, a matter of primary importance because the efficiency of a viscous lubricant decreases rapidly with increasing temperature. Furthermore, the presence of a viscous, in addition to an adsorbed, film of lubricant on the surface of work will result in the formation of a reservoir adjacent to the critical region of high pressure where viscous lubrication ceases to exist ; this reservoir will facilitate the formation of a continuous, adsorbed film upon the surface of the entrant metal. Also, if the shape of the tools is suitable, viscous lubrication may be continued for a distance further than might be imagined owing to the drawing-in of lubricant between the work and the die by wedge action, a well-recognised phenomenon to which plain bearings in most machines and engines owe their efficiency.

In short, although within the critical region of the tools boundary conditions of lubrication will probably obtain, it seems logical to utilise the advantages of viscous lubrication right up to the furthest possible point. When a solid-suspension or filler type of lubricant is employed true boundary conditions may not be attained, and the provision of an adequate supply of lubricant becomes still more desirable to enable a continuous, separative film of appreciable thickness to be drawn into the region of high pressure.

As no large flow of lubricant can take place between the die and the work during the actual operation of drawing, no appreciable cooling of the contacting surfaces can be obtained by the provision of a copious supply of lubricant in the manner normally employed with cutting lubricants.

Healing Power. Lastly, attention must be drawn to what may be described as "healing power," which is merely another aspect of spreading power. When local rupture of the lubricant film separating sliding surfaces takes place, whether or not and with what speed the film will be re-established when the contact pressure is reduced will depend upon the mobility and spreading power of the lubricant. It needs little thought to show that this particular aspect of spreading power is of great importance and, furthermore, that it is associated closely with speed of drawing, a factor considered in other chapters. The higher the speed of drawing, the greater is the heat generated and the more is the film strength of the lubricant reduced in consequence.

This is recognised, yet little appreciation is usually evinced of the fact that the higher the speed of drawing the less is the time allowed for local ruptures in the lubricant film to heal. With fairly viscous lubricants, particularly those containing a filler, it seems likely that the speed of movement of the film is of the same order as that of the sliding metal surfaces. For this reason alone, speed of drawing often merits more careful consideration than is usually accorded to it.

Ease of Application. As regards ease of application, it will be obvious that the degree of completeness with which it will be necessary to cover with lubricant the surface of any article, to ensure the formation of a continuous film before the region of high pressure in the tools is reached, will depend to some extent on the shape of the article but, principally, on several related attributes of the particular lubricant employed. Of these attributes, viscosity, surface tension, and wetting power have already been mentioned, and it has been pointed out that they are each related directly to the inter-molecular forces functioning between the molecules of the lubricant, its adsorbed film on the surface of the metal, and the metal itself.

The carelessly placed, light dabs of lubricant which, frequently, is all that is applied is evidence of the excellent spreading power of the commonly used light lubricants, although it must be conceded that the surface of the tools will bear some lubricant left from previous articles which have passed through them. Nevertheless, it is questionable whether moderate-size articles, particularly in steel, always receive a proper modicum of lubricant even when this is of what is termed the "light" variety. With the more viscous lubricants, such as are employed during heavy draws on thick steel, a certain amount of care in application is essential to ensure a degree of distribution sufficient to prevent local scoring and fouling which could be avoided were an adequate supply of lubricant present.

In view of the virtual impossiblity of ensuring careful spreading of lubricant by press operators drawn from the cheaper type of labour, a high degree of "spreading power" is a very desirable attribute in any drawing lubricant and one which should receive due consideration when a selection is being made. When for certain reasons a lubricant possessed of relatively poor spreading power has to be used, steps should be taken to ensure that it is applied at a suitable part of the blank and spread in an adequate manner. Mechanical application of lubricant can often be arranged with advantage for flat blanks; adaption of mechanical application to shaped articles presents obvious difficulties. In either instance, complete immersion in a bath of lubricant of suitable wetting power, consistency and adhesiveness appears to constitute the ideal, if not always an economically practicable, method of application. Application by spraying seems to offer little advantage in the instance of thin lubricants; the spraying of the more viscous kind is not possible.

7. Adhesiveness. Although the essential facts concerning the practical aspect of this property have been enumerated in the first brief list of desirable properties, some elaboration may be of use now that the nature of certain other properties of lubricants has been discussed more fully.

Fundamentally, the adhesive power of a lubricant is dependent primarily upon the strength of inter-molecular forces operating in the manner already described but, in addition to this, the degree of smoothness and porosity of the metal surface will, clearly, exert a purely mechanical "keying" effect. It must be borne in mind that good adhesion produced by strong inter-molecular attraction or by mechanical keying and entrapment may change from a beneficial to a seriously detrimental attribute when the time comes for the lubricant to be removed.

Forms of Adhesion. The property of drawing lubricants here termed adhesiveness may be divided broadly into three kinds: that of the adsorbed film to the metal surface, that of a relatively thick film of lubricant to the adsorbed film, and that of the lubricant within itself.

The first has already been considered in section 2; it does not come within the province of the present examination of bulk-adhesion The second is dependent, as is the first, upon the magnitude of the inter-molecular forces existent between a given lubricant and a given metal; in all probability it is this form of adhesiveness which is of most practical value under all conditions right up to the attainment of pure "boundary" lubrication under extreme pressure. The third is dependent upon the viscosity and characteristics of individual lubricants; on this form of adhesiveness will depend the quantity of lubricant which remains attached to a metal surface when an article immersed in lubricant is removed from the bath, also the ease with which lubricant will drip from an article during handling.

Attainment of Adhesiveness. The very best consistency and adhesiveness of any lubricant will be dependent upon its inherent properties, the particular metal upon which it is used, and the conditions of the press operation given. Hitherto this has been ascertainable only by practical trial; now that more knowledge is being obtained concerning the functioning of the inter-atomic linkages which are believed to produce the property of adhesiveness, both internal and external, it may be possible to make useful predictions concerning the probable behaviour of these forces as exhibited by and between given substances.

The adhesive properties of a viscous film sufficiently thick to extend beyond the influence of the forces which produce and maintain an adsorbed layer will, obviously, be influenced very markedly by the viscosity of the lubricant. In this respect the properties of adhesiveness and spreading power are usually opposed and, as with nearly all those properties which seem desirable in a drawing lubricant, compromise has to be made in their attainment. A "tacky," highly adhesive lubricant will not usually spread as readily as will a less adhesive and more mobile medium. This statement applies only to bulk or viscous adhesion, not to the adhesion of the adsorbed layer.

One solution to this problem is provided by the "evaporating" lubricants described later. These are applied in the form of a liquid having low viscosity and good spreading power; but, on standing for a short period, the solvent or carrier solution evaporates leaving a "tacky" residue of lubricant proper which adheres very strongly to the surface of the metal.

The nature and condition of a metal surface will influence the adhesive properties of a given lubricant; brass and chromium, for example, may act differently toward various drawing compounds Residual traces of substances formed or placed upon work as a result of previous treatment, such as annealing or cleaning, may modify in a profound manner the normal behaviour of a metal with respect to the wetting power and adhesiveness of lubricants placed upon it.

In general, the advantages of adhesiveness obtained by means which produce a tacky lubricant of relatively thick consistency are offset by the care which will be required to ensure that all areas of the work are properly coated. At no time must the problem of removal of lubricant be lost sight of when the advantages of strongly adhesive properties are being considered; as this aspect has already been discussed it is unnecessary to repeat here the several specific instances of strongly adherent lubricants already mentioned.

Measurement of Adhesiveness. A recently marketed machine, known as the Sperry-Cammen "Adher-o-scope," is stated [93] by its originators to measure "the adhesive power of the oil at a certain temperature." This is accomplished by spreading the oil to be tested upon the clean, smooth periphery of an accurately weighed steel drum which can be rotated by an electric motor at speeds up to 20,000 r.p.m. in a chamber equipped with temperature-controlling devices. After rotation for a definite period under constant and known conditions the drum is weighed, the weight of the oil remaining upon it at the completion of the test being employed as a measure of the adhesive power.

A test such as this will certainly determine in a simple and precise manner a comparative value for the adhesive power of a drawing lubricant in the sense in which this term is used and discussed in this section. It is, however, necessary to distinguish clearly between the value determined by this machine, which is probably a measure of the adhesive power of the normal molecules of the lubricant to those of its adsorbed film, and one denoting the adhesive power of the molecules of the truly adsorbed film to those of the metal. This latter value is known to be very great, and it seems highly improbable that centrifugal forces of the order obtainable in the testing machine could detach any but the outer, and therefore relatively loosely attached, molecules of a truly adsorbed film.

Results obtained on this machine confirm that adhesive power is dependent upon the formation by the lubricant of an adsorbed film upon the surface of the metal. It is interesting to observe how the adhesive power of a straight mineral oil is increased by the addition of a small proportion of oleic acid in exactly the same manner as the oiliness is known to be increased very markedly thereby. It is evident that the machine gives a clear indication of the absence or presence of a strongly adsorbed film produced by any lubricant; it seems likely that this particular application may prove to be of considerable practical value, although it is unfortunate that no measure of oiliness in the sense of slipperiness is obtainable by such methods.

Practical Effect of Adhesiveness. As regards the practical effect of bulk-adhesiveness, a lubricant which drips freely off work during its transfer from bin or stack to press is, obviously, unpleasant to use and, also, uneconomical because only that proportion of lubricant which remains upon the work immediately prior to the descent of the punch can possibly perform a useful task. On the other hand, if the lubricant is too adherent or of too thick a consistency a wholly unnecessary and therefore uneconomical amount may adhere to work, particularly when the latter is dipped in a bath.

In addition to the influence of adhesiveness upon the handling of lubricant-coated articles and upon the facility of application, maintenance and final removal of the lubricant, Montgomery [91] states that a lubricant possessed of too high adhesiveness tends to produce an open grain on drawn metal. It may be that an associated lack of spreading power is at least a contributory cause of this observed effect.

8. **Stability.** It is desirable that a lubricant shall not decompose or otherwise deteriorate during storage for a reasonable period under reasonable conditions.

Distinction must be made between two kinds of change which are possible, namely, permanent damage produced by chemical change, such as is brought about by the fermenting of water-bearing lubricants or by the oxidation of animal or vegetable oil constituents, and mere mechanical separation which can be remedied, with varying degrees of difficulty, by agitation prior to use. To these two must be added a third, agglomeration of colloidal and even of non-colloidal suspension ingredients; an irreversible change.

Actual chemical change can be avoided by the deliberate omission of such constituents as are likely to produce an action or, sometimes, by the addition of an inhibitor to prevent anticipated action. With some types of lubricants powerful preservatives are needed to prevent fermentation; benzoic acid is an effective deterrent, and possesses the special benefit that it is harmless to operators. Apart from any loss in inherent properties, the effect produced on operators by a rancid, evil-smelling, if not physically injurious lubricant is not conducive to the full and proper application of such a lubricant to work.

The speed of mechanical separation of an emulsified type of lubricant is influenced by its viscosity, by the size of the emulsified globules, and by the nature of the soaps or other stabilisers which may be added either as primary ingredients of the lubricant or as secondary additions made for the sole purpose of preventing agglomeration. Sometimes chemical action occurring between substances incorporated in the lubricant may destroy the action of the stabiliser.

Mechanical separation of suspended solids such as chalk, mica, zinc oxide or graphite is difficult to avoid, as the suspension is seldom of a truly colloidal nature, although the speed of settling of non-colloidal suspended matter can be controlled within limits by the size of the particles and the nature and consistency of the liquid. Caution is necessary here, for a lubricant which will separate slowly will require prolonged agitation to ensure a return to complete and uniform dispersion. Unless supervision is strict, it is unlikely that a lubricant will always receive adequate stirring immediately prior to use; for this reason the lubricant actually applied to the work may often contain an inadequate proportion of the suspended solid or "filler." This possibility—which is, of course, by no means confined to drawing lubricants—is of more practical significance than might be thought, and forms a serious drawback to the use of many suspension types of lubricant.

Agglomeration of non-colloidal graphite particles is a frequent source of trouble with lubricants containing this normally highly beneficial substance. When large particles are formed in the lubricant and are placed upon the work, they may produce small but often injurious flats or dents in the drawn article. The fact that traces of free acid tend to produce agglomeration of colloidal suspensions of graphite is now well recognised.

9. Corrosiveness. It is desirable that the lubricant used in drawing or pressing operations shall not attack the tools or, of less importance since contact may be of shorter duration, the work itself.

As the lubricating value of an extreme-pressure lubricant is believed to be due to the strength of the inter-molecular affinity between the lubricant and the metal upon which it rests, it will be clear that some measure of actual chemical attack is a natural, rather than a surprising, effect. Both the chemical "combination" of different elements or compounds and also the adherence to a metal of an adsorbed layer of lubricant are due to exactly the same fundamental cause, namely, inter-molecular affinity; the difference is merely one of degree. It is believed that the adsorbed films formed by lubricants containing animal or vegetable oils or fats, *i.e.*, unsaturated hydrocarbons, are attached to metal surfaces by what are termed co-ordinated atomic bonds or secondary valencies exhibited by the lubricant molecules. These forces, although sufficiently strong to produce and maintain an adsorbed film, are insufficiently strong and active to cause the actual chemical combination of elements or radicals necessary to produce chemical attack as manifested on a metal surface by an etch. On the other hand, the very strongly adsorbed films formed by certain substances which have already been mentioned appear to be attached by a stronger and more active form of linkage than that attributable to co-ordinated bonds. To this stronger form the term polar bond or primary valency has been given; it is this form which produces actual chemical combination manifested, in the instance now under consideration, by a visibly etched surface upon the metal being lubricated.

The severity of the attack produced on the work by some lubricants of high efficiency is sufficiently great to render them inadmissible for present use in many industrial deep-drawing operations. Mention has already been made of a number of lubricants which seem to possess an inter-molecular affinity for many metals of such a degree that, although the severity of the visible chemical attack or " etch " is not unduly harmful, the strength and adherence to the metal surface of the adsorbed film is high enough to give unusually good lubricational effects. Sulphurised, chlorine-treated and oleate-bearing oils fall in this useful category. The exact action of chlorinated oils seems as yet uncertain as, apart from the assumed production of very definite orientation of the molecules in the adsorbed film, it has been suggested that the chlorine atom is not normally free to combine with the metal unless the oil molecule is by some means, such as heat produced by mechanical friction, broken down and the chlorine atom thereby liberated.

It is, of course, possible that a lubricant which produces a harmful etch on certain non-ferrous alloys or even on mild steel may be of great value for use with stainless steel, particularly if some form of high chromium or other fairly corrosion-resisting steel can be employed for the tools used in the drawing operations. Again, assuming that ordinary steel tools resist the attack of some particular lubricant to a satisfactory degree, the value of this lubricant may be sufficient to warrant its use for the drawing of certain metals which it attacks provided that the drawn articles can be cleansed immediately. Indeed, provided that the action can always be stopped prior to serious attack, the formation of a slightly etched surface on drawn work may sometimes be of benefit because a surface of this kind " holds " lubricant better than one smoothly polished.

The use of definitely corrosive lubricants is still in the experimental stage but, when their very high lubricating value is borne in mind, enough has been said to show the possible value of this type of lubricant in deep-drawing processes. It may well be argued that the employment of definitely corrosive lubricants renders necessary a degree of strict technical supervision not usually found in shops carrying out deep-drawing operations. This objection must be admitted, yet there is without doubt a slow movement toward the adoption of better supervision in many industrial processes, and it may be that in the future lubricants of the type described may find important and regular use in the deep-drawing industry.

10. Psychological and Physical Effect on Users. Those accustomed to handle labour will appreciate this attribute more readily than theorists. It is no exaggeration to say that press operators may refuse to handle a particularly obnoxious, or even dirty, lubricant. Furthermore, if actual refusal is not incurred, it may be predicted with certainty that an unpleasant lubricant will be used sparingly and even omitted when the supervisor's back is turned. In the instance of a lubricant which actually produced some harmful effect, such as boils, on the operators, their antipathy is justified, although existing factory legislation precludes the use of actually poisonous substances. Smell, appearance, touch and adhesiveness to the human skin are properties which each merit consideration.

The disease of the skin known as dermatitis seems far less prone to occur in press-shops than in machine-shops in spite of the fact that some of the thinner drawing lubricants closely resemble, and indeed sometimes are, cutting oils. One reason for this may be that in press-shops fresh lubricant is used and discarded, and not kept in continued circulation in large quantities open to contamination and deterioration. Present knowledge seems to show that, although the proneness of individuals to this disease varies considerably, the majority do not contract it if the standard of personal cleanliness is reasonably good.

A lubricant may be unpleasant to use yet harmless, as in the instance of graphite—which is very difficult to remove from the pores of the human skin—or definitely injurious, as in the instance of that particularly beneficial lubricating substance white lead. Either effect may be unavoidable, as in the two instances just cited, or avoidable, as in the instance of rancidity brought about through the omission in a compounded lubricant of a suitable, and itself harmless, preservative such as benzoic acid.

11. Miscellaneous Properties. In addition to the ten major properties which have been discussed, certain other properties of a lubricant intended for use in deep-drawing operations are of sufficient importance to merit mention.

If the lubricant is purchased in concentrated form, it is desirable that it shall be capable of being diluted uniformly without undue difficulty. This is of special importance with solid-suspension types of lubricant.

A distinctive colour whereby the presence or absence of lubricant on the whole or on local areas of blanks or work can be instantly observed is sometimes put forward as a selling point, but the usefulness of this attribute is often exaggerated. A more useful function of distinctive colouring would seem to lie in the ready identification and allotment of various lubricants to their proper metals and operations when a number of different lubricants have to be employed in one shop.

It is an established fact that some lubricants tend to promote "season-cracking" in brass and possibly in other non-ferrous alloys. If reasonably quick removal of lubricant from drawn work cannot always be guaranteed, it will be necessary to select for any given metal a lubricant which possesses the least possible tendency to aggravate cracking of drawn work prior to stress-relieving annealing.

Owing to the rapidly increasing use which is being made of inter-stage annealing furnaces in which the charge is heated by exposed elements, and also of controlled atmospheres to produce a clean, if not always a genuinely bright, surface on annealed work, it is desirable that the drawing lubricant should not contain any substance which will injure the heating elements or upset the balance of the controlled atmosphere by its decomposition products. Admittedly, all traces of lubricant ought to be removed from work before it is passed through a modern clean-annealing furnace, but the fact has to be faced that, under present industrial conditions, this is not always done. It is, for example, foolish to go to considerable trouble to remove all traces of sulphur from the gas used in a furnace atmosphere and then to use a sulphur-bearing drawing lubricant; for it is more than probable that, under industrial conditions, traces of sulphur will remain even if the work is carefully cleaned before it is placed in the furnace.

The Compounding of Lubricants for Deep Drawing

In the foregoing review of the nature and means of attainment of those properties of a lubricant such as slipperiness, film strength, spreading power and adhesiveness, which experience and theoretical considerations show to be desirable for the special requirements of deep drawing, a certain amount of reiteration has been unavoidable. The reason for this, on which it is now desired to focus attention, is that many of these properties are the manifestation of *one fundamental phenomenon*, namely, the existence and peculiar nature of what is termed the adsorbed film formed by certain lubricants upon the surface of most metals. This explains why these various properties are related so closely to one another and, furthermore, why certain undesirable properties—such as corrosiveness and difficulty of removal—which are also manifestations of the same phenomenon cannot, by reason of this fact, be eliminated without serious detriment to those which are beneficial. Compromise is, clearly, the only means whereby a lubricant suitable for practical use can be obtained, so far as properties dependent upon the adsorbed film are concerned. It is for this reason that the use of fillers or solid-suspension additions, which are *not* dependent for their proper functioning upon the formation of an adsorbed film, is of great practical benefit because, except in the instance of special substances such as graphite and zinc oxide, they can be removed from work without undue difficulty and do not attack the surface of the metal to a serious extent.

Drawing lubricants can be divided into three broad categories, according to whether their value is dependent solely upon the formation of an adsorbed film, solely upon the action of a solid filler suspended in a relatively non-oily medium or, thirdly, upon a combination of these two.

Lubricants forming an Adsorbed Film. Lubricants in this class may conveniently be subdivided into (*a*) light or soluble oils, and (*b*) heavy oils and greases.

(*a*) In the first subdivision fall many of the lighter drawing lubricants, such as solutions and emulsions of soluble oils and soaps in water and light mineral oils. For light drawing operations, particularly on brass, it is common practice to use "suds," this being the name given to water-base lubricants containing a proportion of soluble or emulsifying oils or soaps, the latter being sometimes added as solid chippings.

It is necessary to bear in mind that the efficiency of suds varies very considerably according to the nature and quality of the additions made. A good quality soluble oil having an addition of lard oil yields excellent results for many press operations which are not of a really severe nature, but a consistency thicker than that commonly employed for cutting operations is usually desirable. It should be borne in mind that the tendency toward fermentation increases with an increasing proportion of water.

A typical soluble or emulsion concentrate may contain :

Light mineral oil . .	60 per cent.
Fixed oil	30 ,,
Soap and emulsifier . .	10 ,,

For ordinary use this would be diluted with from 1 to 5, or even 10, parts of water, depending on the nature and severity of the draw, although for very light draws dilutions up to 1 in 20 are being used successfully.

Lubricants containing chlorine- or sulphur-treated oils also fall in this first subdivision. These are characterised by the marked distinction of forming a very strongly adsorbed film upon metal surfaces which, in comparison with the majority of the light, oily type of lubricants, may result in markedly greater lubricating efficiency under high pressures—a benefit which unfortunately is usually associated with considerable difficulty of removal. Lead oleate compounds constitute another addition comparable in effect to chlorine-treated oils ; these are insoluble in water.

(*b*) In the second subdivision, namely, heavy oils, fats and greases, fall many useful lubricating substances, such as tallow. In general, however, high-viscosity or pasty drawing lubricants owe their condition to the incorporation in them of a fair proportion of suspended solid substance, such as chalk or flour. Really thick oils and greases containing no filler do not appear to be used to any great extent in the deep drawing of sheet, but operators engaged on the drawing of heavy gauge rod and wire through dies frequently make use of a virtually solidified lubricant.

Between the relatively fluid and the viscous lubricants here grouped respectively under the headings (*a*) and (*b*) there is an intermediate, and very useful, range having moderate viscosity. The lubricants in this intermediate group usually consist of heavy fats or greases thinned with a suitable diluent, which is generally a light mineral oil. It need hardly be said that the number of quite good lubricants in this group is very large, and that most press-shop superintendents have their own favourite formula. As a rule there is little point in mixing together a large number of substances, and an excellent lubricant can be made from a good quality grease, tallow, lard oil and paraffin mixed to a consistency determined by the nature and severity of the press operation on which it is to be used.

Non-oily Lubricants containing a Suspended Solid. An example of this type is provided by a water or light mineral oil base carrying one of the previously enumerated solid additions such as chalk. Although characterised by easy removal if the proportion of mineral oil is not too high, this type of lubricant does not seem to be used to any great extent.

Lubricants containing both Oily and Solid Substances. In this class falls perhaps the largest proportion of drawing lubricants and certainly those used on the more severe operations. Many and varied are the formulæ in use, but nearly all appear to have been developed by purely practical trial and it certainly seems as if the double-functioning type possess real advantages. The foregoing theoretical considerations suggest that these advantages are due partly to an appreciable reduction of friction, and consequently heat, by the oily ingredients prior to their breakdown ; partly to an artificial raising of their apparent breakdown value by the mechanical entrapment action of the solid suspension ingredients, and partly to purely solid or mechanical separation of tool and work by the solid particles contained in the lubricant.

Typical Lubricants. The composition of complex drawing lubricants varies very greatly with respect both to the constituents and to their relative proportions. As an example of a simple composition there may be instanced the following, which gives excellent results on moderately severe draws on steel and can be removed from drawn shapes without undue difficulty :—

Soap, good quality, sodium base .	5 per cent.
Castor oil	25 „
Chalk, finely ground	45 „
Water	25 „

In this compound the soap and castor oil provide the oily substances necessary to form an adsorbed film, the chalk is the solid, while the castor oil in combination with water and the soap stabiliser forms an emulsion which prevents ready separation of the solid addition and greatly facilitates the removal of the lubricant by some cheap and simple aqueous solution, such as hot sodium metasilicate.

The following analyses extracted from a table compiled by Halls,[95] accompanied by brief notes on their performance, will serve to indicate the present trend, but this type of lubricant may be superseded in the future by extreme-pressure lubricants of more simple composition. Lubricants 1 to 4 must be diluted with mineral oil; lubricant 5 is sparingly soluble in water, but an oil diluent is preferable for most purposes.

	1	2	3	4	5
Soap (soda)	—	—	—	—	25·0
Soap (lime)	15·5	22·0	9·0	6·5	—
Free acid (oleic)	1·0	1·5	2·5	2·5	5·5
Fatty oil (glycerides)	13·0	7·0	12·5	20·0	6·5
Mineral oil or jelly	7·0	6·5	32·5	30·0	7·0
Water	23·5	23·0	22·5	20·0	20·0
Solids, non-active (French chalk)	—	—	—	—	36·0
Solids, non-active (whiting)	40·0	40·0	21·0	15·0	—
Solids, active (sulphur)	—	—	—	6·0	—

Of these five compositions, Halls states that numbers 1, 2 and 3 separate least during storage; numbers 1 and 2 separate water only, number 3 separates oil and water and will stand far less dilution than numbers 1 and 2. Number 4, a sulphurised fatty-base lubricant, has a bad odour, separates oil on standing, is corrosive toward many non-ferrous metals and, to a less extent, toward steel tools.

It is interesting to observe that there is evidence to show that for the benefits of a solid suspension addition to be made manifest the lubricant must usually contain not less than about 25 per cent. of solid; 25 to 40 per cent. covers the proportion generally added. This fact should be borne in mind when the action of solid additions is being considered. The foregoing statement concerning the minimum proportion of solid does not apply to colloidal graphite, a small proportion of which may make a distinct difference to the properties of a lubricant. It is stated by the originators that small additions of colloidal graphite do not influence the viscosity of a lubricating oil.

As an example of special lubricants, which, as in this instance, may not necessarily be of a complicated nature, there must be given the very simple one of a mixture in varying proportions of white lead with castor oil. This lubricant is extremely efficacious in severe draws, but it is very difficult to remove from drawn work and, in addition, is poisonous. It offers very great resistance to being squeezed out from between heavily loaded surfaces, and probably functions partly by simple mechanical or solid separation of the sliding surfaces and partly by mechanical entrapment and retention of the castor oil, a substance possessed of a very high degree of oiliness. Users of this particular compound invariably speak highly of its actual lubricating value as distinct from its less beneficial attributes.

It seems superfluous to point out that concentrated lubricants must be diluted with a *suitable* diluent, yet the author has come across instances where a perfectly satisfactory concentrate has been diluted with a totally unsuitable diluent, *e.g.*, a non-soluble or non-emulsifying oil has been mixed with water, and the concentrate blamed for the result. Some concentrates require to be mixed with a hot diluent; often a difficult task in the press-shop. Ease and simplicity of dilution is a factor which should always be taken into consideration when choice is being made of a lubricant for prolonged and extensive factory use.

A word of warning may also be added with regard to the compounding of really complex lubricants by persons unacquainted with the precautions which have to be observed in such procedures. This warning must not be interpreted as an exhibition of favouritism toward the suppliers of ready-mixed proprietary lubricants, but the average press-shop seldom possesses the necessary equipment for the proper measuring, mixing, and even heating of the various ingredients, while the standard of cleanliness observed during these operations is rarely of a desirable order. When proper facilities and supervision are available there is, of course, no reason why a factory should not mix its own lubricants; but, in their absence, a factory-made lubricant may prove greatly inferior to its counterpart made to the same formula under proper conditions.

Graphited Lubricants. Graphite is usually suspended in an oil "carrier", which may or may not contain other lubricants or some form of filler; but, particularly with stainless steel, an aqueous suspension is used occasionally.

It can be said quite definitely that best results are obtained when the graphite is in a colloidal form, that is in an extremely fine state of division obtainable as a proprietary product under the name of "Oildag" and "Aquadag," these varieties being suspensions in oil and water respectively. Attempts made to mix ordinary powdered graphite with oil or complex lubricants often prove unsuccessful, because such mixtures rarely impart a uniform graphoid film to the whole surface of the metal being drawn, and sometimes particles of appreciable size persist and make actual indentations in the surface of the wall of the drawn article. Another disadvantage is that powdered graphite separates from the carrying solution with time, no matter how finely it is ground, whereas colloidal graphite will not separate unless some constituent of the carrier produces a chemical action which causes the colloidal graphite to coagulate.

In view of the fact that the exceptionally good lubricating properties of graphite cannot always be used industrially owing to the difficulty of removing the graphite from pressed articles, particular interest must be attached to the suggestion of Stuart [96] that in the case of steel which has to be spray-painted it is not the graphite itself, but the *oil* which normally is associated with it, which prevents paint adhering properly.

If a drop of boiled linseed oil is placed on a steel surface which has been cleaned, treated with Aquadag (colloidal graphite suspended in water), and wiped clean with cotton wool, it will spread. If on the other hand a drop of oil is placed on another area which has been cleaned, treated with Oildag (colloidal graphite suspended in oil), and degreased with petroleum ether, it does not spread no matter how thoroughly this degreasing process is carried out. The inference is that a graphoid film *when free from oil* actually assists paint to spread on a steel surface.

A point of theoretical interest is that a graphoid film renders iron less anodic, and should thus hinder corrosion when the paint becomes scratched. Be this as it may, the fact remains that, by substituting a water-base for an oil-base graphited lubricant, it may be possible to use graphite as a lubricant under conditions which, for the reasons stated, now prevent its use in many press-shops engaged in the production of steel pressings for automobile bodies and other purposes.

Evaporating Lubricants. A type of lubricant which is very efficient in many instances is that distinguished industrially by the term "evaporating." The essential feature of this type is that the lubricating substances proper, which are often of either a waxy or a soapy character, are dissolved or suspended in a suitable volatile solvent or carrier, for example in trichlorethylene. When work is immersed in a bath of this lubricant, drained and allowed to stand for a short period, a thin "tacky" film of the lubricating substance proper remains and adheres with remarkable tenacity to the surface of work during its subsequent passage through deep drawing or pressing tools.

This kind of lubricant is particularly helpful with severe deep-draws on steel when there is a tendency to "foul" or "gall," and also with light-alloy sheet; but it is important to use the particular grade recommended for any given metal and press operation by the makers of proprietary lubricants of this type, and to allow the carrier to evaporate completely, a matter which is sometimes difficult with operators unaccustomed to lubricants of this kind.

Removal of a Drawing Lubricant

A number of troubles which arise as a result of inadequate removal of drawing lubricant have already been enumerated in Chapter III, and, in the present chapter, there has been attempted some consideration of the general principles upon which ease of removal depends. In view of the present lack of appreciation in many press-shops of problems connected with lubrication, a few essentially practical remarks concerning the methods which must be employed to ensure the adequate removal of drawing lubricants may prove helpful.

Drawing lubricants can seldom, if ever, be removed by a simple swill in either hot or cold water, although the efficacy of steam jets and even powerful hot-water sprays is considerable by virtue of the mechanical or cutting action of the impinging jets. Excluding for the moment this rather special application, the following constituents of lubricants cannot in the normal course of events be removed by water: animal, vegetable and mineral oils; greases; solids (used as fillers). The means which must be adopted for the removal of these constituents are, briefly, as follows.

Mineral, Animal and Vegetable Oils. These can be dissolved away by the use of an organic solvent, such as the familiar trichlorethylene, or, which is usually the cheaper method, they can be emulsified or saponified and then swilled away by any convenient liquid. A cheap alkaline solution is usually used for the purpose of emulsification, although it should be observed that a pure mineral oil containing no additions of fatty oils or their derivatives cannot be emulsified or saponified unless there is present in the cleaner a soap or some special colloid. A cleaner capable of dealing effectively with mixtures of mineral, animal and vegetable oils should be so constituted that it can perform both saponification and emulsification.

Greases. These may be removed by either of the foregoing methods with certain differences. An organic solvent will dissolve only the oil constituent of a grease, leaving the soap portion in a relatively free condition in which it can, and must, be swilled or blown away; mere immersion in a bath of organic solvent will not remove thick grease in a reasonable time.

If grease is removed by the second method, *i.e.*, by an alkaline solution containing suitable additions, it must be borne in mind that the action will be slower and that the cutting action of sprayed liquid is even more helpful than with thin oils. As lime-base soaps are usually more difficult to remove than soda-base soaps, it is desirable that the composition of the grease to be removed should be known.

Solids. As a rule these are insoluble in the cleaning solutions usually employed, and need to be removed by mechanical means such as high-pressure sprays, hand wiping or mechanical scrubbing. Substances such as graphite and zinc oxide are not readily removed even by these means.

Assuming that a serious attempt is made to remove drawing lubricants, it will be clear even from these brief remarks that effective removal cannot be secured by haphazard means such as are all too frequently employed. A knowledge of the composition of the lubricant is virtually essential before an efficient scheme for its removal can be devised.

Cleaners. An efficient cleaner for dealing with lubricants of complicated composition may be, and usually is, itself of complicated composition. For this reason, as with the lubricant itself, there exists an undoubted case for the proprietary cleaner unless factories possess adequate facilities and supervision for the making up of solutions to definite formulæ. On the other hand, some formulæ, proprietary and otherwise, are so complicated that the practical value of all the additions may justifiably be questioned.

A good cleaner must possess a high emulsifying power ; to ensure this special additions to the main alkali base, such as colloids and active emulsifying agents, are often made. A high emulsifying power may not be effective unless the wetting power of the solution is also high, as penetration between the oil film and the metal surface or finely divided solid particles in the oil will depend upon a lowering of the interfacial tension between these substances. In addition, the cleaner should possess a capacity to hold solid matter in suspension, and, last but by no means least, it should be capable of being easily rinsed off, carrying solution and emulsification products as well as suspended solids away with it : truly a demand almost as great as that made of the drawing lubricant itself !

The fact that certain cleaners are not always removed by simple water rinses needs to be more widely recognised. Some of the substances which are not so removed are rosin, either powder or rosinate ; sodium silicate or meta-silicate, sesqui-silicate or ortho-silicate ; certain soaps ; and, lastly, solids, such as certain clays which do not react with ordinary pickling acids. The addition of trisodium-phosphate to alkali cleaners greatly facilitates their removal by rinsing ; for this reason it is a particularly valuable one, and is frequently made use of.

Some idea of the relative suitability of several cleaners for removing a given drawing lubricant can easily be obtained by shaking up a quantity of lubricant with, say, ten times its bulk of cleaner and observing the ease and speed with which an emulsion is formed and, when formed, its stability and also the ease with which it holds the solid filler, when one is present, in suspension.

Attention has already been drawn to the value of high-pressure, and usually hot, sprays of cleaner for removing lubricants from work. This value must again be emphasised ; the mechanical action of a high-pressure spray may give entirely adequate removal of a lubricant where, using the same cleaner, no reasonable amount of swilling will do so. In the absence of a really high-pressure spray, mechanical or hand scrubbing of the surface of the work may prove adequate.

Lubricants containing greases and solids, which are particularly difficult to remove from inside edges and corners of articles, can often be removed by the usual alkali-base cleaners if the offending regions are brushed with paraffin prior to treatment with the cleaner. According to Halls,[95] greases containing a calcium-base soap, which are not in the normal course of events readily removed by alkali cleaners, can be so removed if the work is first baked in a steam oven to break down the calcium soap emulsion.

The considerable popularity achieved by the trichlorethylene type of degreasing plant has recently been increased by the availability of more stable solvents containing inhibitors to minimise the etching effect which was previously experienced with some metals. In view of this it may be well again to emphasise the fact that this solvent, although dissolving oil, does not dissolve soaps. For this reason the oil constituent will, given time, be dissolved from a thick grease, but the soap constituent will be left upon the surface of the metal unless removed by some mechanical means.

Trichlorethylene baths are now obtainable in which work is alternately lowered into the liquid and raised to the vapour zone, thus securing a mechanical swilling action. This type of plant will remove far thicker greases than the old type in which only vapour reached the work, but even these will not deal adequately with some of the solids found in drawing lubricants ; these solids must be removed by high-pressure sprays or mechanical scrubbing. It is wrong to regard a trichlorethylene vat as a unit entirely different from other baths or swills which are usually duplicated, and sometimes triplicated, in order to ensure that the last swill is maintained in an almost uncontaminated condition. In some instances the use of at least two trichlorethylene vats in series is a wise precaution. Some authorities are of the opinion that carbon tetrachloride is a more efficient cleanser than trichlorethylene ; but, owing to its higher cost and greater toxic properties, it is seldom used industrially.

A useful procedure to remove simple lubricants consisting of an oil or grease and a solid " filler " is first to remove the oil with the help of trichlorethylene, next to remove the grease and solid matter by washing in hot alkali, preferably by means of sprays, and then to cleanse from alkali by hot-water sprays. Alkalis tend to form an adsorbed film on the surface of metals ; for this reason it is often desirable—particularly if the cleansing just suggested precedes plating and not an inter-stage annealing operation—to follow the water rinse by a swill in a dilute solution of some weak acid, such as an acid tartrate or, which is better for steel by virtue of a slight rust-proofing action, of acid phosphate, for example of potassium. These and other cleaners are, of course, marketed under trade names in the plating industry.

It is worth bearing in mind that if liquid trichlorethylene is introduced into an annealing furnace, as may happen by condensation of vapour or even by the retention of liquid in shaped articles, it is likely to "crack" and give off volatile chlorides which may be deposited on the heating elements of an electric furnace and ultimately cause arcing between adjacent elements.

These remarks are not intended to discourage the use of trichlorethylene degreasing plants for, when their limitations are recognised, they form a most valuable adjunct to any shop in which the removal of lubricants has to be carried out. Caution is, however, necessary because at the present time over-enthusiasm as to the capabilities of this apparatus sometimes leads either to disappointment or to trouble having its origin in this probably unsuspected source.

Choice of a Drawing Lubricant

It has already been said that the choice of lubricants for deep drawing and pressing is usually based upon the results of practical, and often individual, experience. Now that knowledge of a scientific nature is becoming more definite and more readily accessible, this choice can be assisted to a considerable extent by an appreciation of certain known fundamental facts and general principles, some of which have been outlined in this chapter.

In the light of present knowledge it is, however, hardly possible usefully to extend or group the foregoing general indications of the properties of substances commonly used in lubricants for deep-drawing operations into definite recommendations for specific metals or operations, owing to the widely varying conditions which obtain in any type of operation and, as is well recognised by practical workers, even in apparently similar operations under seemingly similar conditions. Small variations in speed of drawing, in clearances, controlling pressures, radii and even hardness of tools may influence to a profound degree the necessary properties of the lubricant employed.

Broadly speaking, it is necessary carefully to balance the actual lubricational value of any drawing compound for any particular combination of metal and tools against its ease of manipulation, against such deleterious properties as it may possess, *e.g.*, corrosiveness and unpleasantness, against its first cost and, of importance, against the cost of its adequate removal when such removal is difficult, essential and necessitates expensive plant and mediums. Little helpful comment can be made upon these various aspects, which are essentially dependent upon the many and varied requirements of individual operations as well as upon economic conditions.

Technical literature shows that proper study of lubricants for deep drawing and pressing, so long overdue, has now been started, and it seems certain that valuable development will result from the practical application of existing knowledge, from the discovery of fresh facts of a fundamental nature, and from correlation and interchange of results between workers in this and other countries on a hitherto unattempted scale.

It is difficult to foresee in what direction useful development will be. The full lubricational value of a number of known substances cannot at present be utilised because of practical difficulties, such as corrosiveness and difficulty of removal, attributable to the very same fundamental properties of those substances which engender their peculiar lubricational efficiency. From the viewpoint of users, the discovery and practical adaptation of lubricants possessed of remarkable efficiency in so far as actual drawing operations are concerned may be of small practical industrial use if, at the same time, cheap and efficient methods for their adequate removal are not also developed.

It is impossible to forecast whether progress may lie in the discovery of new extreme-pressure lubricants which can be easily removed, or in the discovery of methods for the removal of such lubricants as are now known to hold promise from the view-point of high lubricational efficiency. At the present time it seems as if it may be worth while investigating lubricants containing chlorinated oils or some product of oleic acid, which owe their efficiency solely to molecular affinity with metal surfaces, rather than lubricants in which this attribute is weak and compensated for by the addition of an appreciable proportion of suspended solid matter. The separation of suspended solids by settlement is always likely to be deleterious unless entrapment of very fine particles by emulsions of as yet unattained stability can increase the stability of this type of lubricant very markedly, while the slipperiness of the solids now used is not to be compared with that of truly oily films, exception being made of graphite.

This last statement postulates slipperiness as a property of prime importance in drawing lubricants. Although there may as yet be no real justification to doubt the desirability of as high a measure of slipperiness as possible under ideal drawing conditions, it is of interest to record that in given operations a reduction of friction occasioned by the replacement of a normal lubricant by one more slippery can result in the formation of puckers in the drawn article. In view of this it is clear that tools must be designed for use with a given lubricant: yet another instance of the complexity and closely interwoven nature of the problems which confront those whose business it is to fabricate shapes in sheet metal by deep drawing and pressing.

CHAPTER XII

THE TESTING OF SHEET METAL

THE choice and use of tests to evaluate the deep drawing and pressing properties of sheet metal has always been difficult. Many of the orthodox methods employed for the examination of metals destined for ordinary engineering purposes are used for this special purpose; often, it must be admitted, with indifferent success. In addition to these, special tests have been devised which range from simple, quickly made, empirical ones to complicated tests giving results which can only be expressed as recondite mathematical relationships of little use to the practical man in the press-shop until interpreted by a scientist.

In this chapter an attempt will be made to describe a number of tests which have been used or proposed, and to discuss their merits, faults and limitations as an indication of deep drawing and pressing properties in as unbiased a manner as possible. This is not easy, because anyone who uses a certain test continually becomes able to sense intuitively indications missed by others less familiar with it; and also because it happens sometimes that certain tests, which perhaps give little indication of general deep drawing and pressing properties, prove to be of real help in enabling the behaviour of sheet in some *particular* press operation to be predicted.

It can be said at the outset that no single test yet devised gives a desirably adequate or reliable indication of these elusive properties, themselves incompletely understood as yet, which determine the behaviour of sheet metal in the general run of industrial deep drawing and pressing operations. Two facts must, however, be recognised. One is that the application of tests constitutes the only means whereby supplier and purchaser can check the quality and uniformity of the metal which passes between them. The other is that, despite their inadequacy, existing tests can, when used intelligently, be of very real help to the user in ascertaining the suitability of metal for certain specific shaping operations and to the supplier for controlling the quality of the sheet he offers in an attempt to meet the requirements of the consumer. The fact that the properties measured and specified may not always be fundamental in the academic sense does not detract from the practical value of the measurements.

For these reasons the value of many of the commonly used, still more of some of the newly devised, tests must not be underrated on the grounds of their apparent irrelevant or empirical nature. Indeed, since the acquisition of more complete and much new knowledge concerning the elusive properties which determine the behaviour of metal during deep drawing and pressing must come in part from a correlation of precise, quantitative tests with observed performance, a knowledge of both the capabilities and limitations of these tests on the part of all engaged in the industry is very necessary.

After examining the nature and significance of the generally recognised tests, an attempt will be made to assess their value from the view-point of those engaged in the deep drawing and pressing industry. To the research worker, as distinct from the commercial user, *any* test which seems likely to yield information of some value, however small, must claim most serious consideration, if not actual use, as an avenue of approach to his objective.

Chemical Analysis

Chemical analysis is, without question, an important item in the examination of metal destined for the press-shop. It must, however, be conceded that it is of more practical value to the maker of sheet, who should use it as a regular method of examination of both raw materials and finished product, than to the consumer, who can usually detect unsatisfactory sheet by means of physical tests without the luxury of chemical analysis. From the view-point of the consumer it is not of vital importance, except in special instances, whether sheet which behaves as he wishes in his presses conforms exactly to certain ranges of specified chemical composition. From that of the maker of sheet, adherence to certain ranges is often essential if the metal, even assuming correct processing, is to be capable of behaving in the desired manner; the nature and effect of a number of impurities commonly present in brass and steel have already been described. When, as with brass, the product contains a relatively expensive metal, a variation of 1 per cent. above the specified value can mean considerable monetary loss on large tonnages. On the other hand, a variation of 1 per cent. on the low side may reduce the ductility by an amount sufficient to cause serious trouble owing to the negligible safety margin commonly allowed in modern production operations. Close control of major constituents as well as harmful impurities may, therefore, be desirable.

No attempt will be made to describe methods of chemical analysis, for this is a separate and complicated subject only indirectly connected with press-shop practice. It is possible that in the near future more complete analyses will become necessary if and when the purity of metal increases, and that the determination of gases, for example of oxygen in steel, may have to be carried out regularly.

In spite of the great value of chemical analysis in controlling the quality of sheet destined for deep drawing and pressing, the limitations of this method must be clearly recognised. One disadvantage is the time needed to make a complete and accurate chemical analysis;

another, more serious, is the fact that the percentage values obtained by analysis are purely *average* ones. Very frequently it is not the average proportion of some impurity which is harmful but the high local concentrations of this impurity produced by segregation, for example, phosphorus in steel or *beta* phase in brass. For this reason, microscopical examination is often of more use than chemical analysis for detecting the harmfulness of injurious impurities, even though this method of examination is principally qualitative. Again, the *form* in which an impurity, or sometimes even a major constituent, exists is of paramount importance. For example, in two steels showing a carbon content of, say, 0·1 per cent. by chemical analysis, the carbon in one might exist as pearlite or carbide stringers, whereas that in the other might exist as carbide envelopes surrounding the crystal grains, a seriously detrimental condition.

Chemical analysis is, therefore, not always capable of revealing defects or even of enabling the behaviour of metal to be predicted. In spite of this, its use by the maker of sheet is, for the reasons already indicated, always desirable and often essential.

Microscopical Examination

In this method of examination small specimens cut from sheet are prepared by a special technique which reveals the real structure of the metal and enables those familiar with the appearance, nature and influence of observed structures to predict the probable behaviour of sheet under the press and to ascertain the reason for recorded failure or unsatisfactory performance. Description of the methods of preparation of microspecimens and also of metallography itself is beyond the scope of this book, and readers who are unfamiliar with these subjects are referred to the many text-books which deal exclusively with them. For this reason it has been necessary throughout these pages to assume on the part of readers some familiarity with the microstructure of metals, and it is fortunate that the effects and conditions illustrated in most of the photomicrographs will be clearly evident even to those perhaps unacquainted with their real significance.

To those engaged in the examination of supplies of sheet metal, " microscopical examination " usually implies the estimation of the property known as " average grain (or crystal) size," a term which has caused much controversy. Purists point out that, as commonly used, the seemingly simple and self-explanatory term " average grain size " is virtually meaningless, partly because the crystals which form the surface of any micro-section are cut at planes which vary in different crystals from planes of maximum area to mere points representing the apex of a crystal facet. Although this is true, the fact remains that the property known industrially as " average grain size " is of very great importance in determining deep drawing and pressing properties, and increasing attention is rightly being given to it by both suppliers and consumers of sheet metal. To avoid argument it is best if, for industrial purposes, " average grain size " is defined as the *appearance* of a microstructure (etched to reveal crystal boundaries) compared with standard photomicrographs or charts of reference, such as those issued by the American Society for Testing Materials, assumed to represent a series of so-called " average grain sizes." Used in this sense, the term becomes quite clear. Furthermore, it then describes the actual property which it is desired to estimate and compare; although the *regularity* of crystal size, that is the magnitude of the variation in size between the largest and smallest crystals seen, allowing for the natural variation which would be seen on a plane passing through an aggregate of crystals of uniform size, is also of great importance.

That proper microscopical examination, as distinct from mere estimation of " average grain size," is of very great, and in many instances unique, value is amply proved by the various photomicrographs reproduced in this book. It is very unfortunate that the slowness of this procedure precludes its use in routine examination on any but a very small percentage of samples; yet, in the investigation of failure or difficulty, it often proves the most informative test of any yet devised. Another disadvantage from the practical and industrial view-point is that an experienced metallurgist is needed properly to interpret the evidence revealed.

In order to lessen the time taken by preparation and to enable some measure of useful information to be obtained without the assistance of a trained metallurgist, there has grown up the practice of cursory examination for the sole purpose of estimating " average grain size." In this procedure, microspecimens are given only a very crude metallographic polish, and sometimes none at all, before they are etched and examined under the microscope. The appearance of a crudely-polished and etched surface on a piece of brass sheet is illustrated in Fig. 217A (p. 471); when no preparation is given the appearance of the microstructure is often still more indefinite.

Examination of this nature may have its uses, but it is one which does not appeal to the author because important details of structure remain unrevealed, and because in crudely-prepared microspecimens it is difficult and often impossible to see the smallest crystals, which means that a reliable estimation of regularity of crystal size cannot be made. The importance of regularity of size, as distinct from mere average size, is at last becoming recognised.

The suggestion is put forward that, when microscopical examination is included in routine control, the examination of a few properly prepared specimens, carried out in close conjunction with hardness or Erichsen tests made on a much larger number of representative samples, enables an adequate check to be kept on " average grain size " and, in addition, reveals much important information which cannot be obtained by examining microscopically a far larger number of specimens crudely prepared with the sole object of estimating " average grain size." It is the preparation, not the actual examination, of specimens which occupies time. Preparation of routine specimens can be carried out by relatively unskilled labour; and an experienced metallurgist, perhaps occupied on other work, can in a very short time examine and report upon a large number of prepared specimens.

A point worthy of consideration is the angle relative to the surface of the sheet at which the plane of the microspecimen is cut. In acceptance examination, and not infrequently in all examinations, it is usual to examine a surface parallel to, and near, the surface of the

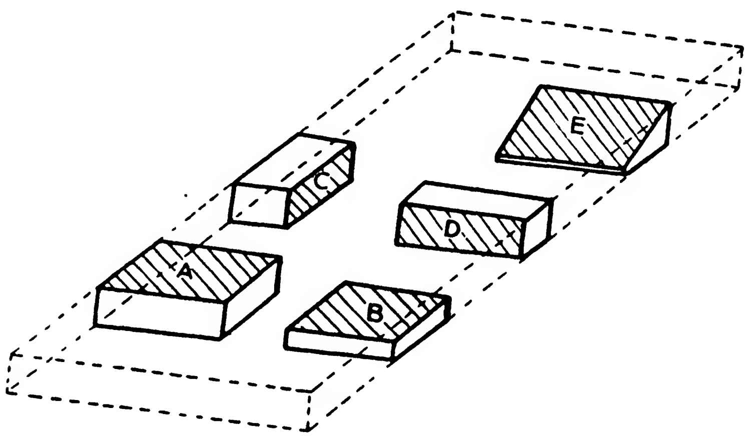


FIG. 216. Diagram illustrating five positions of the polished (cross-hatched) faces of microspecimens relative to the direction of rolling of strip (parallel to long dimension of dotted strip outline).

original sheet. This practice is productive of much misleading information; so, unless a transverse section is made as well, this orientation should *never* be selected for the surface of microspecimens. In contradistinction to a surface cut on any plane parallel to the flat surfaces of a strip (A and B, Fig. 216), a surface cut parallel to the thin edges (C), or sometimes at right angles to these (D), will show up the all-important property of variation in crystal structure from surface to core, in addition to possible internal defects or flaws penetrating inwards from the surface. Sometimes a section prepared at a slant (E in Fig. 216) is useful, but the ordinary edge section is often preferable. It is true that the preparation of a single edge section takes a little longer than that of a surface, but in routine examination edge sections save time because a number of specimens can be clamped together between small screw-clamps and the whole bundle polished as one specimen.

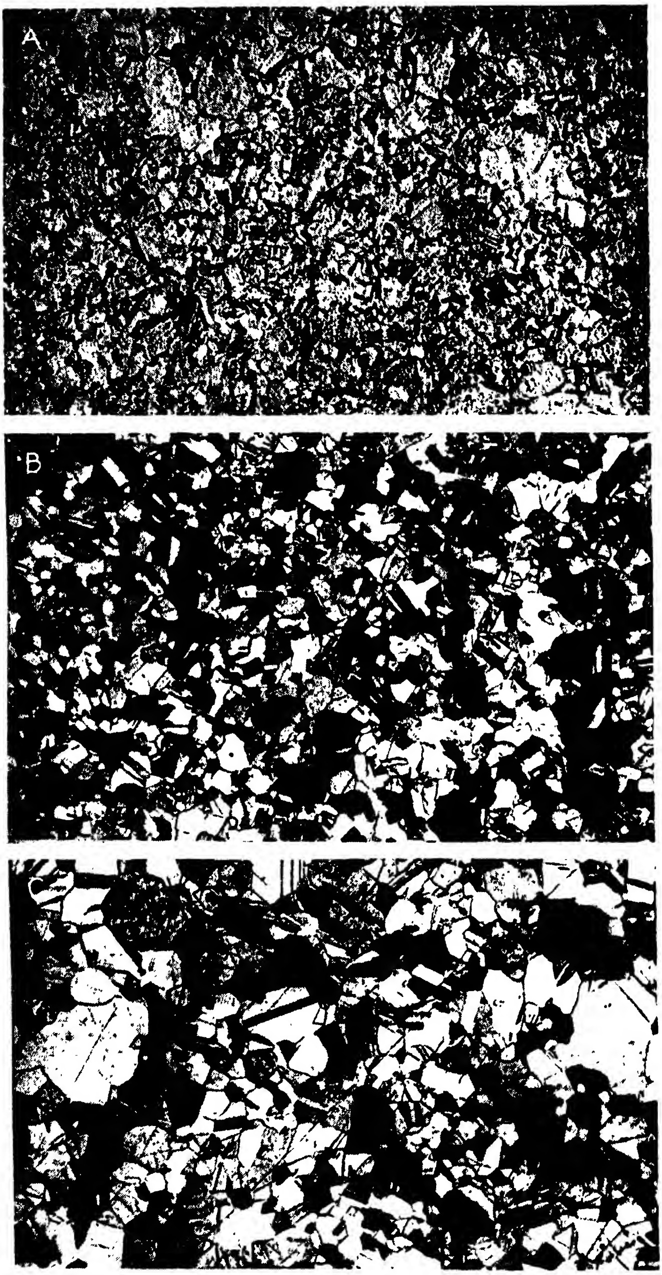


Fig. 217. The influence of (1) degree of polish and (2) distance of microsection beneath the surface of 0·020 inch-thick brass sheet upon the microstructure revealed. × 75.

A. Surface of sheet, crudely polished and etched.

B. Metallographically-polished and etched surface parallel to and about 0·002 inch below original surface.

C. Surface, parallel to and prepared as B, but about 0·010 inch below original surface.

[*To face p.* 471.

The danger of taking surface appearance to indicate crystal structure in the core of sheet is illustrated by Fig. 217, which shows a by no means abnormal example. A shows the appearance of the unpolished, etched surfaces of a piece of brass sheet 0·020 inch thick ; B the same surface, or rather one a few thousandths of an inch below it, metallographically polished and etched ; C shows a parallel surface well down toward the centre of the sheet. The photographs are self-explanatory ; clearly, no surface is representative of the whole thickness of the sheet. Even were this not so, certain nice points of difference will be observed in the conception of the structure given respectively by photographs A and B. In the case of steel sheet rolled from rimming ingots, in which for reasons already explained a marked difference frequently occurs between the size of the crystals forming the core and the surface layers, the significance of mere surface examination may be even less than with brass.

To summarise, microscopical examination is of very great, and in many instances unique, value in two ways. First, it is often the only means for revealing the cause of failure in sheet which has failed or behaved in an unsatisfactory manner under the press. Secondly, it is the only really reliable means for ascertaining, in samples of sheet destined for deep drawing or pressing, the nature, distribution and approximate proportion of inclusions ; for revealing structural characteristics such as planes of segregation or the condition of a second phase ; and, of great importance, for estimating crystal size and regularity. In routine examination, its use in close conjunction with quicker methods, such as hardness or cupping tests, is of very great help. From all aspects, the more frequent use of microscopical examination is to be encouraged.

Hardness Tests

The ease and rapidity with which many hardness tests can be carried out make them popular with those who have to test large numbers of specimens, for example, in the routine inspection of deliveries of purchased sheet. It cannot be emphasised too strongly that, except in so far as they reveal unusually hard or unusually soft metal, *hardness values give no indication whatever of true deep drawing and pressing properties.*

Hardness tests should be made for two purposes only. First, as an indication of the probable similarity of samples. If a certain relatively small number of samples taken from a consignment of sheet prove to have satisfactory properties, as indicated by more searching and more lengthy tests, and a far larger number, tested for hardness only, have the same hardness as the " key " samples, the *probability* is that the whole consignment is satisfactory. If, on the other hand, the hardness of the samples is irregular, the properties of the consignment are, clearly, not constant, and closer examination can be made. Secondly, when the hardness value, falling within the adjudged satisfactory range for any given draw, is known, the tool-setter can make those small yet highly important adjustments to the tools which determine whether scrap, mediocre or good shapes will be produced from a particular batch of metal. Such testing and tool adjustment seem, unhappily, to be instituted all too seldom.

Used thus, hardness tests are of proved value; used without accompanying check tests to determine other properties, they cannot possibly offer reliable information concerning the probable behaviour of metal during deep-drawing.

The most commonly used tests for sheet metal are those known as

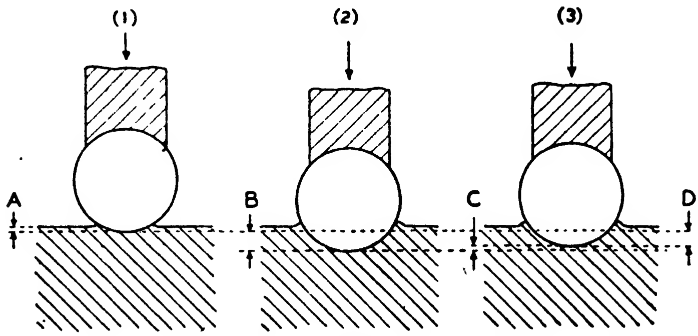
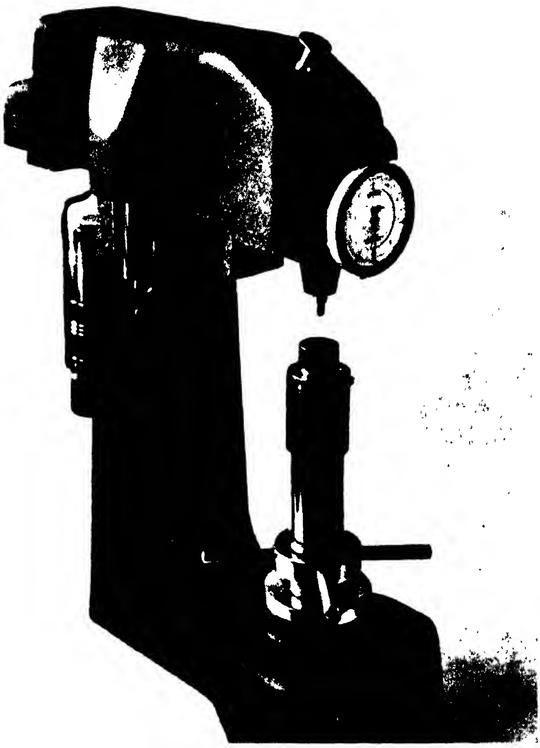


FIG. 219. Diagram illustrating principle of Rockwell test.

(1) Minor load applied giving impression of depth A not indicated on dial.
(2) Major load superimposed on minor load giving indicated depth A + B.
(3) Major load removed, minor load retained, giving indicated depth D, the recorded hardness reading.

the Rockwell, the Vickers and the Brinell, each of which entails the measurement of an impression made by a hard penetrator which is forced into the surface of the specimen under a known load.

Rockwell Test. In the Rockwell test, which is probably the most widely used of any, the depth of the impression made by a $\frac{1}{16}$ inch diameter hardened steel ball loaded with 100 kg. is directly indicated on a mechanical depth gauge of conventional type. The figure so obtained constitutes what is known as the " B scale " reading; useful but less popular scales are standardised for other loads and ball diameters. One of the standard models of the Rockwell range of machines is illustrated in Fig. 218. During recent years a model known as the " Superficial " hardness tester has been added which, because it produces a shallower indentation than the standard models, may in time come to be widely used for testing thin sheet metal as well as the thinly case-hardened steel for which it was constructed originally.



[*By courtesy of the G. H. Alexander Machinery Co. Ltd.*

FIG. 218. Rockwell hardness testing machine.

[*To face p.* 472.

FIG. 220. Vickers hardness testing machine.

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A special feature of the Rockwell test is that, as shown diagrammatically in Fig. 219, a preparatory "minor" load, producing an indentation of unindicated depth, is imposed before the "major" load, producing the indicated indentation, is applied. The Rockwell is the quickest and simplest of any of the conventional hardness tests, a fact which no doubt accounts for its great popularity.

It is important to notice that whereas the Vickers and Brinell tests require a polished surface on the test piece, the Rockwell test can be carried out on an unprepared surface unless this is unusually rough or covered with scale.

Vickers Test. The Vickers test is without doubt the most reliable and fundamentally sound of any available. A 136°-angle square diamond pyramid indentor is forced into the surface of the specimen under a load which can be quickly varied in set increments to produce an impression of approximately the desired dimensions. The size of the impression is measured along its diagonals by means of a microscope attached to the machine, and the ocular reading is translated to a V.P.N. value, or Vickers Pyramid Numeral, by reference to tables. This test is relatively slow, but it has two great merits. First, the load can easily be varied to suit the thickness of the specimen, and, secondly, the impressions are geometrically similar irrespective of size, which is not so when a ball indentor is used. For soft metals the V.P.N. and Brinell values are almost identical, whereas the conversion of Rockwell to Brinell values is so unsafe that this all-too-common practice cannot be condemned too strongly. The Vickers hardness testing machine is illustrated in Fig. 220.

Brinell Test. In the Brinell test, a hardened steel ball is forced into the surface of the specimen under a known load, and the diameter of the impression is measured under a separate microscope. Various standard combinations of load and ball diameter are used to give an impression of approximately the desired diameter or depth ; and it is specified that the ratio of the diameter of the ball to the diameter of the impression must not exceed 0·6, a condition which, unfortunately, is not always observed. For thin sheet metal a ball of 1 or 2 mm. diameter is the largest which can be used. For many years the Brinell scale has been the accepted standard of hardness; but for hard, and even for soft, metals the Vickers scale will probably supersede it.

A number of Brinell hardness testing machines are available. These differ mainly in the method adopted for applying the load, and it is regrettable that, due to friction or other causes, the indicated load is not always the load which is actually applied to the ball. In small, laboratory-type machines, the ball is often loaded directly by dead weights suspended on a stirrup, but for industrial use or for routine testing a system of levers, similar to that used in a weighing machine, is popular. A machine of this kind is shown in Fig. 221. It must be emphasised that for the small diameter balls and light loads used for testing thin, soft sheet the sensitivity required is considerably greater than that needed for the balls of 10 mm. or even 5 mm. diameter which are used for testing thicker specimens. For this reason tests using small balls and loads should never be attempted on lever machines built for large balls and loads.

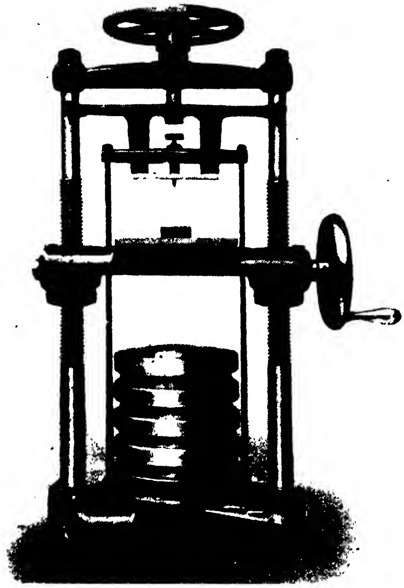
Besides the hardness tests already described, which have come to be accepted as standard and whose values are quoted freely, there exist a number of other hardness tests which, although less popular, are sometimes of value in special instances. Only two of these need be mentioned in connection with the testing of soft sheet metal.

Scleroscope Test. In this test, which is of more value for testing hard than soft metals, a small hammer having a specially shaped nose is allowed to fall from a set height down a glass tube. The height of the rebound is estimated visually by means of a scale attached to the tube, and a number of tests usually have to be made to get a fair average reading. Fig. 222 shows a scleroscope. The vertical tube can be raised off the base by means of a rack and pinion actuated by a knurled handle to enable a specimen to be inserted, after which it is lowered to clamp the specimen firmly in position. The hammer is raised and released pneumatically by means of the bulb seen connected to the glass tube of the instrument.

The scleroscope test is of doubtful value for the testing of thin, soft metal; with other more reliable tests available, its use for this particular application is not recommended. The readings tend to be erratic, and are unreliable unless all thin specimens are flat and in perfect contact with the supporting anvil; conditions which are not easily achieved.

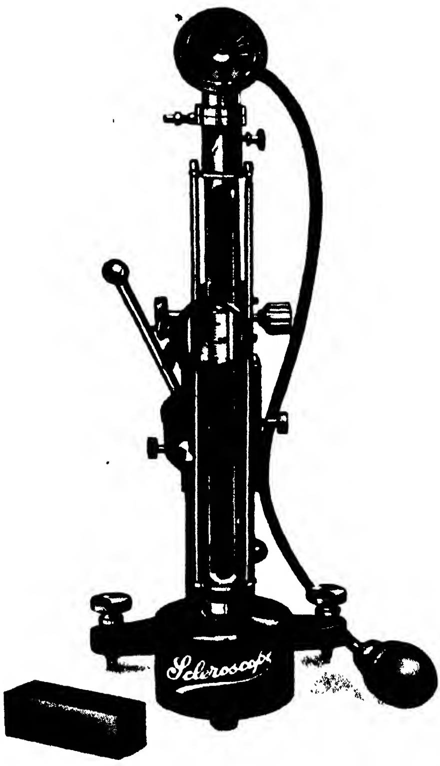
Herbert Pendulum Test. The Herbert pendulum, one model of which is illustrated in Fig. 223 (p. 475), is a novel and ingenious instrument which has not yet come into general use. The pendulum consists of a heavy balanced frame, of the shape seen in the photograph, having as its fulcrum a hardened steel ball. This ball is rested on the test specimen, displaced through a certain small angle and allowed to swing, the time of swing being the measurement usually taken, although sometimes other values are recorded.

The special feature claimed for this test is that, besides giving a measure of hardness, when used in a certain way it indicates the capacity of a metal to work-harden. As this property is of very great importance in any metal used for deep drawing and pressing, the test is one which must arouse the interest of all who are concerned with this application. Its value as a routine test seems doubtful, but as a research instrument it deserves the attention of those who have the



[*By courtesy of Alfred Herbert Ltd.*

FIG. 221. Brinell machine for use with balls of small diameter.



[*By courtesy of the Coates Machine Tool Co. Ltd.*

FIG. 222. The Shore scleroscope.

FIG. 223. The Herbert pendulum tester.

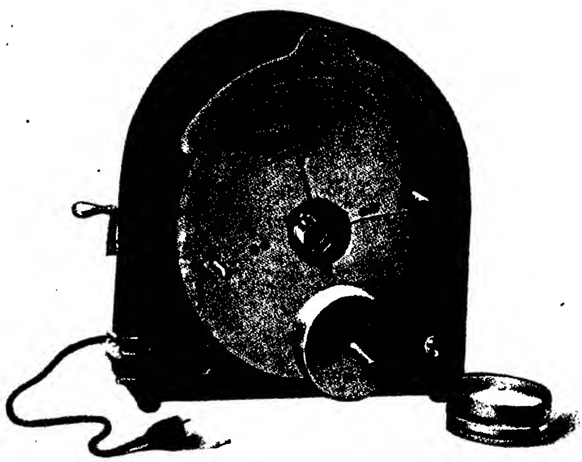


FIG. 224. Tour-Marshall bend-test machine.

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opportunity to master the rather skilful manipulation which is needed to obtain consistent results and the ability to interpret these in the light of present knowledge.

The great difficulty associated with the measurement of the hardness of sheet metal by indentation tests lies in the ease with which the indentor can penetrate sufficiently deeply for the impression to be influenced by the supporting anvil. To overcome this, departures from standard procedure have frequently been made with the result that, prior to the advent of the Vickers test (with its readily available light load for use on thin sheet) as a true standard for all thicknesses of sheet, considerable confusion arose owing to the use of different testing conditions in different works. It is quite common for Rockwell and even Brinell tests to be made upon sheet so thin that the hardness and smoothness of the supporting anvil influence the indicated readings to a considerable extent. To overcome this, two or even three thicknesses of sheet are sometimes placed under the indentor. This practice is bad because, unless all the specimens in the pile are flat and clean—*i.e.*, are in really good contact—true hardness values will not be obtained. With the Vickers machine a load as low as 1 kg. may be used, the impression produced by this minimum being so small that true hardness values may be obtained on very thin sheet, always provided that its surface is smooth and well polished. To minimise experimental errors it is, however, always advisable to use the heaviest load which the thickness of a thin specimen will allow.

Opinions differ as to the minimum thickness of sheet in relation to the depth of the impression which is necessary if true hardness readings are to be obtained by indentation tests. In Great Britain the issue of British Standard Specifications has helped to some extent to encourage the use of a proper minimum ratio between thickness of test specimen and depth of impression in static indentation tests. B.S.S. 240 (1926) adopts the recommendations of Moore,[97] who states that the depth of a ball impression should be not more than one-seventh the thickness of the test piece. B.S.S. 427 (1931), referring to the standard 136° diamond pyramid indentor, states that the thickness of the test piece should be not less than one and a half times the diagonal of the impression. While the figures just quoted may be satisfactory for steel, many authorities are of the opinion that they are inadequate for the softer non-ferrous metals, for which there have been suggested relative thicknesses of metal ranging up to twice the values just stated for ball and pyramid respectively.

Fortunately a very simple and in most instances safe check exists : if, after the test, any visible mark appears on the side of the specimen which is in contact with the anvil, indicated hardness readings may be erroneous. A very slight mark is usually indicative of only a small, and often negligible, error; although aluminium provides a notable exception to this generalisation.

In the routine testing of sheet metal, particularly with the Rockwell machine, conditions are often such that a very definite mark is formed on the reverse surface of the specimen, and the indicated value is certainly not a true one. Under these conditions the rapidly-made Rockwell test can still be of real help as one of *comparison* (as indeed a large proportion of works tests are) provided that at no time are the values so obtained returned as, or compared with, true ones. When the surface of the anvil is kept smooth and of constant hardness, this method of test tends to be more reliable than the one in which an attempt is made to obtain true hardness values by using a specimen consisting of two or more pieces of sheet placed one upon the other.

To conclude this review of hardness testing machines, warning must be given against the practice of converting readings obtained on one type of machine into readings or values which belong to another (for example, Rockwell readings into Brinell numbers) by reference to published conversion tables. Values obtained by conversion this way are often incorrect and therefore misleading and productive of errors. A different conversion scale or factor is needed for different metals and, moreover, even for different states of the same metal. For example, different scales are needed for the conversion into Brinell numbers of Rockwell values obtained on, say, annealed brass, work-hardened brass, annealed steel and cold-worked steel. If for some reason it is desired to express hardness on two scales, it is always better to give separately determined values; the fact that these values will usually differ from supposedly equivalent ones given in published tables need cause no apprehension.

Bend Tests

This group embraces such widely different tests as simple flexure of the corner of a sheet between human fingers, the 180° bend, and also the recording of precise measurements of load and deflection made on specially prepared strip specimens with the aid of a delicate machine.

Flexure between the fingers is probably the simplest test of any which will give at least a slight indication of the probable behaviour of sheet under the press. In this way an experienced man ean certainly form some opinion as to the hardness and "spring" of thin sheet, but the claims which are sometimes put forward for the significance of this test are grossly exaggerated. It is true that this test can enable any marked change to be detected in the hardness of sheet of assumed constant quality fed to the press; those who claim more find themselves at a loss when asked to predict the behaviour of samples of sheet of different metals and hardness without the help of standards.

One very important use of the bend test, often overlooked, is its ability to reveal the presence of severe internal discontinuities in sheet of outwardly satisfactory appearance ; it is, for this reason, of particular value as a rapid test for steel sheet in which this defect is suspected. Fig. 122 (p. 188) shows the kind of blister developed on the surface of apparently sound yet actually " laminated " steel sheet bent through approximately 90 degrees over the edge of a bench and then straightened. The simple bend test is also useful in confirming the existence of defects of the " spill " variety suggested by visual inspection of the surface of purchased sheet.

In many specifications there is included a clause which stipulates that the sheet shall be capable of being bent through an angle of 180 degrees and hammered flat upon itself, both ways of the grain, without showing cracks. As almost any deep-drawing quality sheet will pass this test, little useful selection can be made by it ; but, if the appearance of the outer surface of the bend be judged in the same way as in the Erichsen cupping test, it may be possible to obtain a useful indication of crystal size by comparison with known standards. If, having been bent through 180 degrees, the test piece is opened up until it cracks, some distinction between sheets of reasonably good quality is often possible, although it is questionable whether the physical properties thereby indicated are the ones which are of most importance during deep-drawing operations.

Crude bend tests are usually made on a strip cut from a sample by gripping one end in a vice and bending the free part of the strip over with pliers, either square-cornered or radiused vice jaws being used according to the fancy of individuals. A number of simple bend-test machines, devised primarily for " repeated reversed flexure " tests, are on the market, but many laboratories make their own machines for this purpose. There is available, however, the specially interesting machine shown in Fig. 224 (p. 475) which raises the bend-test from a qualitative test to a precise, quantitative method of measurement. Indeed, this simple machine, although employing bending as the method of deformation, enables a stress-strain curve resembling that obtained in a tensile test to be recorded with a fair degree of accuracy. A flat strip specimen, which may be either parallel-sided or —as appears desirable when a stress-strain curve is required—shaped to localise the deformation in a small area, is clamped to a spindle which can be rotated at the centre of a disc having its periphery graduated in degrees. As the free end of the specimen bears against a roller attached to a system of weights and levers by means of which a load can be applied and varied, rotation of the spindle produces a cantilever bending action in the specimen ; readings of load and deflection can be taken at desired increments of bend.

It is claimed that an accurate stress-strain curve can be obtained in this way, and published examples [98] reveal those differences in "yield-point elongation" which form such a useful indication of the tendency of steel sheet to develop stretcher-strain markings during deep drawing and pressing. In addition to the properties revealed by the tensile test, the "springiness" of sheet, a property which indicates the tendency of a pressed shape to "spring back" after release from the tools, can be measured by this test far more accurately than by hardness tests, the method usually employed. Correlation between the shape of the curve obtained and the "average grain size" of the specimen has been attempted with apparent success, but the fallibility of such a correlation must be acknowledged because hardness produced by cold-work will completely upset any relationship which may be justifiable in fully annealed metal.

This refined elaboration of the simple bend test possesses some advantages over the orthodox tensile test, chief among these being the low cost of the machine and the small space which it occupies, the elimination of an extensometer together with the manipulative skill needed for its successful use, and the relative speed with which a stress-strain curve can be obtained. Upon the evidence yet available, there seems no reason why this test should not become deservedly popular in routine examination as a substitute for the tensile test even when proper tensile testing apparatus is available and is still employed for special investigations.

A condition inseparable from the employment of bending as the method of deformation from which a stress-strain curve is constructed is that the properties of the outer layers of the specimen will be those which will be revealed in greatest degree, because these layers will suffer the greatest amount of deformation; whereas in a tensile test the values obtained will represent an average of those existing throughout the thickness of a strip specimen. This theoretical difference between a bend and a tensile test must not be lost sight of when tests are made on sheet which is suspected of being non-homogeneous, for example on "cored" steel sheet rolled from a rimming ingot.

Slotted-strip Test

A simple test devised by Siebel and Pomp [99] to give an indication of elongation under tensile stresses combined with bending stresses is that illustrated diagrammatically in Fig. 225. Two parallel slots, terminating in round holes to avoid tearing, are cut near the centre of a rectangular test piece. The slotted part of the test piece is then placed between a circular die and clamping ring, as in the Erichsen test; but, instead of a 20 mm. diameter hemispherical punch, a 20 mm. diameter roller having its axis at right angles to the slots in the sheet specimen is used to press the strip of metal bounded by the slots into a loop, as shown in the diagram. Fracture of the loop marks the end point of the test; the depth of the depression and also the elongation, measured after the loop has been flattened, are recorded.

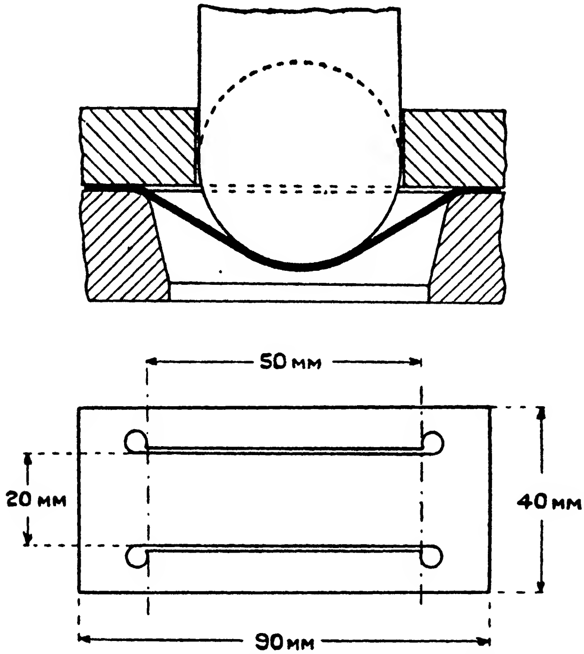


FIG. 225. Diagrams illustrating principle of slotted-strip test.
Top : Sectional elevation through tools and specimen.
Below : Plan of standard specimen.

This test is in some ways intermediate between the tensile and the Erichsen test, but it differs from the Erichsen in that no compressive stresses, causing "crowding" of the metal, are imposed on the

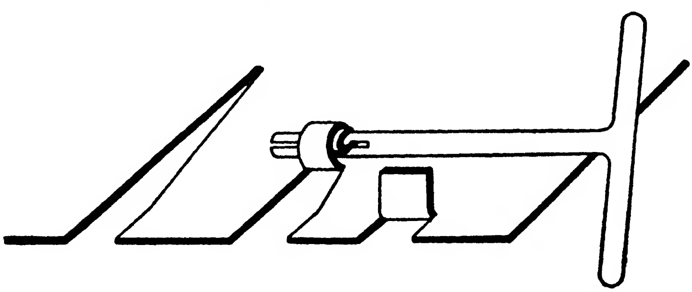


FIG. 227. Diagram illustrating use of slotted winding key in the "tear-length" test.

specimen. Therefore, although percentage elongation, a simple fundamental property of the metal, is measured, this test does not imitate industrial pressing conditions as closely as does the Erichsen test. The depth of the loop-depression must never be confused with the depth of an Erichsen dome, because the conditions of stressing and plastic flow are quite different in the two tests, and the percentage elongation value is not truly comparable with that obtained in an orthodox tensile test in which bending stresses are absent.

Tear-length Test

In the original form of this test, which the author believes is due to Brownsdon, two parallel slots are cut 1 cm. apart in the edge of the specimen parallel to the direction in which it is desired to make the tear. The resulting flap is gripped with pliers and pulled so that a triangular-shaped piece is detached from the sheet, the height of the triangle, measured in centimetres, being known as the tear-length value. In the typical example shown in Fig. 226 (opposite), tears have been made in three directions, namely, at 0, 45 and 90 degrees to the direction of rolling. The tendency shown by the 45 degree tears to turn from this direction into the direction of rolling is clearly visible.

Instead of using pliers the author prefers to wind back the flap of metal by means of a round, slotted rod in the manner indicated in Fig. 227. This refinement gives more consistent results, and enables thicker sheet to be tested than when the crude method of pulling by hand is used.

More frequent use of the tear-length test might well be made, for it is extremely simple, can be carried out without the aid of expensive equipment, yet yields information of genuine value concerning the severity of directional effects and, though in a less precise manner, the somewhat complex property best described by the unscientific term " tenacity."

Cupping Tests

The principle underlying all cupping tests is that a cup is formed in the sample of sheet to be tested by means of a punch and die mounted in some suitable press, usually with the assistance of a pressure-plate or clamping-ring. The depth of the cup which has been formed when fracture occurs is generally taken as the unit of measurement, but other values are used occasionally.

Sometimes it is claimed by practical workers that cupping tests give a wholly adequate forecast of the behaviour of sheet metal during deep drawing and pressing operations. Although this claim is unquestionably exaggerated, it is true that such indications as are given are specially valuable because the conditions of this test imitate more closely those which obtain during many actual deep drawing or pressing processes than, for example, do hardness or tensile tests. Because of this and also because they are simple and can be made quickly on small sample pieces of sheet, cupping tests have been deservedly popular in industry, and a cupping-test value sometimes forms part

FIG. 226. Result of tear-length tests made in three directions on 64/36 brass sheet 0·030 inch thick.

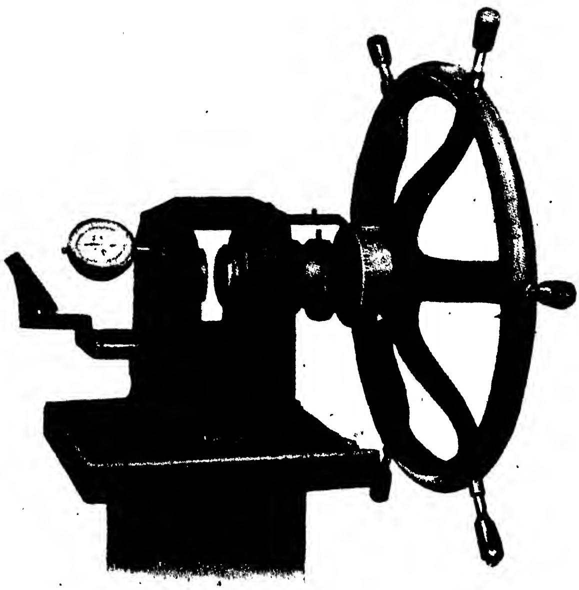


FIG. 229. Standard Erichsen Model I machine equipped with manometer gauge for indicating punch-pressure.

[*To face p.* 480.

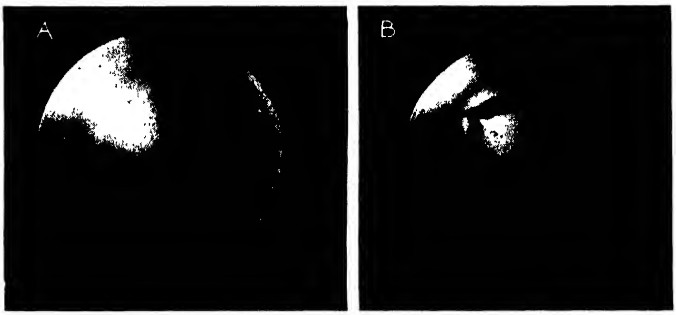


FIG. 232. Appearance of fracture in Erichsen domes as an indication of directional properties in the sheet tested.

A, sheet relatively free from directional properties.

B, sheet having pronounced directional properties.

[*To face p.* 481.

of a purchase specification for sheet which has to be worked under the press. The limitations of cupping tests have, however, long been recognised by all investigators who have made a study of the deep drawing and pressing properties of metal; so, now that more informative tests have been developed, it is possible that the use of simple cupping tests may tend to become less widespread. On the other hand, they may continue to be used to indicate the "probable similarity" of samples, in the manner already described for hardness tests. The special value of particular forms of cupping test will be discussed later.

The Erichsen cupping test has been, and probably still is, used more extensively than any other. This form will, therefore, be discussed in some detail, after which brief descriptions will be given of the Avery, Olsen, Amsler, Guillery, Jovignot, K.W.I. and A.E.G. cupping tests.

Erichsen Test. In this test, illustrated diagrammatically in Fig. 228, a flat, sheet specimen is held between a radiused die or draw-ring and a pressure-plate C, and a spherical-ended punch A is advanced by means of a screw and hand wheel. The "cup" or depression thus formed is increased in depth by advancement of the punch until the wall of the cup fractures locally. The depth of the cup expressed in millimetres is known as the "Erichsen value," and it is claimed that this gives a useful indication of the deep drawing and pressing properties of the sheet tested. This value, being the depth of cup, is indicated by a scale and graduated ring and can be read off at a glance. The punch pressure is not recorded as a rule, but the manometer attachment seen in Fig. 229 can be obtained for indicating the punch pressure throughout the test; it also gives a clear indication of the end-point of the test which, with soft sheet that fractures gradually, cannot always be ascertained as accurately as is desirable.

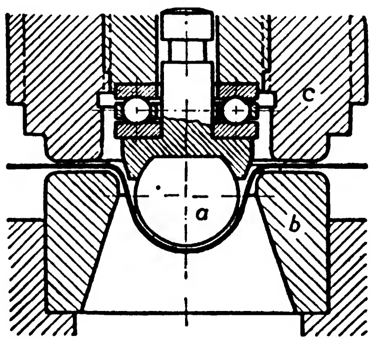


FIG. 228. Diagrammatic sectional elevation illustrating tools and principle of standard Erichsen cupping test.

The machine itself is of simple and robust construction. It consists essentially of a frame which carries the die and, when one is fitted, the pressure-indicating attachment. On the opposite side of the space left for the insertion of the specimen, the frame carries a screwed hole in which moves the spindle of the machine. This spindle consists of an outer screwed member which carries the clamping ring C (Fig. 228) and an inner screwed spindle which carries the hand wheel at one end and makes contact with the punch A at the other end through a ball race, so that the punch itself does not rotate with the spindle.

Before making a test it is necessary to adjust, and then lock, the clamping ring so that it leaves a definite clearance between itself and the face of the die in which the specimen can move. It is usual to screw the clamping ring up tightly and then to unscrew it to leave a clearance of 0·05 mm., the graduated ring of the machine being set to read zero *after* this adjustment has been made.

The machine illustrated in Fig. 229 is the standard Model I, which is suitable for testing sheet up to 2 mm. thick. Another model, having reduction gearing between the hand wheel and the punch spindle, is supplied for testing sheet up to 6 mm. thick. The standard tools comprise a punch with a hemispherical nose 20 mm. diameter and a die 27 mm. diameter. To enable proper comparisons to be made, it is essential that these standard tools are used whenever possible, but smaller ones are available for testing strip which is too narrow to allow a specimen of standard size, which is 90 mm. or $3\frac{1}{2}$ inches square, to be obtained.

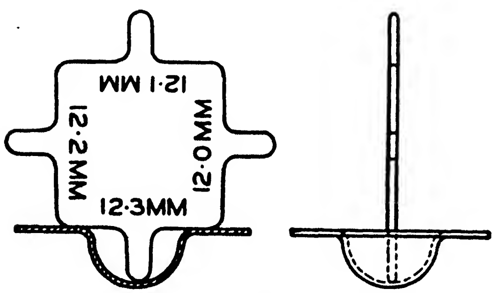
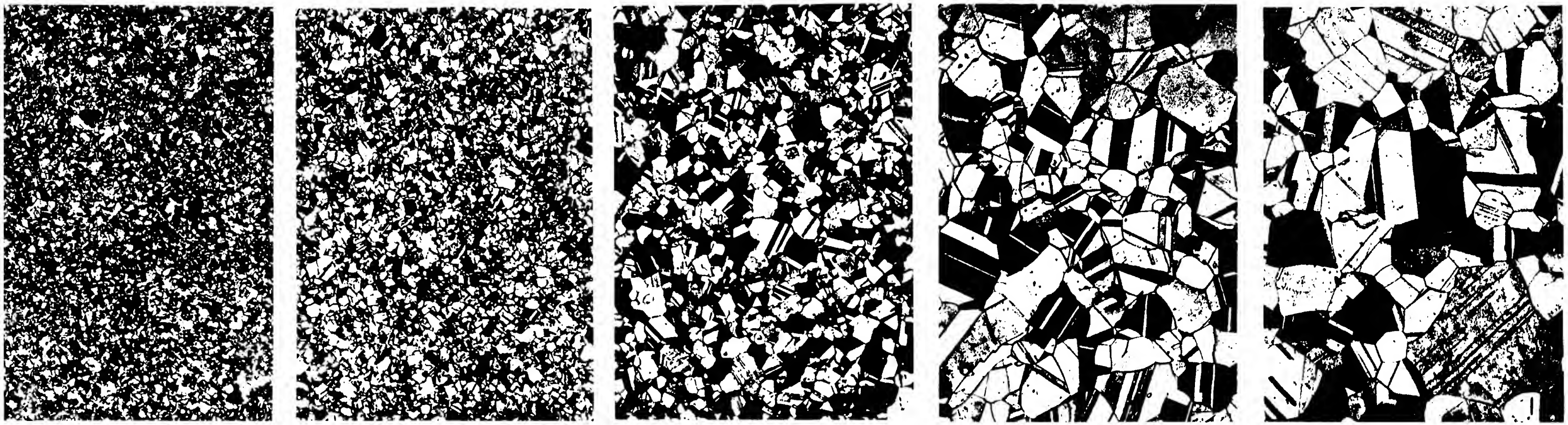


FIG. 230. Four-sided gauge for measuring depth of Erichsen cups.

Although the depth of the cup is indicated by the scale on the standard Erichsen machines, some laboratories find it useful to have a series of depth gauges by means of which the depth of an Erichsen cup can be quickly measured after a specimen has been removed from a machine and, perhaps, after pencilled figures made on specimens have become illegible. A typical gauge is shown in Fig. 230; prongs of various length are tried until one is found which, when placed inside the cup, allows the flat edge at the base of the neck to rest on the flat of the specimen while the tip of the prong just makes contact with the top of the dome.

Of equal importance to the numerical value which represents the depth of the cup made is the appearance of the surface of the dome after the test, as the degree of roughness is closely related to the crystal size of the metal. For this reason the appearance of the dome must be observed carefully and recorded in some manner. So close is the relationship between surface appearance and "average crystal size" that it is common practice to estimate the "average grain size" of samples representing bulk supplies of sheet by means of Erichsen tests alone. It is, however, highly desirable that proper microscopical examination should be made on a few specimens as a check.



0·014 mm. 0·025 mm. 0·045 mm. 0·10 mm. 0·20 mm.

12·5 mm. 13·0 mm. 13·5 mm. 14·6 mm. 14·6 mm.

Fig. 231. Relationship between crystal size and surface appearance of Erichsen dome with fully annealed 70/30 brass sheet, 0·040 inch thick.

Upper series: photomicrographs, × 75, with adjudged "average grain" size.
Lower series: convex sides of corresponding Erichsen domes, × 3, with height.

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Fig. 231 shows a typical comparison of "average grain size" as estimated by comparison of microstructures with the appearance of Erichsen domes. In this instance the metal is 70/30 brass of 0·040 inch thickness.

Intelligent operators can become remarkably skilful in assessing the deep drawing and pressing properties of metal from the appearance of the Erichsen dome, and can sometimes differentiate with certainty between roughness arising from too large an "average grain size" and the condition shown in Fig. 106 (p. 149), in which isolated crystals of a large size occur in a matrix of crystals of normal size. Mention has already been made of the rough surface sometimes produced during the deep drawing of brass which has been quenched; this roughness is revealed on Erichsen domes when no evidence is provided by microscopical examination of the metal itself.

In addition to the depth and the smoothness of the surface of the cup, the appearance of the fracture should also be noticed whenever an Erichsen test is made. If the fracture runs in an almost continuous circle round the wall of the dome, it is an indication that the sheet does not possess marked "directional" properties. If, on the other hand, the fracture tends to run in straight lines, the sheet certainly possesses marked directional properties. Fig. 232 (p. 481) shows two Erichsen cups which illustrate this difference quite clearly, but it is more usual for a "directional" fracture to take the form of a straight tear on one side, or sometimes on opposite sides, of the dome. A right-angle fracture such as that illustrated is relatively uncommon.

As is to be expected, the Erichsen test possesses certain disadvantages. One of these is that although any skilled operator can obtain very close and consistent results, the results obtained upon the same piece of sheet by different operators may not always agree within 0·5 mm. or even more. This is because the procedure adopted in making the test influences the results obtained, the principal variables being tightness of clamping between the rings, the state deemed to represent the end-point of the test and the amount of lubricant present on the specimen. End-point is difficult to define precisely, but attempts have been made to control the other two variables. It is, for instance, usually stipulated that the clamping rings shall be screwed up tightly (although "tightly" is not a precise term) and then eased off a definite amount, usually 0·05 mm., before the punch is operated. Similarly, it is often stipulated that brass shall be tested dry or that steel shall be covered with lubricant which shall be lightly wiped off with a rag prior to the test being made. Another variable condition which needs to be watched is the flatness of the specimen, for the use of too small, or curved, buckled or wrinkled pieces of sheet can affect the results obtained to a serious degree.

A factor not usually considered, which is undoubtedly the origin

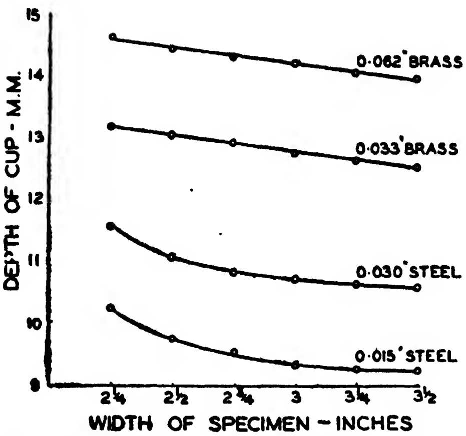


FIG. 233. Curves relating Erichsen value to width of strip specimen for annealed 64/36 brass and low carbon steel.

of some of the puzzling variations obtained in cupping tests based on the Erichsen principle, is the size of the test specimen. The standard size of 90 mm. or 3½ inches square is rarely adhered to in industrial routine testing; yet the very considerable influence of the size of the specimen upon the Erich sen value obtained from it, other conditions remaining constant, is illustrated by the curves reproduced in Fig. 233. These curves, which have been selected from a number obtained by the author, are to be regarded as illustrative rather than as charts of reference. It will be seen that, with brass sheet of the thicknesses commonly used for deep drawing and pressing, an increase in Erichsen value of no less than 1 mm. can occur as the size of the test square decreases from 3½ to 2½ inches, a range of size which is no greater than that found in ordinary works' testing practice. This variation is sufficient to allow the acceptance of unsuitable, or the rejection of suitable, sheet.

Other properties remaining constant, the Erichsen value is influenced by the thickness of the sheet upon which the test is carried out. Many graphs relating depth of cup to thickness of sheet have been published, but it is to be feared that some of these have been constructed without the exercise of a desirable amount of care in ensuring that the sheets of varying thickness used in the experiments did not vary in properties other than thickness; for example, in "average grain size." For

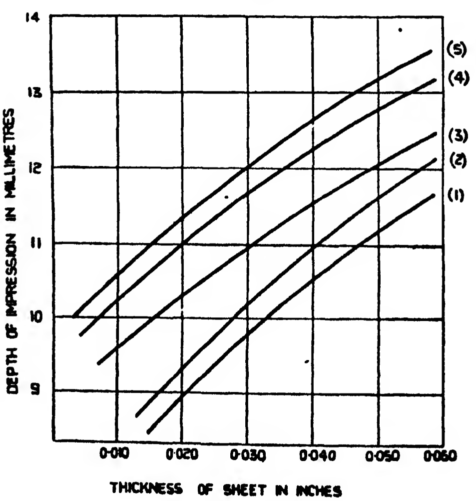


FIG. 234. Curves relating thickness of specimen to depth of cup obtained in Erichsen test.

(1) Low carbon steel, normalised.
(2) Low carbon steel, close-annealed.
(3) 63/37 brass, annealed.
(4) 65/35 brass, annealed.
(5) 70/30 brass, annealed.

this reason the curves shown in Fig. 234 are offered as a general indication of the relationship which exists and not as accurate charts from which values may be read. As stated in the caption, these particular curves represent the behaviour of brass and steel, and it must be emphasised that although the behaviour of many other metals is similar there are some exceptions. For example, the Erichsen values obtained on austenitic-steel sheet increase only slightly as the thickness of the sheet increases and—a notable exception—those obtained on magnesium-alloy sheet of "Elektron" type *decrease* as the thickness of the sheet increases.

In the tensile test it is established, although not always recognised, that percentage elongation values are influenced by the gauge length upon which this value is measured, and the gauge length is, or should be, always stated as, for example, "40 per cent. elongation on 2 inches." It is regrettable that a similar procedure is not always adopted with Erichsen values, as such a practice would render these values more readily comparable when the effect of thickness of specimen is appreciated, and would remove the confusion which sometimes occurs when it is not. This idea is commended to readers who, by adopting it, can increase the usefulness of their own results and help to make the practice a general one.

It seems fairly well established that the reliability of the Erichsen test as an indication of deep-drawing properties diminishes as the thickness of the sheet being tested decreases. For example, from the purely manipulative aspect its significance when used on tinplate of about 0·008 to 0·010 inch thickness is considerably less than when it is used on sheet of 0·020 inch or more thickness.

It is uncertain whether the speed with which the Erichsen test is made, particularly with the later type of low-geared machines, exercises any appreciable influence upon the results obtained. Gough and Hankins [100] state that with brass the influence of speed is negligible, but add that this may not be so with other metals. Mathewson, Trewin and Finkledey [79] record an appreciable variation in the depth of cups made at speeds varying between 0·34 and 5 feet per minute on zinc sheet.

In spite of its limitations, the Erichsen test remains, in the opinion of many practical workers, one of the most useful of any easily-applied routine test yet devised for use by operators of limited scientific attainments. It does not provide the reliable and complete indication of deep drawing and pressing properties which has sometimes been claimed in the past; but, when used for the routine examination of supplies, it does enable genuinely unsatisfactory sheet to be quickly detected. When, in addition to mere depth of cup, the appearance of the surface of the dome and the nature of the fracture are taken into consideration, a useful prediction of the probable behaviour of sheet during many deep drawing and pressing operations can often be made by men of experience.

Avery Test. The Avery cupping test, developed in Great Britain, is similar in principle to the Erichsen, both the punch and the draw-ring being of the same diameter and shape. The essential difference is that the draw-ring and clamping ring, which are easily reversible, are each serrated on one face. The specimen, which is in the form of a strip 2 inches wide, is tested first between the smooth faces adjusted to a clearance of 0·05 mm. as in the Erichsen test; a procedure which, of course, gives an actual Erichsen value. The tools are then reversed, the specimen moved along to expose a flat area, the serrated faces screwed up to grip the specimen tightly so that it cannot now flow over the radius of the draw-ring, and another cup is made. The depth of the second cup will be less than that of the first, and it is claimed that the difference, expressed numerically, gives a useful measure of certain properties, not measured by the ordinary Erichsen test, which are of importance during deep drawing and pressing operations. It may be that this test distinguishes between the two somewhat different properties termed "ductility" and "tenacity." If so, it is to be regretted that it has not attracted more attention, because in many industrial press operations the balance between these two distinct properties is of considerable importance.

A feature of the Avery apparatus is that it is portable and can be held in any substantial vice, whereas the Erichsen machine has to be fixed to a bench unless, as is done sometimes, it is mounted on a trolley which can be wheeled around a stock room. A disadvantage compared with the Erichsen test, when used for the routine examination of a large number of samples, is the longer time needed to make the full Avery test.

Olsen and Amsler Tests. These tests resemble the Erichsen in principle. Both have a spherical-ended punch 20 mm. diameter, but the diameter of the die or draw-ring is 50 mm. instead of 27 mm. as used in the standard Erichsen test.

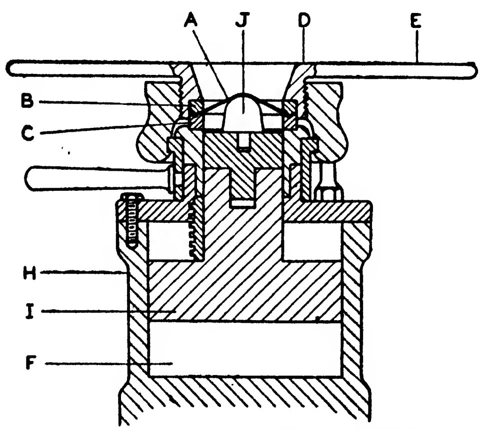


Fig. 235. Diagrammatic sectional elevation of Guillery cupping test machine.

Guillery Test. The Guillery test, developed in France, resembles the Erichsen in principle but, instead of pressure being transmitted from the screwed spindle to the punch by direct metal-to-metal contact, the punch is loaded by oil pressure generated by a screw pump forming part of the body of the machine. The pressure applied is indicated continuously throughout the test by a gauge connected to the pressure-chamber. The hemispherical-ended punch is of the same diameter, namely 20 mm., as that used in the standard Erichsen test, but the diameter of the die is 50 instead of 27 mm. although the test piece remains 90 mm. square. The test is stopped when the pressure gauge indicates a maximum value, both the pressure and the depth of cup being recorded. It is claimed that the Guillery apparatus gives a more precise end-point than that obtainable with the screw type of press as used in the Erichsen and similar machines.

Fig. 235 shows the Guillery machine represented diagrammatically. The specimen A is gripped tightly between clamping rings B and C, which have a mating ridge and groove to facilitate the making of an

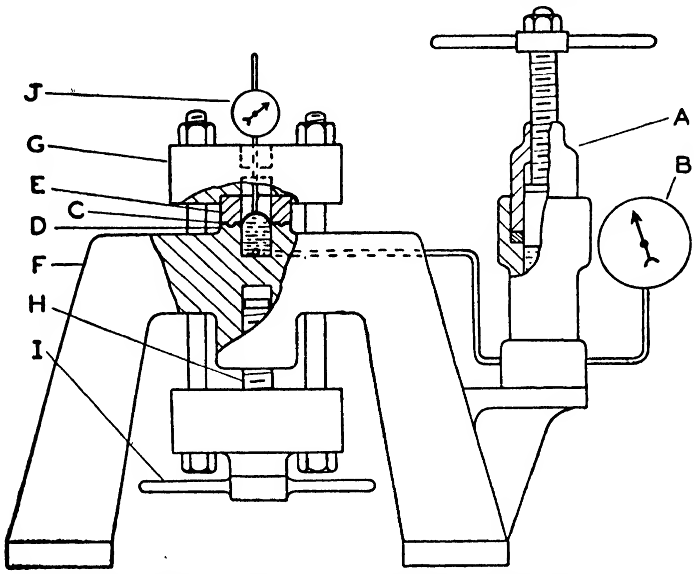


FIG. 236. Diagrammatic sectional elevation illustrating tools and principle of Jovignot cupping test.

oil-tight joint, forced together by means of the rotating top member D having handles E. Pressure generated in the chamber F in the main body of the machine H forces the piston I, and hence the punch J, upward.

Jovignot Test. The Jovignot cupping test, also developed in France, differs fundamentally from the ones already described in that the cup is formed not by a solid punch but entirely by fluid pressure acting on one side of a specimen clamped tightly between the flat faces of two rings. The Jovignot machine is illustrated diagrammatically in Fig. 236 from which it will be seen that fluid pressure, generated by a screw pump A and indicated on a gauge B, is applied to the underside of the specimen C which itself is clamped tightly between two rings D and E on whose faces there is a ridge and a groove to assist in the making of an oil-tight joint with the specimen. The lower ring D forms part of the main body F of the machine, while the upper ring E is attached to a sliding head G which can be raised to insert and remove specimens and pressed down upon the lower ring by means of the screw H and the handwheel I. A dial gauge J mounted on the head indicates the height of the dome formed. The Jovignot test can also be made in a Guillery machine in which the standard punch has been replaced by a piston and cup-washer, and the necessary modifications made to the clamping rings; but it is better to reserve this adaption for the testing of relatively thin sheet. The standard diameter of the ring used in the Jovignot test is 50 mm., although other sizes are used sometimes.

In making a test, both the depth of the cup at breaking point and the pressure applied are recorded, the Jovignot value or, as the originator describes it, "cupping coefficient" being the average increase in surface area of the test piece per unit area. This can be calculated from the simple formula

$$\text{Cupping coefficient} = \frac{h^2}{r^2}$$

where h is the height of the cup at fracture and r is the radius of the ring.

It will be seen that this test is in no sense a true drawing test; it can best be described as a "bulging" test. However, experience shows that it is not less useful than the more usual forms of cupping test in enabling the behaviour of sheet under the press to be predicted, and it possesses at least one unique advantage, namely, that if the dome is assumed to be spherical, the stress in the metal can be calculated by applying the formula for a thin sphere

$$\text{Stress} = \frac{PR}{2t}$$

where P is the pressure of the fluid, t is the thickness of the sheet and R is the radius of curvature of the sphere, or $\frac{r^2 + h^2}{2h}$. By taking a series of simultaneous readings of the pressure and the height of the dome, it is possible to construct stress-strain curves comparable with those obtained from readings obtained in an ordinary tensile test. But, because in the fluid-pressure cupping test the specimen is stressed uniformly in all directions, the curve will represent the behaviour of the sheet in its *weakest* direction, whereas a tensile test will represent behaviour in the *direction in which the test piece has been cut.* For this reason it is claimed that a single fluid-pressure cupping test provides more useful information regarding the tensile properties of sheet having "directional" properties than several tensile tests made on specimens cut from the original sheet at different angles, because none of the chosen directions may be the weakest.

The use of the Jovignot form of test to record both a "cupping coefficient" and also a stress-strain curve is particularly interesting, and has attracted the attention of several investigators. Pursuing this study, Gough and Hankins [100] have devised what they have termed the N.P.L. (National Physical Laboratory) machine, which, being of

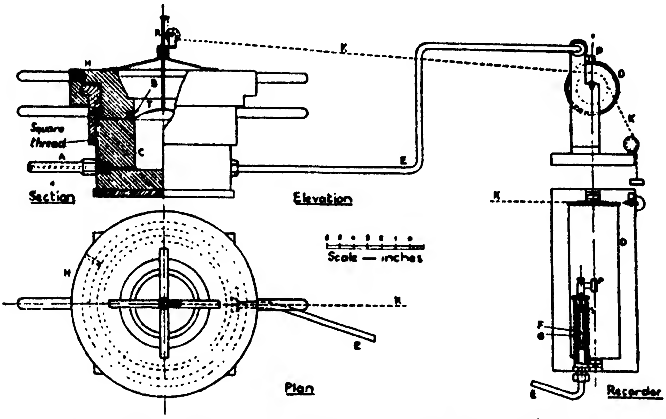
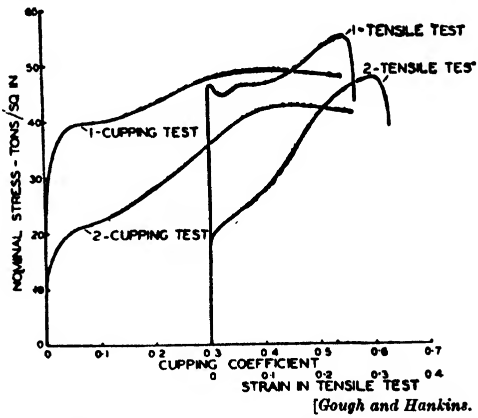


FIG. 237. N.P.L. oil-pressure cupping test machine.

very robust construction, can be used to test relatively thick sheet, and possesses the advantage that it automatically records a load-height curve on a revolving drum while the test proceeds. This machine, which is illustrated diagrammatically in Fig. 237, embodies a leather packing washer to facilitate the making of an oil-tight joint near the periphery of the specimen, thus eliminating a troublesome practical difficulty often experienced with the Guillery machine when thick sheet is being tested, and consequently high pressures used.



[*Gough and Hankins.*

FIG. 238. Comparison of stress-strain curves obtained on two samples of steel sheet 1 and 2 in (*a*) fluid-pressure cupping tests and (*b*) tensile tests.

Fig. 238 shows typical stress-strain bicurves obtained by the investigators just mentioned by means of the fluid-pressure and also the ordinary tensile test. It will be seen that the two sets of curves agree, but that no "kink" at the yield-point is discernible in the fluid-pressure curve. This may be due to relative insensitivity of the recording device, or else to the fact that in the cupping test the indicated yield-point stress is actually a *range* of stress, because the yield-point will vary in different directions of the sheet, whereas in a tensile stress the yield-point in only one direction is indicated. When it is desired to record the shape of the stress-strain curve at the yield-point, as in the testing of temper-rolled low-carbon steel, the fluid-pressure test cannot, therefore, be used to replace the ordinary tensile test.

Advantages claimed for fluid-pressure cupping tests compared with tests in which a solid punch is used are that errors attributable to friction between the metal specimen and the punch and die, due in part to varying degrees of lubrication, are eliminated; that the end-point of the test is more precise, and that results are consistent and reproducible, whereas those obtained with solid-punch machines of the Erichsen type are known to vary appreciably with different machines and operators. The principal disadvantage is that the method of deformation inflicted in fluid-pressure cupping tests is even more unlike that found in industrial deep drawing and pressing operations than in the Erichsen and similar types of test. Minor disadvantages are the practical difficulty of securing an oil-tight joint between the specimen and the clamping rings, and the unpleasant discharge of oil when the specimen fractures.

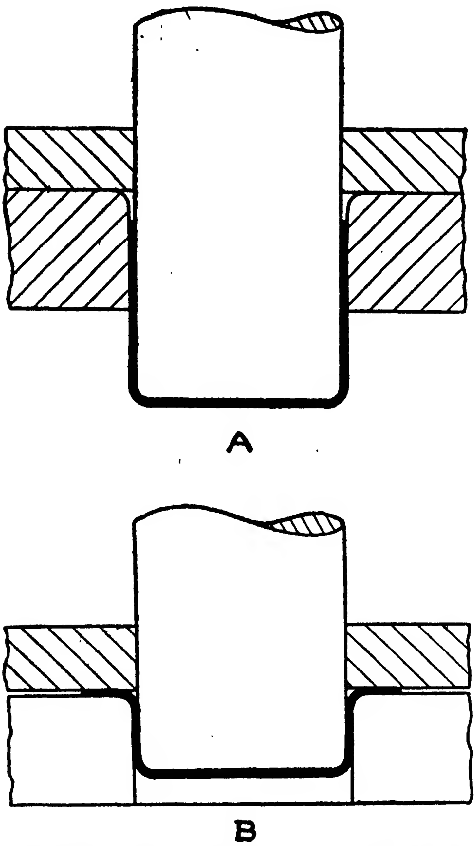


FIG. 239. Two methods of using cupping tools of A.E.G. type.
A. Cup drawn completely through die.
B. Flange of blank retained in clamping ring.

A.E.G. and Erichsen Deep-drawing Tests. These two important tests differ from the Erichsen, Avery, Olsen, Amsler, Guillery and Jovignot cupping tests in that the depression formed by an advancing punch is not hemispherical, but takes the form of a flat-bottomed cup with parallel sides. These tests will be discussed more fully under the heading of "actual drawing tests" because, as a rule, the cup is drawn right through the die as shown diagrammatically in Fig. 239A, and the property measured is based on the diameter of the blank which can be drawn without the cup tearing. They can, however, be used as a true cupping test in which the edge of the specimen is retained between clamping rings, as illustrated in Fig. 239B, and the depth of cup which can be drawn is taken as the recorded value. Used thus, however, their full capabilities are not taken advantage of; for this reason they are purposely not included in this review of true cupping tests in the generally accepted meaning of the term.

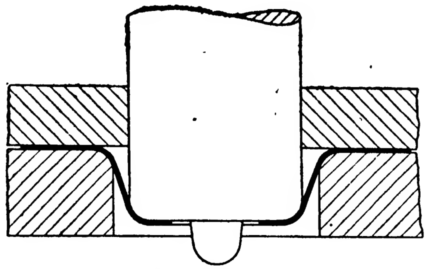


FIG. 240. Diagrammatic sectional elevation illustrating tools and principle of K.W.I. cupping test.

K.W.I. Test. The K.W.I. test, standing for Kaiser Wilhelm Institut where it was developed by Siebel and Pomp, is not really a true cupping test nor yet a true drawing test, but it may conveniently be included in the former category. It is sometimes described as an "expanding test." A machine similar in principle to the Erichsen is used, but the punch, instead of being hemispherical, has a flat, radiused bottom with a central circular projection which fits in to a hole made in the middle of a square specimen. By means of this punch, aided by the usual clamping ring and a radiused draw-ring, a flat-bottomed cup is drawn, the end-point of the test being the appearance of radial cracks at the edge of the hole. The K.W.I. value is expressed as the percentage increase in diameter of the hole at the end-point of the test, although sometimes the depth of cup drawn is also recorded as a second value. For the standard test, which is illustrated diagrammatically in Fig. 240, the diameter of the reamered hole is 12 mm., the test specimen is 90 mm. square, and the punch 40 mm. diameter with a 5 mm. radius.

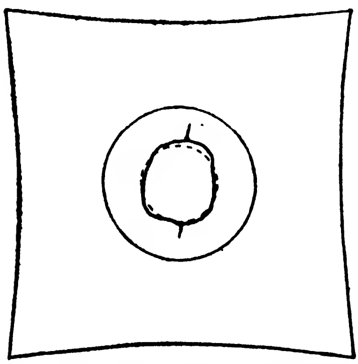
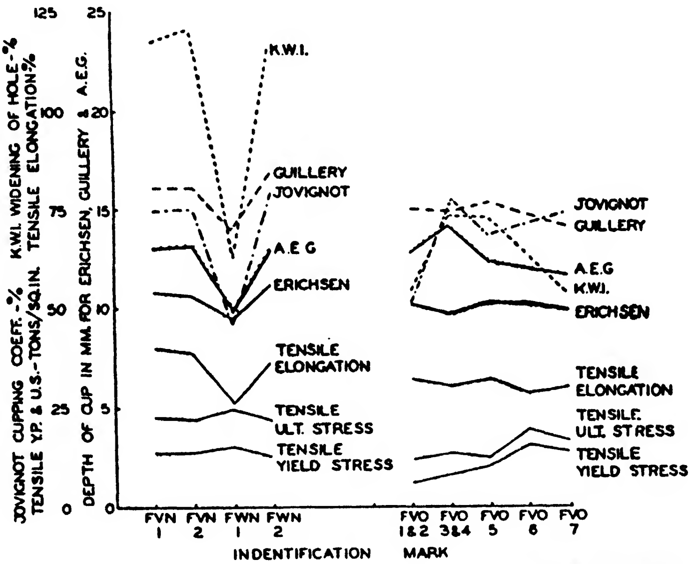


FIG. 241. K.W.I. specimen after test.

It is important that the hole in the specimen be drilled under-size and finished to size with a sharp reamer. If this is not done, values obtained will not be comparable, because the condition of the surface of the hole influences the diameter to which the hole can be expanded in sheet of constant quality.

The shape of the expanded hole is not circular when the standard square specimen is used, and an average diameter has to be estimated, although sometimes the diameter on the diagonals of the square is adopted as the value to be measured. A somewhat exaggerated impression of a square specimen after test is given in Fig. 241. The dotted line indicates the estimated mean diameter of the expanded hole. This departure from the circular arises from two causes, namely, the influence of the square specimen normally used and the influence of directional properties in the sheet itself. Owing to the restraining influence of the corners, the parts of the hole nearest the flat sides of a square specimen are more easily drawn away from the original circle; the influence of directional properties in the sheet needs no explanation.



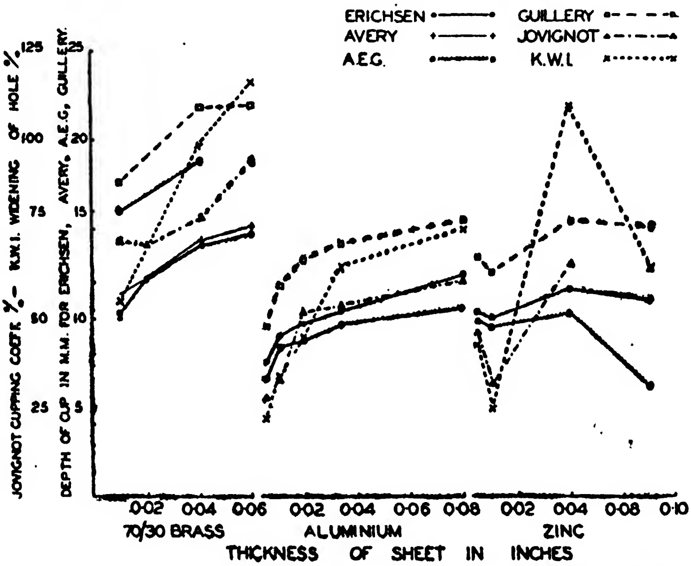
[*Gough and Hankins.*

FIG. 242. Comparison of cupping test values on samples of soft low carbon steel, bare (*left*) and coated with cupro-nickel (*right*).

Because of this, it is preferable to use a 90 mm. diameter *circular* specimen even though this increases the time taken to prepare specimens, a serious drawback in any routine inspection test.

It is claimed that the K.W.I. test distinguishes important differences in the deep-drawing properties of sheet which are not revealed by cupping tests of the Erichsen type, and that the indication of directional properties is better. Because of this, it is argued that the extra time needed to prepare specimens for the K.W.I. test is more than justified. The K.W.I. test is certainly of great interest, and it is to be regretted that its general use has not extended beyond the Continent.

Comparison of Cupping Tests. Many investigators have compared the results given, on specimens of similar sheet, by some or all of the cupping tests described in the preceding pages, and have attempted to correlate their findings with the ascertained behaviour of sheet in the press-shop. It is extremely difficult to draw definite conclusions from any of these comparisons. Sometimes general agreement is obtained between the results given by various cupping tests, as shown by the left-hand set of curves reproduced in Fig. 242. At other times the results given by some forms of cupping test are not in agreement with those given by other forms of cupping test or with the results obtained in tensile tests, as indicated in the right-hand set of curves in this same figure, and correlation with ascertained behaviour proves to be virtually impossible. A factor which renders comparison of cupping



[Gough and Hankins.

FIG. 243. Comparison of cupping tests on annealed 70/30 brass, aluminium and zinc, showing influence of thickness of sheet.

test values particularly difficult is that the influence of the thickness of the sheet tested varies with different metals and different forms of cupping test, as shown by the curves reproduced in Fig. 243.

It is not possible to single out any one cupping test as being superior to others. Certain peculiarities of each have already been mentioned, and it must always be borne in mind that not all measure exactly the same combination of physical properties. For example, the K.W.I. test, which seems to give a more "open" scale of values, stresses sheet differently from ordinary cupping tests of the familiar Erichsen type, while the same may be said of fluid-pressure "bulging" tests.

In spite of these discrepancies the fact remains that cupping tests are often very useful, during the routine examination of sheet, as an indication—with recognised limitations—of probable behaviour under the press, and even for the laboratory investigation of so-called deep drawing and pressing properties. It must, however, be emphasised that cupping-test values cannot be used as a *direct* indication of the probable behaviour of sheet in each and every press operation; indiscriminate use in this manner explains the discredit into which some of the popular cupping tests have fallen among both industrial and laboratory workers.

Actual Drawing Tests

Actual drawing tests can vary from a trial of a full-size blank in the actual tools used to form an article, to small-scale tests made in a miniature press which produces shapes either similar to, or dissimilar from, the article for which the metal is ultimately intended.

Little comment need be passed on full-scale tests. When they can be used, their value is unapproached by any other test as a means for ascertaining the suitability of a certain consignment of sheet for deep drawing or pressing under some particular tools; but sight must not be lost of the fact that full-scale tests do not give precise data concerning fundamental physical properties of sheet metal. Other disadvantages of full-scale tests are the expense of testing whole sheets of large size and, in many works, the fact that, if the appropriate tools do not happen to be assembled in a press when a consignment of sheet is delivered, tests cannot be made until these particular tools are set up and, in all probability, the sheet is urgently needed to enable production to be started.

Small-scale tests can be divided into two general groups. Those in which a model of the article to be produced is drawn in one or more stages under miniature tools, the only result of the test being the success or failure of a sample of sheet, no measurements being recorded; and those in which a simple cup is produced in a single-stage draw or, sometimes, in two successive draws in two sets of tools. In tests of this kind measurements are taken of diameter of blank, depth of cup —in which case the test becomes virtually an ordinary cupping test of the type already considered—or, occasionally, of some other value, such as blank-holder pressure.

Dealing with the first group, it can be said that this kind of test is not used to any extent. In the opinion of some authorities it is useful in determining the best shape for the tools needed to form a full-sized article, but it is necessary to observe certain precautions. For example, if sheet of the same thickness as that used in the full-sized article is used in the miniature tools, conditions will not be truly comparable. On the other hand, if sheet of much thinner gauge is used in the small-scale tests, fresh errors are introduced, for the familiar Erichsen test demonstrates very clearly that the depth of draw under a given set of tools is influenced by the thickness of the sheet used. Again, the speed of drawing is an important factor and, no matter whether this is made equal to the speed of the full-scale operation or modified to give a proper scale-effect, errors will be introduced.

Because of these and other difficulties, results obtained using miniature tools seldom provide a certain indication of the behaviour of sheet of given quality under larger tools used under industrial conditions. The main value of actual drawing tests lies, therefore, in the forming of some simple shape, usually a straight-sided cup, by methods which enable measurements to be recorded and an estimate of what are best described as fundamental deep-drawing properties to be made. Having these data, men of experience can often form a reasonably good estimate of the probable behaviour of sheet in any given industrial press operation.

Apparatus. Before examining the various procedures which can be adopted in the carrying out and recording of results of actual drawing tests, it is necessary to describe briefly the kind of machines used for such tests. These vary widely in size and sensitivity. The simplest is a hand-operated " fly " press of conventional type, in which the punch is attached to a slide actuated by a quick-action screw rotated by a handle which usually carries a heavy weight. No accurate control of speed or measurement of punch pressure is possible with a press of this kind, which is only useful for determining, with a certain margin of error, whether a blank will or will not draw through given tools. In spite of these shortcomings, useful results obtained on such presses have been published, although their value is not equal to that of results obtained under more closely controlled conditions.

The same criticism must apply to ordinary power-driven presses, although with these the speed of drawing can be kept more constant. With either kind of press the pressure-plate, when one is used, is independent of the press and usually loaded and controlled by adjustable springs.

For the proper study of actual deep-drawing tests in the laboratory more sensitive and elaborate apparatus is necessary. Investigators often construct machines to meet their own special needs, but an excellent example of apparatus suitable for general purposes is to be found in the standard A.E.G. machine designed originally in the laboratory of the Allegemeine Elektricitäts-Gesellschaft and since used by a number of workers.

This machine, illustrated diagrammatically in Fig. 244, consists of a stand A which supports the die and contains in its upper part a thread. Through this thread is screwed the main spindle B which can be turned with a hand-wheel and drives the punch through the die. The punch C is not fixed rigidly to, and is not rotated by, the spindle, but is attached to it by the pins D positioned in a relieved neck. The load is taken not by these pins but by the ridge on the punch-holder E.

from which it is transmitted to the membrane of the box F. This box is filled with liquid, for example glycerine, and the force applied to the die is thus transmitted to the liquid and registered on a pressure gauge connected to the box F. The die or draw ring E can easily be changed, but the standard diameter is 27 mm. with a 2-mm. radius. Attached to the base of the frame are pillars L on which slide both the pressure-box F and also the second pressure-box H for recording the pressure applied by the lower face of this unit which acts as a pressure-plate or clamping-ring, gripping the blank in the usual manner.

This machine can, obviously, be used either as a simple press for measuring the size of blank or depth of cup which can be drawn in the standard or in any other tools, or else as a valuable research tool for

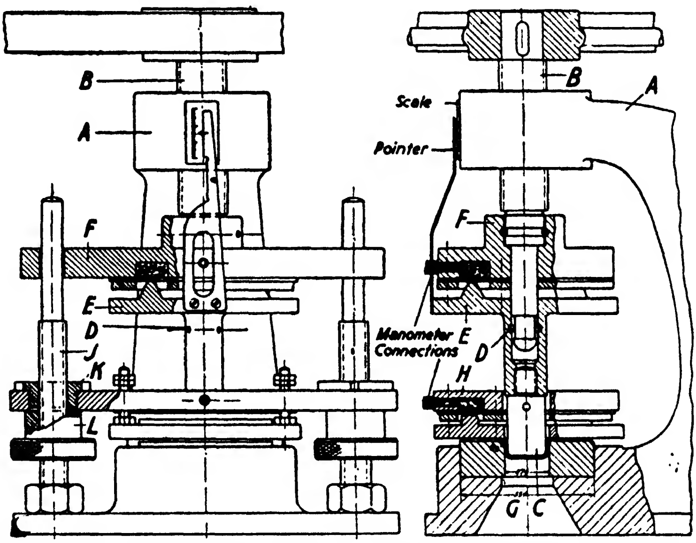


FIG. 244. Part-sectional front and side elevations of A.E.G. cupping machine.

measuring, in addition to these items, the punch load and pressure-plate pressure at all stages of a draw. It is therefore suitable for comparatively rapid routine testing as well as for more lengthy investigations, and forms a most valuable adjunct to any laboratory which has to deal with the testing of sheet metal and the general problems of the press-shop.

Other machines of this kind are available, but it is hardly necessary to describe these in detail. For example, certain models of the Erichsen cupping machine, one form of which has already been described (see Fig. 228, p. 481), can be fitted with standard tools of the kind illustrated in Fig. 245 by means of which parallel-sided cups can be drawn instead of the hemispherical cup which is usually associated with the name "Erichsen." A gauge can be fitted to indicate the *combined* load applied to the punch and pressure-plate.

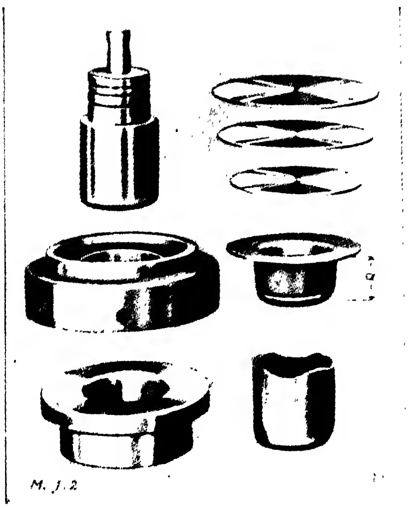


FIG. 245. *Left :* Set of first-operation tools for deep-drawing a standard cup in the Erichsen machine.

Right : Blanks, fractured cup drawn to depth " a " and completed cup.

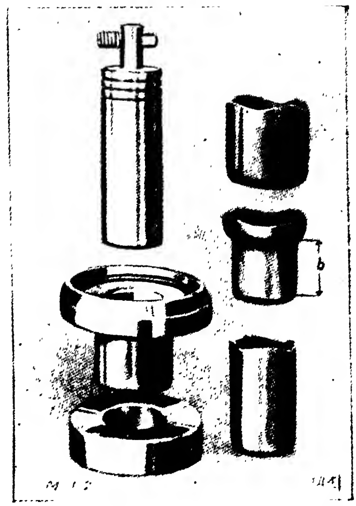


FIG. 246. *Left :* Set of re-drawing tools for deep-drawing a standard cup in the Erichsen machine.

Right : Cup from the first draw, fractured cup drawn to depth " b " and full-drawn cup.

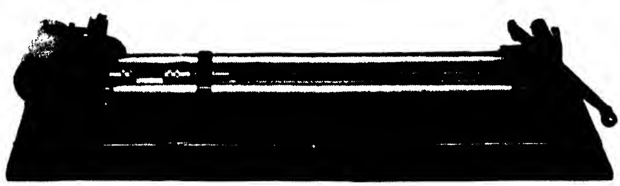


FIG. 248. Hounsfield tensometer.

[*To face p.* 496.

Fig. 246 shows a second set of standard tools which can be fitted to the Erichsen machine to enable a two-stage draw to be carried out. This is a useful addition and one which is not necessarily confined to the Erichsen range of apparatus although, as far as the author is aware, it is not listed as standard equipment on other machines. The advantages of a two-stage as distinct from a single-stage draw are discussed elsewhere.

Methods of Test. Turning from the machines on which actual drawing tests are made to the procedure used in making the test, it is easily seen that a number of properties or measurements can be recorded and used to express the result of any test.

On simple machines not equipped with pressure-indicating devices, records are usually restricted to the measurement of the maximum depth of cup which can be drawn from a blank of standard diameter or, alternatively, the maximum diameter of blank which can be drawn completely through the die, standard tools and as far as possible the same speed and standard conditions of lubrication being used in each instance.

The first method, which takes no longer than the ordinary hemispherical Erichsen cupping test, is by far the quicker. Some authorities are of the opinion, however, that a more useful indication of deep-drawing properties is given by the second method, which entails the accurate machining of a series of circular blanks of different size from the sample of sheet it is desired to test. Because of this, the first method can be substituted for the Erichsen cupping test in routine examination, but the second possesses many advantages when used for the less hurried laboratory examination of sheet. A compromise can be made in the routine examination of sheet of fairly constant quality by machining three, or in some instances only two, discs of a size which experience has shown to be such that their success or failure indicates whether the sample is up to standard. It is said that the greater sensitivity of this procedure over the " depth of cup " method justifies the time taken to machine the large numbers of test discs needed for the proper routine examination of purchased supplies.

Whichever method is used, the result will be influenced by the tools used and by the thickness of the sheet. Attempts are seldom made to express results in a manner indicative of fundamental deep-drawing properties. " Depth-of-cup to diameter-of-blank " ratios are sometimes quoted, but these are apt to be misleading unless considered in relation to thickness of sheet and shape of tools. The first variable is one which cannot be made constant; but standard tools could, and ought, to be accepted universally as has been done in the case of the Erichsen cupping test. Until this is done, proper comparison of the results of the numerous investigations made in many countries is impossible.

It has been said that in some instances a two-stage draw seems to be preferable to a single-stage draw. The real reason for this is not yet understood fully but, as first shown by the classic work of Gwyer and Varley [60] on the testing of aluminium sheet, a two-stage draw may reveal important differences in the deep-drawing properties of sheet which are not revealed by a single-stage draw.

Until more knowledge is obtained it is difficult to formulate any definite procedure for the carrying out of a two-stage drawing test, but two distinct aspects deserve attention. First, the ability of this test to reveal fundamental deep-drawing properties has to be investigated. Secondly, there has to be appreciated the great value of a two-stage laboratory test for determining in a precise manner the ratios of the first and second draws which will enable the maximum total depth of

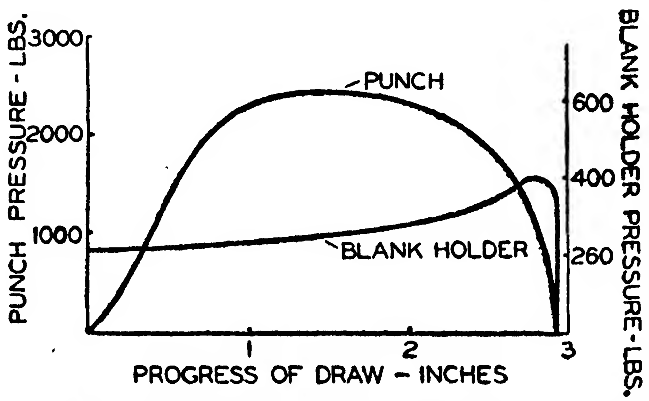


FIG. 247. Curves showing variation in load on punch and blank-holder during the forming of a simple cup 1 inch diameter from a brass blank 1¾ inches diameter and 0·020 inches thick.

draw to be accomplished. This is a most important matter, because available evidence shows that this ratio is of unsuspected significance, particularly in the case of certain metals, for example aluminium and the ferritic varieties of corrosion-resisting steel.

The value of simple drawing tests of the kind just described cannot be assessed too highly whether they are regarded merely as an acceptance test for sheet metal or as a means for investigating true deep-drawing properties. Still more information can, however, be obtained by the intelligent use of machines equipped with load-indicating devices, of the kind already described, which enable curves to be made relating punch pressure and pressure-plate pressure to depth of draw or any other property. A typical curve of this kind is shown in Fig. 247.

By means of tests of this kind it is possible to investigate not only the deep-drawing properties of sheet metal but also the influence of pressure-plate pressure, radii on punch and die, die angle, clearance between punch and die in relation to thickness of the sheet drawn, and many other important items. It can be predicted with certainty that increased knowledge of both deep drawing and pressing processes and also of the metal used in them will come very largely from results obtained during investigations made with the help of machines of this kind, that is, ones in which loads are indicated continuously during the deep drawing of a cup, these loads being studied subsequently in conjunction with the usual measurements of blank diameter, depth of cup and perhaps hardness and thickness maps of the walls of the cup drawn. To these data there may also have to be added certain physical properties of the metal, including the special forms of stress-strain curve mentioned elsewhere which give the best picture yet available of the behaviour of metal during the process of plastic deformation.

This review of cupping and actual drawing tests may well be concluded with another caution regarding the important, yet often forgotten, influence of speed of drawing and conditions of lubrication. Laboratory tests in the machines described are usually made at a much slower speed than that used in industrial practice, and this difference must always be borne in mind when attempting to relate laboratory tests to press-shop behaviour. At very slow speeds of drawing it is relatively easy to maintain adequate lubrication between the tools and the metal. Therefore, even though the same lubricant is used in the laboratory and the press-shop, proper allowance must be made for increased friction during most industrial deep drawing and pressing operations. Failure to appreciate the influence of speed of drawing and of lubrication often accounts for at least some of the observed differences between the behaviour of metal in the laboratory and in the press-shop.

Tensile Tests. The tensile test is so well known to all having any interest in the physical properties of metals that no detailed description of the testing machines used or of the procedure adopted in making this test will be given. It is hardly necessary to discuss the relative merits of single lever, multi-lever or hydraulic testing machines. Each kind has its advocates, but it may be accepted that any good machine, well maintained and used intelligently, will give results sufficiently accurate for all industrial testing and even for genuine research work unless extreme accuracy or special manipulation is needed.

The caution just given regarding the necessity for *intelligent* use is in point because too often a tensile testing machine is regarded as a kind of cash register into which the specimen is placed, a handle turned, and certain indicated values read off. If testing is done in this way, the best of machines will not indicate the true tensile properties of the metal being tested. For this reason proper supervision and the selection of trustworthy and well-instructed assistants for routine testing is essential.

Small firms are often deterred from tensile testing because of the high price of the orthodox form of machine. A miniature machine, which can be purchased for a small fraction of the cost of an ordinary tensile testing machine, is, however, available in the form of the Hounsfield Tensometer shown in Fig. 248 (p. 496). Although of such small size, this machine is admirably suited for the testing of standard, full-size tensile specimens of soft sheet metal up to a gauge length of 8 inches ; its accuracy has been well proved, and a useful attachment is available whereby stress-strain curves sufficiently accurate for most industrial testing can be plotted on a rotating drum as the test proceeds.

The tensile testing of sheet metal for use in the press-shop may conveniently be studied under two headings ; ordinary testing, in which the commonly-measured tensile properties are determined as simple numerical values, and special testing, in which some kind of stress-strain curve is plotted from readings taken during the test.

Ordinary Tensile Testing. The value of tensile testing as applied to sheet metal destined for the press-shop lies in the ability of this test to indicate precise quantitative values representing certain assumed fundamental physical properties, such as limit of proportionality, ultimate strength, percentage elongation and percentage reduction of area, which are not determined by the more empirical tests which sometimes seem to furnish a better indication of the probable behaviour of metal during deformation under the press. Its chief disadvantage is the time needed to carry it out, which, compared with the time taken to carry out a cupping or hardness test, is considerable.

During the making of a simple tensile test it is usual to record some or all of the following tensile properties : limit of proportionality (or else elastic limit or yield point), ultimate stress, percentage elongation and percentage reduction in area. Much confusion arises over the interpretation of the terms " limit of proportionality," " elastic limit " and " yield point." Unhappily, many laboratory workers regard these terms as synonymous with the methods adopted in their own practice, without thought of their true meaning. *Limit of proportionality* signifies the stress at which the stress-strain curve departs from a straight line. It is a property which can be determined only by making an accurate stress-strain curve, and the actual value obtained will vary considerably with the sensitivity of the extensometer employed, the skill with which the test is made, and the human factor in deciding the precise point at which the curve obtained departs from a straight line. *Elastic limit* is a term which is often used, quite incorrectly, in industrial testing to describe limit of proportionality and *vice-versâ.* The true definition of elastic limit is the stress at which a specimen just fails to return to its original length when the load is removed, as checked by an extensometer or, as is often done in industrial testing, by the crude method of applying dividers to a gauge-length marked by centre-punch dots or scribed lines on the bare, chalked or painted surface of the test piece. The value obtained will depend upon the sensitivity of the extensometer or the skill of the operator using dividers ; it will also be influenced by the finish on the test piece, and the value recorded may differ appreciably from the limit of proportionality. Both limit of proportionality and elastic limit will be influenced by speed of straining. *Yield-point* is the term reserved for the stress at which, as the load on the specimen is gradually increased, the beam of a lever machine drops or the pointer of an hydraulic machine recedes due to the specimen undergoing a relatively large increase in extension at a constant, or nearly constant, stress. This value is influenced by the skill of the operator and also by the speed of loading, while the distinctness of the " drop," as the fall of the beam in a lever machine is often termed, varies considerably with different metals. Each of these three values indicates, with varying degrees of accuracy, the stress, usually expressed as stress per unit cross-sectional area of specimen, at which strain changes from an elastic to a plastic nature.

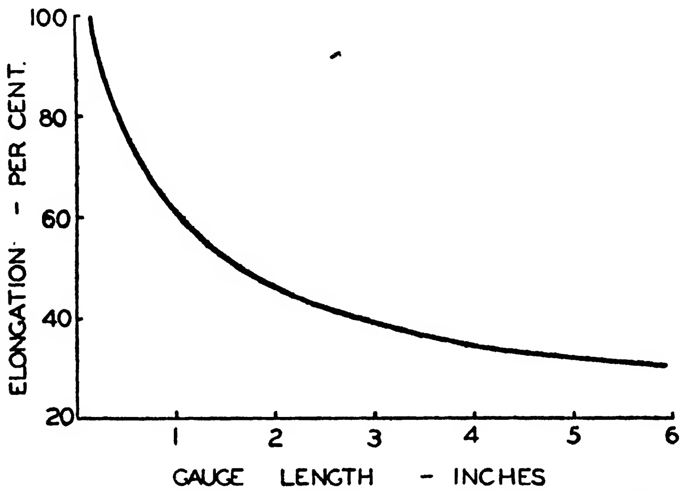
These cautions should be borne in mind when tensile values obtained from different sources are being compared. In some instances it may happen that the wrong terms have been used to describe certain values ; so, unless the conditions under which the tests have been made are known, it is usually best to regard values for the three properties just described as approximations. Ultimate strength, on the other hand, is a value which can usually be determined with fair accuracy on ductile specimens under normal conditions of testing.

The ultimate strength, or maximum stress, of a metal is the maximum load indicated by the machine during a tensile test converted to stress per unit cross-sectional area of the unstrained specimen. It is the most easily measured and most commonly quoted tensile value, and certainly forms a useful basis for comparison ; yet its true, and really empirical, nature ought never to be lost sight of. This aspect, which is discussed later in this chapter, arises from the fact that, due to the reduction in cross-sectional area which a specimen suffers during a tensile test, the area which sustains the indicated maximum load may be considerably less than the original area, which is the one upon which the maximum stress per unit area is calculated.

Percentage elongation, calculated from measurements made of the distance, before and after the specimen has been tested, between two marks made on the parallel portion of the test piece, is a tensile property which is often assumed to give a good indication of the ductility and, hence, of ability to suffer plastic deformation. Unfortunately, it is a property which is influenced very markedly by the shape of the specimen tested, particularly by the " gauge length " relative to the cross-sectional area; the longer the gauge length the lower the apparent percentage elongation of any given metal.

Many attempts have been made to relate percentage elongation to gauge length; the curve shown in Fig. 249 is typical of many which, although they may be true for some particular metal in a given condition, ought not to be applied indiscriminately to test specimens of all metals. This fact alone ought to bring about the universal adoption of test pieces of standard size and shape.

For the present it is essential that any numerical value for percentage elongation should always be qualified by the gauge length used. In Great Britain this is usually either 2, 4 or 8 inches, independent of the cross-sectional area of the test piece; although



[*Rollason.*

FIG. 249. Effect of gauge length upon percentage elongation of a low carbon steel tensile test piece 0·564 inches diameter.

sometimes 3 inches is used to accommodate certain popular makes of extensometer. In other countries it is usual to vary the gauge length in a rational manner to suit the cross-sectional area of the test piece. Sometimes the gauge length is made equal to $11{\cdot}3\sqrt{\text{area}}$ or $5{\cdot}65\sqrt{\text{area}}$, these values being equal, respectively, to ten and five times the diameter of a round test bar.

Another factor of considerable, and often unappreciated, importance is the thickness of the specimen, which is nearly always that of the sheet being tested. Standardisation of thickness would mean much laborious and difficult machining to prepare test pieces and, even then, a range of standard thicknesses would have to be adopted. Readers unfamiliar with the influence of thickness of specimen upon percentage elongation values are referred to a paper by Cook and Larke [101] which contains some interesting graphs and tables of results obtained with copper, brass and cupro-nickel showing how percentage elongation decreases with decreasing thickness of specimen, other conditions remaining constant. For fully annealed metals this drop is often very pronounced below thicknesses of 0·025 inch.

Reduction of area is a property which, in the opinion of many authorities, gives a better indication of ductility than percentage elongation. The reason for this is that, in a specimen of normal proportions, it is not seriously influenced by the length of the parallel portion, and also that the somewhat complex combination of physical properties indicated by percentage reduction of area measurements is even more closely related to actual deep drawing and pressing properties than percentage elongation.

Reduction of area is calculated by measuring the diameter of a circular test piece, or the two sides of a rectangular test piece, after fracture and relating these to the original area of the unstrained specimen. Exact measurement of the end of a broken test piece is often difficult and, unfortunately, particularly so in the case of thin strip specimens. Because of this, full use cannot be made of the important property of percentage reduction of area in the tensile testing of the relatively thin sheet usually used in the press-shop, and all values obtained in this way should be regarded as rough approximations unless special methods, too lengthy to be used in ordinary routine testing, have been employed.

The apparent simplicity of an ordinary tensile test engenders forgetfulness of a number of factors which can influence the results obtained to an appreciable extent, and can thus lead to the acceptance of untrue and therefore misleading results from recorded observations. It is hardly necessary to comment upon such very obvious sources of error as the insensitivity of extensometers, the degree of skill with which dividers are used to obtain an approximate indication of elastic limit, the accuracy with which distances between "pop-marks" or scribed lines are measured and, a matter of great importance yet real difficulty with thin strip specimens, the accuracy with which the area of the fractured ends is estimated. Important factors which are seldom appreciated by operators unfamiliar with the theoretical aspect of tensile testing are the shape and finish of the test piece, the methods by which the test piece is prepared, the angle at which the test piece is cut relative to the direction of rolling in a sample of sheet, the alignment of the test piece in the machine so that truly "axial" loading is obtained and, last but not least, the speed of straining.

Shape of Test Piece. The shape of the test piece used may have an important influence upon the results obtained, and it is regrettable that some standard specimen has not been accepted universally. Various bodies, such as the British Standards Institution, various Government Departments, the American Society for Testing Materials and others have laid down different standard shapes and sizes; but these are not always adopted in industrial testing. Some of them do not allow the limit of proportionality, or related value which forms part of the same specification, to be measured by certain popular

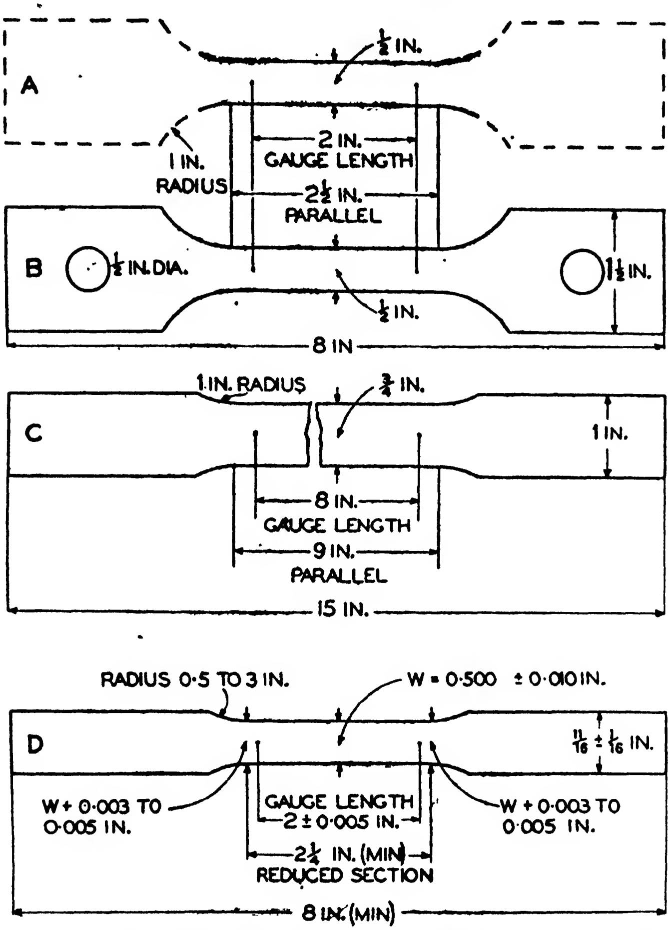


Fig. 250. Standard forms of tensile test piece for thin sheet metal.
A. British Standards Institution test piece for wedge grips.
B. British Standards Institution test piece for pin heads.
C. British Standards Institution test piece with 8-inch gauge length.
D. American Society for Testing Materials test piece.

forms of extensometer: a lamentable state of affairs which ought not to be tolerated in this age of supposed "scientific control." For this reason, comparison of tensile properties obtained by different investigators may lead to the forming of misleading conclusions. Universal standardisation of test pieces is needed badly. It is fortunate that, being relatively plastic, tensile specimens of the kind of sheet metal used for deep drawing and pressing are not as a rule influenced so markedly by radius of shoulder as are ones of less ductile metals. In spite of this, generous radii, merged smoothly into the parallel part of the specimen, ought always to be given, while the edges of the parallel portion should be as smooth as possible.

Fig. 250 shows several standard forms of tensile test piece for thin sheet metal. A is the standard B.S.S. (British Standards Specification) test piece having a 2 inch gauge length and plain ends to be gripped in ordinary wedge or V-type grips. B is the same test piece with the addition of holes in the ends which are placed over pegs in the two heads of the testing machine. Using this method it is easier to obtain an axial pull because the specimen is free to move, as it will always try to do, into proper alignment when stress is applied; it is a pity that this form of test piece is not used more widely. C is the standard B.S.S. test piece having an 8 inch gauge length which is recommended when accurate measurement of percentage elongation is desired. D is the standard A.S.T.M. (American Society for Testing Materials) test piece. It will be seen that certain dimensional tolerances are given, that the radius of the shoulder is not definite but may be any size between 0·5 and 3 inches, and that a slight taper towards the centre of the parallel portion is actually specified.

The purpose of the taper is to encourage the test piece to break centrally between the gauge marks and not close to one gauge mark, or even outside the gauge length, in which case a normal value for percentage elongation will not be obtained. The practice of tapering test pieces having assumed parallel sides in this way is not uncommon, and the provision of definite instructions relating to the degree of taper to be used is therefore very desirable because the amount of taper does influence the results obtained, particularly those relating to percentage elongation. Rodgers and Wainwright,[37] investigating the influence of a gradual "waist" made in the middle of a strip specimen of form C, Fig. 250, have published the following table of values for low carbon steel sheet in the annealed condition and also cold-rolled to 20 per cent. reduction in thickness.

Annealed

Total Reduction of Waist. In.	Final Dimensions. In.	Maximum Strength. Tons per sq. in.	Elongation on 8 in. Per cent.	Elongation on 2 in. Per cent.
Parallel	0·704 × 0·038	24·95	28·15	39·5
2 × 0·0025	0·698 × 0·038	24·35	24·55	37·0
2 × 0·005	0·694 × 0·038	24·65	24·40	35·0
2 × 0·010	0·685 × 0·038	24·55	21·15	32·0
2 × 0·015	0·670 × 0·038	25·25	19·95	26·75
2 × 0·025	0·651 × 0·038	25·10	17·45	26·0

Cold-reduced 20 *per cent.*

Total Reduction of Waist. In.	Final Dimensions. In.	Maximum Strength. Tons per sq. in.	Elongation on 8 in. Per cent.	Elongation on 2 in. Per cent.
Parallel	0·706 × 0·038	36·65	2·5	6·0
2 × 0·005	0·694 × 0·038	36·6	2·3	6·25
2 × 0·010	0·685 × 0·038	36·75	1·75	5·0
2 × 0·025	0·651 × 0·038	36·8	1·1	3·05

These results show that a "waist" representing a reduction in width of specimen of only a few thousandths of an inch can influence the indicated percentage elongation in a marked manner. It follows that the all-too-popular practice of tapering specimens at the discretion of the mechanic making the test piece cannot be condemned too strongly, and that even when, to facilitate testing under industrial conditions, a very slight taper or waist is allowed, it is questionable whether the values obtained ought, as is usually done, ever to be returned as true ones, particularly in the case of percentage elongation. For laboratory investigations, it seems most desirable that a truly parallel test piece be used always.

From the results just quoted it will be apparent that the standard A.S.T.M. test piece shown at D in Fig. 250 will, by reason of its taper amounting to a reduction in width of from 0·003 to 0·005 inches, give results for percentage elongation which are noticeably low.

Method of Preparation. All the commonly-recorded tensile properties are influenced by the condition of the edges of the parallel portion of the test piece and, consequently, by the method of preparation used. This is due to two distinct causes, namely, surface irregularities and local work-hardening.

Without doubt the most satisfactory method for preparing tensile test pieces from thin sheet metal is to clamp a strip between thick plates and to machine the whole assembly to the desired shape with a spiral milling cutter, care being taken to avoid "chatter" markings. To save time it is convenient to machine a number of strips, clamped tightly together between plates, at one time, and a further saving can be made by starting with roughly-shaped blanks and clamping plates. During the final stages of shaping, very light cuts with a really sharp cutter should be taken to ensure that the unavoidable surface disturbance penetrates to as small a depth as possible.

Even when batches of specimens are milled together this method of preparation is slow; so, when large numbers have to be prepared for routine examination, a common practice is to blank the complete test piece from the sample by means of a punch and die set up in a press. This is quite satisfactory provided that the cutting edges of the blanking tools are kept sharp, that several sets of tools having clearances suitable for sheet of different thickness are available and that, to avoid changing the tools, sheet is not blanked in tools having an unsuitable clearance. The use of blunt tools or unsuitable clearances will produce a badly burred and work-hardened edge on the test piece, which will then give misleading tensile values. Experience shows that less severe work-hardening is produced at the sheared edges of test pieces if each side is blanked separately, because, when this method is adopted, it is possible to adjust the punch and die to finer clearances than when the two sides are blanked together. A suitable stop is easily arranged to ensure that the width of the test piece is correct when the two-operation blanking method is used.

It is a debatable point whether the edges of blanked test pieces should be finished off with a fine file. Some workers prefer to do this; but, unless care is exercised to avoid the formation of scores and distinct file marks, the last condition may give even more misleading results than the first. Provided that care is taken to obtain a cleanly cut, sharp-edged blank, it is probably best to leave the edges untouched, particularly when, as is usual, the results of routine tests are needed for the purpose of comparison rather than as true fundamental values for the properties of the sheet tested.

It is recognised that the effect of notches of appreciable size is to reduce the percentage elongation obtained on a test piece and to alter the other tensile properties in rather less degree. It is interesting to observe that although what may be termed "micro-notches"—for example, those left by a fairly smooth file—influence the tensile properties in the usual manner, their presence also tends to make a stress-strain curve lean further away from the load axis. This is explained by the fact that, owing to the high local stress concentrations produced at the roots of the tiny notches, small amounts of localised permanent strain take place well below the nominal elastic limit of the steel being tested.

Angle relative to Direction of Rolling. It is explained elsewhere that many of the physical properties of sheet metal differ according to the direction, relative to the direction of rolling, in which these properties are measured. This fact must always be borne in mind when a tensile test piece is being prepared or when the results of tensile tests are being considered.

As a general rule tensile test pieces are cut parallel to the direction of rolling, unless several pieces are cut from one sample of sheet at different angles for the express purpose of investigating the degree of "directionality" in the sample. When single tests are made, this direction, or some other dictated by special requirements, should always be adhered to; results obtained with test pieces cut at random angles from different samples do not enable a proper comparison of tensile properties to be made. It is necessary to remember, however, that in any metal which possesses distinct "directional" properties the values obtained in *one* direction are not typical of the sheet as a *whole*. In consequence, a sample which gives a good figure for percentage elongation in a tensile test may fail under the press owing to the elongation in some other direction being below normal.

Alignment of Test Piece. The ease with which strip test pieces can be inserted and gripped in the V-block jaws of a tensile testing machine often leads to the use of grips and heads which do not strain the test piece in a truly axial manner. Fortunately the softness and high ductility of deep-drawing quality sheet renders errors due to non-axial loading, and also to stress concentrations produced by unnecessarily large "pop-marks" or scribed lines for divider or extensometer manipulation, less serious than might be expected; but this should not be construed to mean that reasonable care in the preparation, setting up and testing of specimens is unnecessary when results of any degree of accuracy are desired. The use of pin heads in conjunction with the form of test piece shown at B, Fig. 250, instead of ordinary wedge-type grips, is always a wise precaution even with soft metals.

Speed of Straining. Little attention is usually given to the influence of speed of straining during the making of a tensile test. It is often assumed that, within the range normally used in both laboratory and industrial testing, variation in speed has a negligible influence on the results obtained. This assumption is not always true; indeed, unscrupulous operators sometimes take advantage of the increase in indicated limit of proportionality, yield point and ultimate strength which can be obtained by increasing the speed of straining. This increase is due partly to simple over-running of the indicated load and partly to a genuine raising of these properties by increasing speed of straining. The first cause hardly calls for comment, but the second is one which has attracted the attention of a number of investigators. In particular, it has been shown that limit of proportionality and the shape of the stress-strain curve can be influenced in a marked manner by varying the speed of straining, an interesting fact which has already been illustrated in Chapter VII in connection with stretcher-strain markings in low-carbon steel. The other tensile properties are also influenced by speed of straining and, although this influence does not usually seem to be considerable until relatively low or relatively high speeds are reached, it ought not to be assumed that the influence of speed is entirely negligible within the range of speeds ordinarily used in industrial tensile testing. The increasing popularity of hydraulically-actuated tensile testing machines, which greatly extend the range of speed available by a mere turn of a valve, makes this caution all the more necessary.

These observations will at least serve to show that care and a certain amount of knowledge is essential if true results are to be obtained in the tensile testing of thin sheet-metal. It may be argued that the precautions indicated are necessary only when accurate results are desired during an investigation of the properties of sheet in the laboratory. Although this may be true to a certain extent, it is equally true that the somewhat haphazard methods sometimes used in industrial routine testing give results which may be genuinely misleading. In such instances the exercise of a little more care, coupled with the recognition of facts which by now should be common knowledge, would enable relatively reliable and accurate results to be obtained with very little increase in the time or expense of routine tensile testing.

Until a test piece of standard form becomes accepted universally, proper comparison of tensile values obtained by different investigators is rendered difficult, and often impossible. Published values ought really to be accompanied by particulars of the dimensions of the test piece, the method of preparation, the angle relative to the direction of rolling of the sheet, the amount of taper when any is given, the gauge length, the method used to determine the limit of proportionality or elastic limit, and even the rate of straining. It is too much to expect all these particulars to be given in every report of a tensile test, yet they ought not to be omitted from a report of any investigation of a research nature which is likely to be read by other investigators who will compare the values given with their own or with those given in other published work.

TEST PIECES OF SPECIAL SHAPE. A variation of the tensile test, which must be classed as an "ordinary" kind because only the ordinary tensile properties are recorded, is one in which a tensile specimen of special shape is used. The most usual form is one of normal outline but having a hole situated in the middle of the parallel portion. It is claimed that a test piece of this kind gives a better indication of the probable behaviour of sheet under the press than one of standard form, but its value as a test is lessened by the fact that the "tensile" properties recorded on it are not comparable with those recorded on a standard specimen, and ought never to be quoted as such. Critics of this test point out that it adds yet another to the many forms of special tests already devised, and that it is undesirable because it is of a more empirical nature than an orthodox tensile test. On the other hand, if experience shows that it gives a better indication of deep drawing and pressing properties than the ordinary tensile test, its neglect would be foolish. It is perhaps not a coincidence that the inclusion of a hole in the specimen used in the cupping test, a feature of the K.W.I. test described elsewhere, is claimed to increase the value of this test as an indication of the probable behaviour of sheet under the press.

It is difficult to assess the value of ordinary tensile testing as an indication of deep drawing and pressing properties, whether it be used as a routine or as a purely investigational test. The use of the special methods described later gives much more information, but, unfortunately, they take even longer than the simple tensile test which is itself criticised adversely as a routine method of examination on account of the time needed to carry it out.

Percentage elongation—still more percentage reduction in area when this property can be measured with reasonable accuracy—certainly gives a useful indication of ductility. On the other hand, the common assumption that a low limit of proportionality associated with a high ultimate strength represents the best combination of tensile properties is not always justified. The peculiarities of each particular metal, and also of the shape to be formed under the press, must be taken into consideration.

Whether, as a general rule, simple tensile tests are more informative than some of the much quicker cupping tests is a debatable question which can only be answered by experience under given conditions. The suggestion is offered that, when a " simple " tensile test is made, the extra time taken to make a " full " tensile test would often be well worth while unless tests are being made in large numbers in the course of routine examination.

Special Tensile Testing. Ordinary tensile testing, in which numerical values for certain tensile properties are measured—usually as rapidly as possible—is of unquestionable value in the routine examination of sheet when the main object is to check its uniformity, but it is explained elsewhere that the common tensile measurements give little indication of true deep drawing and pressing properties. If, however, special methods are adopted, the tensile test can give a really useful indication of these peculiar properties. In most instances these special methods entail the making of some form of stress-strain curve, and the first stage of this procedure is the measurement of the elongation or reduction in area suffered by an ordinary tensile specimen at small increments of stress. This is a laborious and lengthy task, but one absolutely necessary in order to obtain the data necessary to construct the special forms of stress-strain curve just mentioned. Elongation is usually measured by means of an accurate extensometer up to the limit of proportionality, but when this is passed the relatively rapid elongation of the test piece makes it necessary to estimate extension with the aid of dividers or, if more accurate methods are desired, with the help of some dial-gauge or " clock " form of extensometer. The advent of some device which would record these changes, particularly reduction of area, automatically yet with a high degree of accuracy would be very welcome, and would give a great impetus to the use of this special form of tensile testing which at present has to be confined to research investigations in which time is relatively unimportant, and which are even then limited to a relatively small number of specimens.

Stress-strain curves may conveniently be studied under three headings : " ordinary," " actual " or " true," and " derived " curves.

ORDINARY STRESS-STRAIN CURVES. When the ordinary tensile test is performed with precision a stress-strain curve is made autographically during the test or, which usually gives more accurate results, plotted afterwards from measurements of elongation made at small recorded increments of load during the test. Values are usually expressed as stress per square inch, calculated on the original cross-sectional area of the specimen, and elongation expressed as a percentage of the original gauge length. This gives the familiar form of stress-strain curve illustrated by the lower curve in Fig. 251.

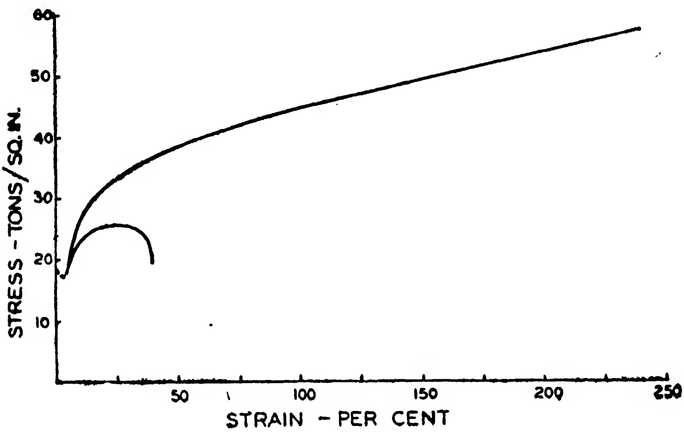
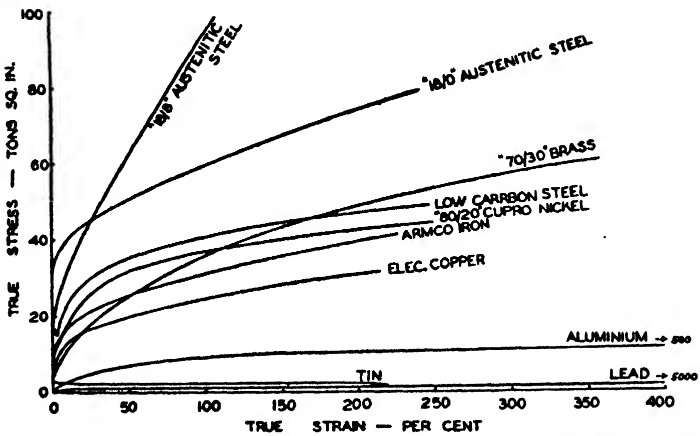


FIG. 251. Comparison of " ordinary " and " true " stress-strain curves obtained on the same specimen of low carbon steel. The lower curve relates nominal stress, and the upper curve relates true stress, to average elongation measured on a 2-inch gauge length.

A curve of this kind is of considerable, although limited, value in enabling the deep drawing and pressing properties of sheet to be assessed. Some laboratory investigators go so far as to say that the behaviour of sheet under the press can be predicted with certainty from a study of such a curve. This claim is certainly exaggerated, for a curve of this kind does not indicate, for example, directional properties —unless tests are made on a number of specimens cut at different angles relative to the direction of rolling of the sheet tested—" average " crystal size nor regularity of crystal size ; neither does it give a desirably complete picture of the way in which a metal work-hardens. It is, however, a useful aid in the comparison of different metals and even of different samples of sheet of the same metal, as well as in the study of true deep drawing and pressing properties. Unfortunately, the plotting of a stress-strain curve is too lengthy a procedure to be used in most routine testing, yet it is a task which should always be undertaken in any special examination, and one which is often pursued as a matter of interest even when the more informative "special" curves described later are constructed.

"True" (or "Actual") Stress-strain Curves. Continued familiarity with the tensile test as usually made has led to forgetfulness of its actually empirical nature. To construct an ordinary stress-strain curve, increments of stress are plotted against increments of strain, stress values being expressed as stress per unit area of the *original cross-sectional area of the unstrained test piece.* Clearly, as the test piece suffers a reduction of area during the test, the stress at the completion, and indeed at any stage, of the test ought to be expressed *in terms of the true cross-sectional area of the specimen at that stage,*



[*Swift and Sommer.*

Fig. 252. "True" stress-strain curves of some metals commonly used in the press-shop.

not that at the beginning of the test. When this is done, a true stress-strain curve is obtained which is very different in shape from the one usually drawn. Fig. 251 shows what is often termed the "actual" stress-strain curve for a specimen of annealed low-carbon steel; the lower curve represents the nominal stress calculated on the original cross-sectional area of the test piece and the upper curve represents the true stress calculated on the actual cross-sectional area of the test piece at any stage of the test, both kinds of stress value being related to average percentage elongation indicated on the horizontal axis of the graph. Up to the limit of proportionality the two curves can be assumed to be identical for most practical purposes, but it will be seen that, after this point is passed, the "actual" stress-strain curve departs abruptly from the "ordinary" curve and rises continuously to a stress value which, when the specimen breaks, is greatly in excess of that known as the "ultimate tensile strength" of the metal being tested. The terminal irregularity sometimes found at the end of curves of this and similar kinds is due to the difficulty of estimating the true cross-sectional area of the specimen at the fracture.

Clearly, the stress calculated on the actual area of the test piece at the breaking point is of much greater significance fundamentally than the nominal "ultimate tensile strength," and "actual" stress-strain curves of this kind give an informative picture of the behaviour of any metal within the range of plastic deformation. Fig. 252 shows typical "true" stress-strain curves plotted for a number of common metals from results obtained by Swift[102] and Sommer.[103]

From the particular aspect of deep drawing and pressing, an even more useful picture of the behaviour of metals within the plastic range is given by a "true" stress-strain curve in which the true stress is related not to the *average percentage elongation* but to *percentage reduction in area* calculated from measurements, made throughout the test, of smallest diameter at any position on the test piece, that is at the "neck." A typical curve of this kind is shown in Fig. 253. A point of interest in connection with this form of curve is that if the straight part of the curve is produced backwards, as indicated by the dotted line in this figure, it cuts the vertical axis of the graph at a stress value equal to the ultimate tensile stress of the metal determined by the orthodox method.

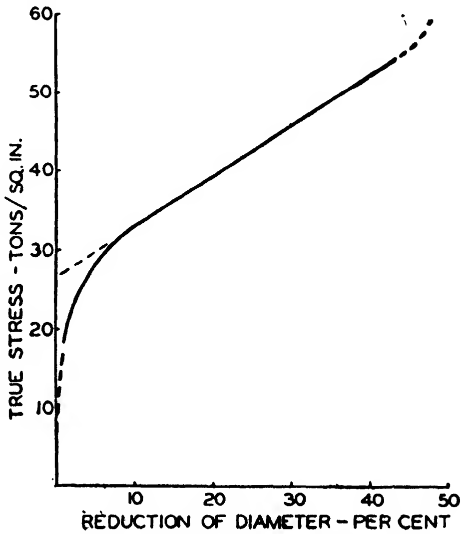


FIG. 253. "True" stress-strain curve, obtained on low carbon steel, relating true stress to reduction in diameter.

From a true stress-strain curve there can be seen the reduction in area which a certain stress will produce, the true stress which the metal will withstand—which is much greater than its nominal ultimate stress—and an idea can be formed of the rate of work-hardening of the metal being tested. This last item, which is of very great importance, is indicated by the slope of the upper part of the curve. Fig. 252 shows the true stress-strain curves of several of the common metals, and it will be seen how the slope of the curve of each metal differs.

Another form of curve is that in which true stress is plotted against true elongation. As normally measured the value described as elongation is actually an entirely *average* value, and it has already been shown how this value alters with the gauge length upon which it is calculated; that is, according to the length of specimen having a relatively large cross-sectional area which is included on either side of the "neck" for the purpose of calculating a percentage value. Even in a pronounced neck it can, however, be assumed that there exists an ideal, flat element of very small thickness which has suffered what may be termed *true* elongation; and if, during a tensile test, the cross-sectional area corresponding to each recorded increment of load is recorded, the true elongation can be calculated in a round specimen from the equation

$$E = \frac{A_o}{A} - 1$$

where A_o is the original cross-sectional area and A the area at any subsequent stage. Fig. 254 shows a curve relating true stress to true elongation for an annealed low-carbon steel.

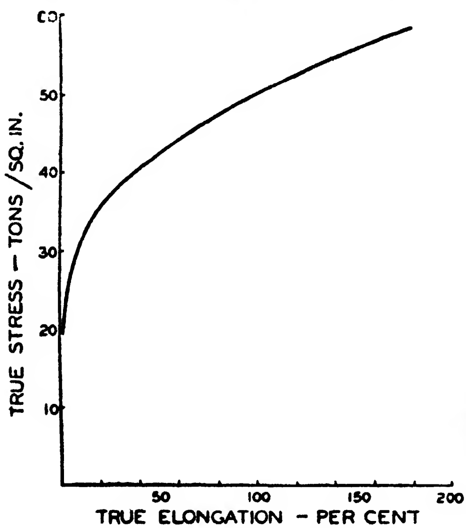


FIG. 254. "True" stress-strain curve, obtained on low carbon steel, relating true stress to true elongation.

"DERIVED" STRESS-STRAIN CURVES. Starting from one of the various forms of "actual" or "true" stress-strain curves, a number of "derived" curves can be obtained which, in the opinion of most authorities, give a still better indication of the behaviour of metal in the plastic range and, by inference, of deep drawing and pressing properties.

Norris [104] observes that curves relating true stress to true elongation, as shown in Fig. 254, display the form of a logarithmic curve of growth

$$S = KE^m$$

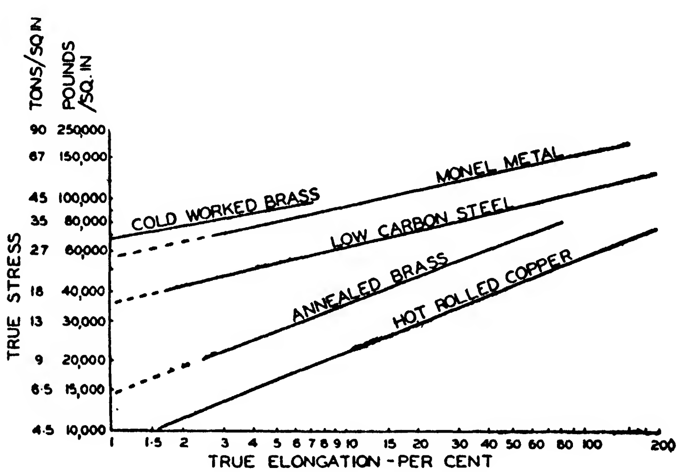
By plotting results on log-log paper this investigator obtained graphs of the form shown in Fig. 255, and found that the points always lay on a straight line except at the extreme ends. The small deviations at the beginning were attributed to yield-point phenomena, and those at the end to errors in measurement of the cross-sectional area of the specimen and to the release of elastic strain through fracture.

Norris points out that these straight lines indicate the relationship

$$\log S = m \log E + \log K,$$

where S is the true stress, E the true elongation and m and K are constants for any given metal. K can be regarded as a strength index, while m indicates the rate of work-strengthening, a most important item. The values of these constants can be calculated by selecting two points on a line, inserting the respective values for S and E in the equation given above, and solving the resulting equations simultaneously for the values of m and K. These two values appear to be of a more truly significant and fundamental nature than any of the common tensile properties, for upon them depends the mechanical behaviour of a metal within its plastic range.

An advantage claimed for logarithmic graphs of this form is that the behaviour of any metal throughout its entire plastic range is



[*Norris.*

FIG. 255. Logarithmic curves relating true stress to true elongation.

indicated by a straight line, a fact which greatly facilitates comparison and points to the existence of a common law of plastic flow for all metals.

Sommer has devised an entirely different type of "modified" stress-strain curve which deserves wider recognition because, although open to the criticism that it is of a somewhat empirical nature and does not measure simple, fundamental properties, it does enable the deep drawing and pressing properties of metals to be compared in an instructive and, usually, reliable manner.

Having evolved certain mathematical relationships based on a study of stress-strain curves relating true stress to true elongation,[103] this investigator discovered that graphs giving very much the same information could be constructed in a relatively simple manner without having recourse to advanced mathematics. This method consists of dividing the ordinates of the true stress-strain curve by the nominal ultimate stress of the metal being examined, and substituting the quotients for the stress values in the true stress-strain curve, as shown in Fig. 256. The curves so obtained do not represent absolute values of the extent of deformation in deep drawing, but the *position of different curves relative to one another* enables the deep-drawing properties of the respective specimens to be compared, while the shape and slope of the curves show the relative rates of work-strengthening. These curves are, therefore, most useful in comparing the deep-drawing properties of some new metal or alloy with those of others whose behaviour is known from experience, or, in like manner, in comparing the curves of a number of samples of some particular metal with an adjudged "standard" curve for that metal. Furthermore, the shape of the curve shows very clearly the best way in which to apportion successive draws in order to obtain the maximum possible plastic deformation without annealing. The interpretation of these curves is discussed more fully in a later chapter, but readers familiar with the behaviour of metals under the press will see at a glance that the curves shown in Fig. 256 do represent the behaviour of the metals named relative one to another.

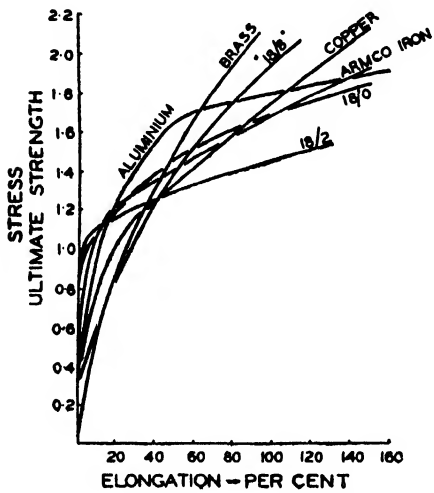


FIG. 256. "Modified" stress-strain curves devised by Sommer.

In the opinion of many authorities the construction of "true," and still more of "derived," stress-strain curves gives a better indication of deep drawing and pressing properties than any other procedure yet devised. Although this claim has much to justify it, it must not be forgotten that, during deep drawing and pressing operations, sheet is rarely stressed in pure tension as it is in a tensile test; compressive stresses, which at times may exceed the tensile stresses, are often imposed at some stage, while bending stresses also occur as the metal flows over the radius of the die. For this reason, although special stress-strain curves of the kinds described certainly give a most valuable picture of the behaviour of any metal under pure tensile stress, it may not be safe to regard them as a *direct* indication of deep drawing and pressing properties without qualification.

To summarise, the ordinary tensile test is of unique value in measuring certain fundamental and universally recognised physical properties of sheet metal, but its usefulness is lessened by the lengthy nature of the test and by the inability of the values obtained to provide a reasonably complete indication of deep drawing and pressing properties. If a full stress-strain curve is plotted from the readings obtained, a more reliable prediction of the behaviour of metal under the press can be made; but, unless accurate autographic recording is used, the plotting of such a curve often renders the test too lengthy to be used in routine examination. If a "true" stress-strain curve, or one of the special or "derived" curves, is constructed, the test becomes so lengthy that it is of use only in special examinations or genuine research work; yet the value of curves of this kind is certainly very great, although their practical significance is not yet understood fully.

It is likely that a better understanding of the behaviour of sheet metal under the press and also increased knowledge concerning the fundamental deep drawing and pressing properties of various metals will come mainly through the construction and study of special forms of stress-strain curve, perhaps in conjunction with results obtained on corresponding samples of sheet during actual drawing tests made under controlled conditions, for example, on the manometer-equipped A.E.G. machine, already described. If so, it may be that curves of special type, for example, those suggested by Sommer, will become a recognised standard for the comparison of the complex effects manifested as "deep drawing and pressing properties" and that less importance will be attached to single properties such as hardness, tensile strength and elongation. This does not mean that these simple properties will not be measured singly during the routine testing of sheet destined for the press-shop, if for no other reason than that the construction of special stress-strain curves is a skilled and lengthy task. It will mean, rather, that the results of such tests will be regarded more as indications *of the probable similarity* of samples than as a direct indication of deep drawing and pressing properties, and that the usefulness and popularity of quick tests will in no way diminish as knowledge and understanding of true deep drawing and pressing properties increases.

In view of the emphasis which has been laid upon "actual" stress-strain curves, whether used as plotted or as the basis for various forms of "derived" curves, readers are reminded of the caution given regarding the dangerous practice of assuming that tensile properties measured in one direction of a sheet are necessarily typical of the sheet as a whole. Such, indeed, is rarely the case. Owing to the difficulty of measuring accurately the cross-sectional area of thin strip specimens, "actual" and "true" stress-strain curves are usually recorded from circular test bars of substantial diameter. In drawn bars, directional properties are often even more pronounced than in sheet, and the curves obtained will usually indicate the highest values. This fact must never be forgotten.

Errors attributable to directional properties in sheet metal are avoided when a stress-strain curve is obtained by means of a fluid-pressure cupping test in the manner already described. Unfortunately, with this method of test it is very difficult to measure the reduction in thickness of the specimen at successive increments of load; so that its advantages cannot be used for the construction of "true" stress-strain curves, because it is unsafe to assume uniform thinning over a certain area of the dome, and thus to calculate the reduction in thickness mathematically, using formulæ for a sphere.

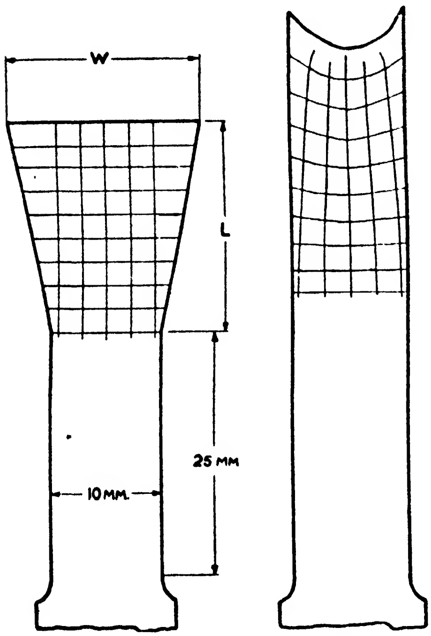


FIG. 257. Specimen used in Sachs's wedge-drawing test: A before test, B after test.

Wedge-drawing Tests. The wedge-drawing test, which appears to have been devised in its original form by Sachs,[105] has for its main object the imposition of compressive stresses on a strip specimen during a tensile test. One important difference between the conditions obtaining in an ordinary tensile test and in deep-drawing operations is that in the tensile test the metal is unrestrained on all four faces of the test piece, whereas when passing through deep-drawing tools sheet is always restrained in a direction parallel to its surface by compressive stresses set up by the continually decreasing periphery of the blank as the draw proceeds and, should "ironing" occur, in a direction normal to its surface as well. In the wedge-drawing test a strip specimen is restrained on its edges but not on its flat faces, although there is no reason why the tools could not be modified to reproduce "ironing" in addition to "free" deep-drawing conditions.

In the original Sachs's wedge-drawing test a specimen of the sheet to be tested is cut, or cleanly blanked with sharp tools, to the shape shown at A in Fig. 257, the taper being 1 in 5 and the dimensions L and W determined in the manner described later. The lower end of the test piece is gripped in the bottom jaws of an ordinary tensile testing machine, the upper or taper end of the specimen being inserted in the device shown in Fig. 258, the prong E of which is itself gripped in the upper jaws of the tensile machine. For obvious reasons it is desirable that the machine be equipped with freely-moving spherical-seated jaws. The device consists essentially of a rectangular chamber having three smooth, rigid faces of which the two narrow sides D are fixed at the same taper as that of the sides of the test specimen, *i e.*, 1 in 5, and a fourth face B which can be adjusted by means of the screws C to accommodate specimens of different thickness. This fourth face is adjusted so that the specimen is not gripped at the start of the test but is nevertheless prevented from buckling.

The test itself consists of gradually increasing the load upon the parallel portion of the test specimen until either its taper portion is compressed and drawn completely through the fixed taper chamber or else rupture takes place in the parallel portion. Diagram B in Fig. 257 shows the shape of the standard specimen A after it has been pulled completely through the tapered die. The lines on the surface indicate the nature of the flow which occurs, although lines are not usually marked on a specimen for a wedge-draw test unless a modified version of the test, described later, is being made.

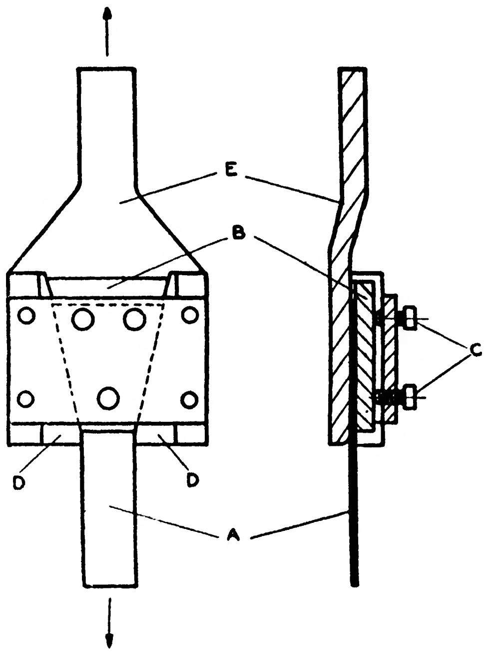


FIG. 258. Diagram illustrating the die used in the original wedge-drawing test.
A. Specimen, the end of the parallel part to be gripped in lower jaws of tensile testing machine.
B. Plate to prevent specimen buckling.
C. Screws to adjust plate B.
D. Side pieces forming tapered die.
E. Prong to be gripped in upper jaws of testing machine.

If the length L, and hence the width W, is too great for any given piece of metal sheet, the taper on the specimen will be drawn a certain way through the die and the specimen will then break in its parallel portion. By testing a number of specimens of different length cut from the same sample, a certain length L will be found at which specimens will just draw completely through the taper die without fracture. The ratio W to L of these border-line specimens, known as the "deformation number," forms the basis for comparison between different specimens. Under border-line conditions the stress required to compress and pull the tapered part of the specimen through the tapered die is equal to the stress required to break the parallel portion.

It will be seen that the conditions of this test do imitate those obtaining during deep drawing to an appreciable extent, hence its acknowledged value. This will perhaps be seen more clearly if the specimen be envisaged as a small sector of a disc being drawn into a cylindrical cup, as indicated diagrammatically in Fig. 76 (p. 106); but this analogy also shows the entire absence in the test of the bending, and consequent additional work-hardening, which occurs in actual deep-drawing practice as the sheet flows over the radius of the die.

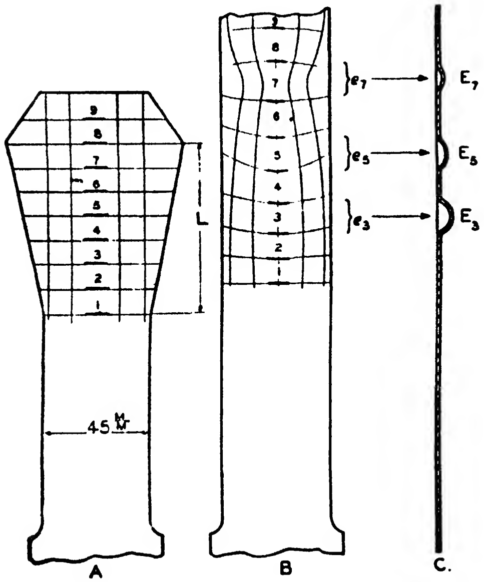


FIG. 259. Specimen used in combined wedge-drawing and cupping test: A before test, B after test, and C showing miniature Erichsen impressions E_3, E_5 and E_7 made in selected zones of deformation e_3, e_5 and e_7 on specimen B.

As is to be expected this test, which has received most attention on the Continent, reveals the suitability of sheet metal for deep-drawing purposes in a far greater degree than the ordinary tensile test, but published results obtained by it are at present inadequate for its true value to be assessed. It is recorded that several drawbacks to its proper functioning have been encountered: one is that friction on the taper edges leads to erratic results; another, met with when thin specimens are being tested, is a tendency for the specimen to thicken up more at the taper edges than in the central area; another, that lubrication of the taper affects results in a marked degree, yet is difficult to control.

It will be evident that to obtain the "deformation number" of strip of unknown properties may entail the making and testing of a considerable number of specimens. However, when sheet of approximately constant quality is being tested continually, the testing of three or even two specimens of each sample may serve to indicate whether all are up to the normal standard. Used thus, the wedge-drawing procedure becomes a reasonably quick routine test which, in the opinion of those who have used it, provides a forecast of actual drawing properties unequalled in sensitivity and reliability by any yet devised.

The original wedge-draw test has been modified by a number of investigators. The most interesting modification is probably that due to Kayseler,[106] who uses a considerably larger test piece of the shape shown in diagram A, Fig. 259, and divides the test into two distinct stages. First, a certain predetermined amount of plastic deformation, measured by lines marked on the surface of the specimen, is imposed by drawing the upper part of the specimen through a 1-in-5 taper die, as in the original version of the test; next, Erichsen cupping tests are made in chosen positions on the specimen using a punch having a diameter of 14 mm. instead of the standard 20 mm., the standard 27 mm. diameter die being retained. The nature of the flow which takes place and the way in which the deformation can be measured by

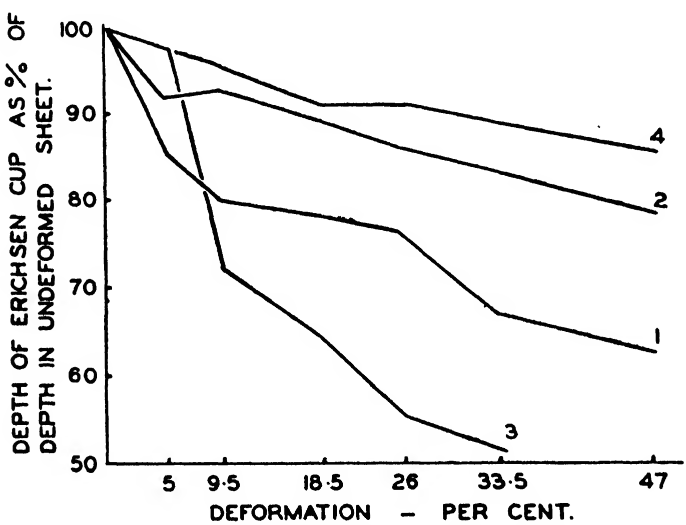


FIG. 260. Graphs relating four specimens of low carbon steel sheet plotted from results obtained by combined wedge-drawing and cupping test.

means of lines, conveniently made on the surface of specimens by means of a rubber stamp, is illustrated in diagrams A and B, Fig. 259. Diagram C shows how the miniature Erichsen impressions are made; in the specimen illustrated, impressions E_3, E_5 and E_7 correspond to zones e_3, e_5 and e_7 on the test piece, the respective average elongations of which can be measured. Stelljes and Weiler [107] propose a test piece having a much longer inverse taper at the top, thus allowing a greater number of Erichsen impressions to be made on each specimen.

In this modified wedge-draw test the dimensions of the test piece are chosen so that the taper part can be drawn through the die into a parallel shape without danger of fracture in the original parallel neck, and the maximum length L which can be drawn through the die is not the principal measurement recorded. Instead, the depth of each miniature Erichsen impression made on the unstrained sheet is recorded, and a curve is usually plotted relating this percentage value to the average elongation which the particular zone of the wedge corresponding to each impression has suffered. Four typical curves of steel sheet are shown in Fig. 260, and it will be seen that each of the four curves is different, No. 3 markedly so, yet it happens that Erichsen tests made on the unstrained sheets gave practically similar values for all four samples of sheet.

It is certain that this particular test detects differences which are not revealed by an ordinary Erichsen, tensile, or even wedge-draw test, and it is probably no coincidence that in this combined wedge-draw and cupping test, as in those tests in which a simple cup is deep-drawn by means of a punch and die, a two-stage as distinct from a single-stage deforming operation enables finer differentiation to be made between different samples of sheet. A point which needs to be borne in mind, however, is that when the metal being tested is one which strain-age-hardens, the second part of the test must be made immediately after the first if consistent results are to be obtained. It must also be mentioned that in order to draw the larger test specimen through the die a lubricant is often used, whereas it is usual to make the ordinary wedge-draw test on an unlubricated specimen.

At the present time the most that can be said of wedge-draw tests is that they detect differences which are undetectable by other precisely controlled, as distinct from actual drawing, tests, and that they imitate to some extent the conditions imposed upon metal sheet during many actual deep-drawing operations. As a basis for the comparison of different test pieces such tests must have a use, but, as in many of the other tests which have been devised to measure deep drawing and pressing properties, the values obtained seem to represent the combined influence of a number of properties. Whether this "combined" value is as truly informative as several separate values representing simple fundamental properties must, for the present, remain *sub judice.*

Magnetic Tests. Many attempts have been made to utilise magnetic methods to test all kinds and conditions of steel, the attraction lying in the possibility of measuring some property or ascertaining some condition rapidly and without destroying the specimen, as is necessary with chemical, metallographic and most physical methods of examination and testing. The use of magnetic methods to estimate the percentage of carbon in quenched samples of steel during the steel-making process has already been mentioned, but magnetic methods can also be used for other purposes.

Aksenov and Grigorov [108] have shown that a useful quantitative measure of directional properties, or, to give its scientific name, anisoptrophy, in annealed or normalised low-carbon steel sheet can be obtained by magnetic measurements made by suitable methods, and that the results obtained agree closely with the behaviour of automobile body sheets under the press. This test should appeal to those who wish for one of a more scientific nature than the crude yet very useful tear-length test already described.

Much attention has been given to the development of a magnetic method for detecting the presence of small internal defects in steel, for example, cavities in castings, discontinuities in welds and cracks in machine components. A number of the methods devised have proved reasonably successful, and it seems likely that some would detect a severe internal " lamination " or discontinuity in thin steel sheet. If so, a very useful, non-destructive test would become available for what is certainly one of the most troublesome defects found in low-carbon steel sheet of industrial quality.

X-Ray Examination. X-rays are not yet used for the regular routine examination of sheet metal used for deep drawing and pressing. Knowledge gained during the employment of this method of examination in research work shows that it can provide useful information concerning directionality, " average grain size," and the amount of strain or, conversely, the completeness of recrystallisation existent in sheet ; all important items. The application of X-ray examination to sheet metal is studied from the particular viewpoint of the press-shop in Appendix B.

Dynamic-ductility Tests. A serious disadvantage of all the usual tests which are applied to sheet metal to determine deep drawing and pressing properties is that deformation is carried out at a rate far slower than that used in industrial press operations. The important influence of speed of deformation is emphasised in other chapters, and it is regrettable that very little attention has been given to testing sheet metal at speeds comparable with those normally used in the press-shop. An increasing amount of attention is being given by research workers to tensile testing at high speeds, and also to impact testing at high velocities, but the results of such tests can only be related to the behaviour of sheet metal under the press by somewhat strained inference. The very few attempts which have been made to carry out high-speed cupping tests are, therefore, of great importance, and the classic results obtained by Mathewson, Trewin and Finkleday [79] should be studied by all who doubt the importance of speed of deformation as a factor in cupping tests.

Using the Olsen cupping tools, described earlier in this review, mounted in an ordinary crank press instead of in the usual hand-operated slow-motion screw press, these investigators compared the results obtained at punch velocities ranging from 0·34 to 163 feet per minute. Tested at slow and high speeds, zinc sheet gave a depth of cup of 0·405 and 0·150 inches respectively, and 70/30 brass sheet a depth of 0·585 and 0·405 inches respectively—a smaller yet still considerable difference.

It is to be hoped that the influence of punch velocity upon the results given by many of the recognised forms of cupping test will be studied more carefully, and that investigations into the influence of speed of deformation will be extended to embrace the special forms of tensile test already described and also wedge-drawing tests. Only in this way can the deep drawing and pressing properties of sheet metal be measured by such tests in a way which will enable laboratory results to be related directly to industrial press-shop practice. If the importance of speed of testing does not seem to be emphasised sufficiently, it is because the main object of this review of the testing of sheet metal destined for the press-shop is to describe the appliances and procedures in common use. Experience in the press-shop, the results of high-speed tensile and impact tests, and also those of the few high-speed cupping tests which have been made all point to the fact that speed of deformation is a factor of considerable importance. Its continued neglect in relation to deep drawing and pressing properties is strange.

The Practical Value and Limitations of Available Tests. To assess the real practical value, from the industrial aspect, of the various tests which have been described is a matter of the utmost difficulty. These tests may be divided into two main groups : rapid tests, often of an empirical nature, which give a useful but incomplete and not wholly reliable guide to the probable behaviour of sheet in certain press operations, and lengthy tests which provide information of a more fundamental nature regarding the general deep drawing and pressing properties of the sample tested.

The author confesses a preference for tests of the second group, for example, the plotting of special forms of stress-strain curve, which reveal fundamental physical properties. Only by the use of tests of this kind will real knowledge of the truly essential properties be accumulated. Unfortunately, such tests are usually too lengthy to be used in the routine examination of purchased sheet, and their use has perforce to be confined to occasional samples and to research investigations. The specially useful form of stress-strain curves based on "true" as distinct from nominal values for stress and strain possess the additional disadvantage that they are obtained much more readily, and with greater accuracy, on round bars than on thin sheet test specimens.

On the other hand, it must be admitted that, apart from the question of speed, attempts to select sheet wholly by tests of this kind sometimes end in disaster and thereby hinder the establishment of the sincere co-operation between plant and laboratory, and between practical and scientific workers, which is so very desirable in the deep drawing and pressing industry at the present time. A skilled shop-foreman can sometimes tell more accurately from the feel of a sheet between his finger and thumb whether it is or is not suitable *for a* *particular shaping operation with which he is familiar* than can the laboratory worker from results obtained, far more slowly, on expensive and accurate mechanical testing devices. Nevertheless, it is equally certain that accurate control of the quality of metal, and the tracing and rectification of defects in it, can be ensured only by scientific testing assisted by the application of the continually increasing fund of metallurgical knowledge which is accruing from both research and practical experience.

The simple tests have, therefore, a definite place in any scheme devised for the examination of sheet metal. First, because they can be made, often by partly-trained helpers, on a large number of samples. Secondly, because, paradoxically, they often reveal certain very important characteristics which are not immediately discernible from the results of more complicated tests giving information of a more scientific but perhaps general nature. For example, the simple tear-length test will, in a few seconds, furnish clear evidence which will enable sheet possessing unusually marked " directional " properties to be rejected, whereas a full stress-strain curve taken in one direction of the same sample might, after many hours' patient toil, indicate excellent properties and thus mislead an unwary examiner.

It is quite certain that no single test yet devised will determine in a complete manner the magnitude of those properties, themselves incompletely understood, which render sheet suitable or unsuitable for some particular deep-drawing process. One reason for this may be that none of these tests reproduce either the exact conditions under which sheet is deformed in press-tools—except, perhaps, some varieties of simple cupping operations—or, of importance, the speed of deformation. Many investigators have tried to devise a single, all-sufficient test, but an impartial judge having practical press-shop experience can quickly point to serious shortcomings in every one, and it seems very unlikely that the ideal single test will ever be realised.

It must be borne in mind that, as a rule, supplier and purchaser use routine tests for a different purpose. The purchaser carries out tests in an attempt to prevent the entry into his works of metal which, from past experience, he knows will not stand up to the demands he will make upon it, with little thought to the accumulation of useful fundamental data on drawing properties. The supplier carries out tests for the purpose of ascertaining whether his product is likely to meet the demands of the purchaser and of checking up the effectiveness and regularity of his mill operations without thought, again, of the compilation of really fundamental knowledge unless some special investigation is being pursued.

In mitigation of this unsatisfactory state of affairs, it must be conceded that present industrial conditions often render the accumulation of what may appear to be not immediately applicable knowledge difficult. Definite research work seems to be the only means by which necessary fundamental knowledge can be obtained and suitable tests devised.

Pending the attainment of this knowledge, the scheme of testing about to be outlined will, when used intelligently, provide a useful though admittedly incomplete indication of the probable behaviour of sheet metal during deep drawing or pressing operations. At the present time it seems as if a really effective specification might have to include not only limiting values obtained during certain standard tests, but also detailed schedules of sheet processing, and even clauses relating to the casting of the ingots from which the sheet is to be made.

A Suggested Scheme for Routine Testing. The nature of any scheme of industrial testing will depend primarily upon the amount of money those in authority are willing to spend on testing. This amount will vary according to the attitude of the executive toward laboratory work and whether they regard the non-productive expenses of testing as a useful insurance or, as still happens sometimes, as a modern fad which must be tolerated but kept to as small a scale as possible.

Anticipating conclusions arrived at in the next chapter it can be stated that, in the majority of deep drawing and pressing operations, the behaviour of annealed metal, if treated intelligently, will depend primarily upon two factors. These are :—

(*a*) Crystal size and regularity.

(*b*) Directionality.

From the viewpoint of the maker and consumer of sheet for shaping by deep drawing or pressing processes, these properties seem to be indicated most conveniently on a large number of samples, although not determined either precisely or completely, by the continual and combined use of not less than three tests. These are :—

(1) Hardness tests, which can be made very quickly and cheaply on a large representative percentage of samples, it being clearly understood that hardness values are to be regarded purely as an indication of *probable conformity* of samples to some standard, and are therefore quite useless without more informative check tests made occasionally.

(2) Microscopical examination, a test which in the past has been made all too rarely during routine examination as distinct from special investigation. A regular crystal structure, of suitable "average grain size," and free from defects such as pronounced inclusions or planes of segregation, is an essential property of sheet of good quality. Only by proper microscopical examination can this property be examined, although its influence may be manifested in results obtained by purely mechanical tests.

(3) Tear length tests, which are very simple, quickly made, and

give a most useful indication of the severity of directional properties, often an item of vital importance.

This selection, obviously, may not be the best in all instances. For example, a carefully made stress-strain curve is the only indication yet found of the tendency of steel to form stretcher-strain markings, while certain properties of special significance in some particular press operation may be revealed most readily by some of the other tests described in this chapter, or by special tests devised to meet special conditions. When sheet is not in the fully-annealed condition, its behaviour under the press cannot always be predicted in a reliable manner by inspection of its crystal structure ; unfortunately, hardness tests do not always provide an adequate indication of the degree of cold work which has been imposed, particularly when the amount is small as in the case of temper-rolled steel, and other tests may be necessary. Used intelligently, the combined use of the three tests just enumerated will, however, enable the deep drawing and pressing properties of most sheet to be predicted by men familiar with both the kind of sheet used and the press operations through which it has to go.

In the past the well-known Erichsen cupping test has proved the most popular test of any, and there are still many who feel more comfortable if sheet is submitted to this, or a similar form, of cupping test which functions in a manner that bears at least some resemblance to that of many press-tools. Because of this, the Erichsen test can be regarded as an optional fourth test in the series of three just proposed, and it may be remarked that it is often most useful when sheet is not in the fully annealed condition, because then even the combined results of hardness tests and microscopical examination may not provide adequate information. The merits and the faults of the Erichsen test have already been discussed, and it is not necessary to recapitulate ; but the caution may be repeated that, although this test provides useful information when used intelligently, its results ought *not* to be regarded as a reliable indication of behaviour under the press in all instances, and results obtained with one machine and one operator ought not to be compared with results obtained with other machines or even with the same machine and other operators. In the opinion of many users the Erichsen test will always be useful for quickly detecting definitely unsatisfactory sheet, but it must not be relied upon to distinguish fine, yet often important, differences in sheet of good or moderately good quality. To reveal these finer variations in properties, an actual drawing test or possibly some form of wedge-drawing test may be useful, although the last-named test seems at present to be regarded with disfavour for routine examination, as is the tensile test, because of the time it occupies and the need for interpretation of the results obtained.

The popularity of the Erichsen test should not be allowed to obscure the merits of other forms of cupping test. For example, Gough and Hankins [100] draw attention to an apparent greater sensitivity of the K.W.I. form of test, and the potentialities of the Jovignot type with the addition of an autographic recording attachment seem very great. It is possible that this one, fairly rapid test may estimate, simultaneously, both probable "average grain size" and also what can only be described as "drawability" and, in addition, provide a form of stress-strain curve which is so necessary for revealing fundamental physical properties with any degree of precision.

It is desired to emphasise the fact that this scheme of testing is offered as suitable for the use of most firms at the present time. Determination of full stress-strain curves, wedge-drawing and practical drawing tests may be capable of providing more useful information concerning fundamental deep drawing and pressing properties; their development is to be encouraged by all possible means, as also is proper microscopical examination, by the supplier for the purpose of controlling the microstructure of the sheet produced, and by the consumer for determining in the first instance the form best suited to particular shaping operations and, subsequently, for checking deliveries. The need for control by chemical analysis on the part of the maker of sheet, and also the serious limitations of this method of examination, have already been pointed out.

Many small firms, although capable of making simple mechanical tests, are not in a position to employ a trained metallurgist. To such firms, simple tests can still provide a very valuable indication of the probable conformity of samples to some adjudged desirable standard of quality, even though the more precise nature of the desirable properties may be unknown and their control left to the goodwill and integrity of the sheet supplier.

PERCENTAGE OF SHEET TO BE TESTED. The question of what proportion of incoming metal shall be tested is one upon which controversy must seemingly always arise. Under the conditions obtaining in many factories seldom a representative, and always a very small, percentage of sheet can be tested. In the scheme just outlined, it is desired to draw particular attention to the possibility of making one simple test, such as a hardness test, upon as large a representative percentage of sheet as possible and using this to indicate the *probable* similarity of the specimens so tested to a much smaller percentage upon which more elaborate tests are made.

It is quite impossible to suggest any definite representative percentages upon which simple or elaborate tests should be made, for this will depend upon the safety margin existing in any particular shaping operation, upon how much a firm is prepared to spend on testing as a form of insurance, upon the uniformity of the sheet usually delivered by any one supplier and upon whether there exists one of those troublesome periods when, for reasons unknown at the time, failures and difficulties are abnormally numerous. In this respect the testing of drawing-quality metal differs markedly from the testing of engineering metals with which, to prevent unsuitable metal passing into service, a fair representative and sometimes a full percentage of supplies or finished articles must be tested. When a reasonable margin of safety exists in certain shaping operations, and when experience shows that the sheet purchased from some particular supplier is of regular and satisfactory quality for these operations, a strong argument can be and usually is advanced that the making of elaborate, and even simple hardness and Erichsen, tests is unnecessary and therefore extravagant. Although this may be true, the omission of simple check tests will sooner or later lead to a batch of unsatisfactory sheet entering the shops and, unless it is very bad, probably passing one or more operations before failure occurs or defects are detected.

Laboratory Personnel. To conclude this review of the methods used to test sheet metal destined for deep drawing and pressing, it seems necessary to add yet another, and very important caution, to those already given. This is, that even when the limitations of any method of test are recognised, the value of the results obtained *will depend largely on the care and skill with which the testing procedure is carried out.* Even the most simple of the tests described cannot be regarded as " fool proof," while many require real skill if the values recorded are to be of genuine significance.

Under industrial conditions the actual carrying out of tests has perforce, often to be done by men who have not had the opportunity to acquire much theoretical knowledge, and it is essential that the individuals chosen for this purpose should be intelligent and, above all, sufficiently conscientious and trustworthy to obey implicitly the instructions given to them. This pronouncement is not intended to reflect upon the status and capabilities of the trained assistant ; indeed, he can often obtain reliable and consistent results when a scientist, having full theoretical knowledge of the test he essays to carry out yet unpractised in its manipulation, will at first obtain erratic results. It is meant, rather, to apply to the wholly-conscientious assistant who, with every good intention, scribes deep-cut gauge-length lines on tensile test pieces the better to see them, or carefully files the edges of blanked test pieces, quite unaware of the fact that by so doing he may make a " waist " which will seriously influence the results he returns for percentage elongation. Little need be said of the type of individual who ceases to do as he is told the minute the supervisor's back is turned, either because it is too much trouble or because he imagines that his own ideas are best. Such persons are quite out of place in either test house or laboratory ; their retention in this particular service proves a continual annoyance, and often leads to the issue of misleading results and reports which, when detected, cannot fail to undermine confidence in the laboratory from which they originated.

This aspect is one which deserves more serious consideration on the part of those in charge of laboratories and test houses. Sometimes too much attention is given to the acquisition of expensive apparatus, to the appearance of the laboratory or test house as it strikes a visitor, or even to the amassing and presentation of large numbers of results. The first object of any laboratory or test house is to obtain *true* results and, no matter how excellent and complete the equipment, this cannot be done if the men who actually make the tests do not possess the necessary psychological and practical qualifications. Many pages have been devoted to a study of machines and methods, and the small space given to personnel must in no way be construed to mean that this item is of minor importance; exactly the opposite is true. Simple equipment, used intelligently, can give results of a useful if limited nature; elaborate equipment, misused, can give entirely misleading results. Personnel is, therefore of supreme importance.

CHAPTER XIII

PROPERTIES WHICH DETERMINE THE BEHAVIOUR OF METAL DURING DEEP-DRAWING

It would have been more logical to have examined the nature and significance of the various physical properties of sheet metal before describing the methods used to measure them. Yet, because in the preceding chapter which dealt with Testing it was convenient to describe briefly what these properties are and how they are measured, readers not familiar with these matters will be in a better position to follow the more theoretical discussion which will now be attempted to show how these properties determine the behaviour of metal under the press.

In earlier chapters a number of defects found in sheet metal have been described, and it need hardly be said that, quite often, the property of sheet metal destined for deep drawing and pressing which the consumer desires most ardently is the elimination of these or any other defects which will affect adversely the normal properties of the sheet he uses. Among these " negative " properties, if they be described in this way, are: internal or external discontinuities; chemical segregation; abnormal or unsuitable crystal structure; variation in physical properties throughout one or many lengths of strip; " directionality "; " ageing "; " stretcher-strain " and " blue-brittleness " phenomena in steel; " orange peel " and " waving " in brass; variation in thickness; mechanical damage to surfaces, or an inherently poor surface finish.

Leaving aside the influence of genuine defects, abnormalities or a clearly unsatisfactory condition, which should not exist in sheet of good quality, the behaviour of metal under the press is determined by a number of what may be called " positive " properties, and its value to the consumer will be proportional to the nearness of these properties to the optimum for any given press operation. It is these " positive " properties with which this chapter is concerned.

At the outset it is well to recognise that, in the light of present knowledge and by the use of those tests and methods of examination commonly applied to metals, it is extremely difficult to ascertain the exact nature of the variation between different pieces of sheet metal which will account for observed differences in behaviour during deep drawing and pressing operations. Those tests which do reveal significant variations are often of an empirical nature and indicate the combined effect of *several* essential properties or conditions. Although in the following pages an attempt will be made to examine a number of these properties or conditions individually, it must be clearly understood that the behaviour of metal under the press is determined by the *combined* effect of these properties and also of other factors extraneous to the metal itself. Sheet metal suitable for some particular deep drawing or pressing operation may be unsuitable for others which differ from it in, perhaps, lubricant, speed of drawing, the shape of the article, the nature and severity of the shaping operation and even the finish desired upon the drawn shape. For this reason it is virtually impossible to enumerate "good" properties or conditions of drawing-quality metal having general significance: only those which, when suitably modified to meet certain operating conditions, influence the deep drawing and pressing properties of the metal can be isolated for separate examination and discussion.

Chemical Composition

The behaviour of sheet metal under the press will, naturally, be determined to a very large extent by its chemical composition, first with respect to the relative proportion of its major constituents, and, secondly, with respect to the proportion of impurities present.

Little need be said here regarding the influence of major constituents. It is obvious that the physical properties of metals are dependent upon the kind, and the proportion, of alloying constituents present, and comparison of the relative deep drawing and pressing properties of different metals and alloys is made, both specifically and by inference, in other chapters. As a rule, a pure metal or a single-phase alloy can be deformed more severely under the press than one having a duplex microstructure, although much will depend upon the size, relative hardness and uniformity of distribution of the second constituent. This is well illustrated by steel, in which the form and disposition of the carbide exercises a profound influence upon deep drawing and pressing properties. It is significant that very few of the metals commonly used for severe deep drawing and pressing operations have a duplex microstructure; indeed, in steel the carbide is usually regarded as an undesirable impurity to be kept as low as possible.

The influence of a number of impurities upon the deep drawing and pressing properties of the more common metals has already been examined in previous chapters, and it is somewhat difficult to formulate useful generalisations covering the influence of impurities because this depends so much upon both the physical and chemical interaction which takes place between different metals and the impurities found in them. It can be said, however, that an element which, in the proportion present, goes wholly into solid solution—for example nickel in steel or silicon in aluminium—will exert a constant influence which can often be predicted beforehand and will depend upon the percentage of impurity present. On the other hand an insoluble or only partially soluble impurity, or a soluble one which forms an insoluble chemical compound with the solvent metal or alloy, will have an influence dependent to a large extent upon the size and dispersion of the insoluble particles and whether or not these are situated in the crystal boundaries. A good example of this is provided by lead in brass: if the particles are very small indeed and dispersed uniformly, the ductility of the brass may not be influenced seriously; if the particles are large, considerable injury may result, and, if the lead forms an envelope structure around the crystal grains, the ductility will be very low indeed. For these reasons the influence of insoluble impurities cannot always be predicted in a quantitative manner when only the percentage present, and not the form of occurrence, is known. When the percentage is very small indeed and the behaviour regular (as in the instance of bismuth, which always forms a dangerously harmful envelope structure surrounding the crystal grains of copper or brass) an intelligent forecast of behaviour can often be made.

A further complication may arise when, as often happens, the combined influence of two or more impurities present together may be out of all proportion to the sum of that of the separate constituents; a condition well illustrated by the influence of very small percentages of iron and phosphorus on the annealing of brass.

In addition to their normal influence in reducing ductility, the action of impurities in producing age-hardening in certain instances must not be forgotten. This may be due to precipitation visible under the microscope, as in Duralumin, or to phenomena which are understood less completely, such as the strain-ageing of steel.

The influence of dissolved or occluded gases upon the physical properties of metals is a subject the importance of which is only just beginning to be appreciated, and it is likely that in the future much more attention will be given to gaseous impurities as well as to the solid impurities now controlled with some care.

Lastly, mention must be made of segregation. It has been explained elsewhere that sometimes it is not the *average* percentage of some impurity which is harmful, but *local concentration* due to segregation of the impurity in the original ingot. This fact is of very great importance, but, as a number of examples have already been given to illustrate the nature and influence of chemical segregation, it is not proposed to discuss it again.

To summarise, it can be said that as a rule the presence of impurities is detrimental from the aspect of deep drawing and pressing; often markedly so. Sometimes certain impurities may be tolerated for special reasons, as in the case of phosphorus in brass; but, with a few exceptions such as this, in which the impurity ought really to be regarded as an addition made purposely, it can be accepted that any metal or alloy destined for severe deep drawing and pressing should be as pure as possible. The importance of this is well demonstrated by brass sheet of industrial quality, in which the decrease in the proportion of impurities which has been made during the past twenty years has brought about a distinct improvement in deep drawing and pressing properties.

Crystal Size

The importance of crystal size in the sheet used for deep drawing and pressing is very great, for, with sheet of given chemical composition deep-drawn under given conditions, crystal size determines the fundamental properties of ductility and tenacity, and also the important attribute of smoothness of surface after pressing. Indeed it is not too much to say that in the absence of defects or special structural peculiarities, such as the fineness and uniformity of dispersion of a second phase, the deep drawing and pressing properties of sheet of any given metal are determined *primarily* by crystal size ; a statement which surely renders further emphasis of the importance of crystal size unnecessary. Yet, until comparatively recently, the fundamental importance of crystal size was not properly appreciated by consumers, often still less by suppliers ; for, unless the sheet exhibited that excessive roughness of surface after pressing which is one of the visible manifestations of an unusually large crystal size, the essentially crystalline nature of the metal being worked under the press was forgotten.

It is not proposed to enter here into any theoretical discussion of the fundamental aspects of the influence of crystal size upon the physical properties of metal. Readers desiring more knowledge of this subject are referred to the many erudite papers which have been contributed by our leading metallurgists and mathematicians. The practical man is asked to accept the fact that, in the sheet commonly used for deep drawing and pressing, an increase in crystal size causes an increase in ductility, a decrease in tenacity, hardness and rate of work-hardening, and an increase in the roughness of surface of the pressed sheet. The converse is equally true. The practical effect of this has been clearly illustrated in Fig. 85 (p. 120), and Fig. 136 (p. 206) from which it will be seen that, under given conditions, an increase in crystal size may so lower the tenacity of the sheet that localised "necking" leading to fracture can occur before the whole blank or partly formed shape has been drawn through the tools.

The illustration just given represents what may be called the nett or visible result of a large crystal size in the sheet offered to the press. Another interesting illustration, which—although perhaps of more direct interest to the scientist—is yet of interest to the practical worker

Fig. 261. Transverse sections through "necking" in walls of two brass pressings, showing how the necks are situated in particularly large crystals. × 75.

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as proof of the influence of crystal size upon the properties of ductility and tenacity, is given in Fig. 261. Incidentally, this illustration demonstrates the genuine need for sheet having a *regular* crystal structure, an aspect considered in greater detail later. The photomicrograph shows sections cut transversely through a zone of local "necking" in the walls of two deep-drawn brass shells in one of which, as a result of culpable over-annealing prior to the last draw, the crystals have grown in some places to such a size that they extend roughly one-third the way through the wall. Further along the wall the neck has developed into an actual fracture. Microscopical examination of sections cut through zones of necking of this kind shows that, as in the particular section illustrated, the neck is situated in unusually large crystals which, as has been said, possess considerably less tenacity but more ductility than the smaller crystals existing on either side of the neck. If this unusually large crystal structure is reduced in the reader's mind to one of normal size, still retaining the same order of irregularity in the size of individual crystals, it is easy to appreciate the stiffening effect which very small crystals will exert upon the aggregate.

Many curves have been published relating crystal size to various properties such as Erichsen value, ultimate tensile strength, percentage elongation, tear-length and even hardness. A word of warning concerning the danger of misusing such curves is necessary, for, even though the accuracy of any particular investigator's observations may be unquestionable, caution is seldom given that individual curves are not capable of general application. As a result, persons unacquainted with the full meaning and limitations of such curves use them for purposes other than that for which they were intended. Needless to say, a relationship between crystal size and, for example, Erichsen value or hardness holds good only for sheets of similar chemical composition which have received the same amount of final annealing or cold rolling; although if "ageing" has occurred, even this limited relationship ceases to exist. In spite of this, there are still individuals who regard hardness tests as a reliable guide to crystal size.

Turning from physical properties to surface effects, the fact that sheet possessing a large crystal size is likely to develop a rough surface during deep drawing or pressing operations was, perhaps, one of the first metallurgical principles to receive recognition throughout the industry. This roughening is commonly attributed to the slip and partial rotation of *individual* crystals which occurs, during severe plastic deformation of the aggregate, due to the tendency evinced by each crystal so to orient its axis that its planes of "easy glide" assume a more favourable position relative to the direction of the applied stress. It is held that when the crystal size is large the effect of this slip and rotation becomes visible to the unaided eye, and the mechanism of this effect has often been illustrated diagrammatically and, in the case of very large crystals, demonstrated conclusively by means of X-ray examination.

This explanation, based as it is upon alterations in surface level caused by movements of individual crystals, is one which has always seemed to the author to need elaboration when used to explain the difference in smoothness of surface on, for example, an article pressed in sheet having a normal "average grain size" of about 0·035 mm. and one pressed in the same tools from sheet having an "average grain size" of perhaps 0·1 or 0·15 mm. What may be described as a single undulation in a so-called "orange peel" surface must embody very many crystals; therefore it seems as if a kind of "block" movement, in which whole blocks of crystals slip and rotate in a manner similar to that observed in a single crystal, must take place in order to produce the surface appearance usually seen. An internal block or "mosaic" structure is known to exist within the lattice of the crystal itself, and it seems possible that this phenomenon may be repeated on a larger scale in the crystal aggregate. Further evidence of block movement of this kind is to be found in special surface effects seen when some metals are strained within the plastic range, as described in Chapter VII.

Visible evidence of definite block movement can rarely be seen on the rough surface of a pressing because the degree of roughening produced, although sufficient to render polishing difficult and costly, is relatively small. Clear evidence of plastic deformation by block movement is, however, often discernible in tensile test pieces, particularly in aluminium bronzes and high-tensile brasses. Fig. 262 shows a typical example from which it can be seen that the size of the block "facets"—to borrow a term normally applied to single crystals—is many times greater than that of the individual crystals composing the aggregate, although the visible result of slip and rotation of these blocks suggests that a block behaves as if it were a single crystal in so far as surface appearance goes. If this "block" hypothesis is accepted for metal having a large crystal size, it is only logical to extend it to metal having a small crystal size. It may be that this super-mosaic structure plays an important part in the mechanism of plastic deformation, no matter whether the crystal size be large or small when judged by standards fixed by the press-shop.

Be this as it may, industrial workers are concerned principally with the fact that a large crystal size usually results in the production of a rough surface after pressing and is, for this reason, a property to be avoided as far as may be possible consistent with the attainment of an adequate degree of ductility.

It is often said that in sheet intended for shallow pressing, as distinct from deep drawing, the property of "average grain size" is of little importance. This is untrue when the condition of the surface

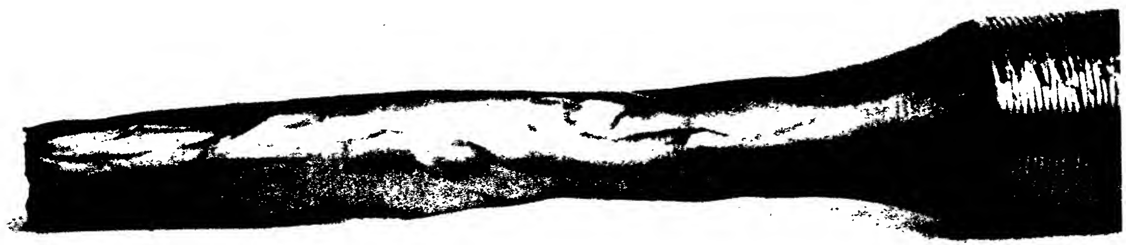

FIG. 262. Uneven surface of tensile test piece of high-tensile brass suggestive of slipping and rotation of "blocks" of crystals rather than of individual crystals.

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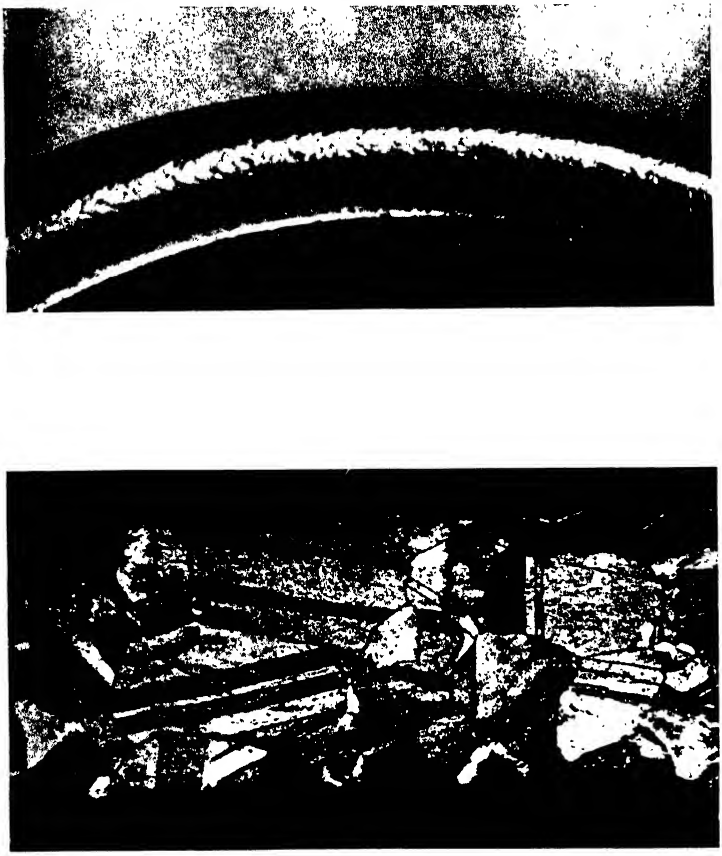

Fig. 263. Rough surface on decorative rim raised on small facia plate caused by large crystal size in the brass sheet used.

Top : Portion of rim, × 4.

Below : Microsection through sheet, × 75.

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of the pressed article has to be considered as, for example, when polishing and plating have to be done. A clear yet not abnormal illustration of this is provided by the small brass facia plate shown in Fig. 263 which has a shallow bevel or beading of triangular shape raised at its circumference. Many hundreds of plates similar to the one illustrated had received the usual—and in this instance quite inadequate—amount of polishing under a piece-work system, and had been plated before a responsible person noticed the unusual and objectionable roughness of the surface of the pressed beading. Upon examination it was found that a consignment of brass strip having an "average grain size" no less than 0·15 mm. had been received and used. The fact that this particular size of strip was known to be for shallow press-work had led to an inexcusable lapse on the part of the supplier and to the omission of adequate testing on the part of the consumer.

Having thus dismissed somewhat briefly the general consideration of the very important property of crystal size, examination of three special aspects is necessary, these being the meaning and significance of the much-abused term "average crystal (or grain) size," the effect produced by pronounced variation above and below the size adjudged to represent the "average" and, lastly, the influence of the special form of "average grain size" to which the name "inherent" is commonly applied.

Average Grain Size. During recent years the property implied by the phrase "average grain size" has achieved a deserved and increasing amount of attention. From time to time the question is rightly raised as to what is meant by this phrase, for little thought is needed to show its futility if interpreted literally, *i.e.*, as meaning a value representing the average size of all the crystals composing an aggregate. To ask only three pertinent questions: how can the true size of a crystal be judged from a section cut in that crystal at an unknown orientation? Is not the area of the planes of "easy glide" of greater significance in relation to the behaviour of a crystal when deformed plastically than the area representing the true geometric average (which is the value commonly implied)? How is it possible to accommodate the fact that the section forming the surface of a microspecimen cuts very few crystals at an "average" section and that, particularly when the crystals exhibit dimensional "directionality," the appearance will vary according to the orientation selected for the cut surface? It is well to bear these questions in mind, lest the term "average grain size" come to be accepted as a value truly representing a definite property.

Notwithstanding the ambiguity and inexactitude of the phrase "average grain size," the possibly remarkable fact remains that the property denoted by it in its industrial, as distinct from its scientific, interpretation is a definite and very important one in relation to the behaviour of sheet during deep drawing and pressing, and indeed during many physical and mechanical treatments. The inverted commas attached to the phrase throughout these pages are intended to indicate that its exact significance is indefinite; it is asked that readers will interpret it as meaning the visual appearance of the microstructure of any specimen compared, for the purpose of numerical designation, with standard photomicrographs or charts adjudged to represent certain "average grain sizes."

Readers who wish to study the literal interpretation of the term "average grain size," or who are interested in the more academic yet very important aspects of crystal size, are referred to papers in which this subject is dealt with from the statistical and mathematical aspect. A useful presentation of outstanding facts has been given by Rutherford and Bain,[109] who have worked out mathematically the numbers of crystals lying within certain ranges of "size" which would be visible on a plane cutting an aggregate of crystals of uniform size.

Interesting proposals have been put forward by Berglund, Hultgren and Phragmen,[110] who point out that a complete representation of grain size distribution within a structure supposes (1) the definition of a suitable grain-size series or classification, and (2) the construction of a "distribution" curve for these standard sizes and the structure in question. These investigators propose the following method of classification based on grain section area where the members form a geometrical series with a ratio = 2, because an arithmetical series is impractical owing to the large range of sizes present in a normal structure:—

J.K.M. grain class .	0	1	2	3	4	5	6	7	8	9 etc.
Grain section area .	1	2	4	8	16	32	64	128	256	512, etc.

When curves based on this classification are drawn up with ordinates representing the total area occupied by all grains belonging to one class, it is found that as a rule they show a distinct peak, and the originators of this method suggest that the maximum size represented by this peak, which they term the "*leading* grain size," is a more significant value than that of so-called "*average* grain size." It is of interest to observe that for most structures the "leading grain size" comes nearer to the size of the larger grains than does the "average grain size."

Turning to the more practical aspect, attention must be drawn to the necessity for exercising proper discrimination when the probable behaviour of sheet during deep drawing or pressing is predicted from the appearance, in the sense of "average grain size," of its crystals when viewed under the microscope. At least three attributes need to be observed carefully and taken into consideration whenever any such forecast has to be made. There must be observed, first, the variation in crystal size above and below the adjudged average; secondly, the proportion of crystals of various sizes intermediate between the largest and the smallest, and, thirdly, the prevalence and severity of local areas of relatively large or small crystals. When these factors are taken into consideration two specimens which, when viewed casually, seem to have a similar average grain size, may be found to manifest markedly dissimilar crystal properties and, by reason of this, dissimilar behaviour under the press.

Little useful indication of the most suitable "average grain size" can be given, for this will vary with the conditions and nature of the press operation and also with the nature and thickness of the sheet itself. In general, a larger "average grain size" can be used, in any given sheet, for pressing or light drawing operations than for severe deformation as produced by deep drawing. Even this generalisation must be qualified by the surface desired on the finish-drawn shape for, whereas it may be possible to draw sheet having a large "average grain size" into a desired shape without the help of inter-stage annealing when a rough surface is admissible, the use of sheet possessing a smaller "average grain size" (which will necessitate the introduction of one or even two inter-stage annealing operations) may be necessary, or at least cheaper, when the finished shape has to be polished, as polishing is an expensive operation. It is not always appreciated that a different "average grain size" is necessary to secure the best results with different methods of polishing, or that the best "average grain size" with respect to pressing as distinct from polishing, for sheet of given chemical composition and physical properties, will vary with the thickness of the sheet. For a draw of certain shape and depth, a rather smaller "average grain size" can be allowed in thin than in thick sheet; the greater ductility associated with a larger grain size is often desirable in thick sheet by reason of the fact that thicker sections seem better able to transmit stress. In other words, although the physical properties of the metal itself may remain constant, the "tenacity" of the sheet manifested under the press tends to be greater with thin than with thick sheet, although this tendency may not hold for very thin sheet only a few thousandths of an inch thick owing to the great influence of mechanical defects.

As a very approximate guide, an "average grain size" of from 0·035 to 0·045 mm. is suitable for the deep drawing and pressing of many shapes in most metals, although a slightly smaller size is permissible in some instances. In general it is desirable, for many reasons, to use sheet having the smallest "average grain size" which will give sufficient ductility to enable the desired shape to be produced with a fair margin of safety. This average will be influenced by the regularity of size of the crystals composing the aggregate: the presence of a considerable proportion of very small crystals will reduce ductility below that which experience has shown to be usual for a certain "average grain size," hence one serious instance of the inadequacy of the property commonly implied by this term. Conversely, the presence of relatively large crystals will produce a rougher surface than might be predicted from the "average grain size" of the sheet used.

The precise practical influence of crystal size upon rate of work-hardening of the aggregate has yet to be established, but it is known that this rate increases as the crystal size decreases. This aspect is, clearly, of great importance industrially, because it is always desired to deform the metal as much as possible without having recourse to annealing.

Regularity of Crystal Size. Although the importance and desirability of a suitable "average grain size" is becoming more generally recognised and accepted, the significance of *regularity* of crystal size still remains insufficiently appreciated. By regular is meant small variation in size either above or below the specified "average" value.

It is important to notice that as the variation between the size of the largest and smallest crystals increases, the characteristic termed "average grain size" becomes more difficult to estimate and of less significance. Indeed, it is safer and more informative to give an indication of the range of crystal sizes present than to give an adjudged "average" value when considerable variation in size occurs.

As the low ductility associated with small crystals and also the high ductility, low tenacity and surface-roughening tendencies associated with large crystals are established and widely recognised, it is curious that the quite unjustifiable assumption is so often made that the natural properties of small and large crystals cancel out in an aggregate containing both. Some small degree of cancellation is to be expected, and certainly does occur, but it is probable that the deep-drawing properties of an aggregate composed of crystals of uniform (and, of course, suitable) size would be remarkable. Practical confirmation of this opinion is often found when examination of a sample of sheet which has shown exceptionally good behaviour under the press reveals no chemical or structural peculiarity other than an unusually regular crystal size. Similarly, sheet which has been found to possess less ductility than its chemical composition, hardness and casually-estimated "average grain size" suggest as being normal, is often found upon closer examination to possess an unusually large proportion of small crystals.

Although the importance of regularity of crystal size cannot fail to strike those who have the opportunity to correlate microstructure with observed performance under the press, more scientific proof is often needed to convince suppliers of the desirability of producing sheet having as regular a crystal structure as possible. Proof of this kind can be obtained by the ordinary Erichsen cupping test in the

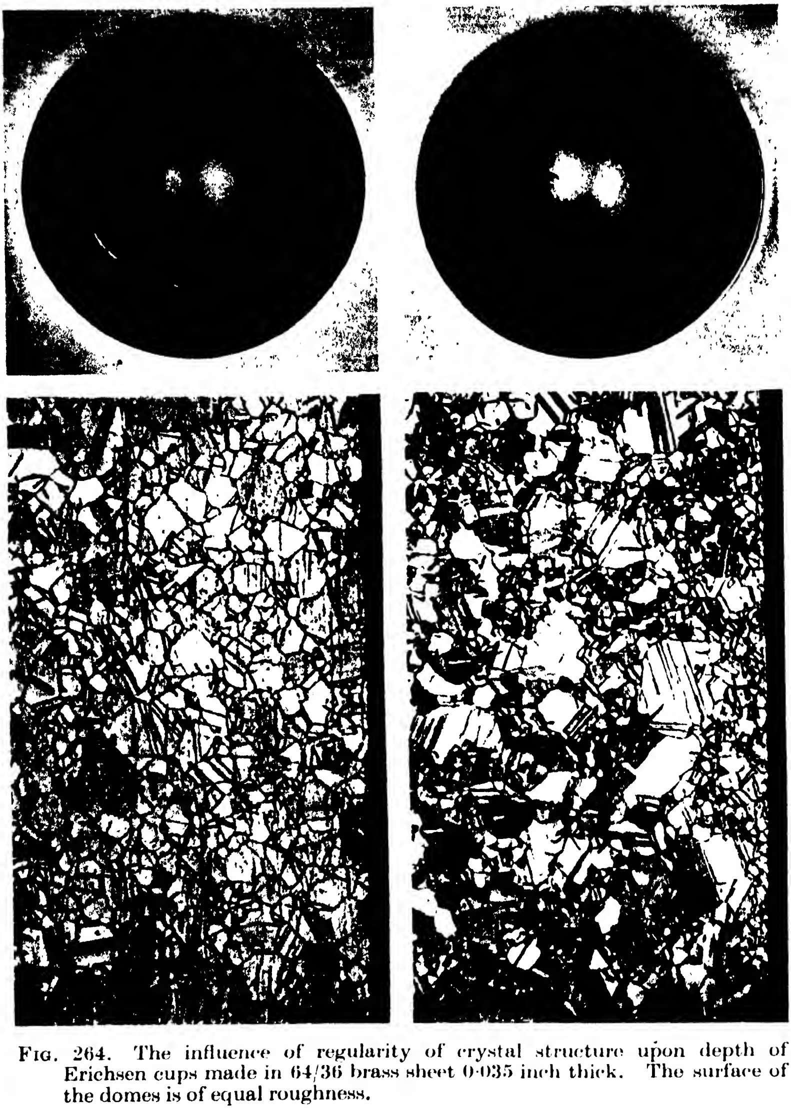


Fig. 264. The influence of regularity of crystal structure upon depth of Erichsen cups made in 64/36 brass sheet 0·035 inch thick. The surface of the domes is of equal roughness.

Left : 12·8 mm. cup given by uniform microstructure.

Right : 12·2 mm. cup given by irregular microstructure.

[*To face p.* 541.

manner illustrated in Fig. 264, which shows the surface of domes made in the two samples of 0·035-inch thick 64/36 brass sheet whose microstructure is illustrated beneath the appropriate domes. The important feature of these two specimens is that the degree of surface roughness is exactly similar, and the adjudged "*average* grain size" approximately similar; yet the depth of cup pressed in the sheet having a relatively uniform crystal structure is 12·8 mm., whereas that in the sheet having an irregular crystal structure is only 12·2 mm. A difference of this magnitude in Erichsen values indicates a distinct difference in deep drawing and pressing properties. Moreover, it should be observed that, to obtain an equal depth of draw on the irregular crystal structure of the kind illustrated, the "average grain size" must be increased; and this will give a rougher surface which will need more polishing if the finished article has to be smoothed or plated.

In steel a tolerably regular crystal structure is often found, although trouble is sometimes caused by the surface zones of sheet rolled from rimming steel having a much larger crystal size than the "core"; a feature which has already been illustrated (Fig. 117, p. 186). In non-ferrous metals no "core" effect occurs, but the regularity of crystal size varies considerably. In brass, the microstructure shown in Fig. 106 (p. 149)—which is typical of a highly irregular crystal structure in other metals—is, unfortunately, all too common; although the "average grain size" of the background of small crystals may be adjudged to be satisfactory for many press operations, the presence of the much larger crystals may be expected to produce, and in this instance actually did produce, such a rough surface upon deep-pressed work that the time to polish it was increased several-fold above that taken normally.

The inability of suppliers, either through lack of suitable control and plant or through less excusable causes, regularly to supply sheet having the desired "average grain size" has already been lamented; their inability to supply sheet possessing in addition the finer attribute of a *regular* crystal size is a matter of no less concern to users, although as yet not always appreciated by them.

These remarks apply to regularity of crystal size within a field of the same *order* of size as that of the crystals themselves. The desirability of what may be described as a "regular average grain size" throughout the width and, what is more difficult to obtain, throughout the length of a strip will be obvious.

Inherent Grain Size. The term "inherent" grain size is usually used to describe the size of the austenite grains or crystals in steel which, although normally invisible and having no relation to the crystals of the ferrite into which the austenite transforms, nevertheless exercise an important influence upon the properties of the (mainly) ferritic material. Expressed differently, some part of the grain boundaries of the austenite phase must persist in invisible form after this phase has changed to ferrite having entirely new, and usually smaller, crystals. It is probable that this persistence in "shadow" form is due to the presence in the original austenite crystal boundaries of minute inclusions or to segregation of impurities, and its importance is becoming more widely recognised.

In steels which have to be heat-treated, a definite "inherent grain size" is often included in specifications; but this practice has not yet been extended to steels used for deep drawing and pressing, in spite of the fact that there is some evidence to show that steel having a small inherent grain size behaves better when severe press operations have to be performed than steel having a large inherent grain size. However, this may perhaps be due to accompanying influences such as the percentage and form of occurrence of oxygen.

Applied to non-ferrous metals the term "inherent" grain size may seem a misnomer, yet the persistence of "shadow" crystal boundaries having no relation to the crystal structure of the sheet offered to the press may prove to be an unsuspected cause of hitherto unexplained poor behaviour. In such instances an almost invisible "envelope" structure formed by inclusions or impurities may conceivably persist throughout several recrystallisations produced by successive annealings. Evidence to support this hypothesis can sometimes be seen in the distribution of oxide particles in copper.

A still more speculative hypothesis is that "inherent" grain size in the form just indicated may even be responsible for the "block" movement which occurs when metallic crystalline aggregates are deformed plastically, a phenomenon which has already been discussed.

To conclude these remarks on crystal size, it is necessary yet again to emphasise the extreme importance of this attribute in relation to the deep drawing and pressing properties of sheet of any kind. This importance is becoming more widely recognised, but insufficient insistence is shown by consumers on being given the form of crystal structure best suited to their particular requirements, and insufficient appreciation of the need of this is shown by suppliers.

The size and regularity of size of the crystals in sheet purchased by the consumer, although influenced to some extent by chemical composition, is determined principally by the treatment which the sheet receives during its processing in the mills of the supplier. Some indication of the influence of both these factors, and also of the effect of critical deformation and annealing temperature given by the consumer during the working of sheet having an originally satisfactory crystal size, has been given in preceding chapters. During recent years a considerable amount of research has been carried out to determine the precise influence upon crystal size, and other related properties, of the final stages of rolling and annealing used in the production of sheet intended for deep drawing and pressing. No detailed consideration of this aspect will be attempted here on account of the necessarily lengthy nature of any adequate survey, and because it concerns the manufacture of sheet and is therefore beyond the scope of this book ; readers specially interested in the manufacture of deep-drawing quality sheet will be familiar with the many papers which have appeared in the journals of technical societies. It is to be regretted that most of these researches deal with steel, and that relatively little attention appears to have been devoted to non-ferrous sheets.

Ductility and Tenacity

These fundamentally important properties have already been discussed indirectly in the preceding sections dealing with crystal size and structure, since all three properties are inseparably interdependent. Although ductility and tenacity are of very great importance to those concerned with deep drawing, precedence has been accorded to crystal size because this property is more readily appreciated by industrial users of sheet metal, who may not always be familiar with the true significance of more fundamental properties.

The ductility and tenacity of sheet are determined first by the nature and chemical purity of the metal or alloy ; secondly by the crystal size ; thirdly by the rate at which the metal work-hardens and, fourthly, by the amount, if any, of work-hardening which has already been imposed upon it. Two other conditions, namely, the shape of the article or test piece and the nature of the applied stresses when these are of a complex nature, are also of importance sometimes. Consideration of reasons for the variation in ductility, tenacity and rate of work-hardening evinced by different metals due to their actual nature will not be attempted, since this would entail a study of the fundamental properties of matter and atomic structure beyond the scope of this volume. This recognised variation must be accepted, and the following general considerations must be interpreted as applying to any particular metal or alloy qualified by the range and values appropriate to it.

As applied to sheet metal used for deep drawing and pressing, " ductility " may be defined as capacity to suffer plastic deformation, usually under the influence of *combined* stresses. It may not, therefore, be truly comparable with percentage elongation as measured in the tensile test, although this assumption is often made without question and the term itself is often used as being synonymous with percentage elongation. That this use is incorrect is demonstrated by the increased apparent ductility manifested by any given sheet under "reversed" drawing as compared with direct drawing. This is easily demonstrated by the Erichsen cupping test, in which the depth of cup given by normal testing procedure can be increased 50 or even 75 per cent. if the cup is drawn some two-thirds of its normal depth, the specimen reversed, centred, and then drawn to destruction. Clearly, "ductility" with respect to deformation by deep drawing and pressing is influenced by the nature of the stresses imposed.

"Tenacity" almost defies precise definition; but, as applied to deep-drawing quality metal, it may be described as capacity to transform stress into strain (and heat), ductility being, by previous definition, merely capacity to suffer deformation. It requires little thought to show that in many deep drawing and pressing operations the property of tenacity is of equal importance to that of ductility, as the sheet, in addition to stretching, compressing and bending, must be able to *transmit* tensile stress in order to draw adjacent portions through the region of maximum pressure of the tools. Since the drawn portion of a blank is of less sectional area, and therefore more heavily stressed per unit area, than the undrawn portion—Fig. 76 (p. 106)—it follows that the property here termed tenacity is inseparably linked with *rate* of work-hardening, a fact which renders its precise definition and even its examination so difficult and introduces the element of time into the problem.

It is often claimed that tenacity can be assessed from the stress-strain curve given by a tensile test. This claim must be questioned, because experience shows that during deformation by deep drawing and pressing *apparent* tenacity, like ductility, is dependent to some extent upon the nature of the imposed stresses. The assumption is often made that as high a ratio as possible is desirable between the limit of proportionality (when one exists) and the ultimate strength of a metal, but in actual fact the optimum ratio of limit of proportionality to ultimate strength is dependent upon many factors, such as the nature of the drawing operation, the shape of the article, the number of draws given without an inter-stage anneal, the rate of work-hardening of the metal and others less definite. For this reason the claim that the behaviour of metal in the press can be predicted accurately from the results of *ordinary* tensile tests seems less plausible than several authorities have suggested. The actual numerical values of the limit of proportionality or ultimate strength are of minor importance from the deep-drawing aspect except in so far as they determine the power necessary to form the desired shape and, to some extent, the wear on the tools.

This difference between simple tensile properties and the combined properties here termed "ductility" and "tenacity" needs to be borne continually in mind, because, in many engineering applications, properties such as tensile strength and limit of proportionality enable a fair prediction of the behaviour of metal in service to be made. One reason for this is that, rightly or wrongly, the static strength of the metal at breaking point, or sometimes at its elastic limit, is held to be the one of paramount importance. From the aspect of deep drawing and pressing, on the other hand, it is the behaviour of the metal while *being deformed* at a certain rate within its plastic range which is of supreme importance; static stress values for ultimate strength and limit of proportionality are of importance only in so far as they determine the force necessary to produce the desired shape under the press and, of course, the static strength of the finished article.

The nature and significance of the various tensile properties has already been discussed in the preceding chapter, but it may be pointed out again that the tensile property having greatest significance from the aspect of the press-shop is, in all probability, reduction of area; for this value does indicate the combined influence of ductility and tenacity although only *under simple tensile stress*, a condition rarely obtaining in industrial deep drawing and pressing operations.

If, instead of the commonly measured physical tensile properties, the behaviour of a metal as revealed by the *shape* of its stress-strain curve is considered, tensile properties become of great importance because the curves indicating these properties—or, rather, the way in which these properties change as the metal is gradually strained to breaking-point—indicate qualitatively, if not always quantitatively, the properties of ductility and tenacity already cited as ones of supreme importance. In the previous chapter it has been explained that examination of "ordinary" stress-strain curves gives certain information concerning the behaviour of metals within the elastic and the plastic range which cannot be obtained in any other way. It has also been shown that "actual" stress-strain curves, in which true stress is related to average elongation, still more "true" stress-strain curves in which true stress is related to true elongation or true reduction of area, give a more correct and much more informative picture of the behaviour of metal within the *whole* of the plastic range which, of course, is the important one from the aspect of deep drawing and pressing. Without repeating what has already been said, a few observations may be made concerning the interpretation of curves of this kind from the fundamental aspect; because previously the subject was approached from the angle of practical testing with only a secondary consideration of the properties revealed by the curves obtained.

Fig. 252 (p. 512) shows "true" stress-strain curves plotted for a number of common metals from results obtained by Swift [102] and Sommer.[103] Readers having experience with these metals in the press-shop, yet unfamiliar with graphs of this kind, will quickly see the relationships which exist; for example, the general slope of the curves indicates the rate of work-hardening. The steep slope of the curve for "18/8" austenitic steel shows that this metal work-hardens rapidly and to a marked degree, as any press-man knows, while the very high actual or "true" tensile stress explains the high punch pressures which are needed to form deep shapes in austenitic steels. On the other hand aluminium, having an almost horizontal curve, work-hardens very slowly, and it is well known that—as illustrated in Fig. 157 (p. 249)—a flat blank of this metal can be deep-drawn into a tube of small diameter without the help of annealing. The curves for copper and low-carbon steel indicate an intermediate rate of work-hardening associated with a moderate "true" ultimate strength.

Logarithmic curves give no more information than "true" stress-strain curves, but, because the graphs are straight lines, this method of expression is sometimes preferred. A number of logarithmic curves are shown in Fig. 255 (p. 515). As already explained, the height of the lines gives a strength index; and, as in other forms of curves, their slope represents the rate of work-hardening. This method of plotting enables precise numerical values to be obtained for strength and rate of work-hardening of any metal. In addition it acts as a useful reminder that all ductile metals appear to obey one law of plastic flow and, furthermore, *that this law obtains throughout the whole range of plastic flow.* "Ordinary" stress-strain curves of the kind shown in Fig. 251 (p. 511) suggest that the method of flow changes at the ultimate tensile stress, but this impression is due to the empirical nature of this value which does not represent the true stress sustained by a specimen as its cross-sectional area is reduced, a fact which has already been emphasised sufficiently.

The "modified" stress-strain curves of Sommer, constructed by replacing increments of stress on a true stress-strain graph by the quotient of true stress divided by ultimate tensile strength, give a particularly instructive picture of the behaviour of metal throughout the whole plastic range. Fig. 65 (p. 516) shows a number of "modified" stress-strain curves obtained by this investigator. In using graphs of this kind, the main object is to compare the *shape* and *relative position* of any curve with others representing metal the behaviour of which under the press is known, or with standard curves representing the normal behaviour of some particular metal, rather than to measure absolute values. It must be borne in mind when estimating deep drawing and pressing properties by inspection of these modified stress-strain curves that in their construction no account is taken of factors such as the influence of bending stresses, although it seems probable that this is relatively small, and, of more importance, of stresses produced by the friction of the sheet as it passes through the tools. The effect of this last factor is to render comparison less accurate for metals of widely different tensile strength and surface condition, while the possible influence of lubricant, pressure-plate loading and speed of deformation must always be considered.

When these extra factors are taken into account it is possible to obtain most valuable knowledge of the deep drawing and pressing properties of any sample by plotting its modified stress-strain curve in the manner described and comparing the position and shape of this curve with others. Examining Fig. 256 (p. 516) it will be seen, for example, that the peculiar behaviour of the ferritic type of corrosion-resisting steels is clearly shown, for the modified curve changes its position from the worst to the best of any included on the graph. Inspection of such a graph would have shown what took years of press-shop experience to ascertain, namely, that the first draws must be light if breakage is to be avoided although, after a stage corresponding to the abrupt change in direction of the modified curve which indicates a change in rate of work-hardening, a surprising amount of deformation can be accomplished without annealing. Indeed, annealing sheet lightly deformed, yet apparently increasing rapidly in hardness, actually *impairs* its deep-drawing properties by restoring the metal to its original condition, which is one not conducive to easy working under the press.

Aluminium shows a similar curve, but both the initial rate of work-hardening and the suddenness of the change are less pronounced, although the slope of the end part of the curve is even less steep than that of the ferritic corrosion-resisting steel. This agrees closely with observed facts. For example, it is known that the substitution of aluminium sheet which has been lightly cold-rolled for fully-annealed sheet does not usually influence the depth of draw obtainable, whereas substitution of this kind in the case of brass or steel would seriously impair the depth of draw obtained. Further, the slope of the end part of the curve, which is the most gradual of any curve on the graph in Fig. 256 (p. 516), explains the amazing amount of cold deformation which can be inflicted on aluminium under suitable conditions.

Inspection of their modified stress-strain curves shows the relatively constant rate of work-hardening of brass and austenitic steel, and that copper exhibits a slight, and Armco iron a more marked though still small, change of slope. It should be observed that these changes in rate of work-hardening, which are of such importance from the aspect of deep drawing and pressing, are not revealed on ordinary, true or logarithmic stress-strain curves. It is this fact which renders the modified stress-strain curves of Sommer of such value in spite of the limitations and sources of error already mentioned.

From what has been said, it will now be evident that the properties termed ductility and tenacity, themselves dependent upon that of work-hardening, are really the essential ones which determine the behaviour of sheet metal during deep drawing and pressing operations, for happily the important practical question of surface roughness does not trouble the student of theory.

How ductility and tenacity can be measured most usefully seems uncertain, because the results given by tensile testing cannot be translated to give a *direct* indication of the behaviour of metal under the action of a complicated system of combined stresses such as obtain in many industrial press operations. However, in spite of their limitations, the information given by special forms of "true" and "derived" stress-strain curves can be of great help when studied intelligently, and variations of the ordinary method of tensile test—such as the wedge-drawing test in which compressive as well as tensile stresses are imposed on the specimen—seem capable of providing still more useful fundamental information if the results can be interpreted and applied to industrial practice.

Readers may rightly feel that this discussion of the fundamental properties of ductility and tenacity has been of a somewhat vague nature; but present knowledge seems insufficient to enable a clear exposition to be given. Those interested in the more academic aspect of the plastic deformation of metals are referred to the many scientific papers which deal with this difficult yet vitally important subject.

WORK-HARDENING

Work-hardening is the natural property of a metal or alloy which causes it to harden when deformed plastically by cold work. As with other fundamental physical properties already considered, no attempt will be made to discuss the causes of this phenomenon, which is believed to be caused mainly by effects produced at the surfaces of blocks of atoms when these slide one upon another within the crystal grain; by a slight buckling or wrinkling effect imposed by the action of stress upon the crystallographic planes of atoms within the crystal, and perhaps by effects attributable to the behaviour of crystal boundaries.

Were it not for the natural ability of metal to work-harden, necking and *localised* extension would occur and proceed to fracture without any measure of uniform extension occurring throughout a piece of metal strained in tension; for the stress would naturally be highest in the neck of reduced cross-sectional area and the metal in this, if it did not work-harden, would be unable either to resist increasing plastic deformation or to transmit stress to the adjacent less-deformed regions of greater cross-sectional area in order that these, in turn, might be deformed. Clearly, then, in all deep drawing and pressing operations the influence exerted by work-hardening is of fundamental importance; yet its existence and effect is usually accepted by practical workers, and by some scientific students, without due appreciation of its full significance in the processes they study.

When, as a result of severe plastic deformation by deep drawing or any other form of cold-working, a metal has work-hardened a certain amount, it will be necessary to anneal it at a suitable temperature in order to soften it and to restore in full or partial measure its original ductility before further plastic deformation can be imposed upon it. The " certain amount " just mentioned will depend firstly on the metal or alloy and, secondly, on the nature of the deforming operations. For this reason in most deep-drawing operations it is the capacity of the particular sheet being deep drawn to work-harden which determines the total depth of draw which can be given before annealing becomes necessary and, hence, the total number of press and annealing operations required to produce a given shape. As this number is of primary importance in determining the cost of production of any article, the property of work-hardening must rank as equal in importance, commercially, to any.

It might be imagined that the less a metal work-hardens for a given amount of deformation the easier it will be to form into shapes by the usual methods of deep drawing and pressing. Although this may be true if " easier " is interpreted as meaning fewer inter-stage annealings, less wear on tools and less mechanical force, it has already been shown that work-hardening determines to a considerable extent the property termed tenacity, and that a fair measure of tenacity is usually essential if metal is to draw well. For this reason a very low capacity to work-harden is not always an advantage ; a fact well demonstrated by the metal lead. On the other hand, as users of austenitic steels are fully aware, an unusually high capacity brings difficulties of its own, not the least of which are frequent annealings, severe wear on tools and, of importance, the need for special deep drawing and pressing technique. As with many other properties which determine the behaviour of sheet metal under the press, that of capacity to work-harden seems to be most favourable when manifested in moderate degree.

It is difficult to define the capacity of any metal to work-harden. Probably the most precise method is to define this property as the slope of some form of stress-strain curve, such as those shown in Fig. 252, (p. 512), and Fig. 255 (p. 515). For example, in Fig. 252 the steeply rising curve of austenitic steel and the relatively flat curve of aluminium show very clearly the well-known work-hardening characteristics of the respective metals, while the slope of the curves for other metals is also indicative of their known behaviour when cold-worked. On the other hand, a useful pictorial representation of the behaviour of a metal with respect to work-hardening is given by the " modified " stress-strain curve of Sommer illustrated in Fig. 256 (p. 516), which is more readily understood by those who are discouraged from further study by the term " log log curve." Indeed, although the curves of Sommer yield only comparative relationships and not precise values, they are in some ways more useful to the practical man than the straight-line graphs which reveal interesting fundamental relationships to the scientist.

When drawing conclusions from curves of the kind just mentioned it is unsafe to assume—as is done sometimes—that the behaviour of any particular metal with respect to work-hardening will be the same in pure tension as under the far more complicated conditions obtaining in deep drawing, for in this process elongation, compression, flexing and rubbing take place; furthermore, speed of deformation may be an important factor. No further proof of this need be given than the familiar effect observable with the ordinary Erichsen cupping test wherein the normal depth of cup may be increased considerably if the sheet is cupped from one side, reversed, centred and cupped to destruction from the opposite side. When attempting to predict the behaviour of sheet under the press, therefore, the nature of the deformation it has to suffer (in, perhaps, several successive operations) must always be kept in mind.

As, in the light of present knowledge, work-hardening seems to be a natural property of any given metal or alloy incapable of modification except by control of the proportion of impurities, the user of sheet metal is hardly called upon to recognise this property as one under his control or capable of specification in the metal he purchases. Whether in the future a more complete understanding of crystal and atomic structures will enable modification to be made must remain a subject for speculation.

Reaction to Speed of Deformation

This is really an aspect of work-hardening, the property just examined, because it depends principally upon the *rate* of work-hardening; but it is proposed to consider this aspect as a separate subject in order to distinguish between the two properties of capacity or degree of work-hardening, expressed as an increase in hardness, and velocity, expressed in units of time, necessary for work-hardening to occur. The importance of velocity of work-hardening in determining the behaviour of metal during deep drawing and other mechanical operations is as yet insufficiently recognised; indeed, the subject is one which has claimed little attention until comparatively recently.

Winlock and Leiter,[56] studying the effect of speed of deformation primarily in connection with the formation of stretcher-strain markings in steel, draw attention to the existence of a definite time lag during the transition from elastic to plastic straining. Expressed differently, work-hardening seems for some unexplained reason *to take time,* and these investigators cite instances of rapid loading in which failure has occurred in ductile steel at the first stretcher-strain marking when the narrow band of initial deformation has not had sufficient time to work-harden and thus become able to transmit stress to the adjacent softer and more ductile metal.

One hindrance to the study of high-speed tensile testing is the difficulty experienced in recording trustworthy stress-strain curves when the speed of straining is high. This is particularly unfortunate from the aspect of deep drawing and pressing because the importance of the full stress-strain curve is often greater than that of the numerical values recorded for the ordinary tensile properties; but the curves already published for moderate speeds of deformation provide much food for thought.

The fact that work-hardening takes time leads to the obvious and intriguing conclusion that if deformation could be carried out in so short a space of time that the full effect of work-hardening could not become manifested, a quite abnormal degree of deformation might become possible. This object is actually achieved in the industrial process of impact-extrusion described in a later chapter, for it is undoubtedly the time-lag in the manifestation of work-hardening effects which renders possible the quite remarkable amounts of plastic deformation which can be accomplished in this interesting process. It is important to notice, however, that in the impact-extrusion process, as usually worked, the property of tenacity is of little significance; whereas in deep drawing and pressing operations this property must be exhibited in considerable measure if the metal is to be capable of transmitting sufficient stress to enable it to be drawn through the tools without elongating locally and breaking.

Unfortunately the seemingly simple expedient of using a very high speed for ordinary deep drawing and pressing operations is usually impossible because the bottom is torn out of the cup by the impact of the descending punch and, if failure does not occur in this way, the ever-present problem of ensuring adequate lubrication becomes greatly increased owing to the heat generated by friction through the metal rubbing at very high speed over the tools. However, these practical difficulties do not alter the fundamental issue which is that—if it could be used—a high speed of deep drawing or pressing might enable very severe deformation to be inflicted upon some metals. Further discussion would be speculative, and attention can only be drawn to the undoubted importance of the reaction of any particular metal to speed of deformation, to the present lack of appreciation of this aspect and to the need which exists for its examination from both the theoretical viewpoint as attempted by Winlock and Leiter [56] and from the practical viewpoint as attempted by Mathewson, Trewin and Finkledey [79] in their classic "dynamic ductility" tests on zinc and brass sheet.

The statement that the amount of heat generated during a given draw will increase with increasing speed of drawing needs qualification :

although this may appear to be so in practice, the amount of heat generated probably remains constant. The apparent increase in heat generated is explained by the decrease in time available for its dissipation by conduction, an explanation which becomes clear if extremes of speed are visualised.

Hardness

Practical men, whose studies have been of an engineering rather than a metallurgical nature, often place hardness near if not at the top of any list of properties which determine the behaviour of sheet metal under the press. This fallacy has been explained in an earlier chapter in which it has been shown that, as a rule, the only significance of indentation hardness tests lies in their use as a rapid routine method to indicate the *probable similarity* of samples of sheet. When the practical operator speaks of " hardness " he really means a combination of physical properties determined by the " average grain size " plus the influence of any cold-work which has been given to the sheet and, sometimes, the influence of impurities or even alloying elements. In other words, he uses the term " hardness," not in its proper sense, but as a kind of general index of deep drawing and pressing properties ; a significance which it does not possess except perhaps in special instances.

As an example of these special instances there may be mentioned fully annealed sheet of constant " average grain size," constant chemical composition and constant directional properties which has been given a certain amount of cold rolling, as is sometimes done with aluminium to prevent critical-strain crystal growth occurring when partly-formed shapes are annealed. Under such conditions true hardness may be a property of genuine significance because it is indicative of the amount of cold-rolling given ; but caution is still necessary, as shown by the fact that hardness is an unreliable indication of the small amount of " temper-rolling " given to steel sheet.

Even in these special instances there is a likelihood that stated hardness values may not be true ones, and may therefore be misleading, owing to the difficulty of testing thin sheet by indentation methods. These difficulties have been described fully in Chapter XII, but the caution may well be repeated that, unless the depth of the indentation is small relative to the gauge of the sheet and the load applied is actually the indicated load and the impression measured accurately, the hardness value obtained may not be the true one.

There is also a special sense in which the practical operator uses the term " hardness," namely, as an index to the tendency shown by sheet to " spring back " when released from the restraint of the punch and, later, the die. This " spring " determines both the final size of the deep-drawn or pressed shell and, sometimes, the ease with which it can be extracted from the tools. It is, therefore, a matter of considerable importance from the viewpoint of those responsible for tool design and also for press operation. From this angle, the property of true hardness, notwithstanding its small significance as an indication of actual deep drawing and pressing properties, is one which requires to be controlled with some care in sheet destined for certain press operations.

Directionality

In the deep drawing and pressing industry the term " directionality " is used to denote variation in the physical properties of sheet metal relative to some direction, usually that of rolling, in which tests are made or behaviour observed. Although this variation must be classed as a defect, and its effects as such have already been pointed out in Chapter III, some elaboration of the nature and cause of directionality is both desirable and appropriate during this discussion of the properties of deep-drawing quality metal sheet.

Causes. Directionality arises from one or both of two distinct causes, namely, segregation and non-metallic inclusions existent in the original ingot and elongated, during its processing, into threads or planes ; and, secondly, orientation and properties of the crystals composing the finished sheet, a cause not attributable to the original ingot.

Directionality caused by Segregation or Non-metallic Inclusions. Considering the first of these causes, it will be readily appreciated how elongated streaks, threads or planes of inclusions or segregation can produce what is popularly termed a " fibrous " structure and can thereby impart marked directional properties to the sheet in which they exist. Examples of segregation have already been given, and readers are asked to turn back to the appropriate photomicrographs which illustrate the three principal types of segregation which occur. These are :—

(1) Genuine " pipe " segregation of non-metallic inclusions (Fig. 123, p. 188), often associated with actual voids, a defect which, though rare in most non-ferrous metals is, unhappily, fairly common in steel.

(2) Segregation of impurities, as occurs in " ghost " lines or in the thinner planes of phosphorus segregation in steel (Fig. 119, p. 187).

(3) Segregation of major constituents, *e.g.*, *beta* particles in brass of low-copper content (Fig. 96, p. 145), or pearlite particles in steel (Fig. 115B, p. 178).

In each of these three types the segregated planes will possess markedly lower ductility than the surrounding metal which, owing to their presence, will not be able to flow in a desirably uniform manner throughout its section.

The only real remedy for directionality due to these causes is the obvious though difficult one of preventing segregation in the original ingot. Other defects attributable to segregation have already been described, but, beyond the brief mention accorded in the first two chapters, no study of ingots will be attempted; readers desiring more knowledge on this particular subject are referred to the literature which deals with it.

Directionality caused by Orientation and Properties of the Crystals. This the second postulated form of directionality, is of a far more subtle nature and less knowledge exists concerning its exact cause or remedy. One difficulty in the study of this second form is that, in distinction from the first, ordinary microscopical examination sometimes fails to reveal its cause, and examination of the crystal structure by means of X-rays is necessary to show any reason why such directionality as becomes evident during physical tests or actual drawing operations should exist. During this immediate discussion it will be assumed, for the sake of clearness, that no segregational causes exist, but it must be emphasised that these frequently accompany and intensify those due entirely to crystal structure.

Dealing with the visible, and therefore more readily appreciated, causes of directionality attributable to crystal structure, two forms are recognisable. One is the existence of planes or stringers of very small crystals, such as those illustrated in Fig. 57 (p. 85). These planes will possess markedly less ductility than the surrounding metal, and will behave as the planes of segregation which have just been considered; indeed, their existence is sometimes due to segregation of a major constituent causing non-uniform recrystallisation throughout the thickness of the sheet. In the absence of chemical heterogeneity, non-uniform recrystallisation may still occur by reason of variation in the amount of deformation which has been imposed throughout the thickness or even the width of the sheet during previous cold work. The very great influence exerted on recrystallisation behaviour by different amounts of deformation is well recognised in the case of steel and certain other metals, *e.g.*, aluminium and some copper-nickel alloys, and there is evidence to show that this influence may occur in brass to a greater degree than is commonly believed.

The remedies for these two causes lie, respectively, in preventing segregation in the original ingot and in avoiding, as far as may be possible, the imposition of non-uniform and of known critical amounts of deformation on the sheet.

The other (microscopically) visible cause of directionality is the natural elongation suffered by all crystals in the direction of an applied tensile stress; an effect, let it be observed, which may not always be completely removed after apparently complete recrystallisation.

Even slight elongation of individual crystals composing an aggregate can produce directional properties in that aggregate. It is probable that this is due to two causes, first, to the directional properties of each individual crystal as determined by the orientation of its atomic planes, and, secondly, to the purely mechanical effect attributable to the larger number of crystal boundaries cut by a line of unit length running at right angles to the direction of rolling than by one running parallel to this direction.

As regards the first of these causes of directionality, it is well established that the resistance of a metal crystal to deformation, which is believed to occur by a process of "block slip," varies with the angular orientation of the applied stress relative to the crystallographic axes, being least in directions parallel to the postulated planes of "easy glide." The theory of block slip is widely recognised and accepted at the present time as an explanation of the mode of deformation of a crystal, and it will not be elaborated here.

As regards the second cause, *i.e.*, crystal boundaries, the exact nature of crystal boundaries in the sense of atomic arrangement on the space lattice, the exact effect produced by them with respect to physical strength relative to the main body of the crystal, and also their precise influence upon stress distribution throughout the crystal aggregate is not yet established. Readers interested in this fundamentally important aspect are referred to papers dealing with the crystal structure of metals, and are asked to accept the fact that present knowledge suggests that the presence of crystal boundaries increases the tensile strength and lowers the ductility of the aggregate relative to the respective values for the interior of the crystals.

Examination of the diagrams in Fig. 265 (p. 556) will show that the number of crystal boundaries cut per unit length measured on any imaginary straight line varies with the elongation of the crystals and also with the angular direction in which the count is made. The author suggests that this fact may account at least in part for the observed variation in the tensile strength and ductility which occurs in rolled sheet metal according to the orientation of the test piece, and also for the variation in the angular orientation of the directions of minimum and maximum values for these and other properties which occurs with various percentage reductions of sheet. This suggestion must be regarded as speculative, although present knowledge certainly indicates that the numbers of crystal boundaries per unit length is a factor which determines in some degree the magnitude of certain physical properties of the aggregate.

Considering an imaginary line drawn through a crystal aggregate it seems likely that, in addition to the mere number of boundaries cut by this line per unit length, the relative proportion of total or added boundary length (of those crystals cut by this imaginary line) which lies at less than 45 degrees to that which lies at more than 45 degrees to it may be of importance.

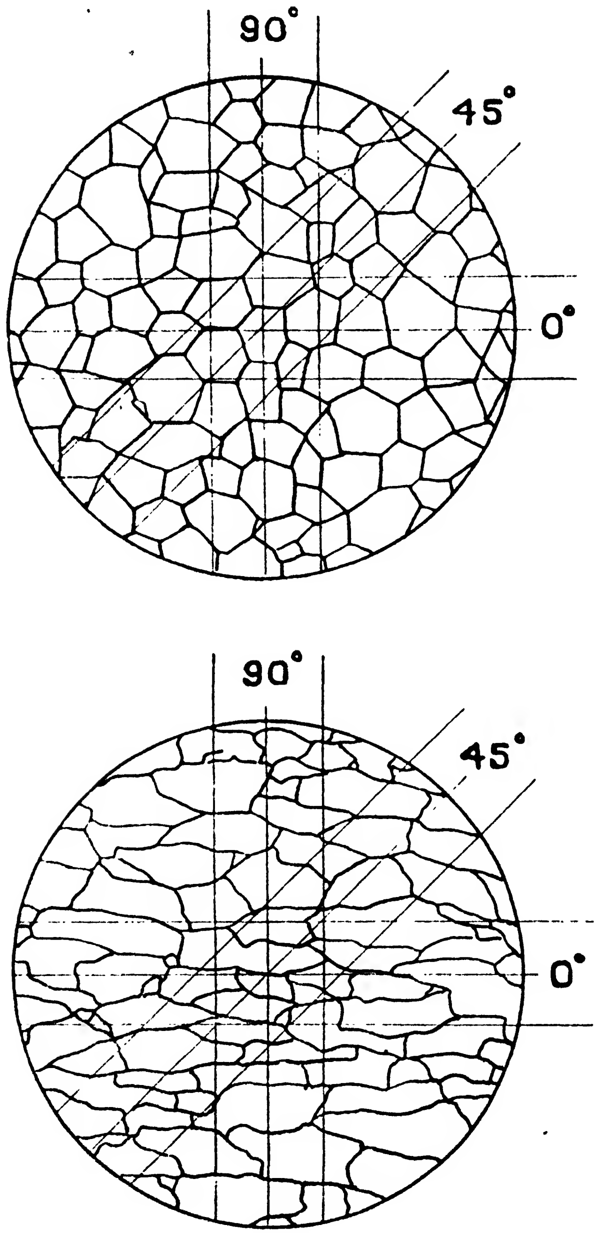


FIG. 265. Diagrams illustrating influence of "directionality" on number of crystal boundaries cut by lines of unit length running at 0°, 45° and 90° to the direction of crystal attenuation. The average number of boundaries cut by each group of three lines, expressed as a percentage, is :

	"Equi-axed" structure	*"Directional" structure*
0°	32 per cent.	19 per cent.
45°	34 ,,	35 ,,
90°	34 ,,	46 ,,

FIG. 266. Annealed *alpha*-brass structure devoid of apparent directional characteristics, yet showing distinct directionality when examined statistically.

Microsection cut parallel to surface of sheet. 100

[*To face p. 557.*

Directionality due to the elongation in one direction of the crystals composing an aggregate cannot, obviously, be prevented ; it can be removed only if and when *genuinely* " equiax " recrystallisation can be brought about.

Turning to the second, or invisible, cause of directionality due to crystal structure, further sub-division may be made into, firstly, the actual but normally invisible elongation of the crystals produced by cold work—to which the preceding remarks will apply—and, secondly, the still more subtle directional effects existent in crystals which are definitely *not* elongated in the direction of an applied tensile stress.

It is well known that a surprising amount of reduction can be inflicted upon an apparently " equiax " crystal structure before visible elongation of individual crystals can be detected by casual examination under the microscope. It is not so well known that even in annealed sheet as free from visible elongated inclusions or segregation and as devoid of apparent directional appearance in the crystal aggregate, when viewed under the microscope, as is the piece of metal shown in Fig. 266, distinct directional properties can be revealed by careful statistical examination of the orientation of the " apparent greatest width " or, of greater significance, of the twinning planes of large numbers of individual crystals. This particular photomicrograph shows one of the specimens actually used by Johnston [111] in an interesting series of experiments, confirmed later by Cook,[112] which demonstrates beyond doubt the existence of distinct preferred orientation in a crystal aggregate which exhibits no trace of this condition when examined casually.

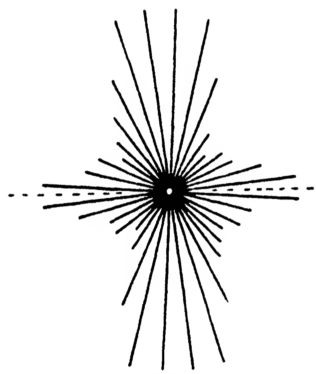


FIG. 267. Diagram illustrating directionality as revealed in brass sheet by orientation of slip planes within the crystals. The length of any radial line represents the number of crystals having their slip planes oriented within $\pm$ 5° of the angle made by that line to the direction of rolling, shown by arrow. [*Cook*.

Fig. 267 shows one of the diagrams obtained by the last-mentioned investigator. In this the radial lines represent the number of crystals, within a given field of rolled and fully annealed brass sheet, having their twinning planes oriented at an angle within 5 degrees on either side of the angle made by the appropriate lines to the direction of rolling (shown by an arrow). It will be seen that marked minima exist at angles of 45 degrees to that of rolling, and it was observed that, in cups drawn from this sheet, ears were formed in directions corresponding with these minima.

Whether directionality is visible or invisible microscopically, X-ray examination can reveal incomparably more precise information concerning its nature and severity. It is important to notice that the sensitivity of X-ray examination in revealing directional properties in the crystal structure of sheet is affected very markedly by the direction in which the X-ray beam is directed on to the specimen. For revealing directionality or, to use a better term, preferred orientation of crystal structure, the X-ray beam should be directed parallel to the surface of the original sheet and at right angles to the direction of rolling. This fact is well demonstrated by Goss in a paper [34] which also indicates the genuine usefulness of X-ray examination as applied to sheet metal. Before the greatly increased sensitivity of the X-ray beam to preferred orientation accorded by impingement in the direction just mentioned had been discovered, investigators had failed to detect quite appreciable, and even suspected, preferred orientation of crystals in rolled sheet.

Preferred orientation in steel sheet has been studied by many investigators using X-ray methods; the work of Gensamer and Mehl,[113] in which the investigators use what they term polar figures to illustrate preferred orientation, is perhaps of special interest, although Wever [114] appears to have been the first to use this method of representation.

In the light of present knowledge, it seems that with steel, and in a rather lesser degree with brass, the orientation of maximum and minimum values for tensile properties relative to the direction of rolling is influenced in a profound manner by the nature of the rolling operations, and that the limiting values do not always lie at an orientation of 0 degrees or 90 degrees to the direction of rolling.

Interesting as these more subtle causes of directionality are to the research worker, the practical user of sheet must for the present leave them to be investigated by such workers as are in the fortunate position of being able to do so, and confine himself to recognising their existence and allowing for their possible influence in the shaping operations he has to carry out. The elimination or definite control of directionality in rolled sheet may be very difficult, and it is certain that much investigational work will have to be carried out before suppliers can offer to users of deep-drawing quality sheet a product free from, or exhibiting very slight, directional properties.

Manifestation and Practical Effect of Directionality. The effect of directionality attributable to planes or streaks of non-metallic inclusions or pronounced segregation has already been illustrated during discussion of failures and defects in previous chapters. The manner in which these planes of low ductility influence the behaviour of sheet is so obvious that no further elaboration will be attempted in this section. The effect of the second form of directionality, namely, that attributable to preferred orientation of the crystals, whether of a simple or obscure nature, is to engender a difference in the physical properties as revealed by most forms of tensile test, by the tear-length test and, sometimes, by cupping tests.

Present knowledge tends to show that both the severity of directionality and also the angles (relative to the direction of rolling) of maxima and minima for various physical properties may be influenced in a profound manner by the treatment, particularly the final stages of rolling and annealing, which the sheet receives. Phillips and Dunkle [115] have shown that for low-carbon steel sheet of deep-drawing quality in the cold-rolled condition the tensile strength measured at 90 degrees to the direction of rolling may be up to 12 per cent. greater than that measured at 0 degrees, *i.e.*, parallel, to this direction, the increase being a gradual one from 0 to 90 degrees. For the same sheet rolled and annealed, these investigators record the interesting fact that the direction of maximum tensile strength varies with the percentage reduction given to the sheet before annealing. Thus, for reductions up to 40 per cent. the same gradual increase from 0 to 90 degrees occurs; for reductions between 50 and 60 per cent. the maximum tends to move from 67·5 to 45 degrees, and at 69 per cent. reduction a marked maximum occurs at 45 degrees. They also record that the height of the ears formed on a drawn shell increases with the percentage reduction given to the sheet prior to annealing, that after reductions of 50, 60 and 69 per cent. the ears lie on lines drawn at 0 and 90 degrees to the direction of rolling, and, at 40 per cent. reduction, always at 45 degrees to this direction.

Cook [112] has made similar experiments with brass sheet, but has obtained values only at 0, 45 and 90 degrees to the direction of rolling, and has not observed any formation of ears in directions other than at 45 degrees and, occasionally, at 135 degrees.

By means of X-ray examination Goss,[34] Gensamer and Mehl,[113] Wever,[114] and many other investigators have studied the effect produced on preferred orientation by different percentage reductions and also by temperature and stage of annealing treatments for steel sheet; but adequate correlation between the results of X-ray examination and tensile tests, still more of practical drawing tests, appears to be lacking.

Using statistical methods of examination under the microscope, Johnston [111] has established the existence in brass of definite preferred orientation undiscernible from a casual examination of the microstructure. Cook [112] has confirmed this work and has related the preferred orientation revealed by this method to tensile properties and height of ears formed during deep drawing.

Attention has been drawn in an earlier chapter to pronounced directionality revealed by the tear-length test, differences of from 100 to 300 per cent. often being obtained in different directions between 0 and 90 degrees. The tear-lengths obtained at intermediate angles between these limiting values are sometimes less than those at 90 degrees, this effect being particularly noticeable with steel; frequently the minimum value is not at 45 degrees, *i.e.*, it does not always correspond to the directions in which ears are formed during drawing and to the minima revealed by statistical examination as illustrated in Fig. 267 (p. 557). When attempting to make tears at angles other than 0 or 90 degrees to the direction of rolling, it is noticeable that the triangular tongue so formed tends to turn into the direction of rolling, giving a curved instead of a straight-sided tongue. This, although a source of error during the test, in itself provides striking evidence of one effect of directionality. The result of tears made in a typical piece of deep-drawing quality brass sheet containing approximately 64 per cent. copper is shown in Fig. 226 (p. 480). The tendency evinced by the 45-degree tears to turn into the direction of rolling, and also the marked difference in the length of the tears made at 0 and 90 degrees, is clearly visible.

Turning from laboratory evidence of directionality to the effect of this property as manifested in the actual press-shop, the two principal effects are local thinning or rupture due to low ductility in certain directions although in others the ductility may be adequate, as illustrated in the split cup shown in Fig. 59 (p. 86), and the formation of local wrinkles or puckers during the deep drawing or pressing of a shape in tools which do not normally produce these defects. In large pressings of irregular shape such as are used in the automobile industry, in which the flow of metal varies very markedly in different regions, excessive directionality may completely upset the desired flow; similar trouble can be encountered in the deep drawing or pressing of quite small articles of irregular shape.

Rather interesting, although industrially unimportant, evidence of directionality is to be found in the flat base of the circular steel shell illustrated in Fig. 151 (p. 237). It will be observed that the ring of stretcher-strain markings has assumed a distinct ovalness, with the major axis lying at 90 degrees to the direction of rolling of the original sheet. This rather striking effect is, presumably, due to a difference in the value for the limit of proportionality or the yield-point elongation of the sheet at 0 and 90 degrees to the direction of rolling; but it seems uncertain whether this assumed difference has influenced the position of the stretcher-strain markings as first formed, or whether it has resulted in initially symmetrical markings being distorted, after formation, through unequal flow in the walls of the cup. The pattern of the stretcher-strain markings rather suggests the first effect as having been the primary cause of the visible ovalness.

Ears, the height of which seems to be proportional to the severity of the directionality present in any sheet, serve as a useful warning to the practical operator of the existence of abnormal directionality in the sheet he is using; if very pronounced, they may themselves constitute a serious defect. The practical effect of ears has already been discussed and several typical examples of ear formation at 45 degrees (Fig. 58, p. 86, and Fig. 61, p. 87), and also at 0 and 90 degrees (Fig. 133, p. 197), to the direction of rolling in the original sheet have been illustrated.

Quite often the importance of the influence of directionality is insufficiently appreciated by suppliers of sheet, tool designers and practical operators. Defects and failures directly attributable to pronounced directional properties are not always recognised as such, and the increasingly severe demands which are being made upon sheet call undoubtedly for both a better understanding of its very real influence and a serious attempt on the part of sheet makers to reduce its severity.

Clearly, a difference of some 12 per cent. in tensile strength and of from 100 to 300 per cent. in whatever properties are revealed by the tear-length test ought, and indeed are found, to exert a very real influence upon the behaviour of sheet during deep drawing and pressing processes. When, as is not unusual in present practice, the press operations by which a shape is produced utilise practically the full capacity of the sheet for deformation, the severity of the directionality existing in any sheet may be the decisive factor which determines the success or failure of the operation. Instances of this are illustrated in the split cup shown in Fig. 63 (p. 92) and the shell shown in Fig. 278 (p. 592) which has orifices plunged in its drawn walls. Greater recognition is needed of the fact, now definitely established, that the limiting values for physical properties such as tensile strength and ductility do not always lie in directions of 0 and 90 degrees to the direction of rolling of deep-drawing quality sheet.

In view of the importance of directionality, no apology is offered for the somewhat lengthy consideration which has been accorded to it in this review of properties which determine the behaviour of sheet during deep drawing and pressing. It is a property to the effect and control of which more attention will have to be given.

Reaction to Annealing

When the manufacture of a deep drawn or pressed article necessitates inter-stage annealing to enable the desired degree of deformation to be imposed upon the metal, the annealing operation should be regarded as a very important one because if proper ductility is not restored to the work-hardened metal subsequent press operations are likely to prove unsuccessful. Therefore, the reaction of a metal toward annealing is a property which in some instances ranks almost equal to its mechanical behaviour.

In previous chapters the importance of correct annealing treatment has been emphasised and some of the effects of incorrect inter-stage annealing have been illustrated. However, different metals respond in a different manner toward the heat-treatment judged most appropriate for their kind, and it is to this aspect to which it is desired to draw attention here.

With any particular metal or alloy three distinct aspects need to be considered : sensitivity to temperature, time and, sometimes, cooling ; consistency of behaviour under given conditions, and proneness toward critical-strain crystal growth. Obviously, the ideal metal would be relatively insensitive to annealing conditions, regular in its behaviour and free from critical-strain crystal growth. Unhappily few metals ever approach this ideal.

As regards the first aspect, different metals vary considerably in their sensitivity to what the average industrial user would call "small variations" in time and temperature. Among the more sensitive metals, "high-purity" aluminium affords a well-known example ; while copper, some copper alloys and steel are considerably less sensitive and therefore need less close control of the annealing cycle to ensure reasonably satisfactory results. The normalising of steel is perhaps one of the least sensitive operations the consumer has to carry out ; for, provided that the critical temperature is exceeded, the temperature, time and rate of heating and cooling can be varied quite widely without harm.

Consistency of behaviour under given conditions is usually dependent upon consistency of chemical composition, in which general term localised segregation must sometimes be included. Brass offers a good illustration of the influence of small percentages of impurities, for results will vary widely if the percentage of phosphorus or iron in the metal varies from heat to heat even though the conditions of annealing are for all practical purposes identical. Localised chemical segregation, on the other hand, may lead to a marked difference in recrystallisation behaviour giving planes or zones of relatively small, or occasionally relatively large, crystals.

The third aspect of reaction to annealing, namely, that relating to the phenomenon of critical-strain crystal growth, is dealt with fully elsewhere and need not be elaborated here. It is obviously a very important one, for the occurrence of abnormal crystal growth may completely spoil a partly-formed article.

As a rule the metal from which any article is to be made is determined by reasons beyond the control of those who have to deal with it in the press-shop ; but, when a choice is permissible, the foregoing remarks will show that it is well worth while choosing one which is as insensitive as possible to annealing conditions. When no choice is possible, the reaction of the specified metal to annealing should be studied as carefully as its mechanical properties, and every effort made to arrange for its peculiarities to be accommodated as far as possible. Some of the ways in which this can be done have been described when the annealing of various metals was under consideration.

Surface Condition

A mechanically sound surface having a smooth texture is usually a most desirable property in sheet destined for the press-shop. When the shaped parts have to be polished and plated—or in some instances when merely spray-painted—the surface condition becomes of very great importance; for, no matter how good the deep drawing and pressing properties of the sheet may be, the cost of smoothing the shaped part may prove prohibitive. Even when a very smooth surface on the drawn product is not necessary, a good surface on the sheet fed to the press is still desirable because irregularities tend to generate very high temperatures in their immediate vicinity and also to rupture the film of lubricant, thus leading to scoring and fouling and, sometimes, to damage to the surfaces of the tools themselves.

Until recently the demand of the consumer and the aim of the supplier has been a surface so smooth and bright that it presents as nearly as possible a polished appearance. It is, however, becoming more widely recognised that a "mirror finish" is not always the best from the aspect of behaviour under the press due, it is believed, to the relative inability of such a surface to "hold" drawing lubricant during passage over the radii or through the restricted regions of the tools. In an attempt to overcome this difficulty, some sheet suppliers grind their rolls to a smooth finish and then shot-blast the ground surface lightly and uniformly. Rolls treated in this way produce sheet having a surface which, though perfectly smooth and of even texture, is slightly "matte" so that it can hold lubricant during press operations. A surface of this kind is often better as a base for paint than one having virtually a mirror finish, while the tiny indentations are so shallow that they can be polished out very quickly. The same effect can, of course, be obtained by a light pickling operation; but it is difficult to ensure uniform attack, and pickling is an unpleasant operation which is to be avoided whenever possible.

The surface of sheet which has been "clean-annealed" in plants employing a protective and sometimes chemically-active protective atmosphere is not always good from the particular aspect of the press-shop. This can arise from two distinct causes, namely, to the fact that, when pickling is not given, the surface of the sheet is more akin to the "mirror finish" condition just considered or, secondly, to some chemical action—for example, the formation of a surface layer of "spongy" iron on low carbon steel sheet—which increases the tendency of sheet to "foul" the tools irrespective of the mechanical condition of the surface.

It may therefore be stated as a generalisation that the surface of the sheet used for severe deep drawing and pressing operations should be as smooth as possible but should preferably have a finely matte finish, and that it should not be in a chemical condition conducive to "fouling." An obvious exception to this generalisation is that of polished and plated sheet which, by reason of this fact, cannot be deformed very severely.

Accuracy of Dimensions

Dimensional tolerances to which sheet or strip must conform are given in a number of specifications, for example, the British Standard Specifications used in Great Britain. However, many consumers consider that the limits for thickness given in these specifications are too large, and arrangements are often made with suppliers to supply sheet to considerably closer limits.

This practice is one which sometimes causes friction. Suppliers contend that inability to accept standard tolerances implies unsatisfactory tool design on the part of any user, because some users are able to work with sheet conforming to standard tolerances without apparent difficulty. Although this view may be correct in some instances, it is certainly not true in others unless it is admitted that in these the whole scheme for producing the desired shape is at fault having regard to existing conditions. Yet, when a certain sequence of press operations has been devised, tried out and proved sound for the forming of some particular article, consumers seem quite justified in asking for tolerances less than the "standard" ones when some, if not all, suppliers are able and sometimes willing to work to smaller tolerances on thickness, often without any increase in price.

Variation in width as distinct from thickness rarely causes difficulty unless presses having automatic feed are used, when an appreciable departure from the nominal width may cause the mechanism to jam.

It can be said that, provided standard tolerances are observed, dimensional accuracy is a property which becomes of vital importance only in special instances. It is a property not of real metallurgical significance and one to which no mystery is attached; the desired limits can be settled only by frank discussion between consumers and suppliers. If suppliers find that competitors can work to closer limits without difficulty, they may well consider the advisability of installing more modern plant or at least of giving more attention to the proper maintenance and use of the plant which they have. If, on the other hand, consumers learn that the tolerances for which they ask do seem to be unduly small having regard to all relevant circumstances, they will be well advised to see whether existing tools cannot be modified, or even the scheme of production altered, so that sheet having slightly greater tolerances can be used without causing trouble.

Cost

As the fabrication of articles or components by deep drawing and pressing is essentially a commercial, and often competitive, production operation, it follows that low cost is a very desirable property of the sheet metal used in it. The basic price of the commonly used metals being more or less fixed at any given time, differences in the first cost of the sheet purchased for any particular article ought to reflect differences in the relative proportions of major constituents (as in brass), in chemical purity, in surface finish and dimensional tolerances, or in closeness of conformity to certain requirements—for example, crystal size in all metals or temper-rolling in steel—desired or specified by the purchaser.

It cannot be emphasised too strongly that supposed economies effected by cutting down the first cost of the purchased metal are frequently entirely illusory. There are three principal reasons why this is so. Firstly, assuming that the nature and sequence of production operations has been fixed, gradual deterioration in the quality of sheet used due to price-paring must ultimately lead to the production of an increasingly high percentage of scrap, the cost of which, strangely enough, seems seldom to be appreciated by those responsible for the purchase of supplies. Secondly, even when the percentage of scrap is not unduly high, the cost of the increased production time necessitated by having to coax metal stressed almost to its limit, and by prolonged polishing of rough surfaces on drawn work, is not always recognised and taken into proper account. Thirdly, when the nature and number of production operations can be altered, those responsible for the purchase, and even selection, of metal do not always realise that an ultimate saving can often be achieved by purchasing sheet of apparently unnecessarily high quality and reducing the number of press operations, inter-stage annealings or final surface-smoothing operations below that required to produce the same article in sheet of inferior quality.

Clearly, the first cost of the sheet metal intended for the fabrication of any given article ought to be studied in relation to variations in the total cost of the *whole sequence* of production operations attributable to variation in the quality of the metal used. Unless this is done, the maxim should be accepted that the use of sheet of low first cost may increase total production costs above the figure obtainable with metal of better quality and slightly higher first cost.

Even when the total cost of production remains unchanged, or only reduced very slightly, the use of much more expensive sheet may be well worth while when by so doing some operation (for example, inter-stage annealing, pickling or rough-grinding) can be eliminated. Apart from the obvious principle that, always provided an adequate safety margin is allowed, the fewer production operations the better, annealing is always a source of possible trouble and operations such as rough-grinding are unpleasant in many ways. Therefore, even though no actual reduction in cost follows, the substitution of more expensive sheet is often a convenience and a profitable insurance against the possible scrapping of work in difficult operations needed only with sheet of low first cost.

Looking back upon the various properties of sheet metal which have been examined in this chapter, it is difficult to choose any of singular importance to the industrial consumer. All are important; for, although certain fundamental physical properties determine whether or not sheet can be deep drawn or pressed under certain conditions, others which may seem of minor importance to the scientist are yet of vital importance to the industrialist faced with the task of making and selling an article at a competitive price. For example, the fundamentally important properties of ductility, tenacity and rate of work-hardening often interest the industrialist less than consistency of behaviour, relative insensitivity to annealing conditions and freedom from " fouling."

The behaviour of the metal in the press and the appearance of the finish-drawn shape will depend upon how nearly each and all of a number of properties approach the desired standard, and upon how nearly the defects which have been discussed in preceding chapters have been excluded during the casting of the original ingot and during its processing into finished sheet. As some of these desirable properties, such as tenacity and ductility, and also ductility and smoothness of surface after deep drawing or pressing, seem to be incompatible, compromise has to be made; and the " desirable " condition for certain purposes will be that which strikes the most suitable balance between the conflicting properties.

The task of the intelligent industrialist is not helped by the incompleteness, already commented upon, with which are now understood some of the fundamental physical properties which determine how the metal he uses behaves when deformed plastically. Nevertheless, only by the gaining of new knowledge concerning these properties, and especially by the translation of this knowledge into a form in which it can be readily applied under industrial conditions, can the craft of deep drawing and pressing be placed upon the scientific footing enjoyed by many industries. Readers who are vexed at the present incomplete state of knowledge can help best by trying to add to it useful contributions which will help to clarify the vague statements they deplore as being of little help to the practical man.

After perusal of the many defects and desirable properties, themselves sometimes vague and incapable of precise definition, which determine the behaviour of sheet during deep drawing, many commercial producers may feel inclined to relegate sheet of a standard desired by consumers to the already crowded limbo of "very-nice-but-impossible." Bearing in mind, however, the very marked improvements which have taken place in recent years, the partial if not complete attainment of the desired standard is, surely, not worthy of such instant and unconsidered dismissal; for valuable knowledge is being acquired through both academic and commercial research, while improvements in industrial plant of great value are being made.

The rapidity and also the completeness of the adoption of such knowledge as may be forthcoming from these two sources will depend, firstly, on continual attempts on the part of consumers to purchase sheet of the desired standard; secondly, on genuine interest and willing and active progress on the part of suppliers and, last but by no means least, on a more sane commercial outlook in which initial cheapness of metal is not considered wholly to outweigh less easily assessable, yet in actual fact more important, costs.

CHAPTER XIV

SPECIFICATION

The properties which determine the behaviour of sheet during deep drawing and pressing and the forms of available tests which purport to measure or at least reveal these properties having been discussed, it remains to be considered to what extent users of sheet can indicate, by what is commonly termed specification, the nature and magnitude of the properties they desire.

With metals used for most engineering purposes, a number of definite physical properties (such as limit of proportionality, ultimate strength and hardness) which can be specified and checked by test without difficulty are of fundamental importance; but the main purpose of most engineering specifications is to attempt to prevent the acceptance and use of metal which might fail during legitimate service *after* the fabricator of the article or component has accomplished his task. The purpose of specifications covering deep-drawing quality sheet is, on the other hand, primarily and often solely to attempt to ensure that the fabricator obtains sheet which will withstand the shaping operations he intends to impose upon it; the mechanical strength, as distinct from the soundness, and even the exact chemical composition of the finished article is frequently of minor importance. The failure of many specifications adequately to cover essential properties lies in the fact that these specifications are based on the form and contents of the engineering specifications now used so extensively, and make no mention of properties which are of the utmost importance from the peculiar aspect of deep drawing and pressing, although a notable exception to this generalisation is to be found in clauses specifying " average grain size " values.

At the outset it is abundantly clear that, in view of the lack of knowledge concerning many of the properties which at the present time are believed to be of primary importance, and of the inability of many commonly applied tests to reveal the complete suitability or otherwise of sheet tested, adequate specification of deep-drawing quality metal sheet is a matter of great difficulty. Results obtainable from the tests which are now in common use do, admittedly, enable an opinion of the probable behaviour of sheet during some particular sequence of deep-drawing operations to be formed by men of experience; but, without doubt, they fail to reveal in a desirably complete manner many subtle yet all-important properties.

The fact that a satisfactory specification of accepted type cannot at the present time be drawn up seems to occasion chagrin to those responsible for both purchase and production, who cannot understand why the laboratory staff is not able to devise and specify simple and "fool-proof" tests. Also, let it be whispered, this applies to not a few laboratory workers who sometimes attempt to attain the desired ends by insistence on compliance to close limits with specified values which, in actual fact, are not of major importance and are unnecessarily irritating to suppliers of deep-drawing quality metal.

After the foregoing attempt to show the small value of many specifications for deep-drawing quality metals, it may seem rather strange to proceed to a consideration of the very type of specification which has been criticised so adversely. Two facts must, however, be borne in mind. One is that the existing form of specification is being used and, perhaps unfortunately, will certainly continue to be used for some time. The other is that, although most reputable suppliers endeavour to ensure that no metal containing major defects leaves their works, those responsible for the purchase of metal feel more comfortable if defective metal can be rejected for not complying with the requirements of some written specification. Furthermore, there are certain specific points, such as crystal size, on which suppliers and consumers re not at the present time in complete agreement; on such points some definite understanding, whose reference can be provided by a suitable specification, is clearly desirable. For these reasons it seems that the use of specifications of existing form must be continued and there is, therefore, all the more need for the encouragement of more intelligent drafting and interpretation than is now always apparent.

An attempt will, therefore, now be made to review the properties which are commonly included in present-day specifications for sheet purchased for the particular purpose of deep drawing and pressing.

Properties Specified

Grade or Quality. This, the first item usually incorporated in a specification for sheet to be used for deep drawing and pressing, is often expressed in one or more of three different ways: chemical composition, method of manufacture, and so-called "grade" or "quality." The two first items will be discussed separately and little comment need be made on "grade" except to point out that, as usually employed, it is often a legacy remaining from the time when specifications were drawn up with less knowledge and in a much more indefinite manner than ought to be exercised in modern times. Sometimes "grade" implies the kind of metal used, some of the manufacturing processes given—for example, some sequence of rolling and annealing—and also the nature or fineness of the surface finish. For obvious reasons it is more satisfactory to define each of these items separately, and they will be considered separately in this review.

Under the heading of " grade " there must also be mentioned the trade names which some suppliers give to certain kinds of sheet which they market. For example, " Armco " has become a familiar word in many countries, while terms such as " Blank's XX " or " Dash's extra deep drawing quality " can be called to mind by most consumers. The desire shown by suppliers to use this kind of proprietary label is understandable, but consumers rightly prefer something much more definite and explanatory than a trade name for the sheet they purchase, even though the name of some reputable supplier may act as a guarantee of good quality carrying considerable weight.

Chemical Composition. It is usual to include in specifications, often with priority of place, certain stipulations for percentage composition for both major constituents and impurities. Although such specification is often necessary in so far as major constituents are concerned (*e.g.*, for the copper content of brass) the importance of clauses relating to impurities is sometimes overrated, because these impurities may be unimportant in the finished article and their presence in undesirable proportion will be reflected in the physical properties of the sheet as revealed by more rapid tests than chemical analysis.

The onus of providing sheet having the desired deep-drawing properties rests with suppliers and, except in special instances, consumers are unconcerned about the exact proportion of impurities present in sheet which behaves satisfactorily. Examples of the special instances just mentioned are the phosphorus content of steel destined for articles which have to be stove-enamelled, and the iron content of brass which has to be annealed. Due to the impurities mentioned, sheet which behaves satisfactorily under the press may be subject to " blue-brittleness " in the case of steel and to erratic behaviour during annealing in the case of brass.

If, in the future, metal of greatly increased purity becomes available commercially, close adherence to specified maximum contents for impurities may become necessary and the importance of chemical composition will then increase. For example, if the oxygen content of steel proves to be as important as recent work suggests, specification, control and routine checking of oxygen content may become a highly important factor in controlling " ageing " properties. In brass which has to be annealed during multi-stage press operations, the incorporation of a definite but very small percentage of phosphorus or chromium may be desired by the consumer in order to relieve the closeness of control which might otherwise be necessary during annealing. With metals of unusually high purity, for example, " high-purity " aluminium, the specification of a maximum percentage for each of the common impurities may seem logical; yet here again the deciding factor is the behaviour of the metal under the press rather than its chemical composition, unless some special treatment—such as anodising—has to be given by the consumer to the formed product.

A most serious shortcoming of chemical composition as a specified property of deep-drawing quality sheet is that only *average* values can be specified, whereas *localised segregation* of impurities may completely spoil the behaviour of metal having a perfectly satisfactory *average* chemical composition. This failing has already been discussed fully.

It is most desirable that a specification shall not stipulate conditions difficult to fulfil yet actually superfluous: but when drawn up and accepted it should be adhered to without deliberate waiving of certain clauses either by supplier or purchaser. For this reason, clauses regulating chemical composition should be drawn with care and with a full knowledge of facts. The copying of whole sections from specifications covering engineering metals serves no useful purpose.

Method of Manufacture. With non-ferrous metals the choice of methods by which sheet is to be made is often left to the supplier, and the only process specified is that which determines the final state of the sheet, for example, whether annealed, pickled or cold-finished. With steel, on the other hand, a certain sequence of mill operations is sometimes specified, for instance, "normalised and close-annealed" is a clause sometimes embodied; and for some purposes the important final process of temper-rolling has to be specified to avoid trouble due to stretcher-strain markings. Also, the steel-making process used—that is whether Bessemer or open-hearth—and the kind of ingot cast—that is whether "killed," "semi-killed" or "rimming"—might well be specified more often when, as is not always the case, consumers are aware of the differences in the finished sheet which these different processes give.

This last aspect is of some importance. In the past consumers have usually accepted any kind of sheet which suppliers have seen fit to deliver, and have in consequence had to tolerate considerable variations in quality. Now that metallurgical knowledge is becoming more widely disseminated, consumers are able to appreciate the differences caused by the various methods of manufacture and, in consequence, are in a position to specify exactly the kind of sheet they wish to purchase for any given purpose and, moreover, to ensure by adequate acceptance examination that they obtain what they ask for.

Elsewhere attention is drawn to the considerable influence, as yet imperfectly understood, which the whole history of metal from ingot to finished sheet exerts upon deep drawing and pressing properties, for example upon the property of directionality. It may be that in the future closer and more sincere co-operation between consumer and supplier may lead to the inclusion in purchase specifications of the whole sequence of operations to be adopted in the manufacture of each kind of sheet purchased. Alternatively, it may be that improvements in quality will be made not by this means (for after all the consumer is seldom genuinely interested in the methods used by the supplier), but by reputable suppliers making a careful study of the influence of definite sequences of operations upon the deep drawing and pressing properties of the sheet they offer for sale. Thus they may be able to supply sheet free from the defects which consumers attempt to control by specifying certain sequences of manufacturing operations.

Quite often the final process is specified simply to ensure that the purchaser obtains the particular finish and surface texture he desires. This aspect is discussed separately under the heading of "surface finish."

Crystal Size. The property of crystal size in the sense of "average grain size" is in many instances the most important property of any, yet it is one which is not specified as often as it might be. One reason for this may be that although a range of "average grain size" is easily specified on paper its regular fulfilment is, as yet, not as common as consumers wish, although it is true that suppliers are paying more attention to the wishes of consumers in this respect. It must be admitted that, as a rule, it is of little use for purchasers to specify an "average grain size" unless they are in a position to ascertain continually whether their specification is being met.

When sheet is annealed in coils it is often desirable to specify, in addition to an "average grain size," a maximum permissible variation in this value *for the inner and outer ends* of a coiled strip. Exactly how far compliance with this stipulation can be ensured is a matter for speculation, for not all consumers are in a position to examine micro-specimens cut from each end of every coil they purchase, and must perforce rely upon such indication of "average grain size" as is given by more rapid tests.

Apart from mere adjudged "*average* grain size," *regularity* of crystal size is an important property which, for reasons explained already, ought to be controlled, specified and checked by routine examination much more rigorously than it now is. It is to be hoped that in time suppliers will agree to supply sheet in which the size of the crystals conforms to definite maximum and minimum limits above and below the nominal average.

Microstructure. Besides the property of crystal size, and even that of regularity of size, quite often it is desirable to specify certain other properties associated with microstructure even though this can be done only in a qualitative, not in a quantitative, way. For example, for most metals it is useful if a clause be inserted in the specification stipulating that the crystals, in addition to being of a certain size and order of regularity of size, shall be "equi-axed." When the micro-structure contains more than one phase, it may be desirable to stipulate that the second constituent shall be finely and uniformly disseminated, perhaps in a certain condition, and not disposed in the crystal boundaries. Again, in metals in which impurities or non-metallic inclusions are liable to segregate, clauses stipulating that serious segregation shall be absent are an advantage.

Thus a specification covering rimming steel sheet might contain a clause such as this after the usual one giving limits for "average grain size": ". . . The crystals shall be 'equi-axed,' and the 'average grain size' of the surface zones shall not be more, and preferably less, than 1½ times that of the core. The carbide shall be present either as small globules uniformly disseminated and not situate as films in the crystal boundaries, or else as small particles of pearlite uniformly disseminated and not elongated into long streaks. The carbide shall not exist as sorbite. The microstructure shall be free from serious planes of chemical segregation and any non-metallic inclusions shall be uniformly disseminated in small particles and not present in the form of large masses or as continuous planes or threads."

By specifying the nature of the microstructure they desire, consumers could obtain exactly the kind of sheet they wish for if only suppliers would interpret in the spirit as well as the letter clauses similar to the one just given as an illustration. The use and proper interpretation of this very useful method of specification is to be encouraged; for, in spite of the fact that it is qualitative and for this reason is viewed with disfavour by some inspection departments, it can indicate the kind of sheet wanted and at the same time can—or ought to—prevent the supply of sheet having the common defects already mentioned.

The qualification concerning proper interpretation applies to consumers as well as to suppliers; for, although under commercial conditions there is a natural tendency for suppliers to underrate the severity and significance of defects in the sheet they wish to sell, it is not unknown for consumers to be unreasonably critical having regard to existing industrial conditions. A famous pioneer metallurgist once made the remark that "Any fool with a microscope can find *something* wrong with a piece of steel." The truth of this dictum makes it very necessary that the rejection of sheet on account of defective microstructure shall be decided only by men of experience, not by enthusiastic but inexperienced men fresh from college and imbued with an admirable yet too partial zeal to protect the interests of their employers.

Hardness. Purchase specifications sometimes include limits for hardness measured by an indentation test; often, it is to be regretted, for no other reason than that tests of this kind are easily and quickly made. For this purpose, Rockwell B-scale values are popular; but Vickers Pyramid Numerals, obtained with a load bearing a suitable relationship to the thickness of the sheet being tested, offer a more reliable basis for comparison and, unless they are used, the conditions of test should be defined as, *e.g.*, " A hardness of 55 to 65 Rockwell B tested on a single thickness on a hardened steel anvil." The futility of vague terms such as " soft," " ½ hard " or " ¾ hard," which have been used in the past, hardly calls for comment. Happily, B.S.I. specifications defining these trade terms in limits of Vickers Pyramid Numerals have now been issued, though not altogether without ambiguity.

Emphasis has already been laid on the total inability of hardness values, as such, to indicate deep-drawing properties and, also, on their genuine usefulness when used as an indication of the *probable similarity* of one sheet with another of similar hardness owing to the ease and rapidity with which some forms of hardness test, such as the Rockwell, can be made. The practice of estimating " average grain size " from hardness tests often gives misleading results even with fully annealed sheet, and a strong warning must be given against the indiscriminate use of various published curves relating these two properties. When sheet has been cold-rolled, conversions of this nature ought, obviously, never to be attempted.

It follows, then, that the inclusion of hardness values in specifications for deep-drawing quality metal is of use only in special instances, with certain qualifications and precautions, and with a full appreciation on the part of the compilers of the specification and the users of the sheet of the true significance of the values specified. Hardness tests are best used by both suppliers and consumers as a private check to indicate the likelihood of the similarity of a large number of samples in the manner already described, not as a measure by which supplies are accepted or rejected unless the value is genuinely abnormal.

Directionality. The property of directionality is one which is seldom controlled by specification. This is strange, because in many industrial deep drawing and pressing operations this property determines evenness of flow under the tools, the severity of the " ears " formed, and sometimes the depth of draw obtainable before cracks appear in the direction of minimum ductility. For the purpose of specification, directionality could be controlled very readily by the simple tear-length test, more precisely by tensile tests made in stated directions relative to that of rolling or, which would be hardly possible under existing conditions, by the amount of anisotropy revealed by X-ray photographs. Another way in which directional properties could be defined by specification would be to stipulate that when a standard cup is deep-drawn under standardised conditions, for example on the A.E.G. machine already described, the " ears " shall not exceed a specified height.

It is to be hoped that in the future the degree of directionality will be a property always included in any comprehensive specification for sheet purchased for deep drawing and pressing, even though suppliers may be loath to accept clauses relating to a property which can only be controlled by a careful study of mill procedure and by close adherence to a definite sequence of operations.

Tensile Properties. Although values for the commonly recognised tensile properties of yield-point, ultimate strength, percentage elongation and reduction in area are sometimes included in specifications for deep-drawing quality sheet, it is a certain fact that the specified values are usually such that compliance with them affords little assurance that sheet represented by the specimen tested will withstand the desired deep drawing or pressing operations, and the specified values are seldom checked by routine examination on account of the lengthy nature of the tensile test.

It is not desired to underrate unduly the significance of the ordinary tensile properties, but it must be conceded that they seldom indicate fine yet highly important variations, and that sheet which does not conform to the commonly stipulated values would most certainly not fall within the category of "deep-drawing quality" and would be detected by less lengthy tests. For these reasons it is open to question whether the inclusion of tensile properties in the form now adopted in the ordinary engineering type of specification is of much practical value in specifications for deep-drawing quality sheet.

In the opinion of some workers a certain ratio, which will vary with the metal and the nature of the shaping operations, between the limit of proportionality (when one exists) and the ultimate strength is important. Whether this is true or not, this ratio is rarely specified at the present time for deep-drawing quality sheet, although it is sometimes mentioned in specifications for engineering steels. It must be borne in mind that with steel, a metal which in its annealed condition has a definite limit of proportionality, this value—and consequently any ratio derived from it—will be modified profoundly by temper-rolling or other forms of cold-working. For this reason both the limit of proportionality and the ratio of the limit of proportionality to ultimate strength is significant only for sheet purchased in the *unworked* condition, because after the sheet has been cold-worked these values will change with time due to ageing effects and thereby render specification almost impossible. With temper-rolled steel some consumers consider it helpful to specify a maximum value for the property of "yield-point elongation."

When a percentage elongation value is specified it is essential that the gauge length upon which measurements are to be made be stated, as this value decreases with increasing gauge length. Also, as the full significance of a percentage elongation value can be appreciated only when the shape and thickness of the specimen be taken into consideration, it is desirable that these dimensions be specified. The thickness of a tensile test specimen made from sheet is usually that of the sheet itself, and one of the shapes illustrated in Fig. 250 (p. 504) is convenient and satisfactory for most purposes.

Special forms of tensile test piece, *e.g.*, ones having a hole in their parallel portion, have been said to reveal deep-drawing properties more accurately than ones of standard shape, but results obtained on such special forms of test piece are very rarely made the subject of specification; other forms of test often furnish the desired information more fully and more rapidly.

In marked distinction to the doubtful usefulness of the commonly measured tensile values, full stress-strain curves can provide most useful information concerning the probable behaviour of metal during deep drawing and pressing operations. In the future it is possible that stipulations concerning the *shape* of the stress-strain curve may be included in specifications, and even checked by regular routine testing. Already it is common practice to stipulate that the stress-strain curve of temper-rolled steel shall show no unduly pronounced break at the yield-point, and there is no real reason why the use of full stress-strain curves should not be extended to other metals when a useful purpose is thereby served.

Wedge-drawing-test Values. Although of undoubted value in the investigation of deep-drawing properties, wedge-drawing test values have not yet gained sufficient recognition to allow them to be included in commercial specifications. If in the future this test becomes popular, and the significance of the results obtained in it understood more fully, it may form a useful addition to purchase specifications because it does measure in a precise manner certain properties which are very intimately related to the behaviour of sheet under the press.

Cupping-test Values. In Great Britain "cupping test" usually implies "Erichsen test" and it should be remembered that in other countries other tests, for example the Olsen, Guillery, Jovignot and K.W.I., are used.

The usefulness of cupping-test values in a purchase specification is a somewhat controversial matter. In the past they have been used extensively, largely because the cupping test is simple and quickly made but also because it does reveal properties which are of real significance in many industrial press operations. On the other hand, the known vagaries of some forms of cupping test, for example, the Erichsen, are a serious drawback because they lead to irritating controversies between suppliers and purchasers who, using different machines, often obtain different results on the same sample. For this reason there is a growing tendency to omit cupping-test values from specifications in spite of their usefulness and of the acknowledged fact that no other test yields information of a comparable nature in such a short time. However, results obtained on one machine by one practised operator are reasonably consistent, and it may be that in the future this useful test will not be discarded but instead will be used as a kind of private check, not as a decisive test for the rejection of purchased metal. It will be recalled that a similar practice has already been suggested for hardness testing. On the other hand, other forms of cupping test which give more consistent results than the Erichsen (for example, those employing fluid pressure) may be used regularly.

To make full use of cupping tests the roughness of the surface of the dome and the nature of the fracture—that is, whether circular or straight—ought always to be recorded, because these characteristics give valuable indications of "average grain size" and degree of "directionality" respectively, both most important properties.

Qualified by thickness of sheet, cupping-test values can be used for three separate purposes: to indicate, first, intrinsic "drawability" as determined by the combined influence of ductility, tenacity and work-hardening; secondly, approximate "average grain size" in the manner illustrated in Fig. 231 (p. 483) and, thirdly, the suitability of sheet of given kind for some particular sequence of shaping operations *as established by previous experience.* The usefulness of the test with respect to the first two purposes has already been discussed in Chapter XII; the third is so widely recognised that explanation is hardly necessary. The point it is here desired to emphasise is that these three separate aspects exist, ready to be utilised in routine examination by those sufficiently appreciative of their existence and significance; the full potential usefulness of this test can be utilised only after recognition of these three separate aspects.

Turning to the matter of actual specification, depth of cup can be specified by precise measurement, but no attempt seems to have been made to specify smoothness of surface. There is no reason why, following the practice of the A.S.T.M. charts illustrating approximate "average grain size" with accompanying designation by single digit reference numbers, a chart resembling Fig. 231 (p. 483) should not be standardised and certain appearances of dome designated by numbers, preferably those representing on the A.S.T.M. scale the appropriate "average grain size" of each dome. Erichsen or other cupping values could then be specified in a form such as: "A cup of 12 to 12·5 mm. depth giving surface 4 to 5 on sheet of 0·030 to 0·032 inch thickness," a statement which would convey much more information than the present one of mere depth of cup accompanied sometimes by a vague clause stating that the surface of the dome shall be "smooth," an adjective upon which different interpretations cannot but be placed by suppliers and consumers.

Practical-drawing-test Values. Although during recent years attention has been drawn to the possible advantages of some form of practical drawing test for revealing the deep-drawing properties of sheet, no form of test has yet been standardised. Agreement between suppliers and consumers is sometimes reached that sheet shall withstand satisfactorily a draw in certain standard tools made up by the consumer and kept for test purposes, but such arrangements can hardly be considered as specifications in the generally accepted meaning of the word, for that would imply some measure of universal significance. Attention has already been drawn to the decided advantage of a two-stage as opposed to a one-stage drawing test.

Notwithstanding its suggested usefulness, even a universally standardised practical drawing test must be a "go" or "not go" test lacking the very valuable qualification of numerically expressible intermediate values unless a series of tests is made on each sample tested. Useful as tests of this nature are for revealing the deep-drawing properties of sheet during investigational work, their inclusion in purchase specifications is, for the reasons just stated, difficult unless standard tests such as the A.E.G. or Erichsen deep-drawing (not cupping) tests come to be accepted universally. If this happens, definite numerical values for depth of cup formed from a blank of standard size in one or perhaps two draws, or alternatively, the diameter of blank which can be drawn to a cup of given depth, may be included in specifications. A test of this kind, although excellent in theory, may perhaps be found to have in practice the disadvantages possessed by the ordinary Erichsen cupping test.

Tear-length Values. These values, which can be obtained so quickly and which can yield such useful information concerning the degree of "directionality" existent in sheet, are hardly ever specified because consumers seem to be unappreciative of their very great value.

A useful refinement of the original form of test has been described (p. 480), and the inclusion of tear-length values on specifications for sheet intended for severe deep drawing and pressing operations has much to commend it. For the reasons explained when the property of directionality was being discussed, it is sometimes desirable to specify directions of tear in certain directions in the sheet other than parallel to and at right angles to the direction of rolling, two directions which should always be included.

Bend-test Values. These are included on some old-standing specifications not originally drafted to cover deep drawing and pressing properties. Unless elaborated in the manner suggested earlier they have little significance, for most soft sheet of good quality will fold flat on itself in either direction of the "grain" without cracking.

Surface Smoothness. Most specifications include a clause which stipulates that the surface of sheet shall be "smooth and free from defects or blemishes," to which is often added in British specifications the rather ingenious requirement that it shall " possess a workmanlike finish." The importance of a smooth and sound surface has already been explained, and some clause to ensure that a certain standard is obtained is, clearly, desirable in any complete specification. As surface condition seems incapable of precise definition within commercial limits, existing phrases, although they must and do lead to controversy between supplier and purchaser, serve a useful and necessary purpose; and it is difficult to see what phrases more descriptive or less conducive to argument can be substituted. Definition and measurement of surface smoothness by optical methods offers little immediate help so far as sheet for deep drawing and pressing is concerned, although these methods may find application in special instances. Various forms of " profilograph " have been devised for measuring smoothness of surface, and it is of great interest to record that these instruments are being used to measure in a quantitative manner the smoothness of the surface of steel sheet which has to be enamelled.

Surface Condition. Sometimes the cleanliness, meaning freedom from surface oxidation, is specified—for example, to avoid the supply of indifferently close-annealed steel sheet having an area of oxide at its edges—and the method of finishing, for example, whether cold-rolled or pickled, is usually stated. It is also desirable to specify in some instances the texture of the finished surface of cold-rolled sheet in other ways; for example, whether a " mirror finish," an ordinary commercial cold-rolled finish or a special surface imparted by shot-blasted rolls is desired.

Dimensional Tolerance. This is perhaps the item of specification most easy to draw up, though indeed not most easy to comply with when very close limits of thickness are called for. Certain standard permissible tolerances have been laid down for sheet of various thicknesses and for strip of various width by institutions such as the British Standards Institution. If in certain instances these tolerances are too wide to ensure the proper functioning of complicated or critically-set press tools, mutual arrangement must be reached between suppliers and consumers: the simplicity of specifying and of checking such tolerances is in no way affected by their smallness.

Attention must be drawn to the futility of specifying dimensional tolerances closer than are really necessary. Owing perhaps to the fact that size is by far the most easily measured attribute of sheet, particular attention seems to be directed to it by inspection departments, and it is not uncommon for perfectly satisfactory sheet to be rejected solely on account of a variation in size which would have no harmful effect during the shaping operations through which it has to pass. Needless to say, rejection such as this is extremely irritating to suppliers, and may ultimately be reflected in the price of sheet. Blame must not be attached to the inspection department, for the most important thing about any specification is that it shall be adhered to: the fault lies with those responsible for the drawing up of the specification. These comments are intended to imply that proper discrimination ought to be made when sheet or strip intended for use in any given set of tools is being specified, not that very small tolerances, sometimes smaller than sheet suppliers wish for, are never necessary.

The Drafting of Specifications

Having reviewed the properties which in varying numbers are found in the specifications now used to cover sheet metal purchased for deep drawing and pressing, a few observations must be made concerning the drafting of specifications, because a badly drafted specification defeats its purpose and, moreover, can cause unnecessary friction between suppliers and purchasers. This subject must be approached from two distinct aspects, namely, the choice of the properties to be specified, and the numerical values to be called for with respect to whatever properties are finally selected.

Properties to be Specified. Considerable stress has already been laid upon the fact that not one of the properties commonly measured by test provides a complete or even reliable forecast of the behaviour of sheet during some particular sequence of deep drawing or pressing operations. For this reason the specification of certain properties is usually of value *only when several are included and considered in relation to one another and also in the light of past experience.*

At the present time all the properties just reviewed are seldom included in one specification; perhaps because as yet few consumers are fully alive to the importance of each and every one. However, assuming that the specified values for each are capable of being fulfilled under existing industrial conditions, no serious objection ought to be raised by suppliers to their inclusion *in toto* and to insistence by purchasers, with the help of routine examination, on their being fulfilled; but it must be emphasised once more that compliance with each and every specified requirement may, by reason of unrevealed differences in the casting of the original ingot and in the processing of the ingot into finished sheet, constitute no guarantee of consistent behaviour under reasonably constant conditions of deep drawing and pressing. In the present state of knowledge, the inclusion in specifications of the whole sequence of actual mill operations through which sheet or strip is to pass, and possibly of actual casting conditions as well, seems to be a necessary, if at present totally impracticable, method of attempting to ensure the regular attainment of desired properties in finished sheet.

Values to be Specified. This second aspect of specification, that is the magnitude of the values specified as distinct from the actual properties which they purport to measure, is usually confined to defining within reasonably close limits the quality of metal as determined by its purity—and in some alloys, for example brass, by the proportions of the main constituents—and by certain physical properties as revealed by tests. This quality will be decided by the severity and nature of the press operations, by whether or not interstage annealing is given, and by the safety margin in production which is permitted by the cost of the article. The more severe the press operations the better and therefore the more expensive will be the quality of sheet required to ensure uninterrupted production. Attention has already been drawn to the false nature of the economy which is often supposed to be achieved by specifying a quality which allows no safety margin in shaping operations, or which renders two stages of drawing necessary when one stage would be sufficient with sheet of only slightly higher first cost.

In works practice a certain sequence of operations is usually planned in advance or worked out by practical trial for the production of an article in sheet of certain quality. This quality will, presumably, be the subject of an existing specification, but modification of this may need to be made as a result of subsequent experience with the production of the article or should any change in methods or speed of drawing be made later.

Any specification must contain clauses calling for certain values or ranges of values of the properties selected for specification, and it is most desirable that these ranges shall be restricted no more than is necessary to ensure the satisfactory production of the article under consideration. The pyschological effect produced upon suppliers by the specification of what are obviously unnecessarily close limits for certain values can be very real, and can seriously hamper that friendly co-operation with the suppliers which is often the consumer's best way of obtaining close adherence to limits placed upon those properties which are of real importance.

It is equally desirable that the specified values shall be capable of fulfilment by suppliers to whom the order is given. Needless to say, consumers will nearly always demand a better quality and a lower price than suppliers may be prepared to offer in the first instance, but frank and friendly discussion will usually enable a satisfactory compromise to be agreed upon and, of importance, will prevent subsequent controversy ; for it is only logical that a specification, once drawn up and accepted by a supplier, must be fulfilled. If it is not, the very essence and object of specification is eliminated ; thus it behoves purchasers to ensure, by routine examination, that their specifications are being complied with consistently. It is also desirable that the method and actual procedure and details of certain tests whose values are specified shall be agreed upon and defined precisely when divergence of opinion is possible. For example, the procedure to be adopted in making certain cupping or hardness tests should be defined in the manner already suggested.

Finally, it has to be admitted that at the present time, apart from such stipulations as to chemical composition and physical condition which will eliminate definitely unsatisfactory or sometimes mediocre sheet, the only essential clause which will attain the desired end seems to be one of highly unscientific nature such as "... will produce the desired article with the desired surface finish." Such a clause possesses the merit that it enables and encourages suppliers and consumers to co-operate in the attainment of the most suitable metal, but the disadvantage that such indefinite standards cannot constitute a specification in the generally accepted sense and, under commercial conditions, must lead to argument over border-line material.

Arbitration. In commercial contracts and in the purely mercantile parts of specifications it is usual to include clauses relating to arbitration having as their object the prevention of litigation or prolonged dispute, yet in the specification of materials no such recourse is, as a rule, provided.

It is a proverb, more cynical than true that, to the purchaser, a sample is the best part of a consignment; to the seller, the worst. Laboratories, too, at times differ: sometimes because the amount of care and degree of skill exercised varies; but more often because, particularly with some of the tests used to measure so-called deep-drawing properties, the results obtained vary quite unavoidably. Results vary in two distinct ways: first, in the actual numerical values obtained and, secondly, in the interpretation of agreed values. When this happens, one solution is to call in an independent laboratory to carry out tests or an independent authority to interpret agreed results, and clauses providing for reference on matters of valuation and interpretation of purely scientific and technical facts could with advantage be included more often in specifications.

From what has been said it will be obvious that no specification can be drawn up for sheet metal to be used for deep drawing and pressing free from one or other form of ambiguity; the provision of clauses of the kind suggested is, therefore, specially necessary. When arbitration is wanted, it is usually wanted very badly and, moreover, urgently. Therefore it is important that the procedure laid down should be one capable of rapid fulfilment and, it need hardly be added, that the chosen arbitrators should have a thorough practical knowledge of their subject as well as general scientific knowledge, so that their judgement will be accepted ungrudgingly by both parties to a dispute.

Co-operation between Suppliers and Consumers

Sincere co-operation between suppliers and consumers is a matter of the utmost importance; for, since it is not yet possible to specify on paper acceptance tests which will determine the properties necessary for sheet to withstand satisfactorily a certain sequence of deep drawing or pressing operations, it is desirable and often essential that suppliers shall select and process sheet specially to suit the requirements of individual purchasers. The unanimity of opinion among reputable suppliers on this point is striking; with the genuine desire to produce sheet which will fulfil the demands made upon it by consumers, they will willingly co-operate in finding the sequence of mill processing operations which will produce the most suitable sheet for any particular use, rather than, as now happens frequently, work with difficulty to some consumer's specification which they know full well is not indicative of the particular properties he actually needs. Without such co-operation suppliers may, indeed, be quite unable to satisfy the consumer's requirements, even when these are capable of being satisfied.

Discussion on the subject of specifications with many suppliers of deep-drawing sheet will, in nearly every instance, bring forth a request for an inspection of the article to be made and also, if possible, of the sequence of operations used in its fabrication. More frequent and more ready accedance to this request would be of very real benefit to both suppliers and consumers. The refusal of consumers to take suppliers fully into their confidence, through supposed reasons for the preservation of secrecy concerning product and production operations, can in these days only be described as foolish.

While the above-mentioned clause "will produce the desired article with the desired surface finish" could, if interpreted sensibly and conscientiously by both suppliers and consumers, prove adequate in itself as a complete specification, its adoption as such under existing conditions of sale and production is admittedly of doubtful practicability. Coupled with more stereotyped *desiderata* it can, however, express completely and concisely many requirements the complete enumeration of which would postulate on the part of consumers a full knowledge of the sheet-processing operations employed by suppliers, as, for instance, when the elimination of stretcher-strain markings in steel is under consideration. For this reason its appreciation and acceptance by suppliers of repute should not be regarded merely as "a consummation devoutly to be wished."

CHAPTER XV

NEW APPLICATIONS OF DEEP DRAWING AND PRESSING

IT is certain that increasing use will be made of deep drawn and pressed shapes, both shallow and deep, in both thin and thick sheet metal, in a great variety of applications. The extent to which this method of manufacture is used at the present time is, indeed, not appreciated generally, and a few minutes' reflection cannot fail to convince any sceptic of the very important part played by the press-shop in modern industry in spite of the fact that no learned societies, no technical periodicals and, indeed, relatively few papers and articles are devoted solely to its study.

Any reasonably complete list of the products of the press-shop would occupy many pages but, as a general indication of fields in which increasing application may be anticipated, there may be mentioned all kinds of engineering components ; domestic and utilitarian articles ; all manner of containers, ranging from large vessls in "clad" metal to collapsible tubes and tiny capsules ; cowls and fairings for aircraft ; bodies, wings and other members for road vehicles and, lastly, ordnance work, a field in which deep-drawn shapes have for some time been used on a large scale.

The more conveniently to study the lines along which development is likely to take place, this review will be divided into four parts, but it need hardly be pointed out that the particular aspects presented in each of these may all join to render possible some new application. For example, only by the combined use of new metals, improved technique and perhaps new processes may it become possible successfully to complete some new application, whether this be the creation of a shape hitherto unproducible or the replacement, with some advantage in quality or a saving in cost of production, of a part hitherto made by other methods. Bearing this in mind, division may be made as follows :—

(1) The replacement of cast, forged, machined, welded or otherwise fabricated articles by deep-drawn or pressed shapes.

(2) The production of shapes which hitherto it has not been possible to produce under the press on an industrial scale.

(3) The deep drawing and pressing of relatively new metals or new varieties of well-established metals.

(4) The development of new processes for shaping sheet metal under the press.

Replacement of Parts now made by other Methods

The replacement of whole articles or component parts, hitherto cast, by either one-piece or brazed or welded multi-piece pressings with a consequent saving in both weight and cost is already proceeding apace. Familiar examples of the replacement of castings are to be found in many domestic appliances, such as irons, saucepans and wringer frames, in agricultural machinery and in very many metal fabrications. A large field of application lies open in machine and engine parts ; a typical example of the replacement of a casting by a one-piece pressing is illustrated in Fig. 268, and Fig. 269 shows a simple multi-piece replacement in which two pressings are copper-brazed to a very easily machined solid centre bush. It requires little imagination to appreciate the extensive nature of the field which lies open to this method of construction, and the saving in weight, machining and cost which it offers. When the solid part is of a more awkward shape than the round bush shown in Fig. 269, further economy can sometimes be achieved by parting it off from bar drawn to special section. Copper-brazing, low-temperature brazing, spot, projection or seam welding may be utilised for joining multi-piece articles under modern mass-production conditions ; even arc or autogenous welding can be used on heavy sections which do not lend themselves conveniently to other methods of joining.

Attention may be drawn to the fact that pressed and deep-drawn steel parts of sufficient thickness may be case-hardened and used to replace many parts hitherto machined from the solid, although an allowance must be made to accommodate possible distortion due to the release of residual stresses in the cold-shaped part. Considerable saving in cost can often be shown in the production of a part having thin walls which otherwise would have to be machined from the solid, and this benefit has already been taken advantage of in the manufacture of ball bearings and roller chain components. It must be mentioned that, when case-hardening has to be done, it is often wise to specify sheet made from "killed," and sometimes from "acid," steel in spite of a consequent small reduction in the depth of draw obtainable without inter-stage annealing. The meaning and significance of these terms has been explained in Chapter II, in which it was pointed out that the bulk of the sheet used in the press-shop is rolled from "rimming" ingots of "basic" steel. It is often found that the core of a case-hardened part made from rimming steel lacks toughness, a fault reflected in the coarsely crystalline appearance of fractures. This behaviour, which is attributed partly to a high oxygen content, has caused little trouble in the past ; but, now that the case-hardening of parts deep drawn or pressed from sheet is increasing, this peculiarity of rimming steel needs to be taken into account.

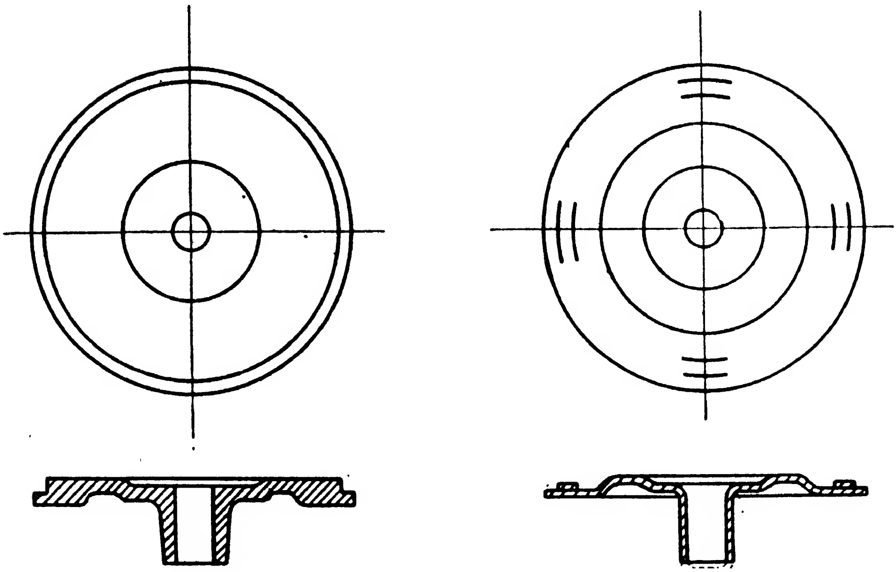


FIG. 268. Replacement of cast iron housing (*left*) by pressed and drawn sheet steel product (*right*), reducing both weight and machining time. Observe sheared and raised locating spigots near rim, and thick wall to sides of thimble produced by special drawing procedure.

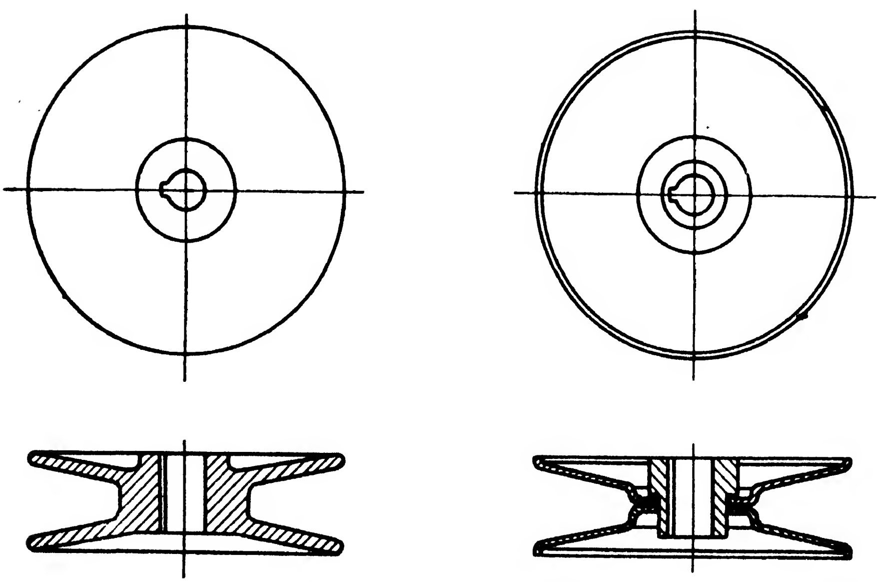
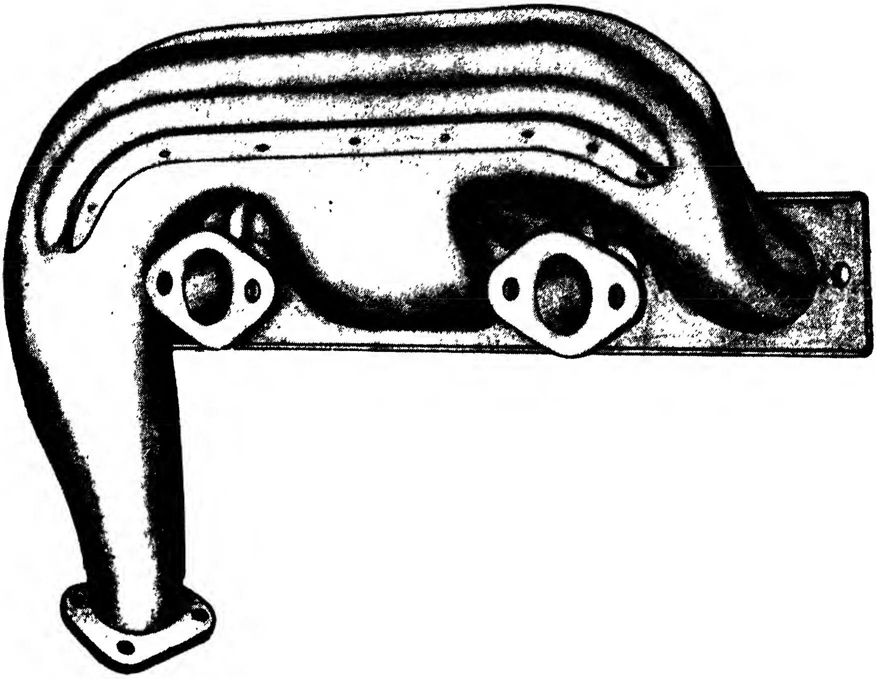


FIG. 269. Replacement of cast iron pulley (*left*) by composite product (*right*) comprising two sheet steel pressings and a solid steel core united by copper-brazing (indicated by heavy lines). The replacement is lighter, needs less machining and is less brittle than the casting.



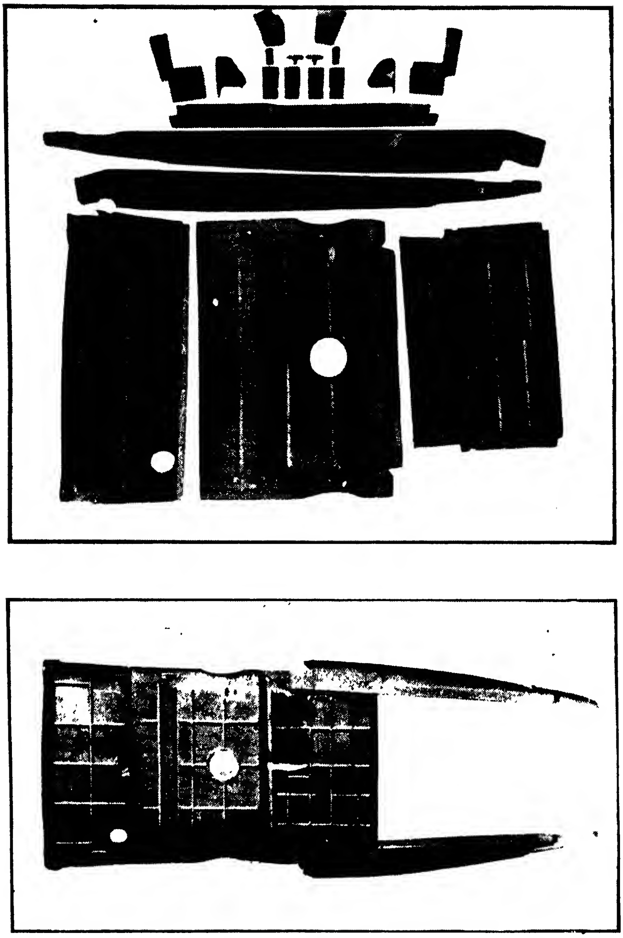
[*By courtesy of Fisher & Ludlow Ltd.*

FIG. 270. Sheet steel pressings copper-brazed to form an engine manifold weighing 6½ lb. Weight of usual casting, 17 lb.

[*By courtesy of Mallory Metallurgical Products Ltd.*

FIG. 271. Two steel pressings being seam-welded together to form an automobile petrol tank. Observe pressed strengthening ribs.

[*To face p.* 586



[*By courtesy of Mallory Metallurgical Products Ltd.*

FIG. 272. Twenty pressings in sheet steel (top) spot welded by hydro-electric guns to form automobile floor board (bottom).

[*To face p.* 587.

Fig. 270, which shows a combined inlet and exhaust manifold for a four-cylinder automobile engine, is an example of a rather more ambitious replacement in which, although the cost of production of the built-up article may not be less than that of a casting, other advantages may render the built-up pressed-steel product preferable. Comparing this manifold with the casting it replaces, its weight is 6½ lb. instead of 17 lb., representing a saving in weight of approximately 63 per cent.; and, in addition, increased engine efficiency is obtained owing to the internal surfaces of the passages being smooth and the openings accurately dimensioned and spaced so that they line up with the ports in the cylinder block. These three advantages, namely, reduced weight, smooth internal surfaces and accurate dimensions may offer advantages in certain articles even when the cost of a casting is rather less than that of the pressed and built-up substitute.

The examples cited so far have been steel; but equal benefits can be derived from the replacement of light-alloy castings by parts built up from pieces deep drawn and pressed from light-alloy sheet. For instance, the vacuum-brake cylinder on a certain commercial vehicle weighed 50 lb. when made as a light-alloy casting. When made of two deep-drawn shells joined together, it weighed 11 lb.; a saving in weight of no less than 78 per cent.

The benefits of pressed-part construction are not limited to components of small size such as the ones illustrated in Fig. 268 and Fig. 269. On a larger scale, deep drawn and pressed parts can be welded together, as in automobile body construction, to replace heavier and more expensive methods of fabrication, often with an increase rather than a decrease in strength and rigidity, although the cost of large press tools can only be met by a guaranteed output of a large number of pressings if the price of each is to be kept reasonably low.

When considering the extended application of multi-piece articles fabricated from pressings and drawings, the recent and continued improvement in the efficiency and scope of spot, seam and projection welding, and also of the rather different process of copper-brazing, must not be overlooked; for the transition of these methods from the category of mere "sticking together" processes to recognised methods of engineering production which can be employed with confidence on stressed parts is of very great importance to the deep drawing and pressing industry.

Proof of this is to be found in modern automobile practice. Petrol tanks are formed by seam-welding together, in the manner shown in Fig. 271, the flanged rims of two deep, rectangular pressings, the sides and bottoms of which may be ribbed for strength. In straightforward seam-welding, speeds of 30 feet per minute are now possible on double-wheel machines. On a larger scale, the twenty separate steel pressings illustrated in Fig. 272 are spot-welded together by semi-portable hydro-electric "guns" to form the floor board of a popular car, a rather striking though not less useful application than the more familiar one in which large pressed panels are welded together to form the body itself. For this specialised form of production there have been developed large welding machines, such as that shown in Fig. 273 which by means of separate spring-loaded electrodes makes thirty-two welds in an automobile door in one cycle of operation, and in Fig. 274 which shows a machine for flash-welding together three pressed-steel panels to form the rear half of a saloon body.

Girders, channels and spars of great variety hardly come within the scope of this book by reason of the relatively shallow pressing operations required in their shaping, but this application and its many ramifications—which may be extended to cover bent and pressed frames, lattice girders and other parts for use in both welded and riveted engineering construction—affords almost unlimited variety.

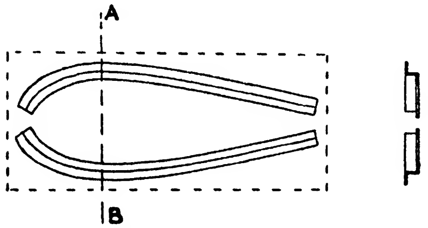
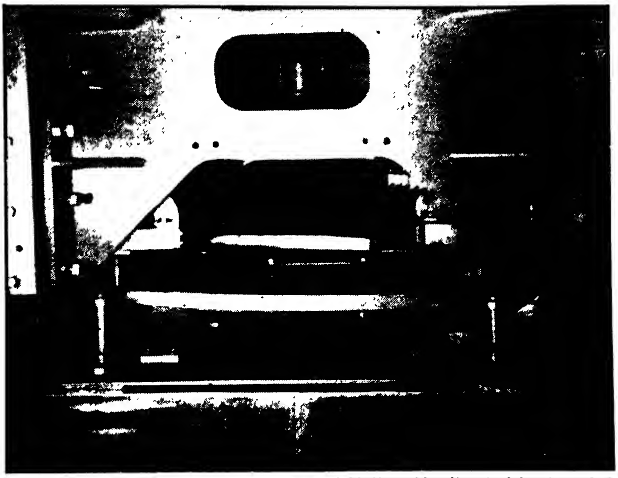


FIG. 275. Typical aircraft wing members formed two at a time by deep-drawing a shallow pan from Duralumin sheet.
Left: Lay-out of members on sheet.
Right: Cross-section through separated members on line A–B.

A field which offers great scope for development is the replacement of rolled or hand-formed aircraft components in heat-treatable light-alloy sheet by parts made more quickly and more accurately under the press. Presses have, of course, always been used in the aircraft industry on light-alloy sheet and strip for operations akin to bending, but there is a growing tendency to make curved members—such as those used in wing construction—from relatively thick sheet by genuine deep drawing and pressing instead of by drawing and rolling narrow strip. Thus in the component just mentioned two members can be formed at one press operation, as illustrated diagrammatically in Fig. 275, the discarded centre portion of the sheet being used subsequently to make smaller parts. This new method is naturally not without its own peculiar difficulties, one of which is the necessity for ensuring that the metal is not thinned beyond a stipulated minimum in certain parts where the shape of the component hinders free flow in the tools. In order to keep the weight as low as possible, aircraft designers will not tolerate the easy remedy of using fairly thick sheet so that appreciable local reduction in thickness can occur before the stipulated minimum is reached. Often a difference of only a few thousandths of an inch on sheet of, say, 0·100 inch nominal thickness is permitted, a condition which calls for great skill and ingenuity in the devising of press procedures and in the designing of tools.



[*By courtesy of Mallory Metallurgical Products Ltd.*

FIG. 273. Multiple parallel spot-welder having thirty-two independent spring-loaded electrodes for welding the pressed-steel door of an automobile body.

[*By courtesy of Mallory Metallurgical Products Ltd.*

FIG. 274. Large machine for flash-welding the entire join between three pressed-steel panels to form the rear portion of an automobile saloon body.

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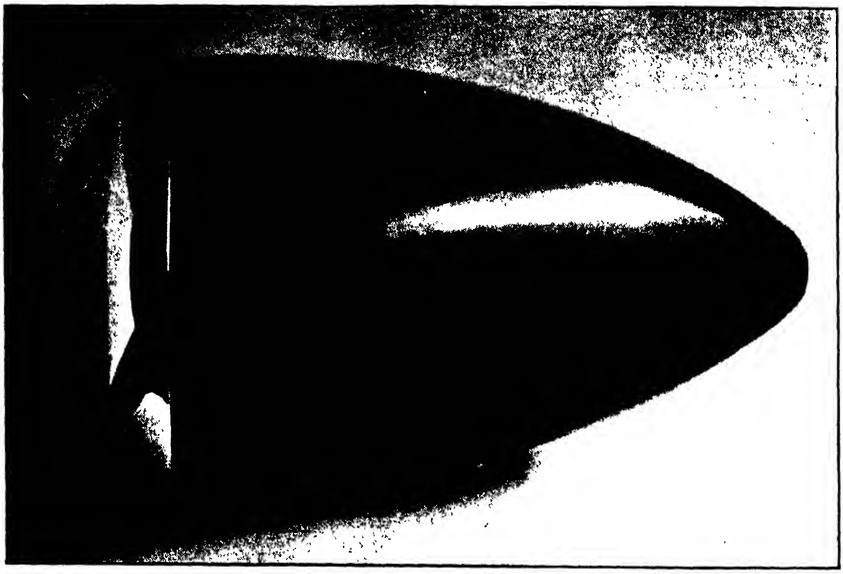


[By courtesy of the Guide Lamp Co.

FIG. 276. Streamline-shaped automobile headlamp.

FIG. 277. Heavy-gauge deep-drawn steel cup used to replace one machined from solid bar.

[To face p. 589.

It is, unhappily, very necessary to emphasise the great importance of *designing* either articles or component pieces so that both pressing—or deep-drawing—and welding operations can be conducted as easily and efficiently as possible. This aspect is seldom given sufficient attention.

New Applications made Possible by an Increased Depth of Draw

It will be obvious that as the depth of draw or the intricacy of pressing which can be carried out with certainty under industrial conditions increases, the field of application of deep drawn and pressed parts will extend. It will usually be possible to attribute this extension to one or more of three causes: the production of new shapes which could only be produced by deep drawing or pressing; the replacement of parts which, prior to the postulated increase in depth of draw, could be made more satisfactorily or more cheaply by other methods and, thirdly, the elimination of inter-stage annealing reducing the cost of pressed and deep-drawn articles for the production of which this treatment has hitherto been essential.

Considering these in order, the production of new shapes, or possibly of old shapes in which certain awkward features have been accentuated still further, is an extension which is continually being urged by designers of all kinds of articles and component parts. Sometimes the new shape is asked for because, although the difficulty of its production is recognised, the shape is genuinely necessary; more often it is demanded for no other reason than that it has been designed without regard to the problems of the press-shop: when this happens it is, strangely enough, often more difficult to obtain concessions regarding the shape of the proposed article, even though the exact shape is in actual fact of minor importance, than when the shape is of real importance. For this reason it is most desirable that whenever possible—and when is it genuinely impossible?—a pressed or deep-drawn article should be designed in the first instance in co-operation with experienced press-shop representatives. Such co-operation would often prevent the adoption of a shape needlessly difficult to press or deep-draw.

The saloon-bodies and mud-wings of modern automobiles offer an excellent illustration of how an increased depth of draw or pressing leads to an increased field of application. Many modern mud-wings are difficult to form as a one-piece pressing, yet their successful production has led to the virtual elimination of the multi-piece rolled wing, and has rendered possible the industrial production at a low cost of certain shapes favoured by body designers if not always by those motorists who essay to grease their cars themselves.

The popular torpedo-shaped automobile head-lamp shown in

Fig. 276 provides another example of how an increased depth of draw has enabled a difficult shape—and the pointed apex of this shell does render it a very difficult one—to be produced successfully in both brass and steel, although only by means of a number of draws and with the help of inter-stage annealing. It should be observed that in this instance the exact contour of the shell has no practical significance and is determined by purely æsthetic reasons, whereas the shape of the parabolic reflector housed inside it is of genuine importance and must conform very closely indeed to the desired contour if the lamp is to work efficiently.

This leads to another aspect, namely, the value of increased *accuracy*, as distinct from mere depth, of pressed and deep-drawn parts. When very close conformity with respect to contour or dimensions is required, it is now usual to give the pressed or deep-drawn article one or more final squeezing operations between dies, a process closely akin to that of " coining " and needing very robust presses and careful tool-setting if mechanical, and not fluid-pressure, actuation is used. When the article is essentially a deep-drawn as distinct from a pressed one, one or more light finishing passes in well-maintained tools will enable very close dimensional tolerances to be met.

The accurate " sizing " of both pressed and deep-drawn articles by suitable finishing operations has in many instances enabled the final rectification of such parts by machining to be eliminated or, sometimes, machined or die-cast parts to be replaced by pressed or deep-drawn parts with a saving in cost yet without serious loss in dimensional accuracy. Reverting to the example of automobile lamp reflectors, at one time some makers deemed it necessary to grind the parabolic form after it had been pressed to shape from relatively thick sheet : modern press-shop practice enables almost equal accuracy to be attained in thin sheet wholly by pressing, although it is interesting to observe that there appear to be at least two schools of thought regarding the best method for attaining the desired end. Of these, one favours pressing in either one or two operations and then " coining " to shape by means of a press or drop-stamp, whereas the other prefers to finish the shaping by several more gentle operations—such as can conveniently be given in the multi-punch automatic press shown set up for pressing reflectors in Fig. 202 (p. 351).

Turning from pressing to deep drawing in its fullest meaning, cylindrical shells and genuine tubes of increasing depth are being deep-drawn from flat sheet which, in the case of tubes, may be many times thicker than the wall of the finished product. It is hardly possible to single out any one item which has been of special value in furthering this end ; improvements in the quality of the metal itself, in drawing technique, in tools, in lubricants and in inter-stage annealing

—a most important operation in very deep-drawing—have all contributed to the more severe draws which are now being attempted.

The reason enumerated second for an increased depth of draw or pressing leading to an increased field of application for the products so formed, is the successful replacement of parts hitherto made by other methods. This subject has already been considered, and it is desired here only to emphasise the part played, in such replacement, by draws of increasing depth.

The formation of the central thimble in the pressed steel cover illustrated in Fig. 268 (p. 586) would have constituted a difficult production operation not many years ago. The improvements mentioned two paragraphs above—particularly those concerning inter-stage annealing—have, however, made this cover so easy to produce by deep drawing and pressing that the sheet-steel product is actually cheaper, as well as lighter and requiring less machining, than the cast iron cover it replaces.

Another illustration is provided by thin-walled brass tubes for automobile radiators. As a result of the same collective improvements it is now possible to produce tubes of the desired length by deep-drawing a circular blank of sheet brass more cheaply than by other means, such as ordinary tube-drawing or welding bent-up strip. Apart from any saving in cost, it is claimed that tubes deep-drawn from a flat blank have a greater uniformity of wall thickness than tubes drawn in the usual way from cast tubes or pierced billets. Examples of this method of tube-making have already been illustrated in Fig. 154 (p. 248) and Fig. 157 (p. 249). Both these examples are in aluminium, and have been deep-drawn without inter-stage annealing ; with metals which work-harden more rapidly, tubes can seldom be formed without inter-stage annealing.

The steel cup shown in Fig. 277 is of special interest because it illustrates the growing tendency to replace small parts hitherto machined from solid bar, or from relatively expensive forgings or castings, by deep-drawn products. Whether or not the major surfaces of the drawn shape need to be lightly machined will depend on the dimensional accuracy demanded and, of course, upon whether " sizing " operations are given in the press-shop. It need hardly be pointed out that, if desired, a steel article such as the one illustrated can be case-hardened, or copper-brazed or welded to some other component part.

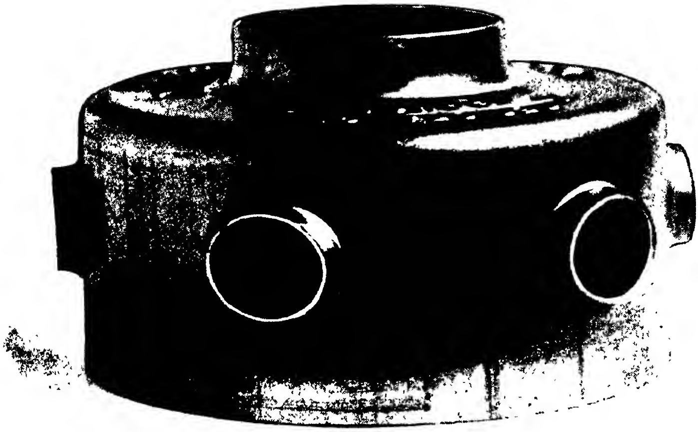
The last of the three postulated improvements leading to an increased application of deep drawn or pressed shapes is the increasing depth of draw or pressing which, through improvements in metal and technique, can be accomplished *without the help of inter-stage annealing*. A series of press operations is, as a rule, a very cheap production sequence, particularly when carried out in a multi-punch press ; if inter-stage annealing has to be given, the progress of the work is hindered, the cost of production increased, extra floor-space, handling devices and labour are needed, and, unless modern annealing plant is used, the danger of incorrect annealing treatment being given will usually be present and the unpleasant operation of pickling may prove necessary. It is not desired that these remarks shall discourage the use of annealing when this operation is necessary; for, with modern plant, the regular production of clean, properly annealed work can be almost guaranteed.

The first example chosen to illustrate this aspect is the article shown in Fig. 278, which is deep-drawn to shape in one operation from a circular blank of steel 0·048 inch thick, and, without any inter-stage annealing, the small circular orifices are pierced and plunged out of the drawn side walls to a depth considerably greater than that of the trimmed projections visible in the photograph. Sizing operations are given to both bottom flange and side orifices, but these are in no sense drawing operations, because the full depth is attained in the first draw. The orifice-forming operation in the already severely worked walls is very sensitive in revealing directionality in the sheet used, and considerable trouble has been experienced in the continued production of this article owing to this cause and also to variation in ageing tendencies. To accommodate this variation as much as possible, the orifices are drawn deeper than is really necessary, so that when splitting occurs the split extremities can, unless the splits are very deep, be trimmed off. These orifices are subsequently subjected to the additional strain of having a screw thread cut in their bores.

Fig. 279, which shows a shell deep-drawn from 0·040 inch-thick steel sheet without inter-stage annealing, illustrates the remarkable depth of draw which is now possible with good tools, good technique and steel sheet of first-class quality. There is, clearly, a limit to the amount of plastic deformation which can be imposed upon any particular metal before annealing becomes necessary; hence the danger that, if theoretical considerations are ignored, much time and money may be spent in attempting the impossible. On the other hand, continued improvement in the quality of metal available, and in the methods by which it is shaped, will enable still deeper draws to be accomplished without inter-stage annealing in many instances.

Fig. 280 shows an automobile lamp body which is pressed and drawn from 0·030 inch brass sheet in one operation without inter-stage annealing; the rolled edge is of course formed in a subsequent operation, but this does not detract from the point it is desired to illustrate.

Articles of rectangular shape are always more difficult to deep draw than circular ones owing to the "crowding" of metal at the corners. The rectangular shell shown in Fig. 281, which is deep-drawn

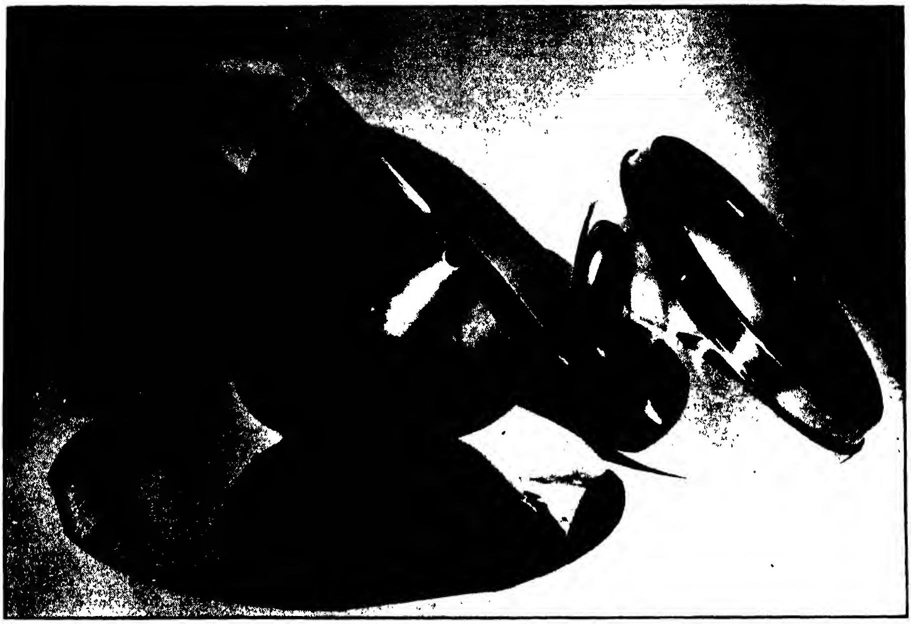


[*By courtesy of Joseph Lucas Ltd.*

Fig. 278. Three-inch diameter steel cover with plunged side orifices.

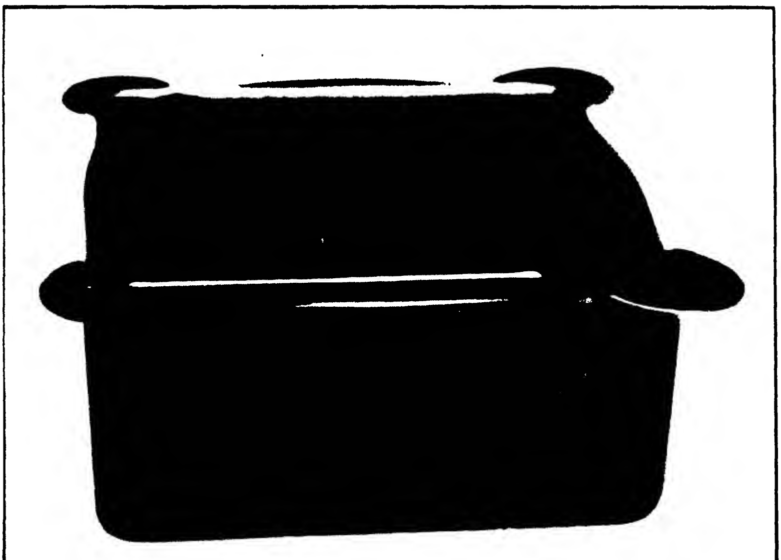
[*By courtesy of British Rolling Mills Ltd*

Fig. 279. A remarkable achievement. Fuse case deep-drawn from 0·040 inch-thick steel sheet without inter-stage annealing. Observe highly polished surface due to use of very smooth tools and zinc oxide lubricant.



[*By courtesy of Joseph Lucas Ltd.*

FIG. 280. A good example of a severe one-stage draw. The lamp body (left) is drawn to the full depth of 8½ inches from a 0·030 inch-thick brass blank of only 63 per cent. copper content. After ring-annealing the rim is rolled in to the shape shown on the right and the impressions raised in it.



[*By courtesy of Taylor & Challen Ltd.*

FIG. 281. 3¼ inch-deep square shell formed from a circular steel blank 0·048 inch thick and 12¾ inches diameter. Only one press operation is taken to draw this shell to the full depth and simultaneously to press a raised design on its base.

[*To face p.* 593.

in one operation from a circular blank, is, for this reason, of special interest. The regular production of this article in one operation would not have been considered possible a few years ago; this and the fuse-case illustrated in Fig. 279 show what drastic deformation is demanded by modern production engineers.

In articles already in production, elimination of annealing as a result of an increased—yet nevertheless *safe*—depth of draw will merely reduce production costs. When the possibility of making a *new* shape by deep drawing or pressing—whether or not this is to be considered as an alternative to other methods of production—is the problem to be decided, the inclusion or omission of an inter-stage annealing operation may decide whether or not the cost of production by deep drawing or pressing proves acceptable. For example, in the making of fair-sized steel drums or containers, the question as to whether the desired shape can be produced without inter-stage annealing may decide whether it will be cheaper to manufacture these by deep-drawing single blanks or by bending and joining separate sheets. It must be borne in mind that the size of the furnace needed to normalise or anneal shapes such as fair-sized containers or halves of kegs may be very large in relation to the actual weight of metal passed through it, a fact which makes the first cost of the furnace high and also renders the conservation of a protective atmosphere difficult.

The examples considered have so far been illustrative of the advantages which can be derived from draws of increased depth on thin sheet, but attention must also be given to another aspect, namely, to the advantages attributable to an increased *thickness* of sheet—more particularly of steel—which can be drawn or pressed into useful, if not extremely "deep," shapes.

These advantages, which are already being exploited in many fields of application, have become possible mainly as a result of improvements in tool materials and, of importance, in presses. The introduction of fluid-pressure actuation has been of great benefit in this direction, and has made possible the production of pressed shapes in steel sheet of from $\frac{1}{4}$ to $\frac{1}{2}$ inch thickness in presses of relatively small size and moderate cost.

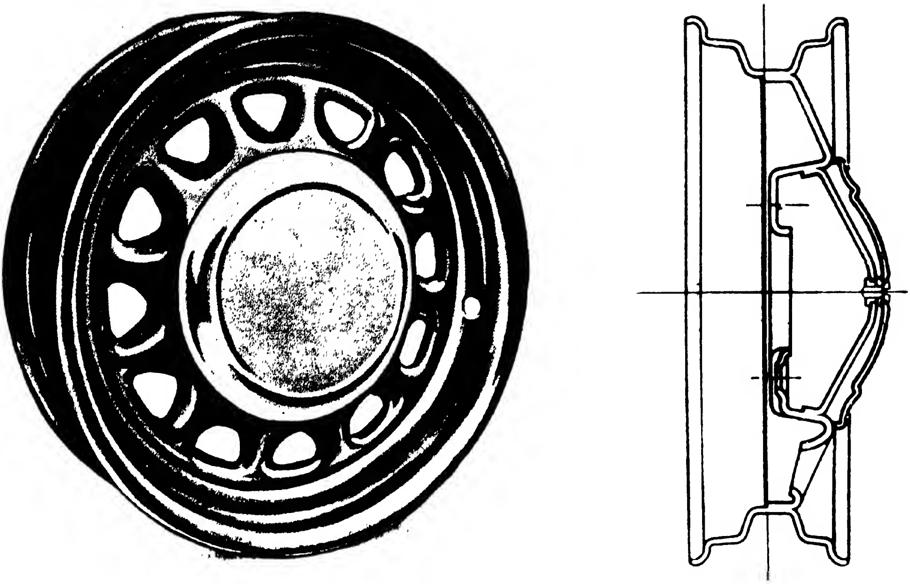
The value of pressings in thick sheet is well illustrated by recent progress in the methods of construction adopted for both automobile and commercial-vehicle wheels. Pressed steel wheels for cars have been in use for some years, but the increased degree of deformation which is being imposed on steel sheet of moderately heavy gauge is shown in the wheel illustrated in Fig. 282.

Turning to thicker sheet, automobile brake drums offer a striking example of progress; heavy drums for commercial vehicles are now being pressed and deep-drawn, often in one operation, from sheet in sizes which until recently were made as hot forgings. It is not implied that the deep drawing of heavy gauge sheet is an entirely new development, for large shell cases and thick-walled tubes have been produced for many years : it is to the rapidly growing application of deep-drawn components produced in large quantities from heavy-gauge sheet to which it is desired to draw attention. As an example of pioneer work, the commercial-vehicle hub shown in Fig. 283 deep-drawn from steel sheet of approximately $\frac{1}{4}$ inch thickness, naturally with the help of inter-stage annealing, is of interest. This hub was produced in fair quantities a number of years ago without the advantages which modern scale-free and closely-controlled annealing can give.

As an example of the thickest sheet which is now deep drawn and pressed industrially in large quantities, there may be instanced that used to form commercial-vehicle road wheels. One popular wheel, 20 inches in diameter, is being pressed to shape in one operation from steel $\frac{7}{16}$ inch thick on 1,000-ton fluid-pressure presses having an output of 6,000 wheels per day. Fig. 284 shows a still heavier pressing for a tractor hub which is pressed to shape from steel sheet of $\frac{5}{8}$ inch thickness ; the depth of the undulations is $4\frac{1}{2}$ inches.

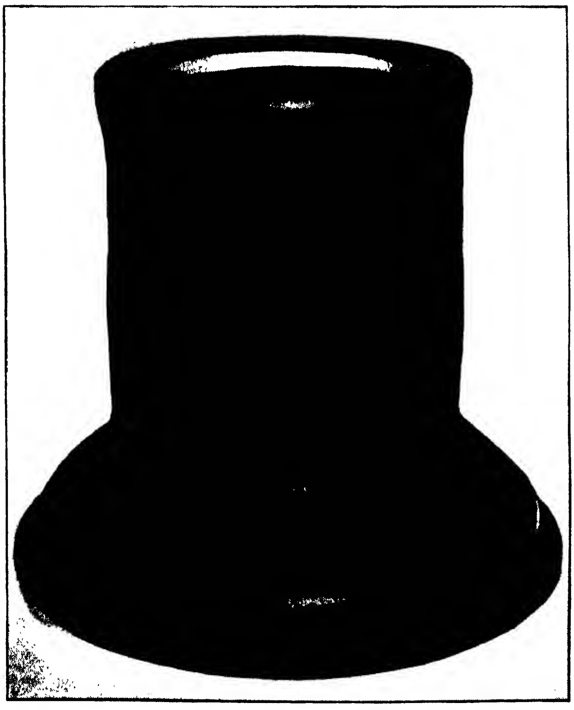
The examples cited so far have been in steel ; but a comparable increase in the thickness of the sheet which is being successfully deep drawn and pressed is to be found in non-ferrous metals, particularly in brass and light alloys. Thus, the thickness of the brass sheet which is cupped as the first stage in the sequence of press operations by which shell cases are made increases steadily ; a change attributable in some instances to the advent of hydraulic presses. In the field of light-alloys, a novel example of an application of a deep-pressed part directly attributable to an increased thickness of the sheet pressed is illustrated in Fig. 285, which shows a 12-inch diameter aircraft brake drum formed from light-alloy sheet $\frac{1}{4}$ inch thick. The alloy used in this instance is that known as "M.G. 7," which, possessing mechanical properties nearly equal to those of Duralumin yet needing no heat-treatment, is proving very popular for deep drawing and pressing. If an easy method could be devised for securely attaching durable liners to deep-drawn drums of this kind, it is likely that this application would extend to road vehicles ; for the saving in unsprung weight would be an advantage, and cast light-alloy drums are expensive, require more machining, and are not as strong mechanically as the equivalent deep-drawn product.

Turning from thickness of sheet and depth of draw to the actual size of the article produced, a striking illustration of progress is to be found in automobile bodies. The pressing of a door or a side panel, hailed as an achievement not many years ago, is now dwarfed by the regular production of one-piece pressings comprising the entire rear portion—sides, rear and roof—of a saloon body. In another field, large washing tubs and—which is more difficult by reason of their non-circular



[*By courtesy of Joseph Sankey & Sons Ltd.*

Fig. 282. Automobile wheel made by welding together component pieces blanked, drawn and pressed from sheet steel.



[*By courtesy of Taylor & Challen Ltd.*

Fig. 283. Commercial-vehicle hub 8 inches deep, deep-drawn from mild steel sheet approximately ¼ inch thick.

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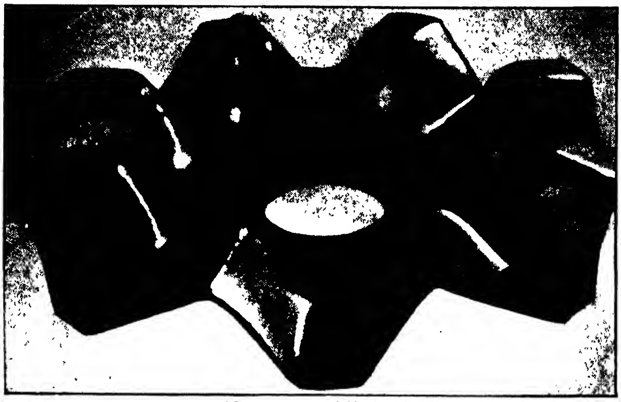


[*By courtesy of Hydraulic Press Manufacturing Co.*

Fig. 284. Tractor hub pressed from $\frac{5}{8}$ inch-thick steel plate.

[*By courtesy of the Dunlop Rim & Wheel Co. Ltd.*

Fig. 285. Shell for 12-inch diameter brake drum deep-drawn from aluminium alloy sheet $\frac{1}{4}$ inch thick.

[*To face p.* 595.

shape—full-size toilet baths, are being formed from steel sheet in a single press operation. These sheet-steel baths are now enamelled, but perhaps the future may see sheet-metal baths formed from Monel metal, "stainless" steel or perhaps "clad" steel sheet, should this innovation not prove unpopular purely on account of æsthetic reasons.

The aircraft industry furnishes many striking examples of the ever-increasing size of parts produced under the press. Indeed, the size of industrial pressings seems to be limited more by the size of available presses than by difficulties of manipulation or of the design and construction of the necessary tools. Fig. 196 (p. 346) shows a typical light-alloy part which, at one time rolled and beaten by hand, is now made more accurately, more cheaply, and naturally far more quickly, under the press. Another interesting example of a very large pressing is that of aircraft wings, which are now being made from two large Duralumin pressings accurately pressed to the contours of the upper and lower surfaces of a complete wing. Here, again, the accuracy of the finished part, the low cost of this method of production when a large number of wings of one design is needed, and the speed of production offer great advantages over the old method of gradual shaping by means of hand-manipulated small tools.

Were it not that the cost of really large press-tools is considerable, and therefore can be borne only when a large number of articles have to be produced or when cost is relatively unimportant, it is certain that many large articles now cast or fabricated would be made by deep drawing and pressing.

The Deep Drawing and Pressing of New Varieties of Metal

At present brass and steel form by far the greater proportion of metal shaped by deep drawing and pressing. This is due partly to the low cost, and for many purposes adequate properties, of these two commonly used metals, and partly to the practical difficulties encountered in the shaping of metals such as austenitic steels and aluminium alloys which, although they need careful working under the press, possess properties which are, or could be, of special value for many purposes.

An increase in the varieties of metals which can be successfully deep drawn and pressed under industrial conditions may become possible from one or both of two causes: modifications to the metal itself as a result of which its deep drawing and pressing properties are improved and, secondly, modification of existing, or the discovery of virtually new, technique for the actual deep drawing and pressing processes. In this section it is desired to direct the attention of readers to new varieities of metals rather than to modifications in technique, as this last aspect is dealt with later; but it may be pointed out that a change, sometimes in only one of many conditions, may enable a metal hitherto considered unsuitable for deep drawing and pressing to be worked quite successfully by these processes. Conditions worthy of special mention are: speed of drawing; lubrication; temperature; severity of first draft and relationship to successive ones; shape, hardness and nature of tool surfaces.

The description " new " cannot be applied to some of the metals—for example, copper and cupro-nickel alloys—discussed in this section, but some are now available in new forms having greatly improved deep-drawing properties. Readers are asked to regard their inclusion in this section as a matterof convenience ratherthan of real significance in every instance.

Free-machining Varieties of Metal. Increased attention is being paid to the possibility of producing deep drawn or pressed parts in special " rapid-machining " or " free-cutting " metals, notable in brass and steel.

Brass. Although the effect of cold-working, as by pressing or deep drawing, is to improve the machining properties of an ordinary *alpha* brass, these properties can only be described as poor when judged by modern machine-shop standards. It is known that the addition of from 1 to 2 per cent. of lead greatly increases the ease and speed with which brass can be machined, but hitherto such an addition has detracted so seriously from the deep drawing and pressing properties that its benefit in other directions could not be taken advantage of. It has, however, been found that if during casting special methods are adopted to ensure the dissemination of the lead in an extremely fine state of division, a very useful amount of deep drawing and pressing can be accomplished with the resulting sheet, particularly if the gauge is not unduly thin.

This discovery may lead to a greatly increased use of press operations as the first stage in the production of cup-shaped or hollow parts now machined from solid bar, often with a very high percentage discard of the weight of bar used. Another benefit is that the cutting of a screw thread, often an unwelcome operation on soft *alpha* brass, will be greatly facilitated on articles already produced by deep drawing and pressing, for example, thin-walled containers having a screw-on lid.

Steel. In the past it has been customary to regard free-cutting steel as an essentially brittle material possessing little ductility, a reputation which has certainly been well founded. Recently, however, remarkable developments have been made as a result of which a useful measure of toughness and ductility have been imparted to the better qualities of free-cutting steel without impairing their machining properties. Strange as it may seem, it is quite likely that in the future there may become available free-cutting steel sheet which will withstand a useful amount of deep drawing and pressing, and thereby enable parts hitherto machined from the solid to be shaped under the press and afterwards finished by machining. The economy of this method of production can be so great that it is finding increasing application in spite of the poor machining properties of the normal grades of deep drawing and pressing quality steel sheet; the advent of "pressing quality" free-cutting steel sheet would therefore be most welcome in a certain section of the industry, and might lead to an increasing use of the method of construction just outlined.

These improvements may be brought about in free-cutting steels of the kinds now used, most probably those of the high-sulphur low-phosphorus type, by preventing the formation of planes of chemical segregation having low ductility and by a more careful control of rolling and annealing. On the other hand, steels of a new kind (for example, ones containing a small percentage of lead in an extremely fine state of division) may be found to give the desired properties more readily.

There is therefore good reason to suppose that, in the future, varieties of steel and brass will become available which, although not possessing machining or deep drawing and pressing properties equal to those of the best varieties of metal developed specially for either of these two distinct purposes, may yet combine a most useful measure of each. When this happens, it will be possible to produce many drawn-and-machined articles—for example, the cup illustrated in Fig. 277 (p. 589)—more cheaply, and having a much better finish on the machined surfaces, than at present; of special importance, the finish on screw threads will be improved greatly.

High-tensile and Alloy Steels. A field in which development may be looked for is that in which alloy steel sheet is shaped by deep drawing and pressing. Hitherto attention has been focussed on the production of steel sheet possessing the best possible deep drawing and pressing qualities *irrespective of the strength of the finished product*; in the future the use of lighter draws and more frequent annealings may be tolerated in special instances in order to obtain a deep drawn or pressed article in, for example, nickel-chrome steel sheet of low-carbon content possessing the greater tensile strength associated with this class of material. In both aerial and land transport there is a continual striving to decrease weight and increase strength; many components can be produced economically only by deep drawing or pressing sheet: the inference is obvious, and must surely lead to an increasing use of alloy steel for parts now made in unalloyed steel when, for reasons of cost, high-tensile light alloys cannot be used.

The advent of all-metal construction for aircraft opened up a new field of application for thin-gauge alloy steel sheet and strip; for, by careful design, it is possible to produce a steel spar of equal weight yet higher fatigue strength than one of thicker section in light alloy. The intricate shapes dictated by designs having for their object the attainment of maximum rigidity and load-carrying capacity for a given weight of strip are often formed by rolling between suitably shaped rolls when possible: yet sometimes the only way to produce the desired shape is to draw the strip through dies.

The simplest example of this method of drawing procedure is that in which a flat strip is formed into circular shape with butted ends prior to welding into a tube. When steels of relatively high tensile strength are being formed, an appreciable amount of "spring back" must be allowed for after the shape emerges from the tools. With alloy steels the problem of securing a reasonable life on plugs and mandrels of intricate section and having a small working surface is usually greater than that of imposing successfully the desired amount of plastic deformation. Only practical experience can determine whether it is better to draw a steel of certain tensile strength to shape and use it in the work-hardened condition, or to draw it to shape in the annealed condition, thus securing longer tool life, and then heat-treat it to give the desired physical properties. A popular practice is to form aircraft spars in annealed air-hardening steel and then to heat them to hardening temperature by passing an electric current through them while, to avoid distortion, they are kept in tension by weights or hydraulic pressure applied to grips at each end, the extreme end portions being subsequently cut off and discarded.

Alloy steel sheet of relatively high-tensile strength can be pressed and deep drawn into shapes of perhaps unexpected depth, a fact which suggests that some of the physical properties of metal regarded hitherto as criteria of drawing and pressing behaviour may not after all possess their imagined significance. No difficulty is experienced, for example, in making the cupped diaphragm shown in Fig. 286 from alloy-steel strip of approximately 45 tons per square inch tensile strength containing approximately 0·15 per cent. carbon, 3·2 per cent. nickel and 1·0 per cent. chromium with small percentages of molybdenum and vanadium.

Under the heading of alloy steels there must be considered those containing copper, and it is interesting to record that copper-steels are already being used for the production of pressed parts, for example panels. The essential function of copper is to increase the resistance of steel to corrosion, and its usefulness for this purpose is well known; an appreciable increase in limit of proportionality is, however, also conferred: a result which, although increasing the difficulty of shaping by deep drawing and pressing, can be of value in some instances because it enables the thickness, and hence the weight, of an article to be reduced without reducing its strength, an important benefit on transport vehicles. The addition of copper will naturally lower the ductility of steel, but it is claimed that *this reduction is less rapid than when a* *corresponding increase in strength is obtained by raising the carbon content:* Furthermore, a useful degree of precipitation-hardening can be produced in low-carbon steels of suitable copper content by a low-temperature heat-treatment.

It should be observed that the protective action of copper is due to the formation of copper and copper-oxide films on the surface of the metal, and that these films are not formed *until* some corrosion has taken place. The addition of copper to steel does not, therefore, prevent the initial stages of rusting, but produces a copper film beneath the initial corrosion products which tends to check further corrosion. An addition of from 0·24 to 0·4 per cent. of copper is stated to be sufficient for this action to occur, and that the addition of a higher proportion confers no further benefit with respect to corrosion resistance as distinct from mechanical properties.[116] From the same source it is learned that paint adheres very much better to steels containing copper, and that a marked increase in the life of a painted coat is noticeable.

Stainless Steels. Owing to the rapid wear on the tools and the frequent high-temperature annealing which is now considered necessary, the production of deep-drawn shapes in austenitic steel has not been attempted on a scale merited by the useful service properties of this metal. Theoretical considerations, for example special or "derived" stress-strain curves which are now known to give a reliable indication of the true capacity of any metal to suffer plastic deformation, show that it should be possible to impose draws on austenitic steel as severe as those imposed on ordinary low-carbon steel and brass. The essential difference between the austenitic alloy and these apparently more ductile metals is that its rate of work-hardening increases very rapidly at first, and that more power is needed to draw it. A better understanding of its work-hardening properties, coupled with the advent of more durable tool materials, better lubricants, and possibly of the practice of temporarily coating the sheet with some metal such as lead to facilitate drawing, is likely to lead to an increased production of deep-drawn austenitic steel articles for many purposes.

Until recently the inter-stage annealing of austenitic steel has proved a stumbling block, and even a deterrent to the use of this metal in many press-shops, owing to the high temperature needed and to difficulties attributable to the formation of scale. The advent of modern, controlled-atmosphere annealing furnaces and, of even greater importance, of more suitable protective annealing atmospheres—for example that derived from cracked ammonia—which are free from small yet injurious proportions of impurities has removed this serious disadvantage, and it is now possible to anneal deep drawn and pressed austenitic steel shapes so cleanly that no pickling is needed.

It is interesting to notice that the addition of copper to the 18 per cent. chromium 8 per cent. nickel variety of austenitic steel increases the corrosion resistance of this material to certain acids and, of great importance from the aspect of deep drawing and pressing, lessens the tendency to work-harden rapidly,[116] thus removing one of the chief obstacles which render the shaping of "18/8" sheet somewhat difficult. Alloys such as Armstrong metal,[117] which has the following approximate chemical composition, may for this reason find a wide field of application for the production of deep drawn and pressed shapes when their properties become more widely known.

Carbon . . .	0·10 per cent.
Manganese . . .	4 to 6 ,,
Chromium . . .	17·5 ,,
Nickel . . .	8·0 ,,
Copper . . .	2·9 ,,

Increasing attention is being paid to the use of low-carbon straight-chromium varieties of "stainless steel," for example that containing about 0·1 per cent. of carbon and about 18 per cent. chromium. Because these varieties have a ferritic as distinct from an austenitic structure they possess two advantages from the viewpoint of the press-shop: they work-harden less rapidly than the austenitic alloys, and thus need less frequent inter-stage annealing and cause less severe wear on tools, and, secondly, they can be annealed at a relatively low temperature. A minor advantage of benefit when—as often happens—stainless steel and chromium-plated articles are seen close together, is that the colour of the ferritic varieties is closer to that of chromium plate than that of the austenitic varieties.

Because these advantages are likely to make ferritic "stainless steels" increasingly popular, emphasis needs to be placed on the fact, sometimes conveniently forgotten, that under some conditions their corrosion-resisting properties are not as good as those of the austenitic alloys. For this reason they should be regarded not as a substitute for austenitic corrosion-resisting steels, but as an additional variety which will prove most useful for certain applications in which the best possible powers of corrosion resistance are not needed.

The well-established use of deep drawn and pressed domestic utensils, such as the selection shown in Fig. 287, is likely to grow, and more recent applications, for example to tankards, table jugs, vases and many other domestic articles, are becoming increasingly popular. Restaurant and toilet equipment, decorative and utilitarian fittings, and even machine parts are already made from austenitic steel sheet by deep drawing and pressing, and it is only that fickle yet decisive dictator Public Fancy which prevents its extensive use for many parts of automobiles, such as radiator shells and lamp bodies,

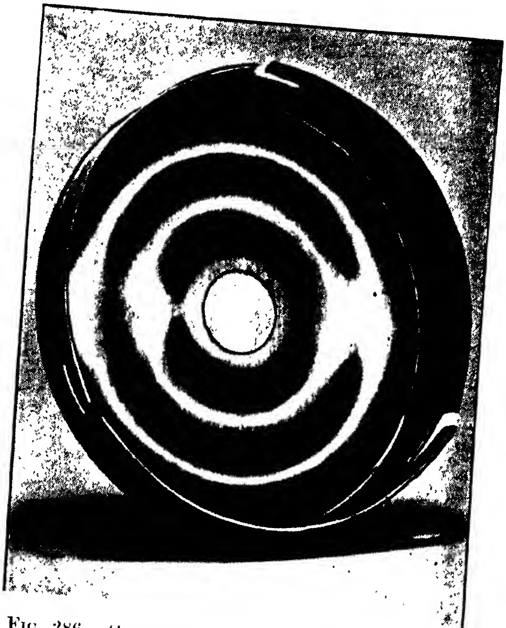
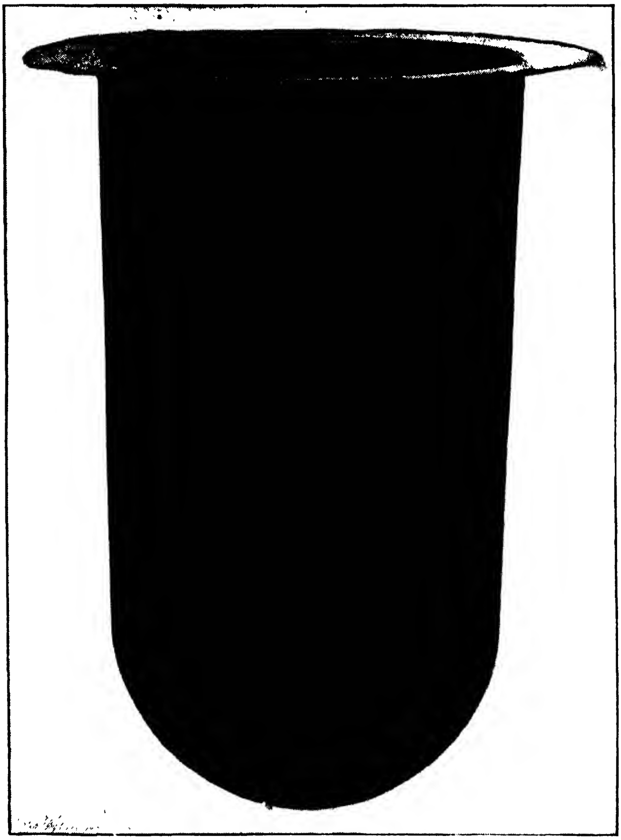


Fig. 286. Cupped diaphragm formed from 45-ton tensile nickel-chrome steel strip.

[*By courtesy of Joseph Sankey & Sons Ltd.*

Fig. 287. Domestic utensils fabricated from austenitic steel sheet. All but the water jugs are deep-drawn or pressed.

[*To face p.* 600.



[*By courtesy of Taylor & Challen Ltd.*

Fig. 288. 14 inch-deep container for electric water-heater deep-drawn in three operations, with inter-stage annealing, from deoxidised 18-gauge copper sheet.

[*To face p.* 601

for both of which purposes it has been tried with success as far as the production side of the matter is concerned.

On the industrial side, containers and pans such as that shown in Fig. 180 (p. 315) are being made and used on an increasing scale, particularly as the relatively high mechanical strength of austenitic steel enables it to be used where other corrosion-resisting materials, such as copper, would be unsafe. Although welded vessels in austenitic steel of the " weld-decay-free " type are satisfactory for many purposes, there are others in which a deep-drawn weldless shell is preferable. When the gauge of the metal is thin and the number of articles to be produced sufficiently large to defray the cost of tool-making, it is often cheaper to make even deep containers—for example the one shown in Fig. 178 (p. 314)—by deep drawing than by welding. When appearance and ease of cleaning are of importance, the verdict must go again to the deep-drawn container—especially if the sheet be thin—because even if a thick, welded seam be built up and then polished down flush with the surface of the parent sheets, small cavities often occur to spoil the appearance and to harbour dirt and perhaps infectious germs. Again, a nicely radiused corner, so easily formed in a deep-drawn shell, cannot be formed in a welded container; and rounded corners are more easy to clean, and sometimes of more pleasing appearance, than square ones.

Copper. The industrial advent of so-called " deoxidised copper," developed primarily to facilitate the successful welding of this useful metal, has been of benefit to the press-man as well as to the welder because deoxidised copper of good quality will withstand deeper draws than ordinary grades before inter-stage annealing becomes necessary. As long as its price is higher, there is no chance of deoxidised copper sheet replacing the ordinary grades for all purposes, yet its use often enables the number of inter-stage annealing operations to be reduced, and, in some instances when only a single anneal is given, eliminated. Webster, Christie and Pratt [71] have shown that the deep-drawing properties of deoxidised copper sheet may be improved still more by increasing the purity of the copper, and it is possible that the future may see an improvement in deoxidised sheet at least as great as that which marked the change from ordinary to deoxidised varieties.

As an example of the extending application of deep-drawn copper shapes there may be instanced containers for domestic water heaters, such as that shown in Fig. 288, which is drawn from deoxidised copper sheet in three operations with the aid of inter-stage annealing. The use of deep-drawn vessels for chemical and industrial cooking processes is likely to grow as the depth of draw increases, because the article produced under the press is in many ways superior to that produced by beating or by welding.

Special Copper Alloys. In addition to the familiar alloys of copper with zinc to form ordinary brass, with nickel to form cupro-nickel and with nickel and zinc to form nickel-silver, a number of others possessing properties which render them useful for certain specialised application are beginning to find their way into the press-shop.

Silicon-copper alloy sheets containing about 3 per cent. of silicon, often with lesser amounts of zinc, aluminium, tin and iron, are, for example, being pressed into various shapes used in the construction of domestic refrigerators. Copper-alloy sheet of the kind just mentioned possesses excellent mechanical strength; yet, when free from defects and having a suitable crystal size, it can be pressed and deep drawn to a useful depth if the radii on the tools are kept large.

When copper alloys specially resistant to corrosion are needed, it should be borne in mind that several alloys have been developed to give a long life in the form of condenser tubes. One of the simplest alloys of this type is the ordinary condenser-tube brass containing from 1 to 2 per cent. of aluminium, but Crampton [118] reports that an alloy containing approximately 82 per cent. copper, 15 per cent. zinc, 2 per cent. aluminium and 1 per cent. of tin is equally resistant to attack by corrosion and dezincification and better able to resist attack by impingement. When still greater resistance to corrosion is desired, cupro-nickel alloys containing from 20 to 30 per cent. nickel, sometimes with a small proportion of zinc, are often preferred. As a last example, the same investigator reports [118] that an alloy containing approximately 92 per cent. copper, 4 per cent. nickel and 4 per cent. aluminium is well suited to resist attack by both water and oil.

The fact that these and other alloys of similar type can be drawn into thin-walled tubes indicates that shapes of useful depth could be formed from sheet by deep drawing and pressing, and it may be that in the future they will come to be used for this purpose when resistance to attack by corrosion is desired.

Another possible development may lie in the use of special brasses, such as those containing aluminium and nickel, which possess a useful measure of ductility in the soft condition but which can be hardened, after having been deep drawn or pressed to the desired shape, by a simple precipitational heat-treatment.

Nickel and Nickel Alloys. The very satisfactory way in which nickel and many nickel alloys behave under the press does not seem to be generally recognised. This is due, perhaps, to the fact that these alloys seldom seem to find their way into press-shops other than the few which specialise in their manipulation and cater for the rather narrow markets which, owing to their high price, articles made in these alloys command.

It is difficult to foresee important new applications of nickel and Monel metal in the form of deep drawn or pressed articles, but an increasing output of the many kinds of articles already in use may be looked for with certainty. Of these established uses there may be instanced cooking utensils, such as those shown in Fig. 173 (p. 293); hospital ware; food containers of all kinds and sizes; chemical plant ranging from small laboratory crucibles and dishes, such as those illustrated in Fig. 289, to large industrial processing vessels; restaurant equipment, and toilet fittings. The kitchen shown in Fig. 290 is equipped entirely with nickel and Monel metal fittings and utensils. Special mention may be made of the Monel metal sink because this illustrates the modern tendency to deep draw and press this class of article rather than to fabricate it by welding. Perfectly satisfactory welds can be made in Monel metal, but deep drawn or pressed shapes are free from objectionable beads or lines of unsoundness where a welded bead has been polished flush, and can as a rule be given more gradual and pleasing contours that a built-up article.

Cupro-nickel alloys, especially those containing approximately 80 per cent. copper and 20 per cent. nickel, must be placed very close to the top of any list of metals arranged in order of excellence of deep-drawing properties. This is due to a fortunate combination of physical properties and, particularly, to a low rate of work-hardening, which allows a remarkable amount of cold-working to be inflicted before annealing becomes necessary. It is regrettable that at present almost the only large-scale application of this class of cupro-nickel is to bullet envelopes which, as shown in Fig. 175 (p. 300), are deep drawn, formed to a point and the lip rolled over an inserted lead core without the help of any inter-stage annealing whatever. Perhaps in the future other useful—and it is to be hoped more economic—applications will be found, and it may be that its substitution for less expensive metal might in some instances cheapen production by eliminating annealing during the production of really deep shapes.

The deep drawing and pressing of nickel-silver alloys is confined mainly to the production of "electro-plate" ware, that is, household utensils, containers and ornaments which, after having been shaped, are silver-plated. Many of the nickel-silver alloys will accommodate really deep draws (though not, as does cupro-nickel, without the help of inter-stage annealing) and it is not unlikely that fresh fields of application, such as that shown in Fig. 176 (p. 302), may be found.

Inconel. This proprietary alloy, containing nickel, chromium and iron, has already been described in Chapter VIII. Owing to its excellent mechanical properties and resistance to oxidation at elevated temperatures it is finding increasing application for parts such as hot-plates and aero-engine exhaust manifolds. Because these and similar parts can often be made most readily under the press, it is an alloy which in the future is likely to find its way into the press-shop more often.

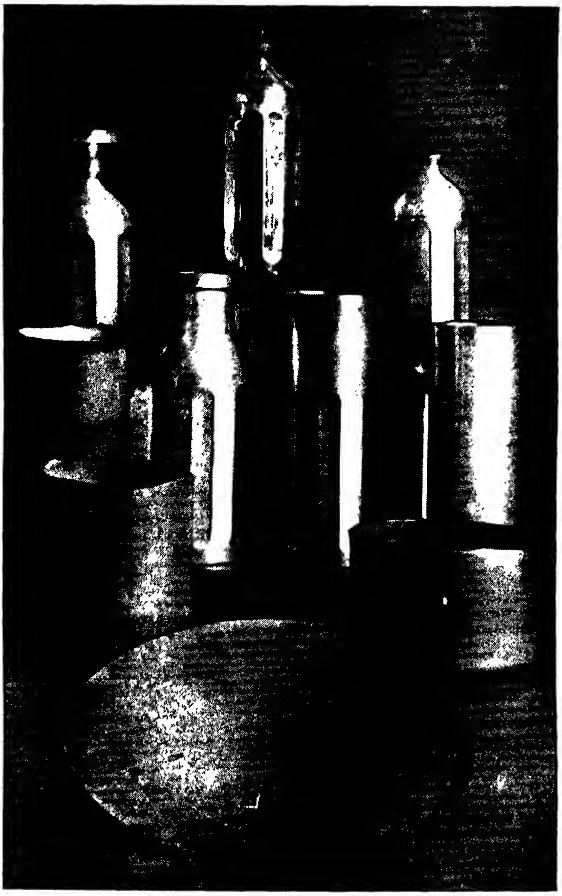
Aluminium and Aluminium Alloys. The use of pressed and deep drawn articles made from pure and alloyed aluminium is continually increasing, and it is safe to predict that the technique of deep drawing and pressing light alloys will develop rapidly.

A small yet significant field is the replacement of built-up tin-plate containers for toilet and household preparations. Not only are aluminium containers lighter, and thus cheaper to transport, but they can be treated anodically to produce decorative finishes more in keeping with modern taste than lithographed tin-plate. Another interesting application is that of pressed dishes and trays, anodically treated, to replace vitreous-enamelled hospital-ware; lightness and freedom from germ-harbouring cracks at chipped regions are claimed as important advantages of this new departure. Further development of anodic finishes, whether of a decorative, durable or light-reflecting nature, may lend an added impetus to the increasing production of deep drawn and pressed aluminium shapes for many purposes.

Deep drawn and pressed aluminium cooking utensils have ceased to be a novelty, and the range of application to domestic articles continues to grow. The hot-water bottle shown in Fig. 291 is typical of this trend and illustrates the increasing depth of draw which is being undertaken on a production scale in thin sheet. The bicycle tyre inflator illustrated in Fig. 154 (p. 248) and the tube illustrated in Fig. 157 (p. 249) afford striking examples of still deeper draws, and the group of articles shown in Fig. 155 (p. 248) is of special interest as an instance of how aluminium can be substituted for brass or steel in many familiar pressings when a saving of weight is an advantage.

It is a fairly common practice to finish deep drawn or pressed articles by one or more blows under a drop stamp, as described later in this chapter, in order to remove puckers from the walls. A curious feature of this stamping operation, more particularly with articles formed from the softer grades of aluminium sheet, is that if an object even as soft and delicate as a human hair is placed on the tools, its impression is clearly recorded on the surface of the stamped article. This opens up interesting possibilities of decorating, at extremely low cost, pressed and drawn shapes with patterns of almost unlimited complication and delicacy impressed on their surfaces from a pattern of paper, fabric, or other suitable medium. If the surface of the sheet is really good, this process is so sensitive that it is possible to obtain a clear—but of course extremely shallow—impression of an ordinary printed page of type or pictures.

The use of pressings in light-alloy sheet in aircraft construction is well-established, and it is likely that both the range of alloys used as well as the depth of draw and the size of the articles made in them will increase as the special requirements of the press-shop come to be appreciated more thoroughly. The trend is aptly illustrated by the large Duralumin pressings shown in Fig. 196 (p. 346). In particular, the use of alloy sheet, which can be shaped under the press in a ductile



[*By courtesy of the London Aluminium Co. Ltd.*

FIG. 291. Stages in the deep drawing and pressing of a hot-water bottle from aluminium sheet.

[*To face p.* 604.

" solution-treated " condition and then " aged " to give considerably higher mechanical strength, must appeal to designers. In this, as in all applications, early co-operation between designer and press-shop while a component is still on the drawing board will prevent unnecessary difficulties, and even failures, during the attempted production of new designs.

It would not be unfair to say that, with perhaps a few exceptions, in the past the press-shop has had to do the best it can with aluminium and light-alloy sheet produced without special regard to behaviour under the press. It may be anticipated that in the future the use of improved methods for annealing, or perhaps closer control of ordinary methods, will lead to a general improvement, and also greater consistency, in the deep drawing and pressing properties of industrial aluminium sheet. How soon this happens may depend upon the insistence shown by consumers on being given sheet of the quality they desire.

To summarise, it can be said that, through a better understanding of the behaviour of aluminium under the press, assisted perhaps by the industrial advent of sheet having better deep-drawing properties, the depth of draw normally obtainable under industrial conditions will increase, and that the use of heat-treatable aluminium-alloy sheet offers an attractive means for making deep drawn and pressed shapes having a very high strength/weight ratio. Although the processes of deep drawing and pressing will certainly meet a most serious rival in that of impact-extrusion for the production of small shapes, there is every reason to believe that the older processes will be used to a still greater extent as the range of application of aluminium and its alloys extends.

Magnesium Alloys. From the economic aspect, the present position of magnesium may be compared with that of aluminium some forty years ago. If, as is not unlikely, the price of magnesium falls very considerably during the next ten or twenty years, magnesium alloys will certainly replace those of aluminium for many purposes.

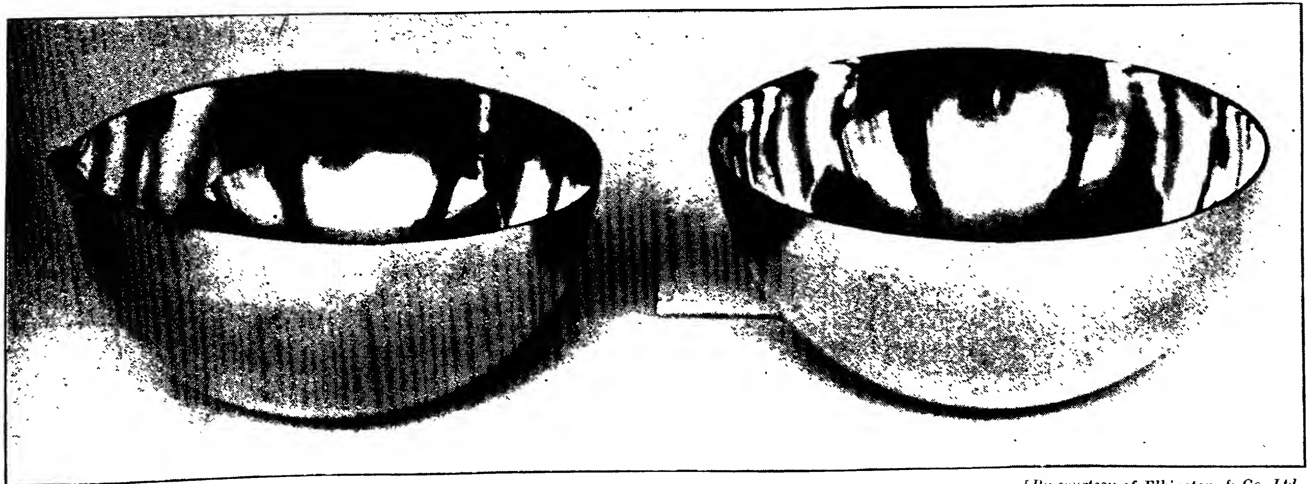
In spite of the present high price of magnesium alloys, their very low specific gravity, coupled with their useful mechanical strength, is leading to their increasing application in aircraft and also in those types of land transport vehicles in which first cost is not of primary importance. It is most unfortunate that the behaviour of magnesium alloy sheet under the press can only be described as poor, even when special precautions, some of which have been outlined in Chapter VIII, are carefully observed. Because the field of application of magnesium alloy parts could immediately be extended considerably if sheet could be deep drawn and pressed fairly readily into even moderately deep shapes, it is likely that this method of shaping will be studied with increasing energy as regards both the technique to be adopted for existing popular alloys and also the development of new alloys which, either hot or cold, would be more amenable to deep drawing and pressing. It is unsafe to predict along what lines this development will proceed, but from now onwards the student of deep drawing and pressing cannot exclude magnesium alloys from the many metals which have to be dealt with in the press-shop.

Zinc. If zinc is to be deep drawn and pressed into shapes of any depth it is necessary to observe certain rather troublesome precautions —such as working the sheet within a narrow range of temperature likely to vary for each individual article produced—which have already been described in Chapter VIII. For this reason any considerable extension in the application of zinc in industrial deep drawing and pressing seems unlikely; on the other hand, the application of zinc parts made by impact-extrusion will certainly continue to extend beyond the present realm, which is mainly confined to cells for dry batteries, small containers and collapsible tubes.

Special grades of zinc are available, such as so-called "ductile zinc," which contain additions of manganese, nickel or copper to increase the ability of the metal to suffer plastic deformation at room temperature, and a variety which, while molten, is treated with boron trichloride to produce an effective and remarkably permanent refinement of its crystal structure. For some reason neither of these special varieties appears to be used to any considerable extent on an industrial scale, and it is possible that, in the future, their industrial recognition may give a fresh impetus to the deep drawing and pressing of zinc sheet into articles for which the natural properties of this metal offer advantages.

Precipitation-hardening Alloys. Interesting possibilities are offered by the use of varieties of metal which can be heat-treated to give values for strength and hardness greatly in excess of those at which sheet can be successfully deformed to any useful extent. Rolled sheet could be "solution-treated" to place it in a ductile condition, pressed or deep drawn to the desired shape, and then heat-treated according to the precipitation-hardening requirements of the particular metal used. It is of interest to observe that, as many precipitation-hardening alloys do not attain their full hardness unless they are cold-worked after being solution-treated, the shaping process would enable full hardness to be attained in many, if not in all, regions of a pressed or deep drawn shape.

Possible applications for precipitation-hardened articles pressed from light alloys of Duralumin type have already been described in an earlier section, and there is no reason why a number of other metals, such as nickel-aluminium brasses and beryllium-copper alloys, should not be used for similar purposes. Quite useful depths of draws could be accomplished in these alloys using present press-shop technique,



[By courtesy of Elkington & Co. Ltd.

FIG. 289. Laboratory dishes pressed from pure nickel sheet.

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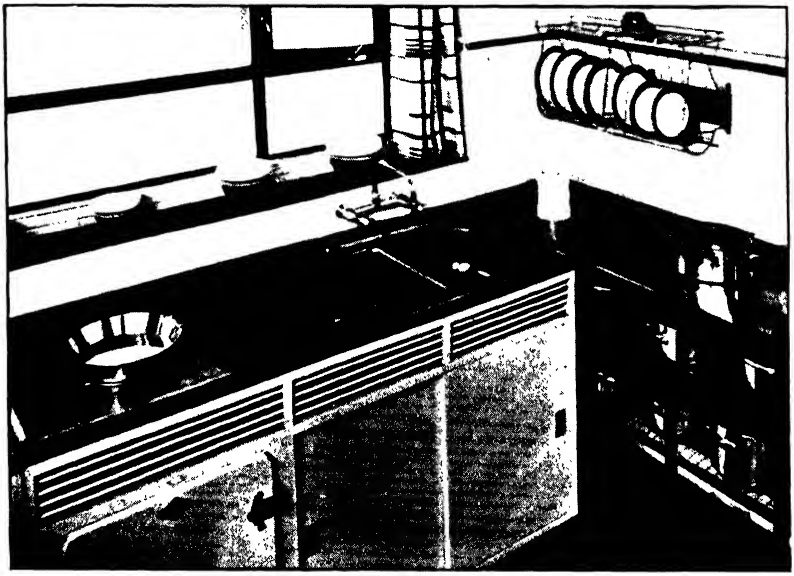

[*By courtesy of The Mond Nickel Co. Ltd.*

FIG. 290. Kitchen in which all fixtures and cooking utensils are deep drawn or pressed from nickel or Monel metal.

[*To face p.* 603.

and there is every reason to suppose that as new knowledge is obtained still deeper draws will become possible with them.

Plated, Coated and Clad Sheet. Having reviewed a number of growing and novel applications of deep drawn and pressed articles dependent upon the use of homogeneous sheet of various metals, there remains to be considered new applications dependent upon the successful deep drawing and pressing of the common metals coated, prior to their insertion in the press, with some dissimilar metal. Future development seems likely to take place in two distinct directions, namely, in the more extensive use of coatings given solely for the purpose of lessening the tendency of the base metal to foul the tools and, secondly, in the more severe pressing and deep drawing of sheet coated with some different metal for the purpose of decoration or protection of the finished article against corrosion.

Lubricational Coatings. The lubricational value of a thin coating of certain non-ferrous metals deposited upon steel is well known. In the deep drawing of steel sheet the beneficial effect of a coating of lead or copper and, perhaps in less degree, tin in preventing fouling of tools and scoring of work is recognised by those whose work enables them to compare the behaviour of coated and uncoated sheet under similar conditions. It is common knowledge that a coating of copper or cadmium enables a quite remarkable increase to be made in the severity of the reduction which can be given during the ordinary drawing of steel into both wire and tube. With austenitic steels a coating of lead confers similar benefits, and forms the basis of the Dudzelle process for the drawing of this metal. Brownsdon,[10] in an interesting series of experiments intended originally to provide precise information concerning the fouling properties of certain non-ferrous metals when rubbed against steel in the presence of various lubricants, has found that—of the range of metals tested—copper, in company with tin-bronze and cupro-nickel, exhibits the least tendency to foul hardened steel under the conditions of his tests.

It may therefore be accepted that, in addition to their recognised protective power against rust and corrosion, copper, tin, cadmium and lead offer genuine benefits as a lubricational coating for steel sheet intended for deep drawing. A coating of copper on certain nickel-chromium alloys facilitates deep drawing so markedly that this operation is thereby changed from one of extreme difficulty to one of relative ease, and shows that the extension of the principle of coating to non-ferrous sheet certainly justifies investigation.

The possibility of using lightly-coated steel sheet for many ordinary articles in which the coating is unnecessary except for the purpose of facilitating deep drawing may seem remote owing to the extra first cost of the coated sheet; yet the consequent increased life of the tools coupled with the marked reduction in the tendency to foul may render its use worthy of serious consideration, especially if in the future the cost of suitably coated sheet becomes less by reason of an increased demand, improvements in the technique of plating, and the introduction of continuous plating processes for strip.

In explanation of observed effects it is sometimes stated that an adsorbed layer of oily lubricant is formed more readily upon, for example, copper than upon steel. How far this assumption is correct, and to what extent any such increased power of lubricant adsorption imparted to the steel sheet as a result of copper-plating is responsible for the observed improvement under the press, seems at present uncertain ; the behaviour of the contacting metals when lubrication breaks down completely may be of equal importance. Until more knowledge is gained, it seems best to accept the fact that under certain conditions a suitable coating can greatly reduce the tendency of some metals to " foul " or " load " steel tools during deep drawing, and, having accepted it, to consider whether the extra first cost of coated sheet may not be justified in special instances. With metals which are notoriously prone to " foul," such as certain nickel-chromium alloys, plating may sometimes be essential if the desired shape is to be deep drawn successfully.

Apart from the advent of a more general recognition of the usefulness of coated sheet, future development will be dependent upon improvement in the quality of the coating, whether this be given by electrolytic or other methods, and upon the use of more smoothly polished tools which will be less likely to injure the coating.

Protective and Decorative Coatings. Lead-coated steel sheet, used mainly for containers and domestic appliances, is deep drawn and pressed extensively, and tin-plated steel is also used fairly widely. In the jewellery industry the pressing of base-metal sheet coated, either by electrolytic deposition or rolling, with precious metals is fairly common. Dull nickel-plated brass is already subjected to severe deformation, and apparent success has attended attempts to press, and even to deep-draw, articles from polished nickel-plated sheet. Clearly, it will be cheaper to polish a few flat sheets or strips than a large number of small embossed articles of awkward shape, and it is likely that this procedure will be exploited by makers of cheap articles. The cheapest possible method for producing plated shapes would be to deep draw or press articles from bright-plated sheet or strip, thus eliminating polishing of either the sheet or the shaped product.

The deep drawing and pressing of electro-plated sheet is an extended application which must be accepted with caution. It is true that in the jewellery industry press operations have been successfully carried out for a long time on brass, cupro-nickel and nickel-silver sheet plated with precious metals. These deposits are relatively ductile, and it is the recent trend toward the pressing of sheet plated

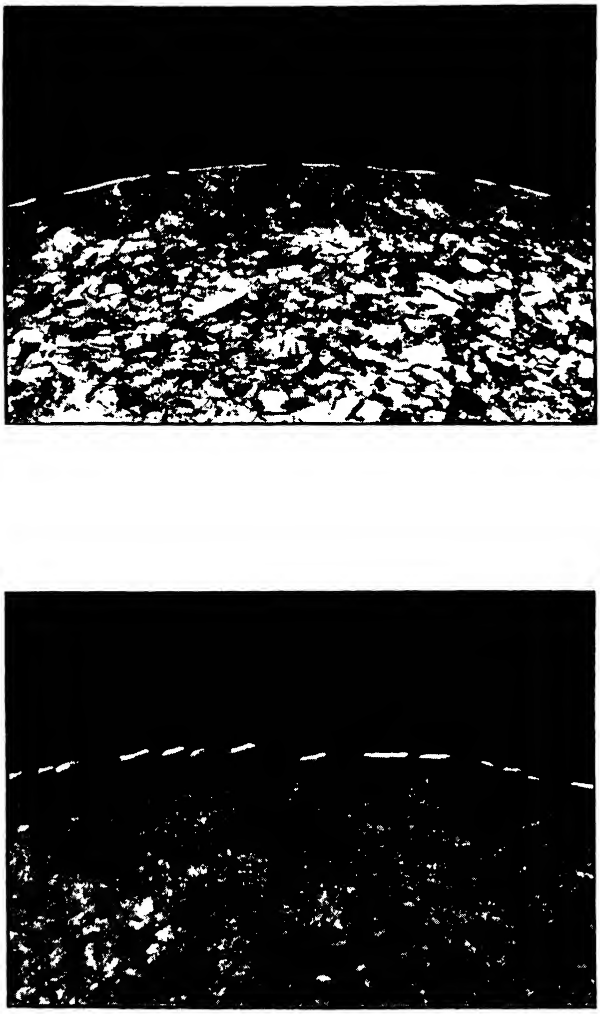

FIG. 292. The effect of raising an impression in the chromium-plated wall of a drawn shell. Photomicrographs, × 100, of sections cut transversely through cracks in an electro-deposited coat of chromium over nickel on a brass base.

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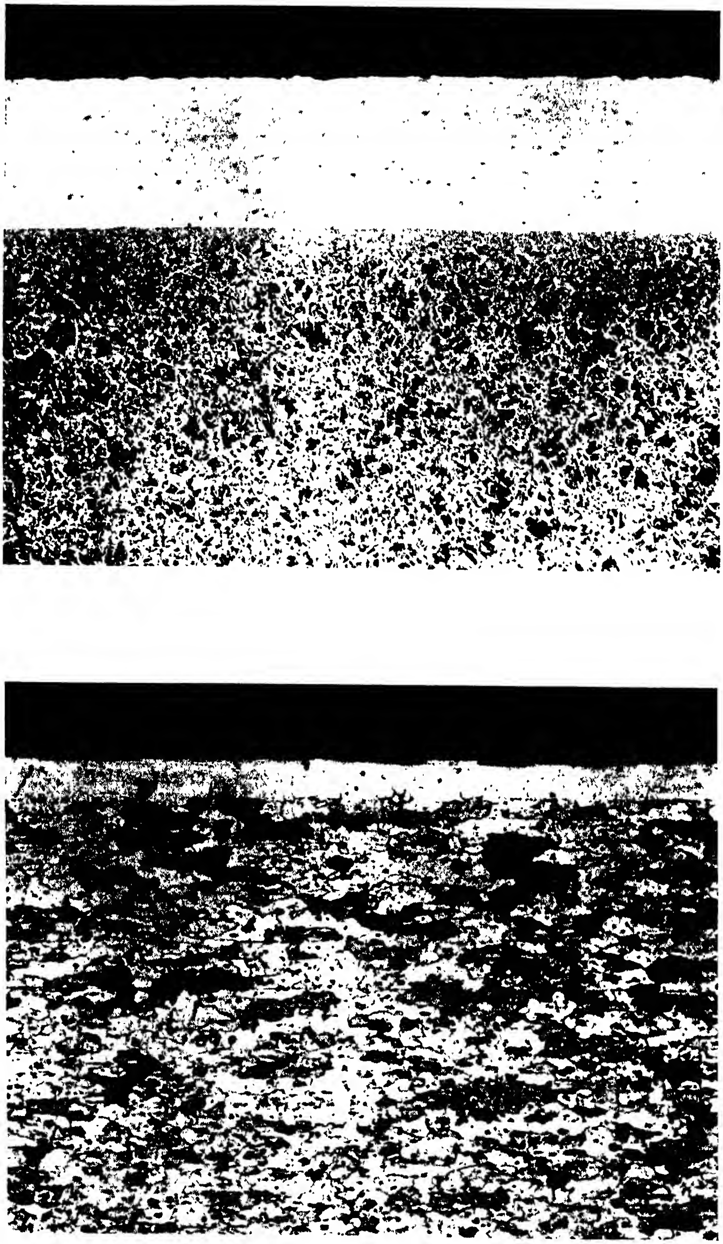


FIG. 293. Photomicrographs illustrating typical appearance of two popular varieties of "clad" sheet.

Top : austenitic steel on mild steel base. × 30.
Below : pure aluminium on Duralumin base. × 60.

Microsections cut normal to surface of sheet and etched to reveal the microstructure of the base metal.

[*To face p.* 609.

with less ductile deposits, such as chromium, which should be regarded with suspicion. It is, for example, becoming increasingly popular to raise quite sharply-defined decorative impressions, and even lettering, on the walls of deep-drawn articles in brass and steel *after* these have been chromium-plated, the main object of this procedure being to save the cost of polishing the irregular contours and small recesses of any design raised prior to plating. Familiar examples of this practice are to be found in buttons, medallions, and automobile parts such as hub covers.

As usually deposited, chromium is a hard, brittle metal; and it would be strange indeed if it proved amenable to deformation of the severity accommodated successfully by its relatively ductile base of brass or steel. Although, when viewed casually, the surface of a design raised in chromium-plated sheet may often seem intact, careful examination will nearly always reveal the presence of a series of cracks. Fig. 292 shows the appearance of microsections cut transversely through shallow impressions raised in the walls of deep-drawn brass shells plated with an undercoat of nickel and an outer coat of chromium. The series of tooth-like cracks is typical of the form which the cracking takes and, other conditions being equal, there is some evidence to show that the distance between successive cracks decreases as the hardness of the deposit increases. It is hardly necessary to comment upon the protective value of a plated coating containing large numbers of tiny fissures nicely shaped to collect and retain moisture in contact with the underlying base metal.

At the present time special attention is seldom given by electroplaters to the requirements of deposits intended to suffer drastic deformation. Recent work has shown how profoundly the properties of a deposit—for example of chromium [87]—can be modified by varying the conditions under which deposition is carried out, and it is possible that the future may see the development of deposits specially adapted to meet the demands of the deep drawing and pressing industry.

Clad Sheet. A new development which opens up a wide field of possible applications is the deep drawing and pressing of so-called "clad" sheet, this being sheet which carries on one or both of its surfaces a relatively thick coat of dissimilar metal which is either cast around an ingot or a partly rolled slab or, sometimes, roll-welded to a slab which is then rolled into sheet.

A familiar example is that of mild-steel sheet clad with austenitic corrosion-resisting steel, pure nickel or Monel metal, all used in the construction of welded vessels for chemical plant, transport or storage purposes. Mild-steel sheet clad on one side with austenitic steel is already being deep-drawn into cooking utensils, and it is likely that many other, and not necessarily domestic, applications will be found in which the use of clad sheet will reduce the cost of a deep drawn or pressed article sufficiently to make its use possible and even popular.

Clad light-alloy sheet, consisting of a base of heat-treatable alloy such as Duralumin having a surface coating of very pure aluminium, is widely used in the aircraft industry and is already being deep drawn and pressed quite extensively. The advantage of this composite sheet is that heat-treated products made in it exhibit the excellent mechanical strength of the Duralumin core coupled with the excellent resistance to corrosion of the pure aluminium surface layer after some chemical treatment such as anodising has been given. A disadvantage from the manipulative aspect is that considerable care has to be exercised to prevent the soft and very thin surface coating being opened up or scored sufficiently deeply to expose the core during actual press operations, or by accidental abrasion either before or afterwards.

Fig. 293 shows photomicrographs of clad sheets of austenitic steel on a mild-steel base, and pure aluminium on a Duralumin base, respectively. It is, for obvious reasons, a difficult task successfully to fabricate containers in clad sheet by fusion-welding processes even when the sheet is of considerable thickness; when the sheet is thin, this method of construction becomes virtually impossible. For this reason the shaping of clad sheet by deep drawing enables this useful material to be used in thin-walled containers which, were they built up by welding, would have to be made in homogeneous—and therefore more expensive and perhaps mechanically weaker—sheet composed entirely of the metal used for the outer layers of the clad sheet.

Both the severity and the technique of the draw which clad sheet will withstand will be dependent upon the natural properties of the base and of the coating, as well as upon the excellence of the bond between them. When the properties are decidedly different, those of the less suitable metal will limit the severity of the draw; with certain combinations of metals proper annealing of both core and coat may prove impossible, and thus limit the amount of deformation which can be imposed. The value of a thin, plated coating given purely to facilitate drawing must not be overlooked when the outer metal of the clad sheet is liable to foul the tools.

New Processes for Shaping Sheet Metal under the Press

It is likely that the future will see the everyday use for certain purposes of entirely new processes, or at least of greatly modified versions of the methods of deep drawing and pressing which are now used. These new methods may be developed either to meet the requirements of metals which at present are not shaped to any great extent by deep drawing and pressing, or else to enable draws of still greater depth to be obtained with the commonly used metals, such as brass and steel.

Dealing first with relatively minor changes in orthodox procedure, considerable benefit could often be derived from alterations to the speed of drawing and from the adoption of a uniform speed. It is only natural that the benefits of the first of these conditions cannot be taken full advantage of unless the speed remains constant throughout the stroke of the press; but, as this matter is considered at some length in another chapter, further elaboration is unnecessary here.

The advent of fluid-pressure actuation as an alternative to that given by a crank opens up great possibilities because, with the hitherto almost exclusive use of crank presses, a working stroke of constant velocity cannot be obtained; for this reason the speed of drawing on a crank press is limited and, furthermore, a value purporting to represent "speed" is often of little significance, because it is an average value. A wide range of drawing speeds is usually available to users of modern fluid-pressure presses, and this of itself is an important change which, coupled with the associated *uniform* speed throughout the working stroke, will enable deeper draws to be performed at one operation. The rather special circumstances associated with a very high speed of deformation will be discussed later.

Warm Pressing and Drawing. A little-used procedure, which needs no alteration to whatever type of press is employed, is that of warm pressing or drawing. This procedure is not to be confused with genuine hot-pressing at a temperature high enough to render the metal quite plastic (and therefore incapable of transmitting the tensional stress required in true deep drawing and pressing, as distinct from extrusion, operations): the term "warm" pressing and drawing is intended to imply that the blanks are warmed to a temperature of perhaps 60° to 300° C., depending on the metal, before being offered to the tools.

Blanks or partly-shaped pressings can be heated in water or oil baths, and sometimes the heating medium can conveniently be the drawing lubricant. Air furnaces may be used *provided* that they have an efficient circulating atmosphere to ensure uniform heating of all parts of a charge. Indiscriminate warming on a hot-plate or over a naked flame, a practice occasionally seen, cannot be condemned too strongly; this method cannot give uniform or controlled heating and can never enable the full benefit of the warm drawing procedure to be realised; indeed it often leads to failure under the press and thus gives a false impression of the value of warm drawing.

Simple and inexpensive though it is, warm drawing seldom seems to be used at present except as a temporary shop "dodge" to prevent production being stopped when a certain operation proves unusually difficult. Systematic investigation of the deep drawing and pressing properties of metals with the aid of a controlled, experimental press, such as the A.E.G. or the Erichsen No. 2 machine, would undoubtedly bring to light much interesting information. Until reliable data have been collected it is unsafe to conjecture in what way the benefits of warm pressing arise, but it seems likely that the important change is associated more with work-hardening effects than with material alteration in any of the commonly-measured tensile properties. For this reason the subject is one which might well be studied in conjunction with the equally important one of speed of drawing.

Bulging, Expanding and Blowing. These processes are certainly among the oldest associated with the craft of deep drawing and pressing, and readers are asked to excuse their inclusion in this chapter purporting to describe new developments. This arrangement is purely one of convenience.

" Bulging " and expanding have for their object the giving of a contour to the wall of a parallel-sided deep-drawn shell. Three methods are used, bulging by means of rubber, bulging by means of oil or water, and expanding by means of multi-piece metal tools.

Bulging by means of rubber is perhaps the simplest of the three. It consists of inserting the shell in a split die shaped to the desired contour, placing inside the shell one or more pieces of rubber, and compressing this rubber by means of a parallel-sided punch attached to the slide of an ordinary single-action press usually having either crank or screw actuation. Recent improvements in the quality of rubber have lengthened the life of the punches used and have increased the pressures which can be applied, and hence the thickness of the metal which can be bulged ; yet the principle of the process is very old. To secure the longest possible life of the punches it is essential that no clearance spaces exist of a size which allows the rubber to be forced up them, because this will cause it to disintegrate rapidly.

The application of this technique to a small elbow which is shaped, in the stages shown, by a " blank and raise " operation followed by two draws and three bulging operations is shown in Fig. 294. By the use of three rubber punches of increasing length it is possible to complete the bulging in one split die and without altering the height of the die or the stroke of the press. Frequent annealing—or, in the case of steel, normalising—is a necessary precaution in most bulging processes. Thus the elbow just described is clean-normalised before each bulging operation, and it will be seen that, as a result, the sharpness of the corners leaves little to be desired. Attempts to bulge work-hardened walls often end in splitting, and always reduce the sharpness of the impression obtained.

" Expanding " usually implies the use of metal tools instead of rubber to force the walls of a shell against the interior surface of a split die. Some of the tools used for this purpose are both ingenious and complicated, but the basic principle is a number of segments which when in close contact can be inserted in the shell. These are then forced outwards in a crank or screw press by means of a tapered

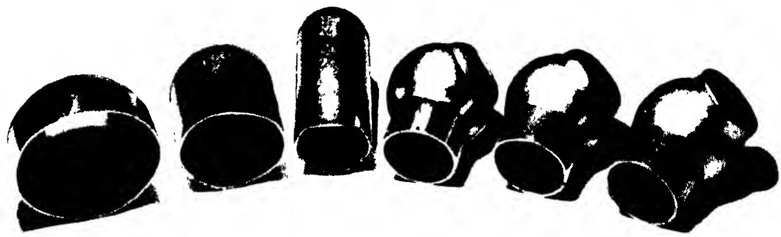
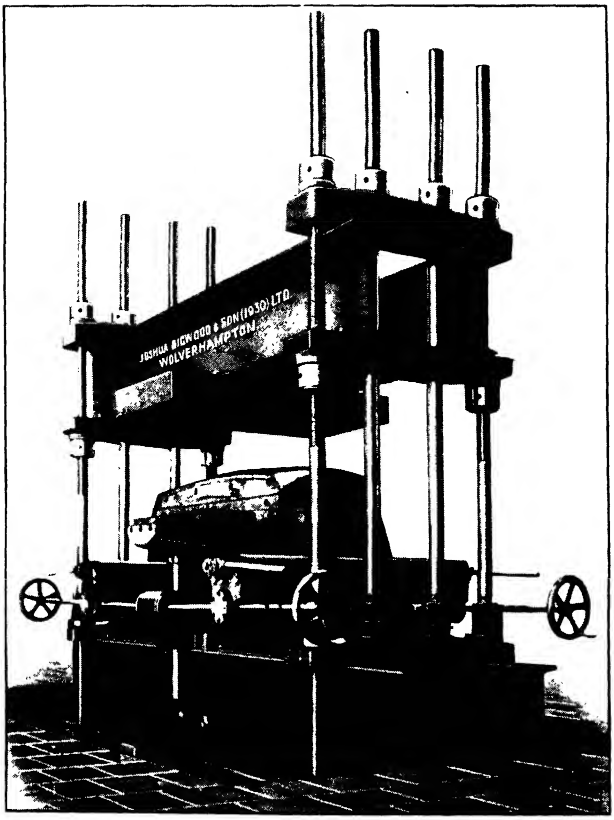


FIG. 294. Stages in the production of a small steel elbow by deep-drawing followed by bulging in a split die by means of a rubber punch.



[By courtesy of Joshua Bigwood & Sons Ltd.

FIG. 295. Hydraulically-actuated stretching press used for forming aircraft and 'bus panels from metal sheet.

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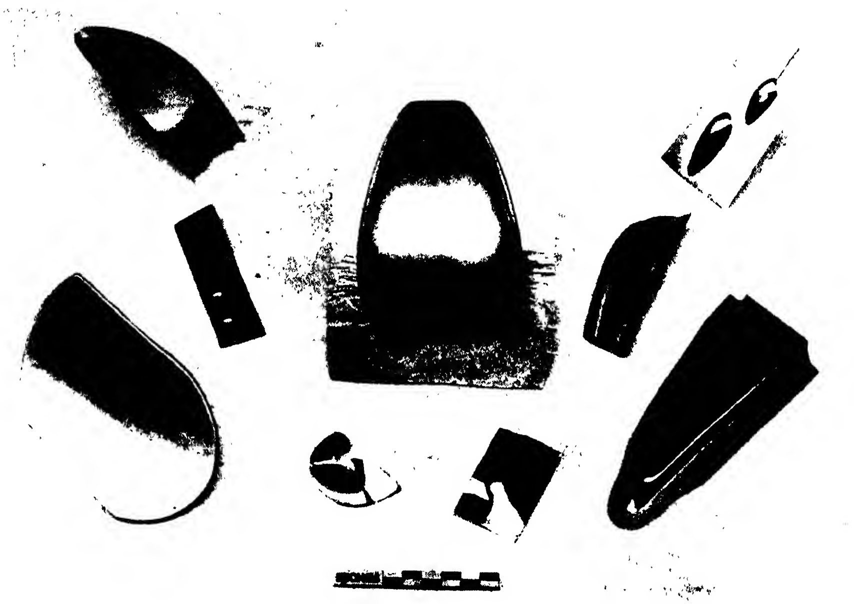


[*By courtesy of General Aircraft Ltd.*

FIG. 296. Group of pressings formed from aluminium sheet under a drop-stamp using cast zinc tools.

[*By courtesy of the Hawker Aircraft Co. Ltd.*

FIG. 297. Three pairs of cast "soft metal" tools mounted on pneumatically-actuated (Cecostamp) drop-stamp producing aircraft panels from aluminium sheet.

[*To face p.* 613.

cone, wedges, cams or toggles, afterwards being contracted to allow the tool to be withdrawn through the neck of the expanded shell. The drawback to tools of this kind is that often they are expensive, and that when the shape is circular they tend to produce a series of ridges on the expanded shell; for example, an eight-segment tool tends to produce an octagon instead of a smooth circle.

"Blowing" is a term used to describe processes in which the walls of a deep-drawn shell are forced outwards by means of oil or water forced into its interior. This method is a very useful one, and the fact that it is not used more widely must be attributed to the difficulty of making a pressure-tight joint between the rim of the shell and the pressure-system, and the mess associated with the escape of oil or water at the end of the operation. An interesting extension of this method is one wherein a shell is not merely expanded in diameter, but actually increased in length, not always in a straight line, to form a taper. It is remarkable what shapes can be produced in this way provided that the original shell has no zones of thinning produced by poor deep drawing and that the metal is of good quality, of a suitable "average grain size," and properly annealed. Tapered vessels as well as curved and tapered ducts of most awkward shape can be made in this way far more cheaply than by hand-fashioning. Articles made thus have the advantage that they are seamless and, because they are made in a die, are of identical size and shape. Dies cast to shape in either zinc or "white brass" are often used for this purpose.

Stretching. A shaping process for sheet metal, more particularly for light-alloy sheet, which is rapidly achieving popularity is that known as "stretching." This process has as its object the rapid production in a press of shaped panels, cowls or fairings—often of large size for use in aircraft or commercial vehicles—which would otherwise have to be slowly beaten to shape by skilled panel-beaters. Apart from the saving in time and labour charges, the stretched shape is free from hammer marks and does not need smoothing or filling prior to being painted.

Stretching differs from pressing—the operation by which steel panels for automobiles are formed—in that the outer regions of the sheet are not allowed to flow, even under the restrictive action of a pressure-plate. Instead, the edges of the sheet are gripped in long, fixed jaws, and a tool having a suitable profile is forced against the sheet, thus causing it to assume the desired shape. Usually only two sides of a sheet are gripped; but for certain purposes all four sides of a rectangular sheet may be held or, again, the periphery of a shaped blank may be gripped between suitable clamping plates.

Fig. 295 shows a type of hydraulic press which has been developed primarily for "stretching" light-alloy sheets into panels for aircraft and buses. Two sides of a sheet are held in the lever-locking gripping-heads seen on either side of the main table, and the table, which supports the forming block, is raised by means of an hydraulic ram, thus pushing the forming block into the sheet and stretching the sheet so that it assumes the desired shape. When the top part of the structure is used, large sheets can be pressed between a punch and die instead of being simply stretched over a single forming profile.

The machine illustrated is designed to meet the needs of manufacturers having an output insufficiently large to justify the expense of laying down the very large press which would be required to carry tools of the size often needed. When large outputs can be guaranteed, huge presses—usually of fluid-pressure type—having a rated capacity of up to 5,000 tons are being installed on an increasing scale to meet the demands of the aircraft industry.

Wooden tools, which are light, cheap and easily shaped, often prove to be sufficiently durable for fairly lengthy production runs on light-alloy sheet. This fact enhances the value of the stretching process itself, particularly when panels of large size have to be made or when the output is too small to justify the cost of large, expensive metal tools.

It should be observed that the physical properties needed to ensure good behaviour during stretching are not necessarily quite the same as those needed for true deep drawing or pressing. A rather larger crystal size often seems desirable, and sheet of greater hardness can frequently be used; yet the precise metallurgical requirements of sheet destined to withstand stretching operations need to be established more precisely.

Combined Pressing and Stamping. In a previous chapter it was said that " puckers " in aluminium and aluminium-alloy pressings are often obliterated by means of a punch and die mounted in a drop-stamp, and that sometimes this device is used to sharpen up the contours of a finished shape by what amounts to a " coining " blow. These methods have been in use for some time, but the recent very large increase in the demand for aircraft pressings, often in relatively small numbers yet of awkward shape, has led to the development of an entirely new technique—to which no proper name has yet been given—for shaping sheet metal under a special kind of drop-stamp. Fig. 296 shows a group of typical parts formed in this way from aluminium sheet. Those shown are of relatively small size, but much larger articles are produced; indeed the size is limited only by the size of the drop-stamp available.

In this new technique, which is illustrated in Fig. 297, a blank is placed under the tools and " persuaded " to shape in easy stages by gentle blows or by gentle squeezes. Usually this leads to the formation of puckers, and it is common practice to hammer these out by hand at frequent intervals in order to prevent the formation of closed folds which would ruin the article even though it were ultimately given the desired shape. Various devices, such as small blocks of wood or rubber, or dabs of lubricant applied in certain places, are often used to secure the desired flow, particularly in the earlier stages of shaping. Finally one or more heavy blows are generally given to " size " the article and to smooth out all traces of puckers. " Soft metal " tools (see p. 402) cast to shape are nearly always used, the die being of zinc or zinc alloy and the punch of the same metal or, sometimes, of antimonial lead.

A characteristic of the process is that shapes which otherwise would be difficult to form can quite often be made easily, and with a considerable saving in discard, by making a symmetrical pressing and then cutting it along the centre line to give two of the desired articles. For example, either the large central pressing or the bottom-right-hand pressing in Fig. 296 could be cut lengthways along its centre line.

It is a mistake to be niggardly with the discard which has to be trimmed off the wanted part of most pressings. Tools should be designed to give a pressing of ample depth so that the top part, which is likely to contain incompletely obliterated wrinkles or puckers, can be trimmed off leaving a smooth surface on the actual article. Wrinkling and puckering can generally be lessened by using shaped blanks instead of rectangular, circular or oval ones having only limited resemblance to the outline of the die or of the article to be produced. It need hardly be said that the best shape for the blank is not necessarily that of the die or the shaped article : variations in the inward flow of metal must always be taken into consideration.

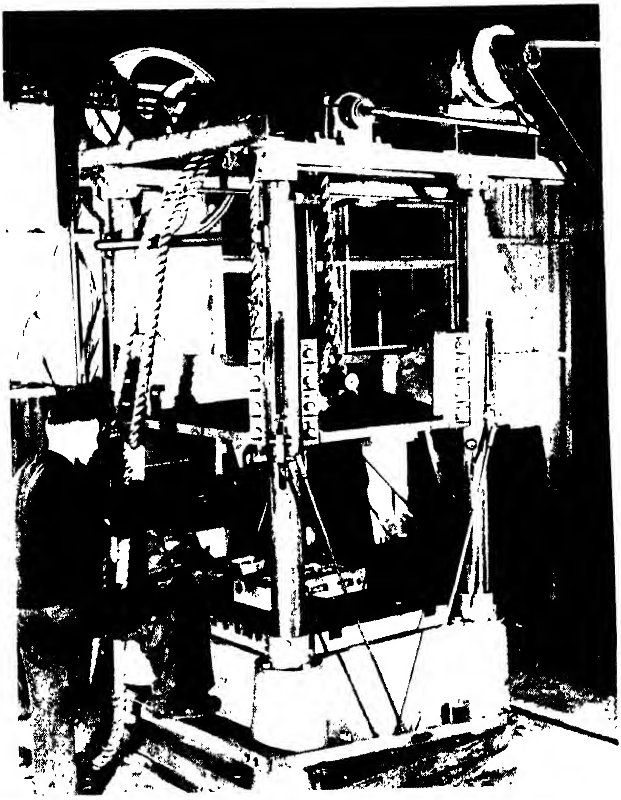
Operators accustomed to make pressings at one stroke of a machine commonly criticise this new technique on the ground that, compared with orthodox methods, it is very slow and that the need for the repeated smoothing-out of puckers by hand is deplorable. This criticism is easily met by showing that, using the methods just described, pressings can be made many times more quickly than by the old method of hand-beating and, moreover, that a number can be made to exactly the same size and shape. The method should not, of course, be compared with orthodox pressing, for that cannot be considered for the production of small numbers of large-sized articles on account of the prohibitive cost of the tools and, often, of the time needed to make such tools. It is not unlikely that the technique may soon be improved so that puckering, and hence the need for hand rectification, may be greatly reduced. Two methods which are already being experimented with are the use of a pressure-plate which restricts the flow of the blank by means of a groove mating with a rubber pad ; and, either with or without this device, the use of more than one set of dies so that a shape can be " coined " in one or more intermediate stages.

A variation of the method just described makes use of a pile of distance-pieces to enable a pressing to be made in a series of predetermined steps instead of in steps determined by the skill of the operator and the sensitivity of the particular drop-stamp used. The purpose of these pieces, which rest on the top of the die and are removed one or more at a time after each blow, is to limit the fall of the punch through the die. They are usually made of plywood with a thin bottom-plate of steel or Duralumin to make contact with the blank. Fig. 298 illustrates the use of distance-pieces in the forming of a pressing from aluminium sheet under a drop-stamp.

The new technique is usually applied by means of a drop-stamp worked either by rope and friction-drum or by a cylinder and piston, actuated by compressed air. Rope-actuated drop-stamps are made specially for this process, and a typical stamp of medium size is shown in Fig. 298. Such stamps have the advantage of being cheap to buy and to run, but they are tiring to operate continuously ; this is a matter of some importance when the success of the process depends upon the niceness with which the operator can control the force and, of even more importance when distance-pieces are not used, the travel of the tup. Another kind of special drop-stamp is the electrically-actuated machine illustrated in Fig. 299. This follows the principle of the common drop-stamp, but the tup is raised by means of two electric motors and has sensitive brakes to enable its movement to be controlled with precision.

An air-actuated drop-stamp of fairly large size is illustrated in Fig. 297 In this stamp the tup, having an 8′ × 4′ plate, slides between two guides and is attached by a rod to a piston working in a cylinder at the top of the frame. By means of a valve in the compressed-air line very accurate and sensitive control over the movement of the tup can be exercised by a skilled operator, and without fatigue to himself. When the piston is double-acting this kind of stamp has the advantage that a powerful squeeze can be given by the tools, whereas in other kinds the severity of the squeeze depends upon the weight of the tup and its attached punch ; indeed, this type approaches the ideal to be aimed at. Any stamp designed for the special process now under consideration should give, at one extreme, a full blow using the full weight and travel of the tup ; at the other, a squeeze devoid of impact yet of any desired pressure within the capacity of the stamp, and, between these extremes, blows or squeezes of any desired nature, coupled with an accurate control of tup-travel.

At first the drop-stamp technique was confined to the shaping of aluminium and light-alloy sheet, but it is now used on thin sheet of much harder metals with complete success. For example, aircraft-engine exhaust-manifolds are shaped from Inconel sheet, and a variety of parts are made from austenitic steel sheet. Because this method shows a great saving both in the cost of tools and in the time taken to



[*By courtesy of General Aircraft Ltd.*

FIG. 298. *Top :* Rope-actuated drop-stamp producing pressings from aluminium sheet by a series of blows between cast zinc tools.

Below : Stack of plywood distance-pieces placed on die to limit the travel of the tup.

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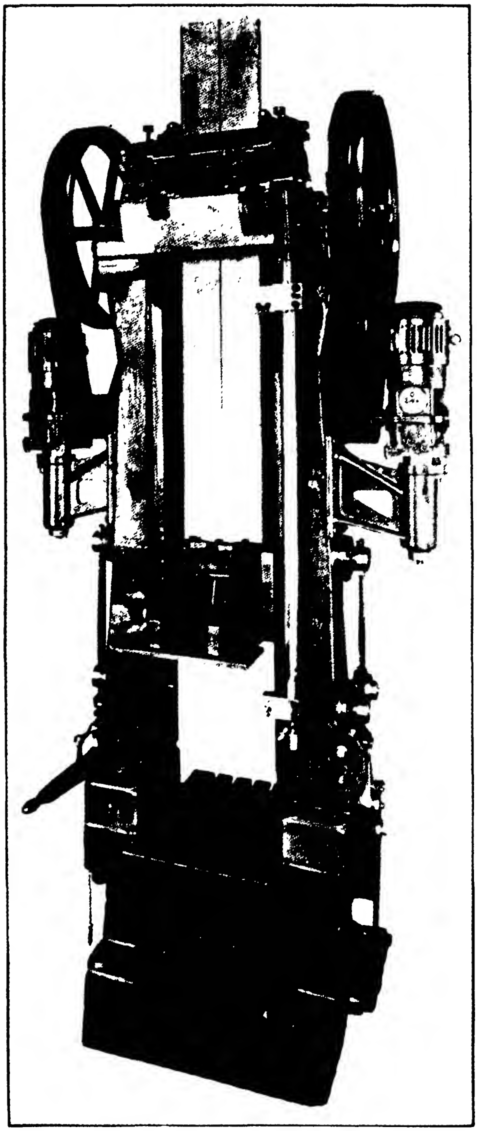


[*Emrich press, reproduced by courtesy of E. H. Jones (Machine Tools) Ltd.*

FIG. 299. Electrically-actuated drop-stamp to give controlled blow suitable for working sheet metal between dies.

[*To face p.* 617.

make them, it is safe to predict that it will be used to shape all kinds of sheet metal into articles hitherto made by ordinary deep-pressing.

The Guerin Process. The use of rubber as the opposite member to a " soft metal " tool, either as a punch or a die, is described in other chapters, but special mention must be made here of the Guerin process. This was devised originally for making shallow pressings from light-alloy sheet for the aircraft industry, but its application is likely to be

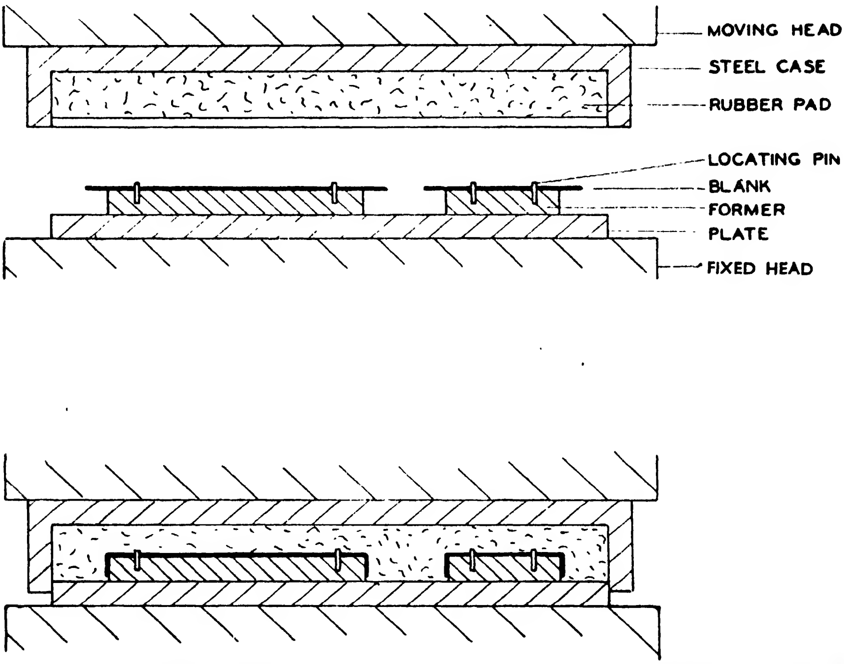


Fig. 301. Diagrams illustrating the principle of the Guerin process for making shallow pressings by means of a rubber pad.

Top : Press open; blanks, located by pins, in position on formers.
Below : Press closed; compressed rubber forces blanks on to, and round, formers.

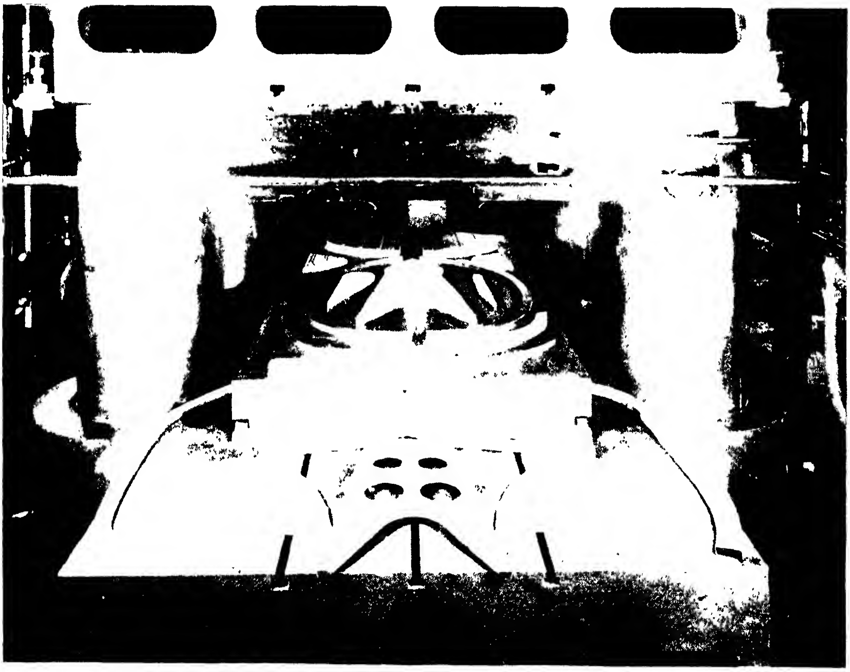
extended. It is particularly suitable for making shallow flanged pressings such as those shown in Fig. 300.

The principle of the process is illustrated diagrammatically in Fig. 301, from which it will be seen that a large, thick, rubber pad confined in a strong steel box is used to force sheet or blanks on to and down the sides of formers or punches placed on, but not attached to, a flat table mounted on the bed of the press. It should be observed that the sides of the box extend below the level of the pad and fit closely over the table on the bed of the press so that the rubber is prevented from flowing out of the box and is made to exert pressure on the tops and sides of the formers placed on the table. Very high pressures are needed when the area of metal to be flanged is considerable, and it is common practice to use large hydraulically-actuated presses of from 3,000 to 5,000 tons nominal capacity, such as the one illustrated in Fig. 198 (p. 348). The process is now so well established that large presses having a rubber pad as a permanent fixture on the movable head are available. Two such presses are illustrated in Fig. 198 (p. 348) and Fig. 302 (p. 619). Arrangements are sometimes made to heat the rubber pad by electric heaters or steam pipes as shown in Fig. 300, so that in the event of damage it can be repaired by vulcanising *in situ*.

When blanks are rested on formers without any means for keeping them in position, there is a tendency for the action of the rubber pad to displace them somewhat. This can be avoided by drilling two or more small holes in the blank, which fit over short pins projecting from the upper face of the former, and thus prevent sideways movement of the blank relative to the former even though the former moves slightly on the base plate, as it is free to do. Both holes and pins can be seen in the pressings illustrated in Fig. 300. Because quite often holes are not wanted in the finished pressing, there is a temptation to make the pins so small in diameter that they soon become bent. As a general rule $\frac{3}{16}$ inch is the minimum diameter which will give satisfactory service.

The formers used in this process are made from a variety of materials and choice is influenced by the kind of sheet to be shaped, the severity of the operation, the size and shape of the part and the facilities which are available for cutting formers to shape. For aluminium and light-alloys, formers cut from a thick sheet of rolled zinc are a popular choice, but for formers of small and medium size compressed fibre—a material sold under a variety of trade names—is often used. For long runs on hard sheet such as austenitic steel, boiler-plate is usually preferable to zinc. This may be flame-cut to shape and hand-finished, and sometimes it is an advantage to flame-harden the working edge and even to cyanide-harden the entire former.

When small pressings have to be made on a large press, a number of formers can be arranged so that the full area of the pad is used at each stroke, as illustrated in Fig. 300. Even then the press will be standing idle for long periods between each stroke while formed pressings are removed, formers rearranged and fresh blanks placed in position ; and a considerable increase in the output of any press can be obtained by the use of up to four plates in the manner shown in Fig. 302. These plates are mounted on rollers to enable them to be run in and out of position under the press so that while one is in position the others are being either loaded or unloaded. When the plates are large it is an advantage for them to be operated by electric or hydraulic means rather than moved slowly by hand.



[*By courtesy of Fielding and Platt Ltd.*

FIG. 300. Group of pressings formed from light-alloy sheet by the Guerin process. Observe steam pipes in movable head of press to vulcanise the large rubber pad *in situ*.

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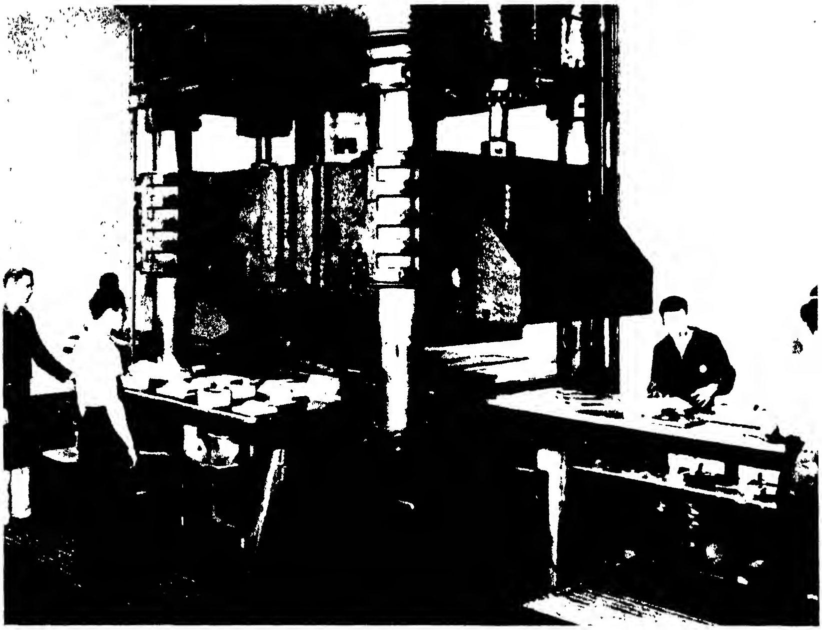

[*By courtesy of A. C. Wickman Ltd.*

FIG. 302. Large hydraulically-actuated press, equipped with four tables mounted on rollers, forming pressings from light-alloy sheet by the Guerin process.

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By means of a suitable arrangement of heaters either in or under movable plates of this kind, the formers used to shape magnesium-alloy sheet can be heated to the desired temperature without being removed from the plate, thus saving time and avoiding the heat-loss which occurs while formers heated in an oven are transferred to the plate and loaded with blanks. When hot-pressing has to be done it is best to use a pad of special heat-resisting rubber ; when, owing to a limited

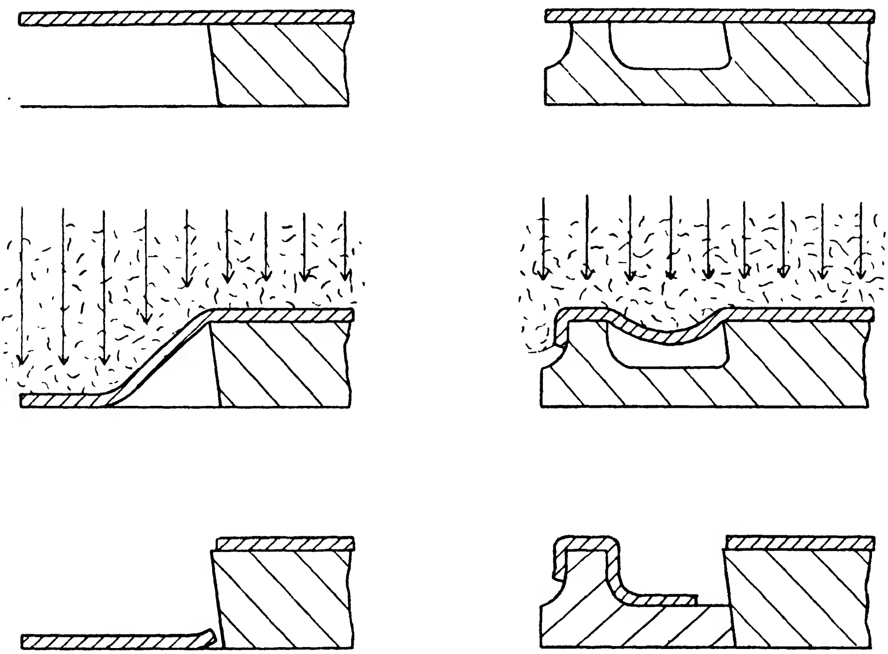


FIG. 303. Diagrams illustrating principle of the Guerin process for blanking by means of a rubber pad.

Left: Simple blanking tool; blank periphery gripped against base-plate.
Right: Blanking tool having an outer ring on which the blank periphery is gripped. (The bottom-right diagram shows an alternative method of construction using a separate outer ring).

use of this process, such a pad is not available, it is a good plan to protect the ordinary pad by a sheet of rubber cemented temporarily to it whenever hot-pressing has to be done.

So far only pressing has been described, but the Guerin process can also be used for blanking ; and in some instances, when the depth of the flange is shallow, the two processes can be combined. A good example of this is seen in aircraft parts in which holes are blanked to lighten the member and, at the same time, the edges of the holes are bent over to give increased rigidity. The mechanism of blanking by means of a rubber pad is quite different from that of blanking in a pair of sharp-edged metal tools, for the sheet is broken by the action of tensile stress and not, as with edge-tools, by a shearing action. The process is illustrated diagrammatically in Fig. 303, from which it will be seen that the blank must extend beyond the line along which it is to be cut for a sufficient distance to enable the rubber to grip it by forcing it against the base-plate.

For light-alloy sheet zinc-alloy tools often have a useful life, but

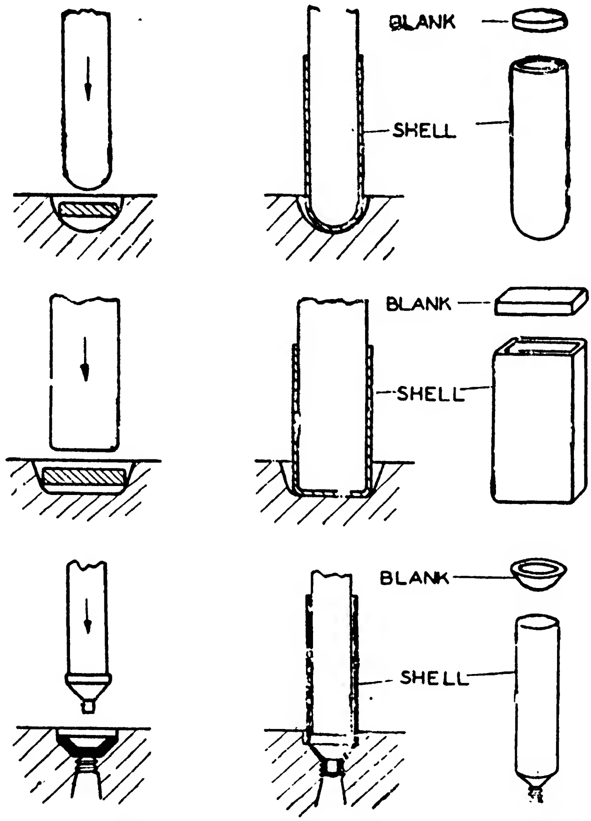


FIG. 304. Diagram illustrating various applications of impact-extrusion process for forming thick blanks into thin-walled shells at one operation.

Top : A hemispherical-ended cylindrical shell.
Centre : A flat-bottom shell of rectangular shape.
Bottom : A collapsible tube with threaded projection.

sometimes it is necessary to attach a steel facing to the cutting edge or to use solid steel tools. For harder sheet hardened steel tools may have to be used. When the tools are of zinc alloy it is sometimes convenient to make them with a depression and surrounding lip against which the sheet can be gripped, as shown in the bottom-right diagram of Fig. 303. In all cases a rake of about 6 degrees should be given to the cutting edge.

Useful as the Guerin process is, it is important to realise that it has its limitations and that if it is applied indiscriminately satisfactory results will not always be achieved. It is best adapted for forming shallow flanged parts of the kind already illustrated and for making shallow depressions such as are used to give increased rigidity to flat panels ; but in its original form it is *not* suitable for making pressings of appreciable depth. The main reason for this is that the depth of the impressions which can be raised is limited by the amount of deformation which the rubber will withstand, and hence to some extent by the thickness of the pad. Sometimes it is possible to increase the depth of impressions formed by the pad by the insertion of strips or blocks of rubber, or even by filling depressions with water, and then giving another stroke of the press. When considering the application of the Guerin process to blanking, it must not be forgotten that very heavy pressures are often needed and that, for reasons already explained, a wide " surround " must always be allowed.

Impact-extrusion. Impact-extrusion is a process which, developed originally for the making of collapsible tubes or capsules such as are used to contain toilet preparations, is rapidly finding increasing application both as regards the metals used and the size and nature of the shapes produced.

The principle of the process is illustrated diagramatically in Fig. 304. A thick blank or slug is placed in a die of suitable shape, and a punch, having a shape corresponding to that of the inside of the article it is desired to produce, is forced at high velocity to a predetermined depth into the metal. This operation causes the metal to flow up the sides of the punch in the manner shown, with the result that a deep, thin-walled shell is formed in a single operation, whereas a considerable number of draws, and probably several inter-stage annealing treatments, would be needed to produce the same shell by ordinary methods of deep drawing.

In addition to accomplishing at a single blow an amount of plastic deformation equivalent to that produced by a large number of ordinary deep-drawing operations, the process of impact-extrusion makes it possible to form many shapes which cannot be produced by ordinary deep-drawing methods, no matter how many operations are used. One of the chief advantages centres round the base of the shape, which can be made as thick as desired relative to the thickness of the walls and may have some special contour which incorporates projections or marked changes in section, as in the instance of the end of the collapsible tube shown at the bottom of Fig. 304. In the softer metals, such as tin, lead and sometimes zinc, it is possible to form an external screw thread on a projection in the manner indicated in the diagram, but this additional economy is not always possible with harder metals. Because of the high pressures to which the tools are subjected it is usual to make the female die which carries the thread impression solid, even though this entails unscrewing each article produced, rather than to split the die diametrically through the impression so that the two halves can be separated to permit the rapid withdrawal of the threaded tip of the extruded article.

Another very useful attribute is the ease with which deep, thin-

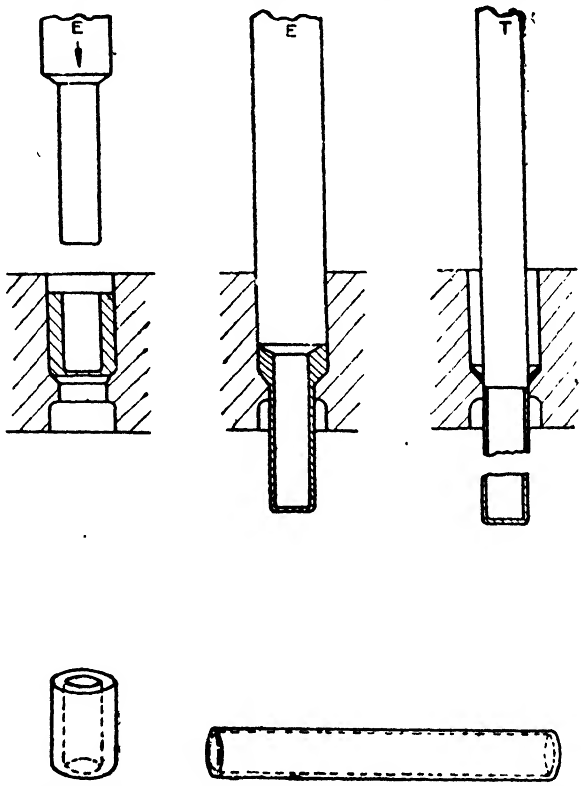
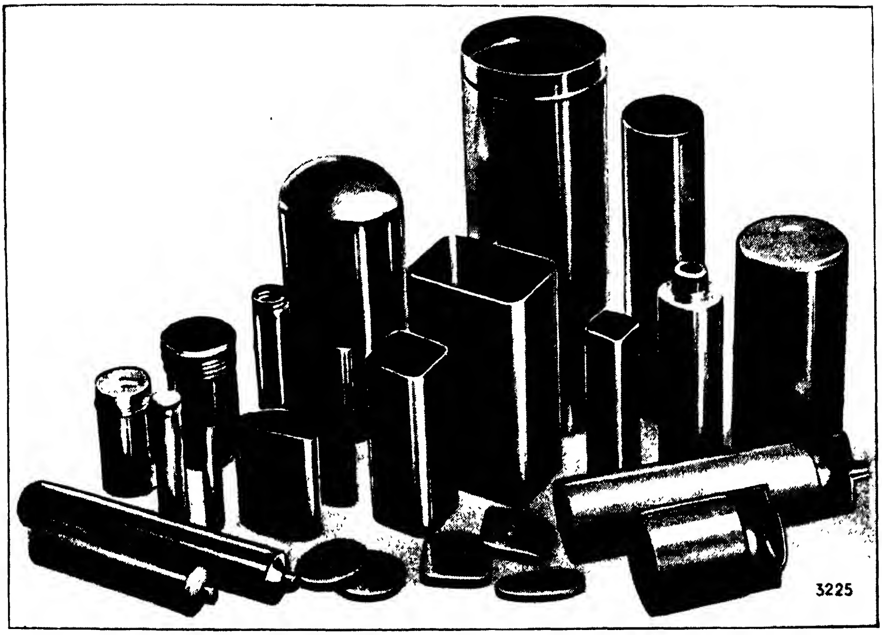


FIG. 305. Diagram illustrating the Hooker process for impact-extruding a thick-walled cup (*bottom, left*) into a deep shell (*bottom, right*).

Top, left: Cup inserted in die below extrusion punch E.
Top, centre: Punch E near the end of its stroke.
Top, right: Extrusion punch E withdrawn, trimming punch T has severed shell from residue and is about to push the shell clear of the die.

walled shells of *rectangular* section can be formed. Owing to the uneven flow of metal leading to alternate thinning and "crowding," the drawing of deep rectangular shells is always difficult, particularly when the corner radius is small; and the process of impact-extrusion thus renders available shapes—such as certain square cases used in the telephone industry—which could not otherwise be produced at a low cost.

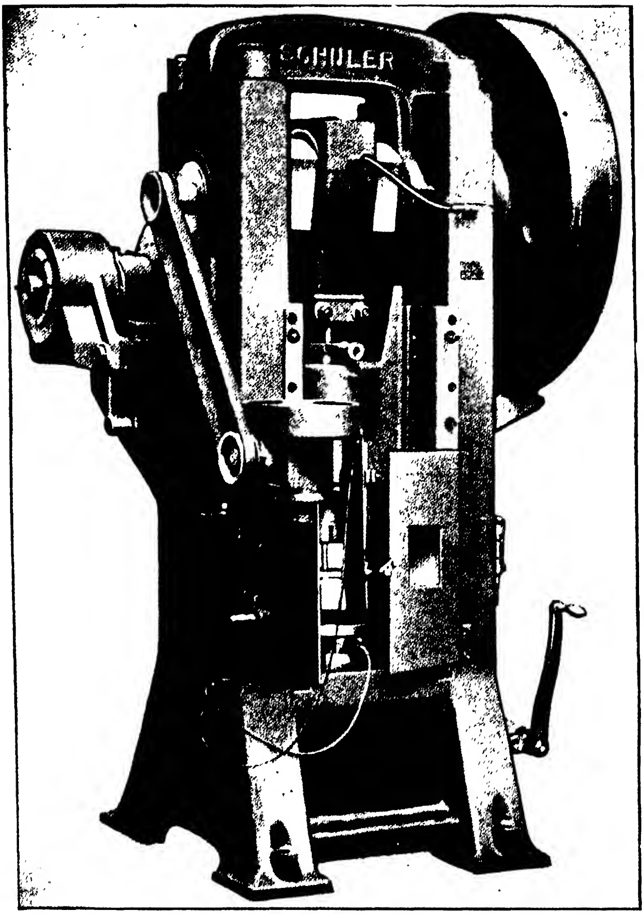
In the majority of impact-extrusion processes a flat or dished blank is shaped by a single blow in tools of the kind already illustrated, but a double process known as the Hooker (patented) process is sometimes



[*By courtesy of A. C. Wickman Ltd. and L. Schuler, A.G.*

FIG. 306. Group of articles produced by impact-extrusion in one operation from blanks such as those seen in the foreground.

[*To face p.* 622.



[*By courtesy of A. C. Wickman Ltd. and L. Schuler, A.G,*

FIG. 308. Impact-extrusion press with automatic feed.

[*To face p.* 623.

used for tube-extrusion because it enables a deeper shell to be produced with less power and, consequently, less wear on the tools. In this process, illustrated diagrammatically in Fig. 305, a thick-walled cup, which is usually annealed after having been formed, is placed in tools which resemble in some respects those used in ordinary hot-extrusion processes, and extruded in the manner indicated. The first punch is then withdrawn, the die swung beneath a trimming punch, and the shell severed from the small residue, leaving a cleanly-cut top periphery. This process seems to be favoured more for copper, brass and aluminium than for the softer metals.

The field of application of impact-extruded products is, naturally, extended when the shape formed by impact-extrusion is subsequently made still deeper by ordinary deep-drawing operations, a procedure which incidentally imparts greater dimensional accuracy to the final product. It is likely that, by reason of the considerable saving in cost effected, impact-extrusion will be used to an increasing extent as a first operation in a sequence of deep-drawing operations.

Some idea of the usefulness of the process in its simplest, or unsupplemented, form can be gained from a study of the group of impact-extruded articles shown in Fig. 306 in which are included some of the punched blanks which are fed to the extrusion tools. Emphasis must be placed on the fact that, excluding such additions as impressed grooves or screw threads at the top edges of containers, the shapes shown have been formed in one operation.

Metals, such as lead, which do not strain-harden appreciably cannot be deep-drawn, because localised necking leading to fracture occurs before any extensive deformation can be imposed ; they can, however, be formed into the equivalent of deep-drawn shapes very readily indeed by the impact-extrusion process. On the other hand, metals such as zinc and aluminium which, although they can be deep-drawn or pressed successfully, present certain difficulties when manipulated by ordinary press-shop methods, do not exhibit these hindrances when impact-extruded. Metals such as copper and *alpha* brass, which can be deep-drawn very readily, can often be shaped by impact-extrusion more cheaply than by the older processes.

Varieties of Metals. Increasing attention is being paid to the impact-extrusion of metals other than the obviously ductile ones—such as lead, tin and zinc—to which it was first applied. A large variety of shapes is produced in aluminium by this process, and aluminium alloys having considerably greater strength than the pure metal are now being successfully shaped on an industrial scale. With aluminium and its alloys, it is found that heating the blanks to about 200° to 230° C. is of great benefit both in increasing the depth of shell which can be produced by the impact-extrusion process and also in reducing the pressure needed to form a given shape. For example it has been shown [119] that, in the case of pure aluminium, heating blanks to 200° C. reduced the force needed in a certain operation by no less than 60 per cent. A shell of greater depth can be impact extruded when, instead of a flat blank, one shaped to a shallow flat-bottomed cup with sides at 45 degrees is used. These dished blanks should be annealed before the actual impact-extrusion operation, and, in the opinion of some authorities, it is well worth while to polish the sheared edges. Many of the articles shown in Fig. 306 (p. 622) are of aluminium.

A wide and useful field of application for impact-extruded parts must lie in the aircraft industry. For example, short tubes with lugs or eyelets on the closed end, such as the article illustrated in Fig. 307, could be produced very cheaply in one operation in soft, solution-treated aluminium alloys of suitable composition which could then be heat-treated to give a high tensile strength.

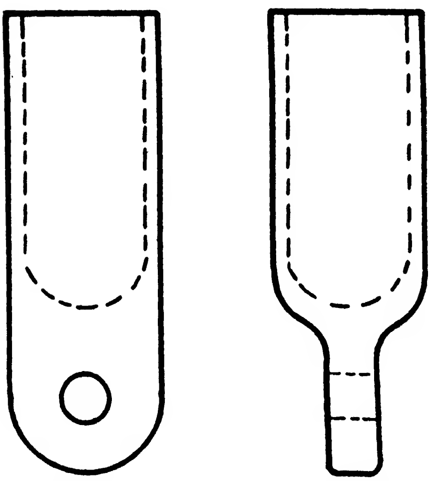


FIG. 307. Typical part suggested for production by impact-extrusion process from blank of heat-treatable aluminium alloy.

Copper has, of course, been shaped by impact-extrusion processes for some time, and the low rate of work-hardening of this metal enables very deep shells to be produced without undue wear on the tools or, curiously, a high degree of work-hardening in the walls of the product. Advantage of this is taken in the making of copper tubes. Thus, starting with a flat blank, what is virtually a tube of a depth equal to many times the diameter can be produced in one quick and inexpensive preliminary operation, and, of importance, the metal still remains sufficiently ductile to withstand several subsequent draws before annealing becomes necessary.

Alpha brasses are now being impact-extruded in the cold, or warmed to a relatively low temperature, into deep thin-walled shells. This process is finding increasing favour as a first operation in the production of deep-drawn tubes, for shallower draws—corresponding to those associated with the manufacture of small arms ammunition cartridge cases—and, in particular, for the production of shells of rectangular shape. Each of these applications is likely to increase owing to the saving in production costs which it can bring.

Of the other common metals, the use of tin, lead and zinc is too well known to need special mention, although it may be observed that with zinc deeper shells can be produced when the blank is heated to about 150° C. Attempts to impact-extrude steel in the cold have not yet proved successful, yet it would be foolish to dismiss ferrous metals as entirely unsuitable for shaping by this process, because the advent of stronger and more durable tool materials might enable a useful amount of flow to be obtained under industrial conditions.

In order to obtain really deep shapes by impact-extrusion it is essential that the majority of the metals used be in the purest possible state obtainable commercially. Copper should be of at least 99·90 per cent. purity, and preferably produced by electrolytic methods; aluminium, unless purposely alloyed, behaves best when of high purity; zinc should be of the well-known 99·99 per cent. purity variety; while *alpha* brasses, which are usually of 70 to 75 per cent. copper variety, should contain as small a proportion of impurities as possible.

Blanks for impact-extrusion are usually punched from flat sheet of suitable thickness, but a number of attempts have been made to substitute die-cast slugs, thus saving the cost of rolling large ingots into the form of sheet or strip, punching blanks and disposing of the perforated scrap. With zinc this procedure has actually been used, but with aluminium and brass it can as yet hardly be described as being established industrially. It is particularly necessary that the tools used for blanking should be sharp and well set if it is desired to impact-extrude deep shells. With aluminium the benefit of actually polishing the edges of sheared blanks is well proved, and it is possible that this benefit may be worth seeking with other metals.

Theoretical Considerations. The theoretical explanation of the process of impact-extrusion has not, as far as the author is aware, received much scientific study; but it is quite certain that one of the essential factors in the process is the high speed of deformation used. Evidence gained from high-speed tensile tests suggests that the effects of work-hardening take a small but appreciable time to manifest themselves, and it is probably this fact which, although undiscovered when impact-extrusion was first developed by practical trial, accounts in some measure for the really remarkable results which are achieved by this process.

Another factor which is held by some authorities to be of considerable importance is the high temperature which is attained by the metal as it flows. Foisy [120] states that copper tubes produced by impact-extrusion are in at least a partially-annealed state when removed from the tools; and, with metals having a greater rate of strain-hardening and a higher temperature of recrystallisation, it seems certain that this rise in temperature greatly facilitates the desired flow. So much heat is produced that, in automatic presses operating at a high speed, the tools have to be cooled with a copious supply of lubricant. Because of its very low temperature of recrystallisation, zinc emerges in a completely annealed condition; indeed, it is sometimes difficult to avoid excessive crystal growth. Owing to these, and perhaps other, causes it is definitely established that the power needed to form a given shape by impact-extrusion is appreciably less than that shown by theoretical calculation to be necessary with metals behaving normally as in deep drawing or in slow extrusion.

It is only natural that the process possesses some disadvantages, and one of these is the rapid wear of the tools which occurs when the harder metals, such as aluminium alloys and brass, are being extruded. By the use of modern alloy tool steels a useful life can, however, be obtained; in some instances chromium-plating and, with certain types of tools, nitriding has proved of considerable benefit.

Presses. It is obvious that presses for impact-extrusion operations need to be very robust. For this reason frames reinforced by steel tie-bars are often used, and motion is often imparted to the punch by means of an eccentric, instead of by a crank, in order to strengthen the main shaft without increasing its size to undesirably clumsy proportions.

Fig. 308 shows a typical impact-extrusion press—in this instance crank-actuated—equipped with self-contained motor drive, tie-bar frame and automatic feed for the pellets or cups, which is capable of an output of up to 4,000 articles per hour. After stripping, the shells are blown from the press by a blast of compressed air. A feature of this press is its clean design and compactness, attributes which are all the more striking when it is appreciated that this single unit can in many instances do the work of a row of deep-drawing presses of equal size assisted by an inter-stage annealing furnace and, should clean-annealing be taken advantage of, its attached gas plant.

Some impact-extrusion presses have a special mechanical motion which causes the punch to descend to the blank, either touching it or pressing into it to a predetermined depth for a brief but definite "dwell," and then to descend rapidly for the proper working portion of the stroke. Some authorities contend that this special action is of considerable benefit and, furthermore, that the speed of the working part of the stroke exercises a marked influence on the depth of the shell which can be extruded. This claim is held to be exaggerated by other authorities who, it must be admitted, manage to produce deep shells in direct-action crank presses; yet, considered from the theoretical aspect, it seems likely to be well founded. Proper investigation is needed to clear up this debatable point.

Lubricants. The choice of lubricant is important, yet little published literature on this subject is available. Vaseline often proves to be an excellent lubricant for the impact-extrusion of zinc and also of aluminium and its alloys, even when the blanks are warmed. This is interesting because it suggests that the properties of a lubricant which are of special importance in deep-drawing operations may not be the ones of greatest importance for impact-extrusion. For example, owing to the speed at which the metal flows, high fluidity is probably essential; yet, although extremely high resistance to breakdown under high temperature and pressure may be desirable at the bottom radius of the punch, it is likely that a comparatively low film strength may suffice on other regions of the punch surface because, in practice, it is found that a certain small yet definite clearance tends to occur between the walls of the extruded shell and the punch even when the latter has parallel sides and does not, as is often the case, carry a slightly enlarged head or "land" at its lower end.

To summarise, it seems likely that the process of impact-extrusion will be used to an increasing extent for at least four reasons :—

(1) Certain shapes can be made in one operation which would need a number of operations—and consequently a number of presses, operators and probably inter-stage annealing furnaces—when produced from a sheet-metal blank by ordinary deep-drawing methods. This reduces production costs very greatly.

(2) Certain shapes—for example the deep, thin-walled square shells shown in Fig. 306 (p. 622)—which would be difficult or even impossible to form by deep drawing can be produced easily in one operation.

(3) Certain metals which it is impossible, or perhaps difficult, to deep-draw can be formed readily into deep, thin-walled shells. It would, for example, be very difficult to deep-draw many of the articles shown in Fig. 306 from zinc or aluminium sheet.

(4) The base of the shell can, when so desired, be left very thick and also shaped to any desired profile—see Fig. 304 (p. 620) and Fig. 305 (p. 622)—a feat which cannot be accomplished by ordinary deep-drawing methods.

So far the process of impact-extrusion has not been studied from the scientific aspect with a thoroughness comparable to that devoted to deep drawing and pressing, its older companions. Continued investigation of tool shapes, tool materials, together with the impact-extrusion properties of various metals at different temperatures and speeds, will undoubtedly render possible the regular production of still more difficult shapes.

CHAPTER XVI

DESIRED IMPROVEMENTS IN METAL

In the preceding pages an attempt has been made to collect, classify and discuss available knowledge concerning the properties of sheet metal, its behaviour during deep drawing and pressing operations, the tools, lubricants and presses used to perform these operations, and, in the last chapter, to indicate a number of new applications made possible by the development of new processes, new metals and a wider recognition of the advantages which deep drawn and pressed products can give in many fields. In this and the following chapter it is proposed to draw attention to some of the more urgently needed improvements in the sheet metal used in the press-shop ; to improvements in press-shop practice which are needed no less urgently ; to suggest ways in which both these improvements can be made ; to examine in greater detail certain matters which it was deemed advisable to postpone till this stage, such as the potential usefulness of X-rays in the examination of sheet metal, and, lastly, to show how necessary it has become to apply scientific knowledge and methods to the craft of deep drawing and pressing, and to suggest how the efforts of the scientist and the practical man can best be united for the ultimate benefit of industry.

Urgently needed improvements in the sheet metal used for deep drawing and pressing are : a reduction in the number and severity of defects which arise in the ingot ; the consistent attainment of a suitable and much more regular crystal structure ; the minimisation of directional properties, and the more complete suppression of certain harmful effects such as localised separation of *beta* phase in brass and the cause of ageing and stretcher-strain marking in steel. In addition, a better surface and greater regularity of thickness would be most welcome on sheet used for many purposes, particularly with steel.

Before discussing means whereby the desired improvements can be produced with particular reference to brass and steel sheet, general consideration of the four improvements just mentioned (which are applicable to both ferrous and non-ferrous metals) will be attempted in order to avoid repetition in the respective sections devoted to them.

Ingot Defects

It seems likely that the first-mentioned improvement, namely, a reduction in the number and severity of ingot defects such as surface blemishes, segregation of impurities, gas cavities and general unsoundness, will be brought about not so much by practical works findings as by research, in the true sense of the word, sponsored by large firms or by research associations. If these researches are, at least during their later stages, conducted in very close co-operation with industrial casting shops, improvement will be the more rapid ; for the application of valuable laboratory findings to works practice is frequently a slow and difficult process unless this close co-operation has been maintained. This statement is in no sense meant to imply that laboratory findings or theoretical considerations of what may at first sight appear to commerical producers to be of purely academic interest may not be of the utmost practical value ; it is meant, rather, to emphasise the need for the development of these findings in close co-operation with essentially practical, but preferably scientifically trained, works production men.

The criticism will certainly be made that highly commercialised research will not lead to a rapid increase in fundamental scientific knowledge. While this may be true, it must be borne in mind that such research will be paid for by essentially commercial firms who usually demand rapid and visible improvement in quality of product if not, as is too frequently demanded, economy in production in return for their outlay. For this reason it is to be hoped that the universities will continue to contribute researches of a nature which, though necessary for the increase of fundamental knowledge and therefore of ultimate practical benefit, may not at present attract the patronage of business organisations.

Melting and Casting. It is unsafe to predict what radical changes, if any, will take place in melting and casting. The benefit of electric furnace melting is recognised and is utilised for brass and certain other non-ferrous alloys ; for steel the cost of electric melting is at present prohibitive for the bulk of sheet and strip. Melting and casting *in vacuo* is, for the same reason, a dream of the future.

One method of increasing the soundness of ingots is that in which a carefully chosen gas—which is sometimes chemically active, for example chlorine, and sometimes inert, for example nitrogen—is bubbled through the molten metal for a short period before it is cast. The passing of chlorine through aluminium alloys is now a recognised practice, and it is possible that in the future other metals may be treated more often with a suitable gas, for the process is a very simple one and of real benefit in many instances.

Many attempts have been made to increase the soundness of ingots cast in ordinary moulds by subjecting the metal to the influence of vibration prior to, and sometimes during, solidification. Although improved soundness has been obtained in some instances, this scheme has not achieved extensive industrial application ; perhaps because of the extra trouble and plant it entails. Curious results, sometimes not of a desirable nature, have been recorded with vibrated ingots. For example, distinct strata of *beta* separation have been obtained in brass ingots, and zones containing cracks in all kinds of metals. In spite of these drawbacks, the process is one which seems to justify continued study and experiment.

Centrifugal casting has always attracted the attention of imaginative foundrymen. Usually the practical application of this process to ingots destined for rolling into sheet or strip takes the form of a machine capable of rotating a mould of ordinary shape at a high speed, and it is not surprising that such an application has met with little success. Centrifugal casting of cylindrical articles, for example gear blanks and cylinder liners, has on the other hand become a well-established practice capable of giving excellent results. Considerable importance must therefore be attached to a process in which a thin cylinder, often several feet in diameter, is cast centrifugally in the usual way, cut longitudinally and opened out into a thin flat sheet ready for finish rolling.

An interesting method of casting which eliminates the usual form of mould entirely is the Hazelett process. In this process molten metal is poured between rolls at a rate and temperature such that it becomes solid (but of course remains at a temperature only slightly below its melting point) before it descends to the narrowest part of the space between the rolls through which it is drawn by the normal action of rolling to emerge, solid, as hot-rolled sheet of any desired gauge. In theory this procedure seems capable of eliminating at one glorious sweep most of the serious defects associated with normal ingot casting, such as piping, slag inclusions, coarse columnar crystal growth, and even segregation; and also of reducing those directional properties which are inseparable from the reduction of thick ingots to thin sheet by repeated rolling. In practice the process will doubtless bring its own peculiar defects, but it is one which should be watched with keen interest by all and experimented with by those sheet producers who are in the fortunate position to be able to do so. If the practical difficulties associated with rapid deterioration of the roll surface—which is particularly serious with metals of high melting point—can be overcome, the process is one which may have a great future.

Electro-deposition of Sheet. A recent innovation which merits careful attention is the production, on an industrial scale, of large-sized metal sheets by electro-deposition on the peripheral surface of large drums from which the sheets are stripped when the desired thickness is reached. From the aspect of deep drawing and pressing, sheet produced by this method will possess two important differences from sheet produced by normal methods: casting defects, including segregation, will be absent, and, secondly, the orientation of the crystals—

a matter which as far as the author is aware has not yet been investigated—will be quite different from that of the crystals in sheet produced entirely by rolling. This in itself may be a most valuable attribute, because it may practically eliminate those undesirable "directional" properties which are so often found in rolled sheet.

A serious disadvantage of the process is, at present, the cost of the sheet produced by it, which increases as the thickness of the sheet increases and makes the process most attractive for sheet of very thin gauge, the reverse of normal production by rolling. Its possible value in the production of "clad" sheet, a development discussed elsewhere must not be overlooked.

Crystal Structure

A more regular—and of course suitable—crystal structure, the second of the enumerated desired improvements, can be produced only by the exercise of much closer control during the whole progress of the ingot into sheet form. It is not suggested that knowledge concerning the influence of various conditions and processes upon crystal structure is complete, or that continuation of both fundamental research and careful observation and experiment under works conditions is unnecessary: on the contrary, more complete knowledge of the influence of ingot structure and variations in breaking-down procedure upon the nature and size of the crystal structure in the finished sheet is needed urgently. The fact remains, however, that such knowledge cannot be utilised unless close control is both possible, and exercised unfailingly, at all stages of mill operation.

Even the practical application of such theoretical knowledge as is now available would enable sheet of far better quality to be produced with fair regularity. The treatment required to produce a certain desired crystal structure is already known—or can be ascertained—with reasonable exactitude: practice lags behind theory in that many plants do not allow the desired conditions to be attained regularly and that, even when these conditions are attainable, inadequate supervision or lack of care often prevents their regular maintenance.

In fairness to suppliers it must be suggested that sometimes they are not fully aware of the genuine importance of a certain narrow range of crystal structure in sheet intended for difficult deep drawing and pressing operations. For this as well as other reasons the closest possible co-operation between suppliers and consumers is to be encouraged; in no other way can sceptical suppliers be assured that the close limits of crystal size asked for by some consumers are not the idle fancy of persons unacquainted with the difficulty of securing close control during rolling procedure.

Control of the size and—the next item to be discussed—the orientation of crystals in sheet produced on a commercial scale is, admittedly, a difficult task, and one which will necessitate the use of modern plant wherein conditions can be controlled with accuracy, the careful apportionment of passes and of annealing treatments in the light of knowledge gained from laboratory research and experiment under mill conditions, and strict supervision throughout the whole sequence of operations.

Difficult though the problem of really close control under industrial conditions may be, recent years have seen the advent of rolling plant and annealing furnaces which can be regulated with a speed, ease and accuracy vastly better than that possible a few years ago. As a result, there is less and less excuse why, assuming the processing schedule for a certain size of sheet is decided upon—as it should be—only after careful experimental work, the specified treatments should not be given to within very close limits. The difficulty is lessened considerably when large outputs of any given size of sheet can be undertaken continuously, as is possible abroad: in Great Britain, the small quantities of widely varying sizes of sheet and strip which of necessity have to be passed through relatively inflexible plant greatly heightens the task, though it is earnestly hoped will not lessen the enthusiasm, of suppliers.

The importance of a crystal structure of both suitable "average" size and desirable regularity has been fully explained in preceding chapters; its value cannot be stressed too much, and its attainment is one of the improvements most desired by many users of deep drawing and pressing quality sheet.

Directionality

Minimisation of directional properties, the next improvement on the list, can be attained only by a reduction of no less than four separate defects or conditions which, it will be recalled, have been shown to produce directionality. These are:—

(1) Elongated non-metallic inclusions: remediable only by improved casting technique and control of solidification of the ingot.

(2) Elongated planes or regions of chemical segregation: controlled to some extent by chemical composition yet dependent largely upon, and therefore only remediable by, conditions obtaining during the solidification of the ingot, although occasionally minimisable by heat-treatment and mechanical working in the rolling mill.

(3) Elongation of the crystals in the direction of the final stages of rolling: minimisable by manipulation during rolling and by the nature, and position in the schedule of mill operations, of annealing treatments.

(4) Directional properties of the crystals which may exist after apparently complete recrystallisation: also minimisable by careful apportionment of, and control during, the final stages of rolling and annealing.

Directionality attributable to these four causes can be modified only with the aid of knowledge gained through planned and carefully conducted research, and by the exercise of very close control in foundry and rolling mill. It is likely that ways and means for their modification will be revealed through investigations originally undertaken to elucidate problems other than the control of directional properties, because it seems that better appreciation of their harmful influence is needed before suppliers can be persuaded seriously to study, still more to explore and to adopt, such means as have yet been revealed whereby the more subtle causes of directional properties can be controlled and lessened. The work of Philips and Dunkle [115] and of Goss [34] on steel, and of Cook [112] on brass, serve to illustrate how these causes can be studied and the knowledge thus gained applied at once to rolling-mill procedure in order to minimise directional properties in the sheet produced.

Surface Finish

Improvement in surface finish can be attained by :—

(1) A reduction in the number and severity of blemishes attributable to the presence of cavities and non-metallic inclusions near the surface of the sheet, a defect which is now more common in steel than in many non-ferrous metals. This can be accomplished by minimising the severity and reducing the number of the original defects in the ingot and, to some extent, by machining off the surface layers of ingots or partially-rolled slabs.

(2) The use, in some instances, of still better roll surfaces and possibly of more suitable lubricants. Some authorities are of the opinion that when a really good surface finish is desired it is better to make the final passes through a single pair of rolls rather than through backed rolls, because with the latter it is less easy to maintain a good surface on the working rolls. The reason given is that when single rolls are used foreign bodies are pressed into the soft sheet and do not damage the roll surface, whereas when such bodies are trapped between the hard surfaces of the working and backing rolls injury to these surfaces may result. Against this advantage of single rolls there must, however, be balanced the greater uniformity of thickness obtainable in sheet rolled in backed rolls. Opinion on this point is not unanimous, yet the alleged advantage of unbacked rolls for finishing passes does seem to be well founded, although naturally modified by factors peculiar to any particular mill, metal and rolling procedure.

(3) The avoidance of injury caused by rolled-in scale, subsequently removed by pickling. Hydraulic and mechanical methods for removing the scale from the surface of hot metal as it enters the rolls are already in common use, and improved or new schemes may be devised. The removal of scale is an important matter because, particularly with

steel, rolled-in scale may produce minute surface markings which, although almost invisible on the finish-rolled sheet, will open up into unpleasant roughening or actual cavities during severe pressing, in the manner illustrated in previous chapters.

In addition to more efficient means for removing adhering scale, the possibility of minimising or even preventing its formation during heating must not be overlooked now that furnaces employing controlled atmospheres are coming into general use. It would, obviously, be better to prevent the formation of scale than to form it and then remove it, no matter how thoroughly: the elimination of pickling operations, which are often troublesome and are always unpleasant, would be an improvement which all sheet producers would welcome and one which is not beyond the realms of possibility.

(4) The avoidance of injury caused by markings inflicted during handling and transport, whether as a direct result of the mechanisms employed or of accidental contacts. Serious scores can be produced by apparently harmless excrescences on guides used in roll stands or in continuous annealing or pickling plants; mechanical fingers can produce dents on finished or nearly finished metal which are difficult to remove completely, while grit picked up from the floors of shops or furnaces can cause serious scratches. Care in the design of mechanical guides and handling devices can reduce the likelihood of damage from this first-mentioned source, but the exercise of care and, of importance, cleanliness is always necessary.

Although the avoidance of accidental damage rests largely with the strictness of the supervision, thoughtful planning can minimise the likelihood of accident in the mill, in the stores and during transport. Deliberate, though seldom malicious, damage by human agency has always to be contended with; for, although trustworthy men employed in the actual mill can be trained to exercise reasonable care, strangers engaged in maintenance work—and how seldom these seem to be absent!—and transport workers have little respect for a surface finish which is the pride of the mill superintendent. Here again a certain amount of planning, aided by suitable protection during transport, can often accomplish what strict, and therefore costly, supervision cannot.

Uniformity of Thickness

Last on the list of enumerated major improvements desired in the sheet used for deep drawing and pressing comes a greater uniformity in thickness, and there is little necessity to emphasise the need which exists for improvement in this direction. In automobile body-work both the size of the sheets employed and the severity of the pressing inflicted have increased remarkably during recent years; irregularity of thickness is likely to cause a sheet to fail, or at least to press in a manner sufficiently irregular to render the pressing unusable, and has even been known to break the very large and expensive cast iron tools used in this particular industry. In smaller pressings, metal having a more constant and uniform thickness would often be welcome, particularly in the product of some of the older mills.

Greater regularity in thickness can be obtained only by the use of improved rolling plant in which the rigidity of both rolls and frames is excellent and the sensitivity of the pinch controlling gear is of a very high order. Detailed discussion of rolling plant is beyond the scope of this essentially metallurgical dissertation, yet mention of one or two items which control the regularity of thickness of sheet can hardly be excluded for this reason.

It is of interest to observe that a multiplication of backing rolls of the "cluster" type, as recently exploited, has not proved an unqualified success, and that a reversion to stands containing only four rolls—two working rolls of small diameter each backed by one supporting roll of large diameter—is now advocated by many authorities. A possible advantage of unbacked rolls over backed rolls for finishing passes has already been suggested.

Increasing rigidity of frames resulting from better design and the use of stronger materials, changes in bearing design and materials—for example the advent of bearings of synthetic resinous substances—and improvement in the sensitivity, ease of control and speed of operation of the mechanisms whereby the pinch is adjusted will all help to increase the regularity of the thickness of the sheet produced in mills of the immediate future.

Continuous automatic indication of the thickness of sheet moving from or between roll stands has been made possible by the introduction of improved forms of flying micrometers. The apparatus usually takes the form of two small rollers, spring loaded and held apart by the strip passing between them. Any variation in thickness is recorded by means of a simple electrical device which moves a pointer on large diameter dials, and it is claimed that changes in thickness of 0·00010 inch can be indicated with accuracy, and of course instantaneously, thus enabling the operator to adjust the rolls with the least possible delay. It is possible that the future may see completely automatic control of thickness through the medium of electric relay circuits operated by thickness-measuring devices similar to those now in use for visual indication.

Automatic control of thickness, a refinement which if efficient would always be desirable, becomes a practical necessity during modern high-speed rolling in which strip may be moving at speeds as high as 1,500 feet per minute. Most authorities agree that the thickness of moving strip cannot be estimated with useful accuracy by means of a hand-operated micrometer when the speed exceeds 300 feet per minute. Even at this speed accurate control of gauge by intermittent "miking" followed by adjustment of the rolls cannot produce the close range of thickness demanded by purchasers in sheet destined for certain difficult deep drawing and pressing operations; and, as the speed increases, the proportion of sheet produced outside the permissible tolerance increases rapidly. Automatic devices which indicate—and sometimes record—continuously the thickness of sheet as it emerges from rolls are, therefore, a welcome and valuable refinement, which in time may come to be installed in small as well as in large mills.

Another useful device is a continuously indicating—and sometimes recording—extensometer, which, attached permanently to a suitable region of a roll frame, measures the elastic elongation produced in this region as the rolls are forced apart by the sheet being rolled. By means of an electrically-operated mechanism this strain is indicated by a pointer on a large dial calibrated directly in pounds, the reading representing the total pressure being applied to the sheet or strip at any instant.

It is often very desirable to know the pressure being exerted by the rolls, particularly when rolling changes are frequent and as a safeguard when pressures are high; furthermore, it is found in practice that a frame equipped with indicating instruments on each side can be "levelled" far more quickly than when no such aid is available and test bars or sheets have to be run through the mill to enable the operators to level it. These strain gauges can also be used to indicate, and thus to control, the amount of cold-rolling imposed on steel sheet during temper-rolling. When, as in this process, reductions are very small it becomes most difficult to ensure that each sheet receives the desired treatment, particularly when the sheets vary in thickness to any appreciable extent.

The introduction and proper use of indicating instruments of the type just described will, in addition to their primary and particular function, facilitate that close control of rolling procedure which, associated with equally close control in annealing, is absolutely necessary to produce deep drawing and pressing quality sheet having the desired crystal structure and physical properties; they are, therefore, doubly welcome and their use is to be encouraged.

General Properties

Ingot defects, crystal size and orientation, surface finish and uniformity of thickness—the four properties just discussed—may be said to be the ones which usually come first to the minds of consumers when the quality of sheet metal intended for deep drawing and pressing is under discussion. It is possible that in the future constancy of thickness and excellence of surface may approach the desired standard, and that the quality of sheet, although still influenced by freedom from ingot defects such as segregation and non-metallic inclusions, will be determined more completely by the nature and regularity of the crystal structure.

It is certain that continued and more widespread study of the properties of ductility, tenacity, work-hardening and of the influence of speed of deformation will lead to a better understanding of the properties—or of the best balance between incompatible properties—which are desired in certain metals intended for certain deep drawing and pressing operations. When this happens it will become the task of producers to make sheet which manifests these definite and desired properties in as nearly as possible the degree or balance desired by users. To perform this task with any measure of success will certainly entail far closer control of rolling and annealing than is now exercised, and the establishment in the first instance of the exact treatment which will produce the nearest possible approach to the ideal. This preliminary work, which will have to be repeated for new mill sequences and sizes of sheet, may necessitate the help of X-ray examination in addition to metallographic examination and physical tests, and it is likely that each of these methods will have to be employed afterwards as a regular routine check upon the quality of the sheet produced as nearly as possible in the scheduled manner.

Crystal size and regularity, although determined largely by the thermal and mechanical treatment accorded to sheet metal, is influenced also by its chemical composition; a fact which leads to a consideration of possible improvements with respect to the proportion of impurities present in the sheet of the future. The control of the proportions of the major constituents in alloys need not be discussed, as this presents little difficulty.

At one time it was thought that metal of extreme purity would possess unusually good mechanical properties, and that for this reason extreme purity was a condition to be desired. Now that the properties of very pure metals have been investigated, it is found that a pure metal often has few industrial applications, at least for deep drawing and pressing; quite often its crystals grow to a large size under the influence of thermal and mechanical treatment, and large crystals tend to be very ductile but low in tenacity, an attribute which when extended from the crystals to the sheet renders the latter quite unsuitable for most deep drawing and pressing operations. True purity may, therefore, be undesirable; so, in its industrial interpretation, " purity " must be defined as the elimination of *injurious* impurities, or at least limitation to a proportion at which they cease to be harmful and may actually become useful in retarding crystal growth and thereby helping to maintain the desired range of crystal size, familiar examples being phosphorus in brass and, although this is controversial, aluminium in steel.

It is, therefore, logical to suggest that the deep drawing and pressing quality sheet of the future will be more free from impurities which seriously decrease its ductility or increase its rate of work-hardening, but that on the other hand certain small additions may purposely be made to retard crystal growth, to minimise undesirable effects (when additions capable of exercising the desired influence yet not injurious in other respects can be discovered) and even to increase the tenacity of very ductile metals so that they can be deep-drawn successfully.

To summarise, in the absence of major defects—such as segregation, planes of weakness, and non-metallic inclusions—the physical properties of sheet of a given metal, and therefore its behaviour under the press, are determined by the size and orientation of the crystals existent in the sheet. In general the tendency is for a large crystal size to confer excellent ductility but inadequate tenacity, and for a small crystal size to confer high tenacity but poor ductility; the attainment of the desired balance between these two essential yet incompatible physical properties is dependent upon close control of crystal size in the original sheet and throughout any thermal treatment given by users.

As the size and behaviour of crystals is partly determined by chemical composition, the latter should be controlled with a view to aiding the maintenance of the desired crystal size as well as for the more obvious and already recognised purpose of limiting the proportion of harmful impurities which, either by segregation at crystal boundaries or by entering into and distorting the crystal lattice, reduce the ductility of the sheet without necessarily influencing the size of its crystals.

Reduction of the proportion of injurious impurities can only be secured by using purer metal for the production of sheet and by avoiding contamination from impure scrap, furnace gases, crucibles or refractory linings. The discovery of beneficial additions is more likely to be made as a result of planned research than through random trial of adjudged promising additions during actual industrial production, when risks cannot be taken and effects cannot be recorded fully nor accurately. Improvement in the quality of sheet available commercially for deep drawing and pressing will, then, depend upon the combined and co-ordinated efforts of research workers both in the laboratory and in the works, of metal refiners, ingot casters and sheet rollers.

The foregoing observations are intended to be of a general nature. Separate consideration will now be given to the lines along which it seems likely that the improvements enumerated at the beginning of this chapter can be made most successfully with brass—and much that has to be said will apply equally well to other non-ferrous metals—and, secondly, with steel sheet.

Brass Sheet

Melting and Casting. Starting with melting, the first stage in the manufacture of brass sheet, it seems likely that for the next few years electric induction furnaces will hold the field in any but small-scale production. During recent years works experience has seemed to show that large ingots give rise to fewer defects, in proportion to the weight of strip produced from them, than do small ones. It is to be expected therefore that, failing some unforeseen and very effective aid to the casting of small ingots, the use of large ingots will increase, as also may the size of what is now termed a " large " ingot, until a brass mill of the future may conceivably be comparable in size with that of a present-day steel mill. As the filling of a large ingot from two furnaces is liable to produce defects caused by the entrapment of dross and by uneven pouring, the size of furnaces should grow in proportion to the size of the mould used. Insufficient information is as yet available to judge the potentialities of the recently introduced rocking-arc type of furnace for brass melting, of the Hazelett process wherein molten metal is poured through rolls and thereby formed into sheet without the production of a cast ingot of any form, or of centrifugally-cast large thin cylinders.

Many melting and casting devices have been invented to facilitate the production of sound brass ingots possessing a good surface; readers interested in this aspect are referred to the book of Genders and Bailey,[2] in which many novel methods of casting are discussed. With the possible exception of the Durville process there seems little indication that any of these special methods is likely to be developed on a commercial scale. Methods not mentioned in the book referred to are the practice of slitting and opening out a centrifugally-cast thin-walled cylinder, and the use of vibrating moulds to influence the structure of an ingot during solidification. This last expedient may be worthy of closer investigation; the potentialities of treatment of liquid—and possibly of solid—metal by vibration, not necessarily of audible frequency, seem very great.

It is difficult to predict what changes, if indeed any, will take place in moulds. For large ingots, hinged water-cooled moulds lined with copper are finding favour owing to the more rapid solidification and improved surface which they give in comparison with cast iron or steel moulds. When one furnace is used to fill more than one mould a fixed mould is preferable to a fixed furnace, owing to the possible occurrence of ingot defects caused by movement of the mould prior to solidification of its contents. Mould dressings offer a fruitful field for experiment which does not yet seem to have been explored adequately.

Benefit would undoubtedly follow a reduction in the number of different sizes of moulds used. It will be evident that in order to secure standardised mechanical and thermal treatment during mill operation the use of only one size of ingot would be ideal from the purely metallurgical aspect, and that for this reason the use of as few sizes as possible will increase the degree of standardisation which can be instituted in mill procedure.

Mill Procedure. No drastic change in mill procedure can be foreseen, but it is to be hoped that closer methods of control and improvements in plant will facilitate the regular production of sheet having properties which approach more nearly to the standard desired by consumers. It has been pointed out that many of the troubles now encountered in the press-shop must be attributed to the *erratic* rather than to the continuously poor quality of the sheet used; as this erratic quality is attributable mainly to variation of the conditions under which the sheet is rolled and annealed, the importance of very much closer control in the rolling mill will be apparent. In the near future purchasers will, quite rightly, become increasingly insistent upon being supplied with sheet having a crystal structure which approaches much more closely to that which they desire and need. This demand can only be met by that improvement in plant and control for which a plea has just been made.

It must be admitted freely that in Great Britain the strict control of reductions and annealing treatments is often rendered very difficult by the relatively small outputs of any one size and gauge of sheet or strip which can be run through a mill consecutively. In this respect consumers could help by standardising certain gauges; for the gauge is, after all, the main factor which controls mill procedure. Even if this could be done, producers of small quantities of many gauges of sheet and strip are at a serious disadvantage in comparison with producers who can adjust the working of their plant to run continuously for long periods on one size. Indeed, it may be that only by long runs can mill procedure be regulated sufficiently closely to produce sheet having the desired properties, a fact which makes some standardisation of gauges—even perhaps an allocation of certain gauges to certain suppliers—all the more worthy of consideration. These suggestions may seem Utopian, yet the fact remains that present evidence suggests that sheet metal of the quality desired by consumers can be produced only in mills operating with clockwork regularity and with every operation standardised and controlled very closely, a state of affairs which cannot be attained—without prohibitive expense—on short runs with different gauges of metal or even with one gauge rolled from different sized ingots. This fact must be accepted, and the best means to alleviate the attendant disadvantages considered, however wild they may seem at first.

Descending to less controversial and more specific matters, attention may be directed to one or two items worthy of consideration. As regards mill lay-out, in large mills the use of several rolls in tandem, electrically controlled, seems to be increasing; but the high first cost and also a certain lack of flexibility of such installations may preclude their adoption by the smaller firms. Automatic methods, dependent upon the tension of the strip between successive stands, have been developed for regulating the speed of the rolls in each stand after the first. When sufficiently reliable and sensitive, such control must be preferable to that exercised by even the most vigilant human operator called upon to regulate the speed of perhaps three roll stands operating in sequence on rapidly moving strip. The installation of automatic devices, described earlier in this chapter, for controlling the speed of rolls by the tension of the strip between stands and also for indicating the thickness of strip and the pressure exerted by the rolls, is to be encouraged quite as much in mills operating on non-ferrous metals as in those operating on steel.

The practice of hot-rolling seems to be finding increasing favour from the aspect of decreased production costs rather than from any associated improvement in the quality of brass sheet; for it seems unlikely that internal and probably oxide-coated cavities will be completedly welded up in the manner usually assumed, but occasionally rightly questioned, to occur during the hot-rolling of a steel ingot. As the temperature, and often the mass, of brass billets is considerably less than that of steel billets, the removal of scale by high-pressure water sprays is more difficult owing to resulting temperature losses caused by the cooling influence of the water, and other methods may have to be adopted.

There seems to be an increasing tendency to machine the surface of billets or partly rolled slabs in order to remove shallow surface blemishes. It is only natural that this practice tends to lessen the care taken to produce a good surface on the cast ingot, an omission which when carried too far may produce defects so deep-seated that subsequent scalping proves only partially effective.

The importance of correct annealing has already been emphasised. By correct annealing is meant uniform heating to a predetermined temperature for a predetermined time, the required combination being determined by the previous mechanical treatment of the metal and the crystal size it is wished to produce. Incorrect annealing, attributable either to the non-attainment by some or all of the metal of suitable conditions thought to be imposed, or else to the full attainment of conditions unsuited to previous mechanical treatment, is still the cause of most complaints made by consumers of deep drawing and pressing quality brass sheet. The desired crystal structure cannot be produced in the finished sheet unless annealing conditions *throughout its whole history* have been correct. The remedy, so obvious in theory, is seemingly very difficult to provide under present industrial conditions even when, as in continuous mills, these seem capable of close control. Annealing, therefore, is the field in which marked improvement is perhaps needed most urgently in the production of brass strip.

With many industrial furnaces now in use it is genuinely impossible to secure the desired measure of control and uniformity of heating; with such obsolete plant the only remedy—which although simple on paper is yet an expensive one to producers—is to install furnaces which really can give the desired performance. Given suitable furnaces, the determination of the correct annealing conditions for sheet of certain gauge subjected to certain previous mechanical and thermal treatment is a relatively straightforward, though laborious, task which ought to be attempted more often and with more enthusiasm than is usually evinced. When, due to a small output, many different gauges of metal have perforce to be put through one furnace, producers must have the sympathy of consumers, who can ask no more than that genuine and continued effort be made to control annealing conditions as closely as possible.

As regards actual annealing methods, the continuous method, often advocated as likely to give very uniform annealing when used on strip, presents difficulty unless large quantities of strip of only one size and gauge can be put through at a time. On the other hand, when coils of strip are annealed in still, or even disturbed, atmosphere furnaces it is virtually impossible to secure uniform heating of a number of coils and, of importance, even of the outside and inside portions of each coil; a fact ascertainable by very simple tests. For annealing loosened coils, the rapid forced-circulation type of furnace offers many advantages. The speed and uniformity of heating given by well-designed furnaces of this type are remarkable, and places it far above others as far as performance is concerned.

One disadvantage of coil or batch annealing is that it precludes the use of large-scale continuous annealing and pickling plant of the type favoured in some modern mills, unless the ends of coils are welded or stapled together. Against this must be balanced the fact that bright, or at least "clean," annealing in a protective atmosphere on an industrial scale is now quite feasible, and that a protective atmosphere can be used in forced-circulation furnaces, no matter whether these are heated by gas or by electricity.

Little more concerning mill procedure can be said that is relevant to the quality of the sheet produced, except that methods of handling and transportation, be these mechanical or manual, must not be neglected; it is, obviously, more costly to spoil a finished or nearly finished sheet or strip than to spoil an ingot which has not passed through the mill, unless the damage is so localised that the affected portion can be cut out. The possible advent of specially polished or plated sheet, which has been considered in a previous chapter, is a development which will bring its own problems of finishing and handling.

General Properties. The various improvements which have already been described as being desirable in deep drawing and pressing quality sheet of any metal need but slight elaboration or modification with special regard to brass.

A continued decrease in the proportion of impurities present in brass sheet of industrial quality may increase its ductility but at the same time decrease its tenacity and increase the likelihood of rapid crystal growth. To counteract these two effects, which from the aspect of deep drawing and pressing are undesirable, small additions—for example of phosphorus or chromium—may be made; although, for reasons explained earlier, some authorities are of the opinion that these additions do more harm than good and that the trend of development will lie wholly in increased purity coupled with the exercise of close control of annealing conditions by both producers and consumers. The possible use of special brasses containing small percentages of lead, aluminium or nickel has been discussed in Chapter XV.

The routine control of the proportion of undesired and desired minor constituents may demand more sensitive analytical methods than those usually employed at the present time. The spectroscope may prove a useful adjunct to chemical methods of estimation, although present experience suggests that for accurate quantitative, as distinct from sensitive qualitative, estimation the expectations at one time associated with the industrial application of spectrographic analysis have been somewhat optimistic.

Irregularity of crystal size tends to be more pronounced in brass than in steel sheet, but it is doubtful whether this is a natural property of the metal itself: unsuitable thermal history seems a more likely cause, because sheet exhibiting a surprising regularity of crystal size is encountered occasionally, and excellent indeed is its behaviour under the press. Because it depends partly upon crystal orientation, the property of directionality varies widely in its severity and tends to be more completely a function of crystal orientation in brass than in steel; for, in steel, elongated inclusions and planes of segregation supplement effects attributable entirely to crystal structure and render the minimisation of directional effects more difficult. Several researches demonstrating how careful planning and close control of rolling and annealing treatment in the mill can influence both the size and orientation of crystals in a beneficial manner are mentioned elsewhere in this chapter; only by the exercise of much greater care in the mill can the desired improvements in crystal structure be obtained.

Regularity of thickness need be accorded no special mention with reference to brass sheet. Owing to its softer nature, and the fact that with rare exception the size of the sheets rolled is less than that of steel, it is easier to control the thickness of brass than of steel sheet, although the exercise of care and the aid of modern rolling plant is still essential if the regularity of thickness desired by some consumers is to be obtained.

As regards surface finish, the last item to be considered, this is usually equal to the demands of consumers except in special instances. Indeed, it may be said that at present the tools and manipulation of many consumers prevent full advantage being taken of the original excellence of surface of the strip supplied to them. Improvement will seemingly tend towards the elimination of scores and of such localised defects as still occur, and towards the production of an actually polished surface for certain purposes when consumers develop tools and processes which will not spoil this very highly-finished surface. However, a "mirror-finish" should not be specified by consumers unless it is genuinely necessary because, as explained earlier, sheet having a finely matte surface—which can "hold" lubricant—usually behaves better under the press when the operation is a severe one.

Steel Sheet

Melting and Casting. Failing the development of some entirely new method of casting, such as the Hazelett combined casting and rolling process, improvement must be sought through research work in which casting procedure, mould design, and the influence of special additions made to the molten metal either before or after teeming are explored. On account of its cost, electric melting may not be used for ingots destined for sheet for some time, even though the superiority of electrically-melted steel is conceded generally. However, high power input with multi-voltage transformers, rapid top-charging and improvements in automatic electrode regulators have been responsible for a marked drop in the cost of electric-arc melting during recent years, and Robiette[121] has shown that the cost of producing common quality basic billets from a modern arc furnace may be much lower than is commonly imagined and, for this reason, worthy of serious consideration. It is likely that the cost of melting steel in electric induction, as distinct from arc, furnaces will remain too high to allow this method to be used for the production of ingots destined for sheet used for industrial deep drawing and pressing, in spite of the greatly improved quality of sheet which would become available.

The influence of casting temperature is becoming more understood, and the introduction of new devices, such as silicon-carbide thermocouples, for the measurement of the temperature of molten steel will facilitate the closer control of this factor. The influence of mould design upon segregation is being studied by many workers in all parts of the world and, although some of the claims made by proprietary concerns for moulds of special shape seem to be more enthusiastic than strictly accurate, it is true that the behaviour of the ingot during solidification can be influenced to a marked degree by the shape of the mould assisted, naturally, by other variable factors.

Ingot defects which influence the quality of sheet used for deep drawing and pressing fall, speaking generally, into three main categories: those caused by major internal discontinuities; those caused by segregation of impurities, and occasionally of carbon; and, lastly, those caused by minor discontinuities, particularly when these are situated near the surface, and by non-metallic inclusions which may or may not be associated with major piping.

Severity of piping, although influenced most markedly by the nature of the steel being cast, *i.e.*, whether this is of the "killed" or "rimming" variety, and also by the design of the "hot-head," is controlled to some extent by the proportions of the discard which is cropped off. The proportion of this discard is decided mainly by considerations of cost, and purchasers of sheet have, therefore, some influence in decisions relating to this important question. It is true that steel producers will generally replace severely piped or, as the press-man terms it, "laminated" sheet, but this is often inadequate recompense to consumers for the cost of at least one press operation and often for disorganised production schedules. It is not unknown for steel suppliers to evince little perturbation at a return, owing to the presence of serious lamination, of, say, 15 per cent. of the sheet supplied, because this sheet can often be resold at a fair price for less exacting purposes. How far this state of affairs is justifiable as a means for keeping the price of deep drawing and pressing quality sheet at an adjudged low level is a matter which consumers and suppliers might with advantage discuss more seriously.

The severity of segregation, for example, of phosphorus, can be influenced by the proportion of the impurities present in the steel, but the reduction of these impurities to proportions which would not be detrimental in the event of segregation seems at present impossible. Furthermore, again choosing the example of phosphorus, it has been shown that the presence of this element in definite proportions can exert a *beneficial* influence on the crystal structure of low-carbon steel by hindering rapid and excessive crystal growth.[4, 122] It seems, therefore, that elimination of segregation by control of solidification may, at least in some instances, be preferable to elimination by reducing the total proportion of impurities to very low values indeed. By what means this end can best be attained with regularity is as yet uncertain, but the progress in research on ingot solidification which has already been made is encouraging.

As long as steel is cast into ingots the problem of non-metallic inclusions will seemingly remain, and it is unsafe to predict whether special methods devised to clear "cloud" inclusions as well as larger particles will come into general use for steel of low price. In one ingenious method, the evolution caused by calcium pellets fired by a gun to the bottom of the liquid ingot is employed to bring suspended particles to the top.. This novel example serves to show that the particular problem of non-metallic inclusions is being tackled energetically, and that improvement may be looked for with some confidence.

Last, come defects attributable to surface blemishes on the ingot. In contrast to the procedure usually adopted with brass, in which the whole of the original surface is machined off, it is usual, except in ingots destined for special purposes, merely to gouge out surface defects with pneumatic chisels or oxy-acetylene torches. Clearly, only major defects can be seen and removed in this way, a fact which explains in part, but not entirely, the greater prevalence of surface blemishes on steel than on brass sheet. Even if the cost of machining the whole surface of ingots or billets could be tolerated, it is undesirable to remove too much of the skin of rimming steel because this skin is of a very pure nature calculated to give a better surface on rolled sheet, and a better performance during deep drawing and pressing operations, than the less pure interior. It seems, therefore, that surface blemishes attributable to the ingot can for the present be minimised only by the exercise of more care during casting, for example to avoid splashing and its resulting defects; by better mould surfaces, and perhaps by the use of mould dressings not yet discovered, as well as by more careful inspection and removal of local blemishes at an early stage in the history of the sheet.

Mill Procedure. The subject of rolling has already been discussed in general terms and also with special reference to brass. It can be taken that, in general, the improvements described apply also to steel-mill procedure, but one or two items peculiar to the rolling of steel deserve mention.

One of the most striking changes of recent years has been the increasing tendency to hot-roll sheets direct from billets to sheet of moderate gauge at one heating, a practice made possible by improved rolling plant, more efficient mechanical handling gear and careful mill lay-out. A disadvantage of these very expensive modern mills is that usually they must operate more or less continuously to prove profitable; on this account the advisability of installing them when markets are limited is often queried. Provided that the billets are not overheated and that rolling is completed before the sheet has cooled to the critical temperature of the steel, both the crystal structure and the surface finish of sheet produced by this modern method tend to be better than that of sheet produced by repeated heating and rolling. However, it seems likely that the installation of continuous mills will be governed more by considerations of cost than of the quality of the sheet produced.

Owing to the high temperatures employed for hot-rolling, the problem of scale removal is a serious one ; because if scale is allowed to remain the surface of the sheet will be impaired. Various devices for removing scale during hot-rolling—such as flexing-rolls, scraper-bars and high-pressure water jets—have already been described, and it seems unlikely that entirely new methods will be devised. A more logical way in which to tackle the problem of scale would be to heat ingots or slabs in a controlled atmosphere, but the kind of furnaces now in use do not lend themselves to this change. Even if the surface of the hot steel were clean when it emerged from a furnace, exposure to the atmosphere during transit and rolling would quickly cause scale to form.

An important phase of mill procedure peculiar to steel sheet is that of temper-rolling and roller-levelling given for the purpose of lessening the tendency to form stretcher-strain markings. This process has already been discussed, so it is necessary only to add that the roll-pressure indicating devices already described can be of very great help in controlling both the magnitude and the uniformity of the pressure imposed during both temper-rolling and roller-levelling, and that, in the first procedure, continuously-indicating thickness gauges are also of value.

The art of temper-rolling and roller-levelling has reached a remarkable state of fineness, yet more general adoption of the mechanical aids just mentioned would enable still finer control to be exercised. Should this happen, attention will tend to become focussed more on the problem of suiting the amount of the imposed deformation to the requirements of the steel being rolled and to the particular needs of each consumer, a change which will necessitate a greater knowledge of the properties of the sheet passing through the mill and still closer co-operation with consumers to determine the particular requirements of any given pressing operation. Although, as will be explained later, X-ray examination offers a new and useful means for checking the severity of the deformation produced by rolling, the use of the new forms of indicating devices in the mill will render it easier to impose the desired amount of deformation on the sheet and thus to reduce the need for continual checking by relatively elaborate methods, a precaution which even now is seldom adopted. As the aid of accurate indicating and measuring instruments is of little practical use unless the rigidity of the rolls and frames (and the sensitivity of control of pinch) is sufficient for the necessary very fine adjustments to be made easily, and thereafter to be maintained, the continued general improvement in cold-rolling plant is doubly welcome.

To control the thickness, even more so the uniformity of thickness, is a more difficult problem with steel than with brass by reason of the heavier pressures demanded and, in some instances, of the much larger size of the sheets rolled. The improvements and devices already described for brass are even more useful when applied to steel; in particular, greater rigidity of rolls and roll frames is needed if adequate control of thickness is to be possible.

It may be conceded that the danger of accidental damage to the surface of sheet is somewhat less with steel than with brass, but against this must be offset the greater force needed to handle and guide the ferrous metal. An added danger with annealed steel exists in the possibility of forming "coil-breaks"—the mill term for stretcher-strain markings—whenever the sheet is deflected sufficiently for the limit of proportionality of the steel to be exceeded. When allowed to "age," such markings persist with remarkable pertinacity, and may remain to spoil the appearance of articles even when, during subsequent pressing in the works of consumers, regions bearing the markings are stretched beyond the elongation at which freshly formed stretcher-strain markings disappear through the complete merging of individual lines or "wedges." More care is therefore necessary with steel than with brass to avoid flexure of annealed sheet, because the resulting slight, localised work-hardening produced in brass is usually of small detriment. Although the proneness of steel to develop coil-breaks is greatly reduced after sheet has been temper-rolled, the advent of steel less prone to develop stretcher-strain markings would lighten the task of producers as well as that of users of sheet.

The annealing of low carbon steel sheet presents its own special problems. Of these, the three most difficult to solve are, perhaps, those attributable to the readiness with which crystal growth occurs, to the difficulty of ensuring even heating over the whole area of sheets of large size and, lastly, to the natural tendency of steel to oxidise at the temperatures which have to be employed. Each of these problems has been and is being tackled, and it seems more likely that improvement will come from continued progress on present lines rather than from the advent of entirely new methods.

Neglecting the possible future aid of inhibitors of crystal growth added to the steel, the occurrence of abnormal growth can be avoided, or perhaps minimised, in at least three ways. First, sheet of uniform structure—in the sense of not having an outer skin of great purity and a core of relatively high impurity-content—can be used. As this would preclude the use of rimming steel it is a condition which at present cannot be entertained, and the ideal heat-treatment would therefore be one which would produce a crystal structure of reasonable size in both the skin *and* the core of rimming steel sheet.

Secondly, the extent of crystal growth can be controlled to a surprising—and very fortunate—degree by the exercise of close control and correlation of degree of cold-work, annealing temperature and time of heating. This method, for the successful application of which great familiarity with mill procedure and the failings of individual furnaces is essential, is the one upon which most reliance has to be placed, and recent researches have added much useful theoretical knowledge to the less precise yet very useful working data obtained from prolonged practical experience. The application of this knowledge will certainly render possible the consistent production of a more regular crystal structure whatever may be the shortcomings of the annealing furnaces which have to be used.

The size, and indeed the regularity, of crystal structure which is sometimes attained in annealed sheet by a fortunate cancellation of adverse influences is surprising in view of the seeming theoretical difficulties which must militate against its production, a fact which is sometimes advanced as evidence that the close "scientific" control advocated by what may be called the newer school of thought is not really necessary. Unfortunately, most users of sheet can furnish many examples of undesirably irregular crystal structure, and usually not a few examples of entirely abnormal growth of the kind illustrated in preceding chapters.

Lastly, annealing may be replaced by normalising. At present opinion is divided as to the merits of sheet produced by either of these two processes; but, even when the final softening is accomplished by annealing, there is no reason why normalising should not be used for previous softening treatments, particularly as this procedure is thought to minimise the severity of preferred orientation in the final crystal structure. In true normalising, which is heating to slightly above the critical temperature of the steel for only a short time and then cooling moderately rapidly, abnormal crystal growth will not occur. Care must be taken, however, that in rimming-steel sheet the critical temperature of the surface zones, which will be appreciably higher than that of the core with its higher content of carbon and impurities, is exceeded; also that the rate of heating and cooling through the dangerous region between the critical temperature and about 680° C. is sufficiently rapid to prevent undesirable crystal growth taking place. This condition, although simple on paper, is not always easy to attain in practice unless furnaces are carefully designed and used intelligently; and, moreover, unless the weight of charge for which they are designed, or for which they are regulated at any period, is not departed from unduly.

These comments have been concerned primarily with the problem of excessive crystal growth; there still remains the not less important one of how to obtain a crystal structure of the desired size and regularity—excluding irregularity due to abnormal growth—and, also, a degree of preferred orientation which will not be unduly harmful during subsequent deep drawing and pressing. The desired crystal structure can be obtained only by the exercise of very close control of rolling and annealing—or normalising—procedure, a matter which readers will allow has been stressed sufficiently during the preceding discussion of brass-mill procedure, both from the aspect of actual control in the mill and that of the application of results obtained from research.

The second major annealing problem, that of ensuring even heating, is concerned primarily with furnace design. Annealing is usually carried out by heating packs of sheet or coils of strip in large annealing boxes; so, particularly when the size of the sheets is large and the weight of the charge several tons, the impossibility of securing entirely uniform heating will be appreciated. The old practice of pushing annealing boxes packed with work into coal, gas or oil fired furnaces, often of tunnel design, is being superseded by the more modern one in which either electric heating or radiant-tube gas heating is used and the furnace is lifted and placed over successive annealing boxes. No further development can be foreseen as regards heating methods, and it is likely that future changes will be concerned mainly with atmosphere and temperature control. Although from theoretical considerations the use of much smaller charges would enable more uniform heating to be obtained, the increased cost of handling and heating will probably prevent any move in this direction. The long heating and cooling times which are necessary may prevent the treatment of sheets or coils individually, or even in small numbers, on an industrial scale.

When normalising, as distinct from annealing, is given, the problem of uniform heating becomes easier. Improvement will certainly lie in the continued development of furnaces of small aperture, although perhaps of great length, usually of continuous belt or pusher type, in which only a few thicknesses—perhaps only one thickness—of sheet or strip is passed through at a time, thus enabling close control of both time and temperature of heating and rate of cooling to be exercised. In the case of strip, more uniform heating and cooling can be obtained when the strip is uncoiled and passed through continuous furnaces than when coils are passed through similar furnaces of larger aperture, and the first procedure is therefore to be encouraged. As with brass, the ends of strips can be joined either by mechanical stapling devices or by welding to form one continuous length.

Refinements in furnace design will probably allow closer control of heating and cooling to be exercised. In continuous, tunnel furnaces it is possible, and usually desirable, to have several zones maintained at different temperatures. Usually the temperature of the first zone is well above that to which it is desired to heat the strip; that of the second is only slightly above it, and that of the last is maintained carefully so that the strip will attain the desired temperature. As pointed out previously, this does not necessarily mean that pyrometers installed in this zone will indicate the temperature of the moving strip itself: an important difference usually exists.

The very uniform and quick heating given by rapid forced-circulation atmospheres, the method advocated for the annealing of brass, does not, unfortunately, possess similar advantages for the normalising of steel. At the temperature required for normalising, *i.e.*, over 900° C., heat is conveyed mainly by radiation; the conveyance of heat from elements to charge by convection is too inefficient to have useful industrial application. It is possible that forced-circulation furnaces could be employed for annealing, but the long heating periods given to steel render the benefits of such furnaces less marked, although their capacity to heat a loosely packed charge uniformly might well be taken advantage of in the annealing of coils as distinct from solid stacks of sheet.

Although no radical change in industrial normalising procedure can be foreseen, it is possible that methods in which large sheets are gripped along the whole length of opposite edges and heated by the passage of an electric current may come to be used.

The earliest method adopted to prevent surface oxidation was to place charges in large pans packed with swarf, but for some years gas-tight containers have been used which, by means of valves, allow a purging atmosphere, often of town's gas, to be passed through them, a process usually confined to the cooling cycle because the products of combustion from adhering lubricant are deemed adequate protection during actual heating. It is likely that improvement will take the form of more thorough purging, perhaps during the whole cycle and by stored and regenerated gases, rather than of any radical change in practice, such as annealing *in vacuo*.

Although the temperature is considerably higher during normalising than during annealing, the retention of a clean surface is usually easier during the first mentioned process because the time of heating is much shorter and, more especially, because the necessary heating and cooling is usually carried out in modern tunnel furnaces employing efficient protective atmospheres. Future improvement will probably lie in the development of more efficient and perhaps less costly protective atmospheres, and in their conservation by recirculation after purification.

General Properties. Although the problem of producing sheet free from defects attributable to non-metallic inclusions, discontinuities and segregation, and also possessing the desired crystal structure is more difficult with steel than with brass, the general quality of the steel sheet used for drawing and pressing has certainly improved more rapidly during the past twenty years than that of brass sheet. This seems to be attributable to two reasons: to more intense and more extensive research, attributable probably to the much greater capital involved in the ferrous industry and to the inauguration of joint researches sponsored by a number of steel producers and, latterly, by consumers of steel sheet; and, secondly, to the impetus given to such research by the recent very rapid increase in the production of automobile body pressings of large size and ever increasing depth and intricacy from the pressing aspect. The difference is discernible in technical literature in that during recent years many more papers have been published describing investigations into the effect of mill procedure upon crystal size and orientation—as revealed by physical tests, microscopical and X-ray examination—in steel sheet than in brass or other non-ferrous metals.

This unavoidable if invidious comparison of past and present activities in ferrous with those in non-ferrous research does not mean that improvement in the quality of steel sheet is not needed urgently, a view which any one actively engaged in the deep drawing and pressing of steel will confirm. For example, a reduction in the number and severity of ingot defects, a crystal structure of more regular and suitable size, elimination of stretcher-strain and ageing effects, a better surface finish and greater regularity in thickness would each be most welcome.

It is unsafe to predict whether in the future the Bessemer process will come to be used more, or whether steel of the fully "killed" or deoxidised type will replace the "rimming" type which is now used so extensively for the production of sheet and strip for deep drawing and pressing. The advantages and disadvantages of each type have already been discussed and need not be re-examined. It is safe to predict that, if only the soundness and uniformity of crystal structure of rimming ingots can be improved, the greater ductility of rimming steel attributable to the cumulative influence of its lower carbon, silicon and phosphorus contents, and the better surface attributable to its surface zones of almost pure iron, would throw the choice in favour of rimming as distinct from killed steel ingots. An exception to this general statement ought perhaps to be made in the case of steels specially deoxidised to minimise "ageing," but it is uncertain whether these special kinds will become a recognised commercial product marketed at a price comparable with that of ordinary sheet.

Until such time as the soundness of ingots is improved considerably, the question of the amount of discard to be cropped from the top and bottom of an ingot must remain a matter for argument between those interested mainly in price and those interested mainly in the quality of the sheet produced. Some producers still argue that, even were the cost not prohibitive, cropping of the drastic nature advocated by some consumers is unnecessary. A ready answer to this argument is to be found in the generally recognised superiority of the "extra" grades of sheet, which invariably are rolled from carefully selected portions of an ingot in which chemical segregation, and also unsoundness due to slag, shrinkage or gas cavities, are known to be lowest. It may be that some adjustment of price may be made by suppliers and that consumers may agree to pay more in order to obtain sheet rolled from only the best portions of ingots.

As regards chemical composition, the need for a reduction in the proportion of those impurities which are common to steel is, in general, not yet acute. It would certainly be a most welcome improvement if the proportion of phosphorus, and possibly sulphur, could be reduced to such a low value that the as yet unavoidable segregation of these elements in the ingot, and the subsequent elongation of zones of segregation into planes, would be insufficient seriously to lower the ductility of the sheet as a whole ; unfortunately this seems to be quite impossible on a commercial scale with the methods of casting and forms of ingot now used. For the present, attention may with advantage be focussed on minimising segregation rather than on eliminating the elements which tend to segregate.

The influence of intended additions, whether added as deoxidisers or for other purposes—for example to control crystal growth—needs to be studied more closely, and several possible developments have been suggested. It is only recently that the importance of the influence exerted by dissolved gases, particularly oxygen and perhaps nitrogen, has been appreciated. Continued research will probably render the action of these gases more clear, and thus pave the way to more careful control of gas content than is now attempted. Special additions—for example, nickel, chromium, copper or lead, the influence of each o which has already been explained—may be made to an increasing proportion of sheet used for special purposes.

The size and regularity of size of crystal structure tends to be better in steel than in brass sheet; yet improvement is still needed, particularly in annealed as distinct from normalised sheet. It is likely that this improvement will come about mainly through closer control of heating and cooling conditions assisted by more careful regulation of reductions and, of importance, more careful matching of reductions to heat-treatments. Much useful information of the kind contained in the typical researches already quoted has been published on the influence of various amounts of reduction and various heat-treatments upon the crystal structure produced ; a great deal more information which has not been published undoubtedly exists, and it must be conceded that, even in the present state of knowledge, the production of an undesirable crystal structure is due rather to lack of application of this knowledge than to effects which as yet are incompletely understood.

In comparison with mills designed for, and confined to, continuous operation on one size of sheet or strip, the problem of control in mills which have to handle many sizes is rendered much more difficult by reason of the relatively small quantities of different sizes which have to be passed through one plant. Nevertheless, in comparison with brass, outputs are larger, heat-treatment conditions are less critical, and the continuous production of a given size of sheet is often approached sufficiently closely to render accurate control possible.

It has been shown [4, 122] that, as in brass, phosphorus can exercise a beneficial influence in retarding rapid crystal growth during the heating of low-carbon steel sheet, and it is unfortunate that, in steel, phosphorus tends to segregate and form layers possessing low ductility in the final sheet. If segregation could be prevented, perhaps by special casting methods, the restraining influence of phosphorus could be utilised more fully. Failing this, it may be that other additions will be discovered which, although producing the desired effect, will not segregate to form planes of low ductility. Both aluminium and titanium influence crystal size, and it is possible that full use of these additions as restrainers of crystal growth is not yet made. Although control of crystal structure will probably remain dependent primarily upon mill procedure, the help obtainable from inhibitors of crystal growth is one which merits more serious study than has hitherto been accorded to it.

The property termed directionality, meaning variation in physical properties in different directions relative to the direction of rolling, is more difficult to control in steel than in brass and much non-ferrous metal sheet owing to the greater prevalence of elongated non-metallic inclusions, planes of segregation and, sometimes, stringers of pearlite, which supplement influences attributable wholly to crystal structure. The means whereby the last-mentioned influence can be minimised has already been considered in some detail; the influence of elongated inclusions, planes and stringers can be avoided only by eliminating the actual sources, an end which can be achieved only by modification of present casting procedure. The harmful effect of directionality has been pointed out more than once; as this defect is usually more pronounced in steel than in other industrial metals the need for improvement hardly calls for further emphasis.

During recent years considerable interest has been shown in the subject of "inherent grain size" in steel, meaning the size of the austenite crystal grains prior to their transformation, on cooling, into ferrite crystals, usually of smaller size. It is postulated that, owing to the presence of segregated sub-microscopic impurities or to effects associated with the lattice structure itself, the original austenite crystal boundaries persist in "shadow" form in a ferrite structure, and much interesting work has been carried out to show how profoundly and in what manner the size of this "inherent," and normally invisible, crystal structure can influence the physical properties of steels which have been quenched from the austenitic range. There is reason to suppose that this influence may be present to an unsuspected degree in the annealed or normalised low-carbon steel used for deep drawing and pressing, and that it may control—at least in part—the phenomena of stretcher-strain marking and ageing, reaction to speed of deformation, and smoothness of surface after pressing, in addition to exercising some influence on directionality and even on the common tensile properties.

It is known that the degree of de-oxidisation of steel produced by the addition of aluminium and titanium, and the stage and manner in which these additions are made, exert a profound influence on the proneness of steel to develop stretcher-strain markings and to age-harden. As these additions are known to influence the inherent grain size, it is possible that the first-mentioned influence is caused really by the second and that it is inherent grain size, not degree of deoxidation, which controls stretcher-strain marking and age-hardening.

Whether or not these speculations are true, the fact remains that a fruitful field for investigation lies open to determine the influence of inherent grain size upon the behaviour of sheet used for deep drawing and pressing. It would be unsafe to predict that, because the property of normal grain size is of supreme importance in determining behaviour during deep drawing and pressing, inherent grain size will be found to exert an influence of comparable magnitude. Nevertheless, it will be surprising should inherent grain size prove to be of insufficient practical importance to justify its careful control in sheet destined for severe operations under the press. It is to be hoped that those workers who have so far confined their researches to heat-treated steel of higher carbon content will extend their investigations to the field just outlined, and that the sheet of the future will possess a controlled inherent grain size in addition to a controlled ferrite grain size.

The advent *on an industrial scale and at a low price* of steel sheet in which the causes of stretcher-strain markings and age-hardening have been eliminated would be a most welcome improvement, because the means which are now adopted to overcome defects and difficulties caused by these effects are troublesome and often only partly successful. Temper-rolling is a difficult operation which needs very careful control and continual adjustment to the needs of each purchaser if the desired benefit is to be obtained, while every user who is not engaged on continuous production knows how difficult it is to carry out all stages of shaping within a short space of time and thus avoid the possibility of loss of ductility caused by the age-hardening of temper-rolled sheet or partly-drawn shapes. Whether the production of sheet entirely free from all tendency to develop stretcher-strain markings or to age-harden can be accomplished on a commercial scale without serious increase in cost remains to be seen. Two proposed methods, successful on a laboratory scale, have been described in earlier chapters ; but it is a disadvantage from the industrial aspect that both apply to killed steel. One utilises a special annealing and slow cooling treatment given to the finished sheet (p. 214) ; the other is based on the addition of a special element such as niobium, vanadium or titanium in sufficient quantity to combine with all the carbon present (p. 213). Unfortunately both methods postulate the use of sheet rolled from " killed " steel ingots which, for reasons already explained, is more expensive and often has a surface finish inferior to that of sheet rolled from the popular " rimming " ingots.

It certainly seems that the proportion, or perhaps the condition, of the oxygen in the steel, or perhaps effects dependent upon this condition, are a most important factor in determining the severity of stretcher-strain, ageing and even blue-brittleness phenomena. The gaining of more knowledge concerning the exact cause of these defects, followed by its practical industrial application, is undoubtedly desired most earnestly by all who are actively engaged in the deep drawing and pressing of steel sheet. The desired end can be attained only through proper research, and it is encouraging to know that much time and money is being devoted to its attainment.

Greater regularity of thickness is needed, particularly in sheets of considerable width. This improvement can be brought about only by the use of better rolling equipment, a matter discussed elsewhere ; but it is necessary to remind consumers that the problem of securing the measure of uniformity which they desire is greater with steel than with brass sheet owing to the greater pressures, causing bigger roll deflections, which have to be imposed during the rolling of the ferrous metal.

Surface finish, the last item to be considered, certainly needs improvement in at least four directions : a reduction in the number of blemishes caused by ingot defects ; elimination of etch pits caused by the removal of rolled-in mill scale during pickling ; the production of a smoother surface by the use of better rolls, and, in some instances, a reduction in the severity of surface oxidation. Each of these items has already been discussed during the preceding remarks upon casting and rolling-mill procedure.

This outline of the probable trend of developments in the quality of sheet metal used for deep drawing and pressing, and of the means by which desired improvements can be achieved, has of necessity been somewhat vague, and perhaps optimistic. Only time will show whether some of these predictions will be fulfilled. Yet one thing is certain, namely, that the improvements in quality desired by consumers can be achieved only by the obtaining and industrial application of scientific knowledge, and by sincere and energetic attempts on the part of producers to give the best they can, rather than a mediocre product which suffices simply because competitors can offer nothing better at a comparable price.

CHAPTER XVII

DESIRED IMPROVEMENTS IN PRESS-SHOP PROCEDURE

PRODUCERS, and also enlightened consumers, will be quick to point out that improvements in the quality and finish of sheet which may result from some of the new methods suggested in the last chapter will be of small avail unless consumers, on their part, initiate parallel improvements or, at least, cease culpably to maltreat good metal. Happily the business slogan of "the customer is always right" does not extend to technical works processes.

In this chapter it is proposed to indicate the nature of some of these urgently needed improvements; but it need hardly be said that the most necessary improvement of any is the correction of those improper treatments which produce the defects and difficulties already considered in several of the preceding chapters. Yet, as it would be redundant to review these again, mention will be made only of matters not dealt with in detail in the chapters just mentioned.

A convenient way to pursue this study will be to examine in their normal sequence all the stages through which sheet must pass between its arrival at the factory of the consumer and its departure in the guise of a finished shape or article. At the end of this eventful passage, the article, be it a tiny deep-drawn case for Madame's lipstick or a complete automobile body welded into a whole from large, intricately-shaped, deep-pressed panels, must perforce be committed to the doubtful appreciation of its future owners while consideration is accorded to one or two important items which, in order to preserve the continuity of the imaginary factory progress, must be reserved for separate discussion.

CHOICE, SPECIFICATION AND TESTING OF THE SHEET USED

More careful and more reasoned choice of the grade of metal to be used for the making of a given shape would be beneficial at the present time, and will be markedly more so when the properties which control the behaviour of sheet metal during deep drawing and pressing become better understood.

It is not proposed to enlarge upon several aspects which have already been discussed in appropriate preceding sections, such as the need for balancing first cost of metal against the cost of extra shaping or annealing operations necessitated by the use of low-grade metal;

the need for adapting the "average grain size" of the metal to the nature of the shaping operations given and to the surface finish desired; the futility of using sheet possessing a very good surface when this will be spoilt by the treatment it will receive, and others which readers will recall. With steel the balance between stretcher-strain markings and decreased ductility, and possible age-hardening effects, has to be decided when the use of temper-rolled sheet is under consideration; and the availability of a greater number of commercial "grades" and finishes with steel renders choice more difficult than with non-ferrous metals. Greater uniformity in the quality of any one so-called grade of sheet would be most welcome, and would render the choice of a grade for a given purpose far easier.

Most important of all is the degree to which any sheet exhibits what at present can only be termed "deep-drawing properties." In the past, practical experience aided by Erichsen values and, latterly, by "average grain size" estimations have formed the main evidence upon which a reasoned choice has been made. There is reason to suppose that in the future much more precise information in the form of certain types of stress-strain curve, of values obtained by wedge-drawing tests, or even by small-scale standardised actual drawing tests, will become available and generally recognised as valuable data to be used freely. When this happens the choice of a suitable sheet for any particular purpose will become easier, but at the same time it will become still more desirable for that choice to be made carefully, with a full knowledge of facts, and by persons well-acquainted with the true significance of these new indications.

In addition to what may be called "general" deep-drawing properties, those relating to special behaviour—such as "directionality"—ought always to be considered, although it is to be feared that at present little choice in the full meaning of the word can be made with the ordinary sheet of commerce. An entirely new field is opened up by the discovery, made with the help of X-ray examination, that it is possible by suitable modification of rolling-mill procedure to produce sheet having a definite preferred orientation of its crystal structure which, instead of being harmful, can be so used that it becomes beneficial for certain special shaping operations; a possibility at which some sheet-producers may cavil.

Until, and even when, more scientific knowledge becomes available to assist in the selection of the most suitable grade of metal for a given purpose, the advice of the experienced press-man ought never to be neglected; all too frequently it is not sought, to the ultimate disadvantage of all concerned. The following instance will illustrate this point. It might seem that the substitution of 70/30 "cartridge metal" for 63/37 "basis-quality" brass would lessen the risk of failure in the deep-pressing of an article in which the margin of safety is very small. However, in some articles the reverse proves to be the case owing to the fact that the more "ductile" metal possesses insufficient "tenacity" to enable the portion of a shape which has passed the die to transmit stress to the portion lying beyond the drawing radius. The scientist might quite easily imagine that the 70/30 quality sheet is the better for deep drawing and that its substitution for 63/37 quality sheet ought to decrease the production hazard or, alternatively, render possible a reduction in the number of draws required to form a given shape. This furnishes a chastening illustration of how incomplete theoretical knowledge may lead to erroneous conclusions.

In point of fact it is sometimes possible to deep-press some shapes in *fewer* operations using 63/37 quality brass than using the more expensive, more ductile, and at first sight better 70/30 quality. For example, it was found possible to deep-press a rather pointed shell, somewhat similar to that shown in Fig. 280 (p. 593), in two operations without annealing when 63/37 quality brass was used; previously, when 70/30 had been used, three draws assisted by an inter-stage anneal had been necessary. Readers will doubtless call to mind instances in which similar considerations apply to metals other than brass and in which the balance of ductility and tenacity is changed by means other than by varying the proportion of the major constituents of an alloy, for example, by the amount of cold-rolling or by the proportion of impurities present.

This particular question of the best combination of ductility and tenacity (within the range obtainable with a given metal) is a very important one to which increased attention will have to be paid as theoretical considerations come to be used more and more in the choice of sheet. In this connection the information given by special forms of stress-strain curves will be most valuable, but speed of drawing —upon which important factor little information exists—will always need to be borne in mind in this as in many other problems.

It is doubtful whether any so-called "best" combination of ductility and tenacity can be expressed in general terms, for so much depends upon the shape of the article being drawn and to what extent "ironing" takes place at some part of the draw. This caution should be borne in mind when considering definite statements which, although true for certain conditions of deep drawing or pressing, may need modification for others. For example, it is often said that the best combination of ductility and tenacity in brass sheet occurs at approximately 68 per cent. copper (see Fig. 20, p. 27). Increasing the copper content above this adjudged optimum will enable more severe deformation to be accomplished before annealing becomes necessary, but this fact can be utilised only when the resulting decreased tenacity is sufficient to enable some particular shape to be made without failure occurring in the drawn portion of an uncompleted shape in the manner just described.

More care is, therefore, needed in the choice of the quality or grade of sheet to be used for forming a given shape ; proper regard ought to be paid to all relevant factors, of which first cost of metal is seldom the most important. In the future more helpful information is likely to become available upon which to base selection ; yet proper use of this new data will necessitate an understanding of its true significance, which may entail some knowledge of the fundamental properties of metals and of their plastic deformation.

Specification. It would be hazardous either to predict what new ways will be found to ensure the purchase of sheet having the properties desired for the deep drawing or pressing of a given article, or the extent to which these ways will be adopted in industry. The subject of specification has been discussed in Chapter XIV, and it has been made clear that really adequate specification may not become possible until more reliable and informative tests have been devised to predict the behaviour of sheet under the press. For this reason the advent of better specification must await the development of new tests or the industrial application of some of the more recent ones already described.

The quality of the sheet, and the range of physical properties possessed by it, is certainly as exacting in deep drawing and pressing as in any existing manipulative or constructional application of metal ; yet, in others less exacting, close specifications are drawn up and, of equal importance, regularly met by suppliers. The reason for this exceptional position is due mainly to the fact that knowledge concerning the precise nature of the essential properties required in sheet intended for drawing and pressing is at present incomplete, yet it must be admitted that suppliers are often unwilling to meet those demands—for example with respect to crystal size and regularity—which are already made by consumers.

For the present, more extensive use of such forms of specification as are now possible, coupled with steady insistence on the part of consumers that reasonable demands be met regularly, would bring about a welcome improvement in the quality of the sheet produced ; and would pave the way for still more useful specifications which will come as knowledge concerning the essential properties necessary in sheet intended for shaping by deep drawing and pressing increases. The need which exists for clauses relating to arbitration has already been pointed out.

Testing. Little can be added to that which has already been said in Chapter XII, in which the nature and significance of a number of tests were described. Emphasis may, however, be given to two matters of outstanding importance.

First, it is essential that whatever tests consumers choose to make be made under the close supervision of men having scientific knowledge and by trustworthy assistants. Nothing can be more irritating to conscientious suppliers than to have large quantities of metal rejected on the evidence of tests made under unsatisfactory conditions, and it is regrettable that, although during recent years there has been a marked increase in the routine examination of supplies, proper supervision is not always provided. To quote one disgruntled supplier: "A youngster is let loose with a Rockwell and an Erichsen machine and "—indicating a stack of rejected metal—" look what happens." The implication is in no way intended to alter the opinion already expressed that rigorous inspection *properly carried out* and, when the need is proved, firm rejection is the consumer's most powerful weapon in his campaign for improved quality. Secondly, the usefulness of new tests ought to be studied. Study of this nature approaches research, a subject discussed later; but it is fitting to draw attention here to the fact that, in view of the recognised shortcomings of existing tests, the exploration by practical trial of the new avenues which have already been indicated is most necessary, and will be to the ultimate benefit of those consumers who still grudge the expense of "non-productive" investigations.

Another difficulty which deserves mention, and one which is very serious in some organisations, is that of testing supplies before they are used. Sometimes because it is the policy of a firm to hold no stocks of any size, and sometimes because of exceptional circumstances, it happens that supplies pass straight from the receiving yard to the press. Under these conditions it is often impossible to make adequate tests even when, as does not always happen, samples are sent to the laboratory as soon as possible; yet as a rule the laboratory is blamed for not having done the impossible and, should the metal turn out to be unsatisfactory, strong opinions concerning the usefulness of the laboratory and its personnel are often expressed in no uncertain terms. Strangely enough, when everything goes well it is not unknown for similar opinions still to be expressed on the grounds that, as the works have got on quite well without its aid, the laboratory is truly the expensive luxury some executives still like to imagine. The way of the white-coated worker is indeed sometimes hard.

Storage and Handling of Metal

Insistent as consumers are in their demands for a better surface finish on sheet supplied to them, it often happens that they themselves make little effort to ensure that this finish is not spoilt between the time metal is delivered and the instant it is offered to the tools.

Suppliers usually take considerable care to protect a surface they have been at pains to produce: so much so that, when a specially good surface finish has been given, sheets and strips are often separated by paper. Methods of packing and transport can be arranged by mutual agreement; but, once the metal is unloaded, it is the consumers' fault should it be allowed to lie about where heavy boots—or even light shoes—can leave their mark upon it, and where dirt and grit destined to score both tools and drawn product can settle. Sheets and coils are often thrown carelessly about, dragged over dirty floors and treated generally as if dents and scratches were of no consequence. Apart from damage inflicted during handling, scores may be produced during blanking by projections or surface irregularities on the guide plates and, occasionally, on the drawing press itself. The remedy is obvious.

The amount of care which it is desirable to bestow upon metal will naturally vary with the initial excellence of its surface and with the purpose for which it is required, yet it is safe to say that in many instances improvement in handling and storage will be essential if the advantages of sheet of initially good surface are to be utilised fully.

Blanking

Blanking is usually regarded as an unimportant operation requiring practically no supervision, yet it has been shown in an earlier chapter that a badly-burred edge due to blunt or badly-set blanking tools can actually cause failure during deep drawing or pressing; improvement, in the form of a more careful watch on blanks and tools, is therefore desirable. This is particularly necessary in view of the increasing use of combined "blank and raise" operations in which the edges of the blank can only be inspected occasionally by stopping the press between the first and second motions.

The use of octagonal in place of round blanks for the drawing of circular articles seems to be increasing. The main advantage which is usually claimed for this change is a reduction in the amount of sheet or strip needed to produce a given number of blanks. Although this saving is valuable when large quantities of metal have to be dealt with, a more valuable yet less frequently mentioned advantage is the shape of the discard produced in the blanking operation. The spidery shapes surrounding circular blanks need considerable space, are difficult to handle, and need to be compressed and baled for storage and transport, whereas the small, separated triangles discarded from the octagon shape are far less bulky and can be closely packed without the help of compression-baling appliances. The saving in strip and the change in the shape of the discard which follows the substitution of octagonal in place of circular blanks is illustrated pictorially in Fig. 309. Octagonal blanks can be seen in Fig. 67 (p. 97).

A disadvantage inseparable from the use of the octagon shape is that the sharp corners which are left on partly-formed shapes are liable to cause injury to the hands and clothes of operators and, being severely work-hardened, may scratch the surface of softer parts of other drawn shapes with which they come into contact.

A change in blanking procedure already predicted is the purchase of ready-cut blanks instead of sheet and strip when large quantities of given sizes are needed. This practice seems desirable from many aspects: the cost of transport of a very considerable bulk of unwanted metal both to and from the works of consumers would be saved;

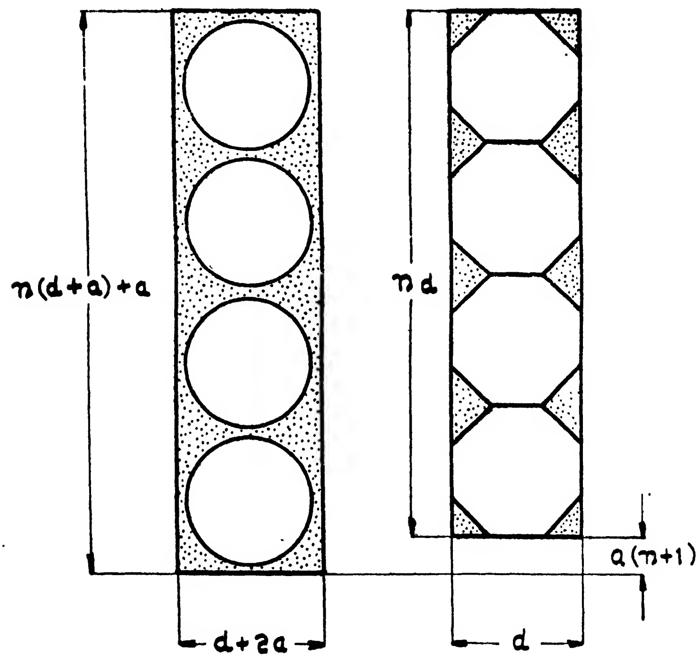


FIG. 309. A comparison of circular and octagonal blanks. Diagram illustrating size and shape of discard and saving in size of sheet needed to produce n blanks of diameter d with a discard of minimum width a.

Saving in length $= a\,(n + 1)$.
Saving in width $= 2a$.

consumers would avoid the cost and inconvenience of handling, baling and disposing of discard, and suppliers would have scrap of known chemical composition, clean and free from contaminatory additions, ready for remelting. Blanks could be packed flat, in a fraction of the space needed for coils or large sheets, and the danger of damage to the surface of the metal during transit would be practically eliminated; indeed, blanks could be transported in cartons or containers right to the side of the press.

One drawback to this procedure is that suppliers could, obviously, stock only a sufficient number of blanking tools to produce certain regularly-used sizes. Even with this limitation, the scheme seems worthy of encouragement for blanks of moderate size; although the use of strip will, of course, continue for articles deep-drawn or stamped in presses equipped with automatic strip-feeding devices.

Another disadvantage is that whereas with coils of strip, and to some extent with batches of sheets, it is possible to isolate small batches of metal for the purpose of testing prior to acceptance, this can seldom be done when cut blanks are supplied. Consumers must not always assume that the contents of a carton of blanks has been blanked from sheet or strip which has received the same treatment in the mills of the supplier, and a blank selected as a sample may represent only a very small percentage of the contents of the carton from which it is taken.

Disposition of Blank. As a rule blanks are cut from strip in a manner which gives the greatest number of blanks from a given weight of strip. When the shape to be made is not circular, it would often be advantageous to cut blanks in such a way that the directions of minimum ductility in the blank corresponded to those of least deformation in the shape. In this way it would be possible to obtain the maximum depth of draw which the strip used could withstand, and in some instances this might more than balance a slight extra cost owing to more strip being required to produce a given number of blanks. Naturally, this practice would be of greatest benefit with strip metal which showed marked "directional" properties; for example, cupro-nickel and, quite often, steel. With large sheets, selected angular arrangement of blanks might be more costly.

Practical demonstration of the value of this suggested practice can often be seen when an article of irregular, and sometimes of square or rectangular, shape is made from round blanks placed fortuitously under the press. When the safety margin is small and, perhaps owing to the arrival of a batch of metal which exhibits more than the usual amount of "directionality," a percentage of articles break under the press, careful examination will usually show that the blanks which have failed are those which have been placed so that the directions of minimum ductility lie near to those of maximum deformation in the shape produced. In such instances the marking of circular blanks so that they can be placed under the press in the most favourable position is well worth the slight extra work and care involved.

Type of Press

In Chapter IX the difference in the kind of motion imparted to the punch by different methods of actuation has been explained, but it may be useful to give here the essential points as they affect the practical man.

The disadvantage of crank-actuation is two-fold. The velocity of the punch varies widely as the stroke proceeds, so that although the speed of the press may seem slow in the eyes of those concerned with output, the speed at some part of the draw may be sufficiently high to cause the lubricating film to break down, causing scoring or fouling. The other, which is of particular significance in second-stage operations (see Fig. 183, p. 331), is that when the punch strikes the bottom of the shell its velocity is near the maximum, thus greatly increasing the danger of the bottom being torn out before the whole shell can be set in motion to follow the bottom as it speeds downwards on the end of the punch. For these reasons some method of actuation which imparts a uniform velocity to the punch is preferable, and it is a proved fact that deeper draws can be obtained on hydraulic or rack-actuated presses than on crank-actuated presses even when the total time of the working part of the stroke is the same.

These remarks are not intended to discourage the use of crank presses in all instances, for often they are quite satisfactory and of simpler construction and easier to maintain and use than others. For severe draws, however, the advantages of other types cannot be overlooked, and when new plant is being purchased serious consideration should be given to the factors just mentioned.

Tools

It is not proposed to enumerate all the minor improvements and alterations in materials, heat-treatment and surface finish which, it is hoped, previous discussion in Chapter X will have shown to be necessary, or at least desirable. A general indication of the probable trend of major development may, however, be added.

As regards materials, it seems likely that cast iron will find increasing use in both the cast and the heat-treated condition by reason of its natural excellence as a working surface and because it can be cast closely to shape, thus greatly reducing the cost of tool production. Now that special irons are becoming more readily available, and their properties more generally recognised, it is likely that their lower cost will of itself lead to their substitution in place of steel tools in many instances. There will undoubtedly be a strong tendency for many small tools now machined from forgings, and not infrequently from solid bar, to be cast closely to shape in cast iron of suitable variety, thus saving much time and money. When cast iron cannot be used, the advantages of nitrided or chromium-plated steel must surely arouse increasing interest, but the importance of a core of adequate strength and, in the case of chromium-plate, of proper deposition needs to be recognised more widely.

It is possible that for tools which are required to take a very high polish—for example, when they have to be chromium-plated—special steels unusually free from non-metallic inclusions may be produced on a commercial scale. The demand for very clean steel for the highly-polished dies used in the moulding of plastics has led to the development of a somewhat novel procedure whereby unusually clean steel can be obtained. Pellets of calcium, fired from an air gun vertically into a mould of molten steel, penetrate slag and metal and strike the bottom of the mould before becoming molten and causing an evolution which collects and carries to the top of the ingot those suspended slag particles which, being too small to rise of their own accord, would otherwise remain suspended. In the future the use of steel treated by this or some equally effective method may become a recognised procedure for special tools.

More care and better equipment for heat-treatment must in some instances be classed as a badly needed improvement. Whether the use of controlled-atmosphere furnaces will entirely supersede the present method of packing in pots is uncertain because, with the atmospheres now available industrially, when perfectly "clean" hardening is obtained on polished tools appreciable surface decarburisation usually occurs. More suitable atmospheres may be developed; but, in view of the very critical conditions separating a decarburising from a scaling action, it is possible that "clean" as distinct from "bright" hardening may represent the best condition obtainable industrially. "Clean" is here meant to imply the formation of a very slight coating of oxide comparable with that found on the best pack-hardened tools. For example, under suitable conditions a protective atmosphere of charcoal gas causes a negligible amount of oxidation without danger of surface decarburisation.

The giving of a much better polish to the working surfaces of tools would in many instances prove of very great benefit. Deeper draws would be obtained, and troubles caused by fouling, loading and scoring would be lessened. This is particularly true in the case of aluminium, yet with other metals much more careful finishing of the tools used would often prove of unsuspected benefit, and comparison of true costs would show that the admittedly high cost of very careful polishing was repaid many times.

As predicted in earlier chapters there is likely to be a big increase in the use of "soft metal" tools made from zinc and lead, usually alloyed to give greater hardness. Although devised originally to shape light-alloy sheet for aircraft pressings, experience shows that they can be used successfully for short runs on much harder sheet, for example steel, austenitic steel and Inconel, when the thickness is not too great. These remarks apply also to rubber, a material which has become specially popular owing to the increasing use of the Guerin process for the production of shallow pressings.

Turning from materials to design, the benefits which would result from closer co-operation between designers, hardeners and metallurgists have already been pointed out, and it is to be hoped that this co-operation will in the future become a matter of normal routine procedure when the material, shape and heat-treatment of tools is being decided upon.

In order to secure better alignment and to reduce the likelihood of "chatter," particularly when old presses have perforce to be used, there seems no reason why punch and die should not be constructed more frequently as a single unit incorporating bushes on one part sliding on pillars on the other, with a floating attachment to the slide of the press, in the manner invariably used on precision blanking tools. An example of this arrangement applied to fairly large press tools has already been illustrated in Fig. 207 (p. 392). Besides ensuring good alignment, this method of construction would greatly lessen the time and skill needed to set up tools in a press, and might well justify the attendant increased cost of tool-making. It would, for obvious reasons, be more easily applied to small tools of short stroke; yet the possibility of general application should not be dismissed.

Considering the shape, as distinct from the materials and condition of tools, more attention should be given to the choice of radii. Often the radius of a die is smaller than that which theoretical knowledge suggests as being desirable; for there seems to be a curious tendency on the part of tool designers who work by rule of thumb or past tradition to make this radius as small as possible for no logical reason. Again, the old practice of making the top face of a die at 90 degrees to its bore is still too common. Very often deeper draws can be accomplished at one operation when the top face makes quite a large angle, for example, 60 or even 45 degrees, with the axis of the bore. This aspect has been treated mathematically by a number of investigators, for example, Fukui.[64]

A small but important detail in tool design which is often overlooked is the depth of the throat of the die, meaning the length of the parallel part of the bore immediately below the radius before it is enlarged to give clearance. As a general rule, this depth should be made as small as possible, and not decided by some convenient unit of measurement on the inch rule of the draughtsman. Those who question the influence of this factor can easily prove it for themselves, and it will be found that on a "difficult" job shortening the throat will give a reduction in punch pressure, thus reducing the likelihood of the walls of the article tearing; will improve conditions of lubrication, thus reducing the likelihood of scoring and fouling; and, should the die happen to be of meagre section, will reduce the likelihood of bursting during service.

Mention must also be made of a matter not yet discussed, namely, the influence of tool shape upon local thinning of the walls of a deep-pressed shape *when the walls are not "ironed."* Sometimes persistent failures, for which the metal is unjustly blamed, can be traced to this cause which, unhappily, is often admitted but grudgingly by those responsible for tool design. Information of a most valuable kind can almost invariably be obtained by sectioning deep drawn or pressed shapes at each stage of their formation and measuring both the thickness of the walls at very short intervals of space and, which is attempted less often, the hardness. In this way thickness and hardness maps of the kind illustrated in Fig. 310 can be constructed which give most helpful, and often unexpected, information.

One feature of such maps is that they are conclusive and thus save prolonged and perhaps heated argument based on suppositions. When, at some stage in the formation of an article, a certain zone of its wall is found to be work-hardened appreciably more than adjacent zones, it is, clearly, foolish to expect this zone to elongate in the next operation as readily as the adjacent softer zones unless a happy balance happens to be made by a corresponding variation in thickness or circumferential measurement. The only way to secure the desired hardening and reduction in uniform thickness is to alter the shape of the tools; no change in the properties of the sheet used will be of avail.

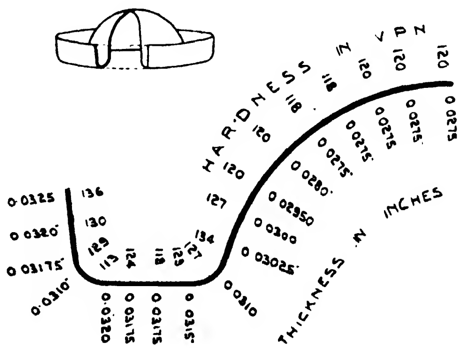


FIG. 310. Hardness and thickness "map" of wall of first-operation shell formed from brass blank of 109 V.P.N. hardness and 0·031 inch thickness.

Another feature is that often maps are more readily appreciated by tool-designers than argument, perhaps unsupported by tangible evidence, could be. Also they have the advantage of showing the exact places where alteration shall begin. The construction of such maps, of the form illustrated, is a lengthy and laborious task, but one which is well worth while and one which ought not to be reserved for a last defence of the metal used, for, even though no failures are experienced, modification to the shape of the tools suggested by these maps will sometimes lead to a reduction in the number of operations needed to produce a shape of given depth.

LUBRICATION

It is likely that lubricants possessing in increased degree the desirable properties outlined in Chapter XI will be developed, but it must be remembered that with the types of lubricant now available certain properties are apparently incompatible. At present it seems that lubricants which form a strongly adsorbed film upon metal surfaces are difficult to remove, and sometimes actually corrosive. The discovery of a non-corrosive lubricant which, although forming a strongly adsorbed film possessing a high degree of slipperiness, could be easily removed and was suitable for use in deep drawing and pressing operations would, therefore, be most valuable.

Interesting possibilities of increasing the load up to which conditions of viscous lubrication will be maintained are suggested by recent experiments on the effect of small additions of certain non-organic substances to refined mineral oils. It is not yet understood exactly how these additions function, but it seems that their action is different from that of the additions usually made to the so-called "extreme pressure" lubricants to produce a strongly adsorbed film on the surface to be lubricated.

Apart from changes in lubricants themselves, improvement in the following directions is needed: more careful selection of a suitable lubricant for a given set of conditions; more thorough mixing or, preferably, the introduction of compounded lubricants which do not separate on standing; more adequate and uniform supply of the chosen lubricant to the work; better retention of the lubricant during the whole of the drawing operation by the production and maintenance of a very smooth surface on the tools used; and, lastly, adequate, and sometimes immediate, removal of the lubricant after the drawing operation. These and other relevant matters have already been studied in some detail.

When a pressure-plate is used, much of the lubricant adhering to the blank may be removed from the very regions on which it is needed most. A possible improvement would therefore seem to lie in provision for the introduction of an additional supply of lubricant, possibly under pressure and through an annular channel close to, but before, the radius of the die. This refinement would be of more benefit with poor lubricants than with ones whose truly "oily" or chemically active nature produced a strongly adsorbed film on the surface of the blank, because this film ought not to be removed, nor even broken locally during the passage of the blank through the pressure-plate.

Should new types of lubricant which form a strongly adsorbed or chemically-active film upon the surface of metal come into common use, the problem of lubricant removal will need to be given much more thought if the defects considered in Chapter III are to be avoided. Even with the lubricants now favoured, the provision—and immediate use after the press operation—of proper and appropriate cleaning devices utilising sprays and vapour cleansing mediums would in many instances constitute a much-needed improvement.

Speed of Drawing

Insufficient attention is given to the very important matter of speed of drawing. In the past, speed of drawing has been—and very often is still—determined entirely by the speed of operation of the presses available, this being fixed partly by the design of the press and partly by the speed of rotation of the motive power employed, be this a built-in motor or line shafting. With either of these sources of power the speed of operation is rarely altered in an attempt to meet, even partially, the requirements of the particular metal and shape being drawn: a state of affairs which recent discoveries concerning the influence of speed upon the ability of metals to suffer plastic deformation suggests as being wholly opposed to the full exploitation of the capacity for deformation in some, if not in all, metals.

Presses having a usefully large and quickly adjustable range of speed will not become available until consumers show an insistent demand for this additional mechanical refinement; the remedy lies, therefore, in their own hands. Although it must be admitted that theoretical knowledge concerning the precise influence of speed of drawing is at present scanty, it will be a good thing if, when purchasing new plant, consumers insist on being provided with whatever facilities for varying speed of operation can be obtained. When this is done they will be in a position to make use of any new knowledge which may be forthcoming and, which is equally important, to experiment themselves in a practical manner.

It is to be regretted that under modern industrial conditions any attempt to reduce the speed of a machine, be it a large, relatively slow-moving press or a high-speed automatic, arouses severe disapproval on the part of those responsible for output. It must be pointed out however that, quite apart from any improvement in the quality of the product which a reduction in speed may cause, the time occupied by the stroke of a press is usually small in comparison with the time-cycle of the entire operation. For this reason a reduction in the actual speed of deep drawing or pressing may not slow-up production to the extent imagined by the opponents of such an alteration.

Some ideas concerning the influence of speed of deformation upon deep drawing properties have already been given in Chapter XIII, and in this consideration of essentially practical matters only three things need be said. One is that when shapes are breaking under the press, or perhaps "fouling" or "scoring" is taking place, reducing the speed of drawing will often minimise troubles of this nature by reason of the better chance given to the lubricant to perform its task and by reason of the decrease in the force of impact of the descending punch. The second is that a few metals, for example, zinc, behave better when the speed of drawing is considerably above that used normally except perhaps in small, high-speed presses. The third is that, in spite of what has just been said, present knowledge suggests that a very high speed of deformation may enable unexpectedly severe draws to be accomplished *provided* that the initial impact does not produce rupture and that lubrication is adequate; but this aspect does not as yet concern the industrial worker engaged on his daily task. Finally, the influence upon speed of drawing of the type of press used, that is whether the punch is actuated by a crank or by hydraulic methods, must always be borne in mind for the reasons explained already.

Pressure-plate Control

The advent of fully-controllable hydraulically-operated presses will undoubtedly enable more severe draws to be accomplished when the skill and experience of the operator enables him to take full advantage of the available degree of control. Far finer control of the pressure-plate will probably be found to be of unsuspected benefit in the production of deep-drawn shapes in one or two operations; the crudeness of the old type of spring-loaded pressure-plate has precluded the following-up in practice of the indications already given by research. The benefits of methods of punch actuation more controllable and less brutal than that of a crank press have been pointed out in Chapter IX.

It is unlikely that these controllable presses, which will need a skilled operator to work them properly, will find general application. Their speed of working will be relatively slow, although not markedly more so than that of crank presses of large size, so that for the production of small articles such as cartridge cases the use of high-speed, direct-action, mechanically-operated presses will certainly continue. Even in these presses it is likely that more attention will be given to the control of the pressure-plate, because the practical drawing tests now being carried out in many laboratories show, for example, that in some metals the depth obtainable on a second draw is influenced to a surprising degree by the loading imposed on the pressure-plate in the *first* draw.

The present practice of controlling the pressure-plate by resilient pressure does not seem sound theoretically. It will be better when there is devised some form of robust mechanical control which will alter the distance between pressure-plate and die as the punch descends yet will not be affected by the behaviour of the blank. It is this *distance*, not the actual *pressure* in pounds per square inch imposed on the blank, which is important. When wrinkling starts the wrinkles will grow and force the pressure-plate away from the die with remarkable force, and an applied load of the magnitude required to prevent serious wrinkling may subject the unwrinkled blank to a pressure so great that the full deep drawing and pressing properties of the metal cannot be used.

In the past recognition of this principle has led to two schools of thought concerning pressure-plate loading. One favours the use of a pressure-plate loaded by a spring, hydraulic or pneumatic methods which, although they will allow the clearance to increase as the draw proceeds, will not always prevent wrinkling unless undesirably high pressures are used. The other favours a virtually fixed pressure-plate held down by very heavy springs or by the dead weight of part of the press mechanism on pegs adjusted to give a certain clearance, a method which allows no useful variation during the stroke of the punch. It has been suggested in Chapter IX that a better way would be to start the draw with a certain clearance between pressure-plate and die, and to increase this clearance at a predetermined rate to a predetermined final clearance by mechanical means actuated by, or synchronised with, the descent of the punch and incapable of alteration by pressure exerted by the thickening blank. The mechanical details of such a contrivance, although complicated, would be simple by comparison with those of many machine tools which function in a perfectly satisfactory and reliable manner.

Control of the pressure-plate in this manner may seem to preclude any control by the operator during the drawing operation, yet by added mechanical devices it would be possible for the operator to regulate the clearance instead, as with pneumatic or hydraulic operation, the pressure; a refinement which seems ideal. Hydraulic operation could still be employed, provided that the arrangement and reserve of pressure were such that a thickening blank could not force the pressure-plate and die beyond the predetermined clearance at any stage of the draw.

Reversed Drawing

By this is meant the practice of forming a depression, often of considerable depth, in a blank and then forcing this depression back through the plane of the blank, in the reverse direction to that used first, to form the full depth and final profile of the desired article. This procedure enables a deeper draw to be accomplished without the help of inter-stage annealing and, whether annealing is carried out or not, enables a thicker and more uniform wall thickness to be obtained in the finished article. Reversed drawing is in press-shop terminology "kinder to the metal" than one-way drawing, and measurements show that for an article of given shape and depth the residual stresses present in the walls after deep drawing or pressing are less when the article is formed by reverse drawing than when it is formed by one-way drawing.

When reversed drawing is used a slightly larger blank is needed to form a given shape than when direct drawing is used. This explains in part the increased thickness of the walls; but the exact way in which the benefits of reversed drawing arise is not always clear, because it might be expected that the extra working imposed by this method would cause the metal to work-harden more, and thus reduce instead of increase the depth of draw obtainable. A more uniform distribution of deformation throughout the depth of the drawn shape may partly explain this apparent anomaly, but it does not seem to provide a satisfactory explanation for the very marked increase in depth of draw obtainable, for example, in the familiar reverse-draw Erichsen impression, which is to be regretted has upon occasion been used for reasons which cannot be described as altruistic.

Reversed drawing will probably be used to an increasing extent, yet its indiscriminate use is to be avoided because its true usefulness will depend entirely on the requirements of the shape it is desired to form.

Severity, Number and Apportionment of Press Operations

Whenever cost of production is an important consideration, the urge to form a given shape in the fewest possible number of draws will always be strong. In the past any reduction in the number of draws needed to form any given article has been a matter of "trial and error" depending entirely on the skill and experience of press-men and tool-designers. There is every reason to expect that in the future there will become available an increasing volume of published knowledge to guide these harassed individuals in their planning by indicating, first, the best way to effect given reductions and, secondly, what can and what cannot be accomplished under given conditions with a given metal. How far this information will be used industrially will depend on the initiative and understanding of those responsible for the planning and supervision of deep drawing and pressing procedure.

In the future the apportionment of drafts with any given metal, although influenced by past experience, will tend to be based more upon theoretical data concerning at least three items:

(1) The maximum allowable deformation under pure tension as indicated by special or "derived" stress-strain curves of the kind described in Chapter XII.

(2) The maximum allowable deformation under complex stresses as indicated by actual drawing tests on machines such as the A.E.G. laboratory press illustrated in Fig. 244 (p. 496), by wedge-drawing tests or by methods not yet devised.

(3) The known habits with respect both to normal recrystallisation and also to abnormal recrystallisation, for example, to critical-strain crystal growth.

It will be obvious that even in articles of fairly simple shape it will be impossible to arrange for the theoretically-ideal amount of deformation to be given in all regions. In spite of this, careful study will usually enable a useful compromise to be made in at least two directions. First, the severity of successive draws can be arranged approximately in the order which the special stress-strain curve, for example, that illustrated in Fig. 256 (p. 516), for a particular metal suggests as being desirable. Secondly, ranges of strain likely to favour critical-strain crystal growth can be avoided as far as possible when inter-stage annealing has to be given.

Concerning the first aspect, curves of the kind mentioned show that for steel and brass decreasing amounts of deformation are, as is well known, needed for successive draws, but that this requirement does not hold for all metals. Austenitic steel of the 18 per cent. chromium, 8 per cent. nickel type needs a severe initial draw if best results are to be obtained, while the 17 to 25 per cent. chromium, nickel-free variety behaves in the reverse manner and needs a light first draw, followed by draws of increased severity. These facts, first suggested as a result of practical shop experience, are now confirmed by the shape of the modified stress-strain curves of the metals mentioned: a clear indication of how, reversing the procedure, special stress-strain curves can show how drafts should be apportioned and how their study could save prolonged and expensive experimenting in the shop.

As regards the second aspect, fairly definite knowledge concerning the ranges of critical strain for the common metals is already available, yet seldom used industrially. For example, a curve showing the range for 0·1 per cent. carbon steel has already been given (Fig. 138, p. 208); while the range for aluminium, though established less definitely, is known to lie between 5 and 20 per cent. reduction. The avoidance of stretcher-strain markings in steel, another troublesome phenomenon, by similar methods has already been suggested. Approaching these problems from another angle, both the phenomena just mentioned can be avoided by using sheet which has been lightly cold-rolled to an extent which, although adequate, reduces the ductility by only a small amount.

The value of the original wedge-drawing test and its various modifications, or of practical drawing tests made in standard cupping tools, as an aid to the apportionment of drafts in the production of articles under industrial conditions is as yet hardly established. At present their most useful application seems to be that of a test for measuring that peculiar combination of fundamental physical properties of sheet metal manifested as what can only be described as "drawability," but it is possible that in the future their application may be extended.

In some press-shops it is a fairly common practice to make up sets of miniature tools before making production tools costing several hundred pounds. Although this practice is useful sometimes, it is unsafe to expect too close a relationship to exist between the behaviour of sheet deformed in very small and very large tools of similar shape. Among the reasons for observed discrepancies there may be mentioned the "scale" effect which has so often dashed the hopes of inventors who base their claims upon the performance of models; the fact that often the same thickness of sheet is used in both miniature and large tools and that even when thinner sheet is used in the small tools the difference is rarely truly proportional, and furthermore that the ductility/tenacity ratio of thin and thick sheet of the same metal is different; that the speed of drawing and the tool clearances may be different, and that conditions of lubrication may not be the same. On the other hand the construction of full-sized experimental tools in "soft metals," an idea put forward in an earlier chapter, has much to commend it and would often prove a profitable insurance.

As an example of how scientific study of the recrystallisation behaviour of a metal, the last of the enumerated trends, can yield valuable information directly applicable to industrial practice, there may be cited the work of Hanemann and Vogel.[135] Studying the recrystallisation of cold-worked aluminium by means of X-rays, these investigators were able to put forward the following principles to be observed in press-shop practice if best results are to be obtained. First, that the region of critical amounts of cold-work for producing abnormal crystal growth during subsequent annealing lies between 5 and 20 per cent. reduction; second, that deformation should be accomplished in as a few a number of blows, passes or drafts as possible and, third, that the deformation should be carried out at a high speed. Admittedly, a general indication of these principles could be deduced from a prolonged observation of successes and failures in the press-shop, but this deduction would not be of a precise or entirely reliable nature and might take years to obtain.

Inter-stage Trimming

When the properties of aluminium were being discussed it was said that it was of great benefit to trim off the top of a deep-drawn cup before proceeding to another deep-drawing operation. This practice, although specially useful with aluminium, often proves to be of considerable benefit with other metals, particularly when "ears" have been formed. When the shape of the article allows the rim to be parted off easily, the extra operation involved will often pay for itself by enabling a deeper cup to be formed before annealing becomes necessary. It is a practice which can be recommended with every confidence.

Storage of Drawn Shapes in process

Except in shops which are engaged in the production of a large output of some particular article, it is rare for shapes requiring several press operations to pass through all stages without some, and often lengthy, interruption. Some of the troubles which can occur as a result of this delay have already been pointed out in Chapter III; when conditions do not allow uninterrupted progress, the only way in which improvement can be made lies in giving partly-drawn shapes a low-temperature, if not a full, anneal. With steel left for long periods this treatment may not prevent some loss in ductility; furthermore, the ferrous metal will require adequate protection against rusting.

Improvement is badly needed in the conditions under which partly-drawn work is stored. Bins or stacks of partly-drawn shapes are often left uncovered in shops, passages and even in the open to pick up grit and, in the case of steel, to rust. The problem of storage is, admittedly, difficult when space is limited, yet it is one which when tackled energetically removes the causes of many irritating and sometimes serious troubles and at the same time assists in the maintenance of a good surface on tools and, obviously, on the work itself. Attempts to reduce polishing costs by the use of good quality sheet, proper annealing and careful deep drawing or pressing can be nullified when the surface of the finish-drawn shapes becomes rusted or pitted by corrosion.

Such conditions may seem improbable to those fortunate enough to work in modern factories, but it must be remembered that a considerable amount of deep drawing and pressing is still carried out in unfavourable surroundings, and that familiarity has led to a lack of realisation of the damage which lengthy storage under bad conditions is, perchance, causing.

Annealing

This, the next stage to be considered in the sequence of operations through which sheet passes in consumers' works, is a very important one. A few years ago it was an axiom among suppliers of sheet for deep drawing and pressing that consumers would ruin any sheet during inter-stage annealing; to-day, although so sweeping a generalisation would certainly be untrue, it must be conceded that in not a few instances grossly incorrect annealing is still given and that in others the closeness of control still fails to reach a desirably high standard.

General recognition is needed of the fact that annealing is as much a "precision" operation as hardening, and that the desired physical properties, upon which the success of subsequent press operations depend, will not be forthcoming in annealed metal unless correct heat-treatment has been given to it. A mechanical operation which spoilt the product would not be tolerated in a production sequence in a modern factory ; so it is curious that when the faulty operation is one of heat-treatment it is often difficult to secure its remedy—and sometimes even its recognition—by responsible persons unappreciative of its metallurgical importance.

Improvement is needed in three distinct directions : the installation of annealing plant which is capable of giving the desired heating conditions ; the provision of instructed supervision, when such plant is installed, to ensure that it operates correctly at all times and, of importance, that the *whole* of each charge placed in or through it receives the desired treatment, and, lastly, the choice of suitable heat-treatment for the particular metal and article being annealed. To these may be added a fourth which in these days can hardly be regarded as a luxury, namely, the provision of a controlled atmosphere capable of producing a desirably " bright," or at least " clean," surface on the annealed metal.

Annealing Methods and Plant. The practice of packing work, either loose or in pans, into large, still-atmosphere, muffle or semi-muffle furnaces cannot be condemned too strongly now that much better methods are available. With the old type of furnace, which is still used occasionally, it is almost impossible to secure a desirable degree of uniformity of heating throughout a large charge, while the use of charges which are small in relation to the size of the furnace chamber is wasteful and will seldom be tolerated in works practice. Some years ago the introduction of water-sealed furnaces carrying work packed in large pans on an endless chain was hailed with enthusiasm ; yet it is a certain fact that, in the absence of a well-circulated atmosphere, large furnaces of this type are seldom capable of heating their charge sufficiently uniformly to satisfy modern demands.

The choice of modern annealing plant should be influenced by at least five considerations : the size and shape of the articles to be annealed ; whether charges will consist of articles of approximately similar, or widely dissimilar, size ; whether continuous operation is required ; the temperature to be maintained, and the degree of surface cleanliness desired upon the annealed articles. For the inter-stage annealing of partially-drawn shapes, present demands can be met most fully by only two types of furnace : those having a heating chamber of large size relative to that of the articles to be annealed but employing a forced-circulation atmosphere to ensure that the whole charge is heated uniformly, and those in which the work passes through a chamber which, although very long, is small in sectional area in relation to the articles to be annealed, no mechanical agitation of the atmosphere being usually attempted. Either type may or may not utilise a protective atmosphere to prevent scaling of the heated charge, and each possesses distinct features which must be borne in mind when a choice has to be made between them.

[*By courtesy of Wild-Barfield Electric Furnaces Ltd.*

FIG. 311. Inter-stage annealing brass shell cases in electrically-heated forced-circulation furnaces equipped with automatic temperature control and recording apparatus.

[*To face p.* 679.

Forced-circulation Furnaces for Batch-annealing. Without question the forced-circulation type of furnace offers the quickest and most reliable means of heating a charge of any bulk uniformly up to temperatures not exceeding 650° C. In these furnaces air or some special atmosphere is circulated by a fan at high velocity over heating elements, which may be disposed either in the main chamber or in a separate compartment, and through the charge. Fig. 311 shows an installation, not utilising a protective atmosphere, which gave great satisfaction in the inter-stage annealing of brass shells. It is interesting to record that, prior to the installation of this particular plant, a high percentage of scrap was common with shells annealed in still-atmosphere furnaces: a convincing proof of the argument put forward in these pages. The rapidity and uniformity of heating of the full charge in such furnaces is remarkable, the time cycle being only a fraction of that required by a normal furnace heating—with questionable uniformity—a comparable charge to the same temperature. Automatic controlling apparatus is practically essential, and recording charts so useful that they can hardly be classed as a luxury; with such equipment annealing can be carried out by unskilled labour with real certainty and regularity.

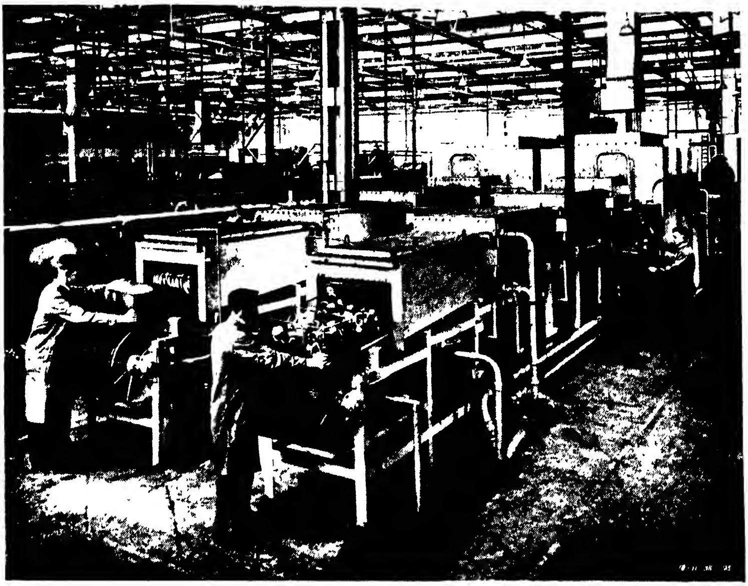
Slow circulation or a "disturbed" atmosphere, induced by fans operating in the chamber of a furnace of orthodox design, is better than no circulation at all, but its effect cannot be compared with that produced by high-velocity circulation, particularly as regards rate of heating. This does not imply that the installation of fans in an old type of furnace chamber is not worth while; on the contrary, the incorporation of a fan has often changed a stress-relieving furnace from a thoroughly unreliable piece of plant into one which, although not ideal, can be counted upon to give at least a certain measure of relief to every article in a charge.

For the annealing of brass or other non-ferrous metals, for stress-relieving, and for any treatment below 650° C., forced-circulation furnaces cannot be equalled; but they are definitely unsuitable for higher temperatures, such as the range of 910 to 920° C. which is necessary for normalising steel of very low carbon content. The principal reason for this is that at the higher temperatures heat transference takes place mainly by direct radiation, not by convection, the effect of a rapidly circulating atmosphere upon the rate and uniformity of heating diminishing rapidly above 700° C. Minor disadvantages of the forced-circulation furnaces at high temperatures are the mechanical troubles associated with fans working at high temperatures and, when clean-annealing is being carried out, the difficulty of maintaining at reasonable cost the special atmosphere necessary to prevent surface oxidation of steel.

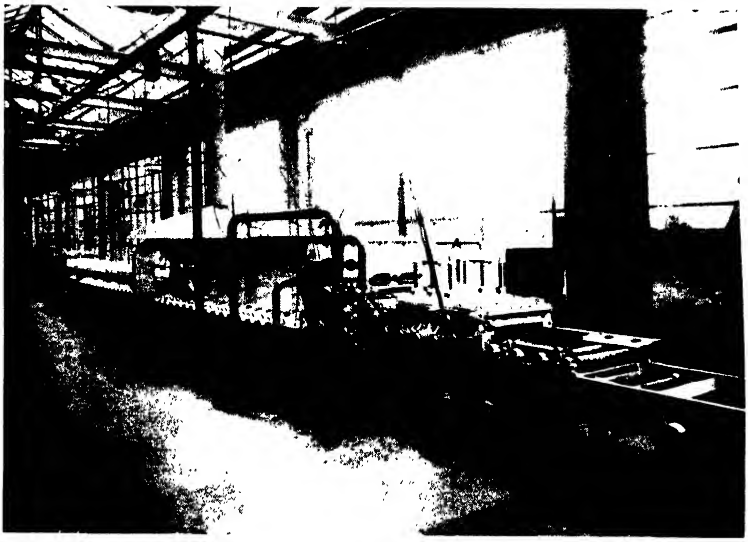
In a preceding chapter it has been pointed out that the only sure way to prevent the occurrence of critical-strain crystal growth in steel pressings is to normalise them instead of annealing at some temperature below the critical point of the steel. Forced-circulation furnaces being unsuitable for this purpose, normalising is best carried out in the second of the two enumerated types of furnace which, of course, can when desired be operated at a lower temperature for annealing non-ferrous metals when a forced-circulation furnace is not available.

Tunnel Furnaces for Continuous-annealing. This second type is essentially the old, chamber or muffle furnace reduced in sectional area so that different parts of the charge are not at widely varying distances from the heating elements nor effectively shielded from them by other portions of the charge. It is usually made in the form of a long chamber through which work, sometimes placed in trays, is carried by means of an endless open-mesh belt woven from heat-resisting wire or else by means of a roller hearth. Only part of the tunnel is surrounded by the furnace proper ; a short length at the entrance end serves to conserve the protective atmosphere which is usuall employed in furnaces of this kind and also to ensure that air is eliminated before the work is heated, but the greater part of the length is surrounded by a water jacket which cools the work to a temperature sufficiently low to ensure that serious oxidation does not occur when it emerges out of the protective atmosphere into the air at the exit end of the tunnel. It is very desirable that the furnace proper be divided into at least three zones, each having its own pyrometer, which can be regulated independently of one another. Without this it is difficult to control the temperature reached by the work passing through the furnace unless it moves at one critical speed, which may not always be the best from the production or economic aspect.

Two typical furnaces are illustrated in Fig. 312. The upper photograph shows two large-aperture furnaces, one annealing brass and the other normalising steel. In both furnaces the pressings are placed in trays and carried through the tunnel on an endless belt of nickel-chromium alloy. Both furnaces have a protective atmosphere of cracked and burnt ammonia and are heated electrically ; the control and recording panel can be seen at the right of the photograph. These particular furnaces are of unusually large aperture and, in order to reduce gas leakage from the ends, the tunnel is not, as is usual, straight and horizontal, but rises from each end to the heating zone. By way of contrast the lower photograph shows a roller-hearth furnace run entirely on town's gas, which is burnt in " radiant tubes " to heat the work and in a separate chamber to a partially-burnt condition to give the protective atmosphere. In this particular furnace the rollers are not water-cooled, but sometimes this refinement is used to prolong the life of the rollers, and their bearings, in the furnace zone.



[*By courtesy of Birmingham Electric Furnaces Ltd.*



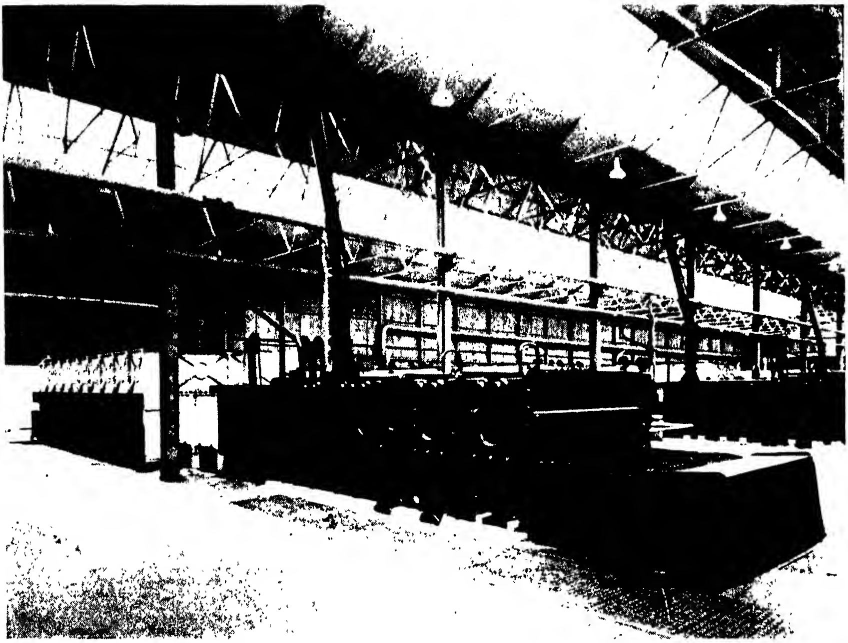
[*By courtesy of the Incandescent Heat Co. Ltd.*

FIG. 312. Two kinds of tunnel furnaces for clean-annealing pressings in a protective atmosphere.

Top : Exit ends of pair of electrically-heated, large-aperture, continuous mesh-belt furnaces utilising a circulating " regenerated " atmosphere of " cracked " and burnt ammonia.

Below : Entrance end of gas-heated, radiant-tube, small-aperture, roller-hearth furnace utilising an atmosphere of partially-burnt town's gas.

[*To face p.* 680.



[*By courtesy of Curran Bros. Ltd.*

FIG. 313. High-pressure spray, continuous, automatic pickling plant attached to discharge end of gas-heated muffle furnace annealing deep-drawn brass cups.

[*To face p.* 681.

Both endless belts and roller hearths have their advantages and disadvantages, and choice must be governed by the kind of work the furnace has to handle. Belts tend to stretch and are expensive to replace; rollers give less efficient furnace operation owing to loss of heat by conduction. As a general rule belts are preferable when work of light weight has to be handled, whereas roller-hearths give better service when heavy trays are used continually.

One drawback to furnaces of the type just described is that, although the maintenance of an efficient gas-seal at each end of the furnace by means of asbestos flaps presents no great difficulty with small articles, when shells of some size have to be dealt with the leakage of gas can become serious and, when an expensive gas is being used, even prohibitive. Curtains made of asbestos strings and, particularly effective when temperature permits, of strings upon which are threaded discs of aluminium have been used to reduce gas losses round large, irregularly shaped articles. Recent developments in nickel-chromium heat-resisting alloys promise a reduction of such troubles as stretching and surface attack or embrittlement of the conveyor belts used in this type of furnace.

Another disadvantage is the great length of the tunnel when space is valuable, but it is difficult to see how this length can be reduced unless the mechanical difficulties inseparable from a horse-shoe or a spiral tunnel are accepted or, alternatively, the area of the cooling chamber is increased and the rate of passage of work through it decreased relative to the rate of passage through the furnace proper, an arrangement which would lead to mechanical complication. A word of warning must be given against using cooling chambers which err on the short side. The author has seen more than one furnace, of a type normally giving excellent results, which produced discoloured work because in order to conserve floor space the cooling chamber had been shortened beyond the furnace-maker's recommended length.

Another type of furnace, in which it is less easy to secure uniform annealing of a charge, is the ordinary bell type of furnace. The modern version of this usually consists of a sealed container over which the furnace proper is lowered during the heating cycle. Gas heating by means of radiant tubes controlled automatically has been applied very successfully to furnaces of this type, and a protective atmosphere is usually employed. Although recent developments have increased the ease of manipulation and uniformity of heating of this kind of furnace, it seems likely that, for the reasons already given, its application will be more to the annealing of coiled strip than to the interstage annealing of press-shop products unless forced circulation by means of fans is utilised, as in the installation illustrated in Fig. 43 (p. 55).

Control and Supervision. With old types of annealing furnace, the eye of the operator was the principal guide to the treatment accorded to a charge. Pyrometers were usually installed high in the roof, were seldom checked and, when relied upon, often proved less useful than the judgment of an experienced man, although very frequently the ill-effect produced by too high a temperature was not appreciated by furnace operators.

With modern furnaces automatic control is, as has already been said, practically a necessity and is usually included as a part of the plant and not as an optional extra. Pyrometers operating electric relays and switches seem unquestionably the best method of control yet devised for electrically-heated furnaces and, with the aid of electro-mechanically operated valves and dampers, for gas-fired furnaces as well. Methods of control which depend on light-sensitive cells are likely to be unreliable unless adjusted to, and used solely for, one metal and one temperature. Bi-metal thermostatic devices are used with some success for low temperatures, and certainly possess the merit of being cheap, simple and compact; but pyrometric control seems preferable for temperatures exceeding 300° C.

The location of the pyrometers used for automatic control needs careful thought. When several pyrometers are employed, the position most suitable for controlling—which is not always the one most likely to indicate the true temperature of the work in still-atmosphere furnaces—should be chosen. The pyrometer actuating the recording apparatus, when this is used, should be placed so as to measure as closely as possible the temperature of the charge at a chosen position in the furnace. With forced-circulation furnaces the problem of temperature measurement is simplified, but it must be recognised that in still-atmosphere furnaces a protruding thermo-couple tube will seldom indicate the true temperature of work passing quite close to it, and proper allowance must be made for this fact. Those who doubt this statement can prove its truth by taking readings in various parts of a furnace chamber and charge with the aid of a sensitive exploratory thermo-couple, and comparing these readings one with another and with those given by the fixed couples installed in the furnace. An exploration of this nature will often reveal a difference of the order of 50° C. where no difference was thought to exist.

Bold claims are often made by furnace-makers as to the closeness with which their furnaces can be controlled. Allowing for possible exaggeration, remarkably close control can often be achieved; yet how foolish it is to pay for the necessarily expensive apparatus required to secure this very desirable condition if the controlling pyrometer is allowed to function unchecked until it contracts an error of perhaps 10° C. or even 20° C.! Thermo-couples will not give constant readings for an indefinite period ; periodic comparison of all couples in use in annealing—or any other—furnaces with a reliable standard couple, used only for checking purposes, should be insisted upon.

Even when the pyrometric installation is reasonably accurate, judgment and experience are still needed with still-atmosphere furnaces to ensure that all parts of a charge are heated to within desired temperature limits for a suitable time. This is particularly true when one furnace has to be employed for annealing a variety of articles, perhaps at different temperatures, and constitutes a strong argument for the use of forced-circulation furnaces when these can be used.

It must not be forgotten that surface condition has a noticeable influence upon reaction to annealing. When two pieces of metal, one having a dull matte surface and the other a bright polished surface but similar in all other respects, are placed at the same distance from a source of radiant heat, it will be found that the specimen having a dull surface absorbs heat more quickly than the other, which reflects a greater proportion of the radiated heat which strikes it. For this reason when annealing conditions are regulated so that strip or pressings having a dull surface are *just* annealed, should similar strip or pressings having a bright surface be substituted it is quite likely that they will not be annealed properly.

Protective Atmospheres. The protective atmospheres used for annealing are becoming cheaper and more easy to control. In some of the earlier installations hydrogen was used, but owing to the cost and the danger of explosion this was soon replaced by butane and later by ammonia.

Ammonia, either dissociated or burnt, is a most useful protective atmosphere because it is reasonably cheap, easily obtained in a state of high purity, and by reason of its simple composition—hydrogen and nitrogen—more easily controlled than atmospheres obtained from the partial combustion of town's gas, a highly complex product. " Cracked " ammonia is preferable when an atmosphere of high hydrogen content is desired, but " burnt " ammonia is cheaper and, provided that the product is thoroughly dried by passage over activated alumina, silica gel or other adequate agents, perfectly satisfactory for readily oxidisable metals. In furnaces of suitable design considerable economy in gas can be obtained by the method of " re-circulation," in which the furnace atmosphere is circulated continuously by means of pumps and mixed in the gas plant with a proportion of new gas, drawn from the ammonia burner. This addition may be as low as 10 per cent. when door-leakage is small.

A very cheap and for some purposes adequate protective atmosphere can be obtained by the controlled, partial combustion of town's gas. It is likely that the popularity of this medium will increase, but for its proper functioning the moisture content must be carefully controlled and, of great importance, sulphur must be virtually eliminated; at least two stages of removal seem to be necessary to remove both organic and inorganic compounds of this undesirable element.

It is unsafe to hazard a guess as to what new atmospheres may be utilised for "bright" or "clean" annealing. Cost is, obviously, a matter of major importance; for this reason the successful application of town's gas offers attractions not possessed by more expensive atmospheres unless a system of "regeneration" can be employed. The choice of the atmosphere to be used in a tunnel furnace may be influenced by the shape of the articles to be annealed, because this will decide to some extent the efficiency of the gas seal at the ends of the furnace tube. With batch-type, forced-circulation furnaces the atmosphere must of necessity be renewed with each charge, and a cheap atmosphere is therefore very desirable.*

Advantages of Modern Methods for Inter-stage Annealing. In the past it has been customary to make every effort to avoid inter-stage annealing operations because work was so likely to be spoilt by them; because the resulting surface-oxidation rendered necessary pickling operations before deep drawing or pressing could be continued; because transport over considerable distances to and from furnaces and pickling vats was often necessary, and because the time occupied by annealing, pickling and transport was of necessity somewhat lengthy and unfavourable to the steady flow desired in modern production schedules and layouts.

With modern plant each of these drawbacks has been eliminated. Properly annealed work, having a surface which although not always truly "bright" is so clean that no pickling is needed, can be obtained regularly in a reasonably short time-cycle, while the furnaces themselves can be placed actually in, or branching off, production lines, thus obviating transport. For these reasons there may come a swing toward more frequent use of inter-stage annealing notwithstanding continued improvement in the quality of metal and the consequent increase in the severity of the draws it will withstand before annealing becomes necessary. This does not mean that efforts will not be made to avoid inter-stage annealing whenever possible, because at present controlled-atmosphere furnaces command a high price and, naturally, involve running and maintenance costs for both heating and gas-producing apparatus; it means, rather, that more severe draws can be attempted with safety, enabling parts hitherto machined, built up, or cast to be produced under the press and therefore at a reduced cost.

As a general indication of this trend there may be illustrated an article such as that shown in Fig. 268 (p. 586). Originally made as a casting, the saving in cost and weight offered by a steel pressing led to attempts at this method of manufacture. Several inter-stage

* See Appendix C, page 713, for more detailed description of protective atmospheres.

annealings were necessary to obtain the desired depth on the central thimble but, when normalising above the critical temperature was used, scaling was excessive and pickling difficulties proved serious; yet, when a lower annealing temperature was used, critical-strain crystal growth caused many failures, and pickling was still necessary. "Clean" normalising in a controlled-atmosphere furnace provided a most satisfactory solution to the problem and enabled the desired pressing to be produced regularly without the help of pickling and, by the help of more draws than would at first sight seem necessary to produce the shape in question, with a thick wall to the thimble portion.

To summarise, it can be said that, with the annealing plant now available and with the scientific help which they should have, consumers have no excuse whatever for spoiling their products during inter-stage annealing. Further, protective atmospheres are now available which, used properly, will give very satisfactory "clean" annealing of such difficult metals as brass and austenitic steel, and, with some metals, the much-abused term "bright" annealing can be applied without disingenuousness.

Stress-relieving

It is to be hoped that the practice of low-temperature or stress-relieving annealing will become universal whenever there exists a likelihood of failure by season-cracking or stress-cracking.

It is necessary again to emphasise that it is *not* sufficient to pack work into a still-atmosphere furnace having a roof pyrometer which indicates the desired temperature, because under these conditions it is most unlikely that all parts of the charge will reach the indicated temperature. For reasons already explained rapid forced-circulation air furnaces offer by far the best means yet devised for heating a number of pressings rapidly and uniformly.

Pickling and Cleaning

The only important change which can be foreseen in this field is the replacement of the old type of pickling or cleaning vats and swills by chambers equipped with high-pressure jets or sprays through which articles pass on conveyors. It is possible that automatic pickling of this kind may lessen the popularity of expensive controlled-atmosphere annealing furnaces, because a plain muffle furnace working in conjunction with a spray pickling plant is cheaper to install and therefore more within the reach of users having a limited output. Which of the two methods will be used will need to be decided by the shape, size and quantity of the articles to be treated as well as by the outlook and pockets of users.

Fig. 313 (p. 681) shows a pickling chamber placed at the discharge end of a gas-heated muffle furnace so that cold-worked articles, in this instance deep-drawn brass cups, can be loaded on to conveying mechanism at the mouth of the furnace and need not be touched by hand until they emerge at the other end of the plant annealed, pickled, washed and warmed so that they dry very quickly. Pickling chambers of the kind illustrated are lined with rubber and have a number of zones in each of which the work passes through high-pressure sprays, first of acid and then of hot water, directed upon it from a number of directions from a frame of fine jets. Usually hot sulphuric acid is used for both brass and steel; a strength of about 2½ per cent. and a temperature of about 60° C. is recommended by the makers of the plant illustrated. The acid is heated by steam coils made of acid-resisting alloy placed in a main reservoir which need hold only a fraction of the amount of acid which would be needed to pickle the same amount of work in the same time when the old methods are used. Hydrochloric acid can be used when no heating is employed; a strength of about 17 per cent., given by a 50 per cent. dilution of commercial muriatic acid, is recommended. The plant can be used for any metal which can be pickled by either of these acids, but it has not been found possible to make it resistant to attack by nitric acid.

The advantages of this method of pickling over the usual ones can be summarised under four headings: a considerable saving in the cost of pickling a given quantity of work; a saving in time, yet more efficient pickling, owing to a marked increase in activity given by the mechanical force of the impinging jets; absence of spray or fumes which enables the plant to be placed amidst presses instead of in a distant, ventilated shed, thus saving transport and avoiding delay; and, lastly, a marked saving in the quantity of acid used. On the other hand, it is necessary to fulfil the condition that the articles treated must be of a shape, and so placed on the conveyor, that all parts receive the acid spray; but this condition is attainable with most deep drawn and pressed products.

Needless to say, units of the kind illustrated in Fig. 313 need not necessarily be made a structural part of an annealing furnace, for the arrangements are such that no acid fumes emerge from either end of the chamber; yet in some instances attachment is most useful.

So far the application of spraying plant of this kind has been more often to degreasing and cleaning processes than to pickling, and it has been explained in a preceding chapter that the action of high-pressure sprays is particularly valuable for removing heavy drawing lubricants. It is likely that this use will increase, and it must be emphasised once more that degreasing plants employing only vapour, for example that of trichlorethylene, will not always remove heavy greases, soaps and the solid "fillers" found in many drawing lubricants unless assisted by the mechanical action of high-pressure sprays. This limitation needs to be recognised more widely lest the real value of this method of cleaning becomes obscured by the odium engendered by mis-application.

A plea must again be advanced for more efficient cleaning, particularly with respect to the complete removal of drawing lubricants. Failure to do this is the cause of much trouble, and may entirely spoil the performance of the most expensive and efficient clean-annealing furnaces. This particular error is one which, like certain others, seems curiously common when scientific advice is ignored. In some instances clean-annealing plants costing several thousands of pounds are producing dirty work solely because pressings are not cleaned before they are annealed.

Polishing

Polishing, the last major operation through which a pressed or deep-drawn shape destined to be electro-plated has to pass, is usually regarded as a necessary evil; for this reason improvement or radical change in polishing procedure would be most welcome. Reduction in the cost of producing a necessary degree of polish is a subject which is continually receiving the attention of those concerned with production costs, and it seems likely that any changes which may occur in polishing methods will be engendered solely by the desire to reduce polishing costs and not by the desire to produce a higher degree of polish. In other words, a certain degree of polish *must* be given to articles which have to be plated; the production of a better polish is unnecessary for the majority of commercial articles.

Obvious aids to the desired curtailment of polishing costs are: a reduction in the severity of scores, fouling and minor tool-marks; the prevention of scaling by the use of properly regulated, controlled-atmosphere annealing; the prevention of corrosion pits by prompt removal of lubricants and by adequate protection of stored work and, lastly, the selection and proper maintenance of suitable machines, mops and compounds for the particular shape and metal being polished. Obvious as these aids may seem in theory, it is sometimes only too apparent that the influence of their combined neglect is not appreciated in practice: the time required to polish an article could often be halved were attention given to the items just enumerated.

It is not proposed to discuss the important subjects of abrasives, polishing compounds and mops because these fall outside the province of the metallurgist and are dealt with adequately in technical literature devoted to electro-deposition. Mention must, however, be made of automatic polishing if only to sound a note of caution against over-enthusiastic application of this procedure by persons lacking practical experience of its shortcomings.

Whether or not automatic polishing will reduce polishing costs will depend entirely on the shape of an article assuming, naturally, that the output of any one shape is sufficiently large to justify the first cost of the necessary automatic polishing plant; in certain instances part automatic and part hand polishing may be cheaper than wholly hand polishing. The two great disadvantages of automatic polishing are the inability of a machine to reach awkwardly located places on articles of irregular shape, and its entire lack of discrimination which renders necessary careful inspection of every article and the services of hand-polishers to remove isolated scores or other markings. Attractive as automatic polishing may appear on paper, the adoption of hand polishing, assisted whenever possible by mechanical jigs, rests, pivots, and the many forms of ingenious devices which are to be seen, will often be found to produce the desired finish more cheaply and sometimes in less time.

Apart from attention to the details already mentioned, there are at least three ways in which the cost of polishing can be reduced: by the use of metal which will be less prone to roughen during deep drawing and pressing, by the giving of a coining or planishing operation prior to polishing, and by the possible advent of entirely new methods for producing a smooth, or nearly smooth, surface.

Within recent years the ease with which deep drawn or pressed shapes can be polished has increased considerably owing to the gradual introduction of metal having a smaller crystal size and, in lesser but still useful degree, a better surface on the finish-rolled sheet and strip. So great is the improvement that in some instances grinding operations have been eliminated, a fact which is not always remembered when the arrival of a consignment of metal having a rather larger crystal size than usual necessitates increased polishing times by reason of an unusual degree of roughness on severely drawn regions.

In some instances the metal now delivered has a crystal size which does not differ markedly from that giving the best deep drawing or pressing properties for the particular shape being produced. For this reason no further help toward polishing can be expected from a change in crystal size, although the advent of metal having a more uniform, in addition to the desired "average," crystal size would undoubtedly reduce the roughness of severely-drawn surfaces appreciably. It is, unhappily, still necessary to add that users must carefully avoid any undue coarsening of an initially satisfactory crystal size by over-annealing or, with some metals, as a result of critical-strain crystal growth.

With steel, the presence of stretcher-strain markings can increase polishing costs to such an extent that, when production schedules are drawn up on the assumption that this defect will be absent or very slight, the introduction of a consignment of sheet which has not been properly temper-rolled may render it more profitable to scrap large numbers of finish-drawn shapes made from it than to polish them. This statement is not exaggerated, and brings home in a striking manner the cost of polishing a rough surface in relation to the cost of actual deep drawing and pressing. Methods for the avoidance or minimisation of stretcher-strain markings have already been discussed in some detail; it is to be hoped that the future will bring sheet rolled from steel which, without the critical and somewhat uncertain operation of temper-rolling, will not develop stretcher-strain markings.

The practice of coining or planishing finish-drawn shapes under very powerful presses, useful as it can be for sizing and removing puckers, is, in the opinion of the author, of doubtful value as an aid to polishing. Excrescences may be flattened and spread out by this procedure, but cavities are not completely filled and the surface will either remain pitted after light polishing or, after heavy polishing, will retain sub-surface cavities likely to become filled with pickling or plating solution which will seep out and will ultimately ruin the painted or plated surface.

It seems likely that present mechanical methods for polishing metal surfaces destined to be electro-plated may be superseded in at least some instances by methods now termed, somewhat misleadingly, "electrolytic polishing." The origin of the term lies in the fact that it was first devised by Jacquet [140] to enable him to study the "Beilby layer" on microspecimens; this led to the general adoption of the method by metallographers wishing to prepare polished and etched microspecimens without having recourse to the usual practice and, later, to its use as an industrial process for smoothing metal surfaces. Jacquet and other workers have called surfaces smoothed in this way "equipotential surfaces"; but this terminology is to be deprecated because this term has already an established use in pure physics.

Under normal conditions of pickling, surface irregularities are intensified; yet, under the controlled conditions imposed during electrolytic "polishing," anodic pickling or "etching" can cause a preferential attack on the high spots, leading to the formation of a plane surface so perfect that the only irregularities are those of the *internal* structure of individual crystals. It is believed that the preferential anodic solution of the high spots—which forms the basis of this process—is caused by the products of the attack forming a relatively viscous and poorly-conducting film adhering to the "valleys" of the rough surface and exposing the "hills" to continued attack until a flat surface is produced. Readers interested in the theory of the process are referred to helpful discussions by Jacquet [140] and Elmore.[141]

Substances which have the desired properties when used as an electrolyte are perchloric, hydrofluoric, nitric and, in particular, phosphoric acids. The brightness of the "smoothed" surface is sometimes increased by the addition of certain organic substances of high boiling point such as glycerine (290° C.), ethylene glycol (197° C.)

and acetic anhydride (137° C.) which produce a change in the electrical conductivity of the electrolyte and anodic products and also retard pitting which the action of the bath, independent of the desired anodic attack, would cause. It is found that to obtain the highest degree of "polish" careful adjustment of the strength of the electrolyte, temperature and current density is necessary.

The industrial application of electrolytic "polishing" to nickel-chromium steels is already established, and it is to be expected that it will extend to some of the other metals handled in the press-shop.

A particularly attractive feature of the process is that the surface which it gives is an ideal base for electro-deposition, whereas it is recognised that the heavily cold-worked surface produced by mechanical polishing is less desirable, particularly from the aspect of adhesion.

Cleanliness

Although a plea for increased cleanliness in shop conditions has already been made, no excuse is offered for again mentioning this highly desirable improvement. If particles of grit and other forms of extraneous matter could be prevented from finding their way on to the tools and the metal offered to them, tool life would be greatly lengthened and the surface of the deep drawn or pressed article would be improved, thereby reducing the number and cost of subsequent polishing operations or, when none is given, enhancing the appearance of the article.

This is a plain statement of fact, not a fanciful, unproven hypothesis. Those who doubt it can prove its truth by instituting and carefully maintaining far better shop conditions: smooth, swept floors; clean bins for the conveyance and storage of blanks and partly-drawn shapes; clean containers for the mixing and storage of lubricants; clean annealing furnaces; in short, cleanliness everywhere at all stages: a Utopian yet at least approachable ideal.

This ends the progress of metal through the consumer's works from the time it enters as sheet or strip to the time the finished shape has left the tools of the last press and perhaps has been polished. It will be conceded that the passage is often a hazardous one, and that under modern industrial conditions, when so much importance is attached to speed, to the elimination of any operation which although desirable is perhaps not absolutely essential and to the straining of the metal used to the greatest possible extent, it is surprising that failures are not more common. Only one of the common metals has a voice—the "cry" of tin when deformed plastically; perhaps this is as well, or the shrieks of protesting metal would surely drown the mechanical noise of the presses, the persuasive cries of exasperated foremen, and the merciless calls of progress-men behind scheduled output.

The severity of the draws which are regularly carried out with success has increased markedly during recent years owing, mainly, to improvement in the quality of the sheet offered to the tools, in lubricants, in tool finishes and to a better control of annealing treatments. In spite of this, it is quite certain that the insatiable demands of production engineers will continue to urge the press-man to perform still deeper draws or more difficult pressing operations in still fewer stages. It therefore behoves those in charge of press-shops to avail themselves to the fullest possible extent of both scientific knowledge and, let it be whispered, pure common sense in order to attain the ends they desire.

Scientific Research

This chapter can be regarded as a broad outline of the ways and means by which those engaged in the craft of deep drawing and pressing can help themselves through instituting improvements suggested mainly by the facts collected and examined in preceding chapters. Because industrialists may regard many of these facts as "scientific," it is fitting that this final chapter should end with a reference to what is perhaps the most fruitful means of exploration and discovery of the scientist, namely, research.

In industry there has been a tendency to divide research into two separate classes: so-called fundamental or "pure" research, and applied research. Thoughtful observers will rightly claim that the distinction is often slight, and nearly always undesirable; and it is a matter for regret that those engaged in industry are sometimes loath to provide adequate financial assistance for what in their opinion constitutes "academic" research incapable of immediate and remunerative practical application. The very valuable laboratory researches to which readers have been referred so often in this book must surely show how short-sighted this policy is even in the limited field of deep drawing and pressing.

The most hardened industrialist must surely allow that the items considered in this chapter have been essentially practical or capable of immediate practical application. It is therefore necessary to emphasise the extreme importance of that kind of research which does not yield results which can be *immediately* translated into a saving in the cost of production of some particular article.

Already there are encouraging signs that industrialists are becoming more inclined to take a long view of the value of scientific research, and therefore more willing to finance investigations which yield no promise of results that can be immediately translated into monetary gain. That such a policy must ultimately prove in the highest degree profitable in no way detracts from the merit of this broader outlook. Large sums spent on extended programmes of research into important yet unexplored regions of our ignorance have invariably turned out to be highly profitable. Whatever the motive, true research is to be encouraged by all possible means because, valuable as chance discoveries often prove to be, the attainment of new knowledge by planned investigation under carefully controlled conditions is to be preferred.

Hitherto researches or planned investigations have been largely confined to large organisations which, perhaps, are able to equip and staff proper research laboratories. Much useful knowledge could be gained by smaller firms, often without the help of expensive instruments and machines, if they would institute planned investigations undertaken by some *competent* investigator *unhampered by routine duties*. Both these qualifications are necessary. Many recorded—and even published—observations are rendered of small value owing to the omission, through ignorance or carelessness, of essential factors. For example, it is all too common for an engineer to make elaborate physical and mechanical tests upon metal of unknown history—sometimes even unknown chemical composition and physical condition—and then publish much-needed results which, when the metallurgist turns eagerly to them, are found to have been obtained on " steel " or " brass," terms which convey little significance. This error is both common and serious ; for months of painstaking and ingenious work may be rendered relatively useless simply because some quite easily ascertainable factors have not been recorded.

As regards the second qualification, that is freedom from routine duties, only those who attempt to carry out planned investigations and at the same time carry on practically full-time routine work know how exasperating and often futile this arrangement can be. On the other hand, the intimate knowledge of the " man on the job " is often an indispensable asset and, as it is often difficult for him to relinquish his duties for any length of time, the only solution to the problem seems to be the not entirely satisfactory one of employing an assistant to carry out directions issued as and when his colleague is able. Whatever the means adopted to obtain the desired information, the more frequent institution of planned and properly conducted investigation in organisations of small and moderate size would be of unquestionable value, and is therefore to be encouraged.

As examples of pure research on fundamental subjects which, having claimed attention in the past, need to be pursued further, there may be given the mechanism of deformation of metals both under simple stresses and under the complicated stresses which are imposed during deep drawing and pressing ; the phenomenon of work-hardening, including the influence of speed of straining ; the influence exerted by the size, regularity and orientation of the crystals composing an aggregate, and the influence of small proportions of impurities upon the behaviour of metal during plastic deformation, *e.g.*, upon the properties of ductility, tenacity and work-hardening.

In the realm of so-called "applied" research there may be grouped subjects such as the influence upon depth of draw of radius of die, speed of drawing, blank size, pressure-plate loading, general tool design, apportionment of successive drafts, and method of drawing, *e.g.*, direct or reversed; lubrication; the phenomena of ageing and stretcher-strain marking in steel and of critical-strain crystal growth in many metals; the discovery of new methods for testing sheet metal and assessing its value for deep drawing and pressing; the development of better methods for annealing under closely controlled conditions, preferably in special protective atmospheres, and many other items of a less general nature.

Should readers find themselves unable to distinguish any line of genuine demarcation between these examples of fundamental and applied research they are to be congratulated; for the division between pure and applied research is being rapidly erased. Academic knowledge often finds—or could find—immediate practical application and, conversely, many practical problems can only be solved with the help of knowledge and research originally thought to be of academic interest only.

EPILOGUE

It may be that some readers, interested in the many scientific facts and technical details which the author has painted on the canvas of the preceding pages, have not paused as it were to step back in order to view the picture as a whole and thus to see the relationship which isolated details bear towards one another. Now, stepping back, the message of the picture should become clear. It is that scientific knowledge must be applied energetically to the craft of deep drawing and pressing if this industry is to keep pace with the rapid progress which is being made in other industries also engaged in the making of that amazing array of metal articles which has become an unquestioned part of present-day life.

It is hardly an exaggeration to say that the deep drawing and pressing industry is the last branch of metal-working to avail itself of the help which scientific knowledge can give when properly applied. Happily the increasing number of published scientific researches and technical articles which is now appearing promises that such an unenviable position may soon be changed.

This tardiness may be explained partly by the fact that, in the past, knowledge concerning the plastic deformation of metals has been scanty and often crudely hypothetical; partly by the fact that, until comparatively recently, metallurgists were not employed directly by this industry, and partly because it is always difficult usefully to apply pure scientific knowledge to a craft into which the acquired skill and intuitive "sense" of the craftsman enter. It must be admitted that a scientist well versed in present theories explaining the plastic flow of metals would make a sorry exhibition should he suddenly be faced with the task, unaided, of designing and using tools for making some article of intricate shape by deep drawing and pressing processes at all, still more if in huge numbers and at a competitive price. Clearly, the scientist who enters the press-shop must do so humbly and must be ready to allow full value to the acquired skill and intuitive sense of the craftsman.

Only by the perfect fusion of scientific knowledge and true craftsmanship can the difficult craft of deep drawing and pressing improve. Those scientists who think differently will hinder this progress and must, when they are sincere, ultimately change their views. Practical men should be willing, for their part, to modify their views, however cherished, in the light of well-proven scientific evidence; but this change will be rendered more pleasant and more rapid when men who have had a scientific training hold themselves continually prepared so that they may offer their knowledge, realising that it is seldom complete, with an open and truly candid mind and above all without condescension.

After all it is "knowing how," not "knowing about," which in the last analysis enables any article to be made, and a single dab of lubricant smilingly given by a craftsman may entirely upset the theories of the scientist and reveal new facts which have to be considered.

Assuming the licence an epilogue confers to take a wider conspectus, the author would ask his readers to ponder whether the indispensable part played by the craftsman does not give to the deep drawing and pressing industry, perhaps in common with that of welding and a few others, an opportunity to play a leading part in overcoming some of those evils of the Machine Age which most thinking men deplore. It is a sad fact that in many modern industries pride of craftsmanship has no place, and the result of the negation of this birthright of man is seen in the modern products and is suffered by the workers who make them. It is very difficult for a man to be proud of his work when all he does is to watch a machine perform one out of hundreds of operations needed to make an article which he may never handle in its finished form, and when he is paid by the number of operations he completes often irrespective of whether these are done well or indifferently. Under modern industrial conditions it seems that this regrettable state of affairs cannot be remedied entirely; hence the desirability for more leisure and for the intelligent use of it. Yet in the press-shop true craftsmanship must persist to the great benefit of those concerned, and executives might well encourage this quality instead, as often happens, of trying to ignore its existence and doing their utmost to cramp its expression. When this encouragement is not given, stressing the oft neglected attribute of *quality* rather than that of *quantity*, irrespective of quality, would induce many workers to take more interest in uninteresting tasks. And, let it be said, quality is not born of advertisement claims; for the intelligent worker often has a surprising insight into the material and workmanship which goes into the articles he helps, perhaps only in some tiny way, to fashion.

Returning to the proper theme of this treatise, the value of both existing scientific knowledge and of proper research to increase this store of knowledge has already been emphasised; yet to those actively engaged in industry the greatest problem often is how to *apply* this knowledge to every-day practical processes and operations with which they have to deal.

In the examination of sheet, in the tracing of causes of failure or of unusual behaviour, and in the control of annealing and other works processes, the works metallurgist—the equivalent of the "general practitioner" of the medical profession—can give genuinely useful assistance. For the rapid and successful application of new knowledge the services of what may be termed a "specialist" seem necessary, and a perusal of modern technical literature shows that the deep drawing and pressing industry can already claim a few such specialists who, by their researches published in several countries, seek to convey at least some measure of their findings to the general practitioners.

It is being recognised that as the volume of knowledge grows with increasing rapidity it becomes more and more difficult for any individual to keep abreast of developments even in one small branch. The true specialist in deep drawing and pressing would, for example, need to know of and understand fully each new discovery connected with the plastic deformation of metals (a study which embraces atomic physics, crystallography and X-ray investigation as well as the more familiar metallurgical studies relating to ordinary and special, *e.g.*, high velocity, methods of deformation and testing) in addition to general knowledge concerning the properties and behaviour of metals which is continually being enlarged, and in many respects modified, as the years pass. Truly an impossible task for any but a super-man, and one which will continue to increase in magnitude as new knowledge is obtained.

The most simple and logical manner in which satisfactory progress can be made seems to be one which embraces close co-operation first between specialist-investigators (or "knowers about") and what may be termed *liaison* officers and, secondly, between these officers and tool-designers and press-men (or "knowers how") and also between production, organising and costing executives. The task of such *liaison* officers is a difficult one, for they will need great patience, tact and enthusiasm in addition to technical knowledge and ability.

In organisations of moderate size the *liaison* officer may have to be the general works metallurgist; in large organisations the services of a specialist will ensure a far more intense and understanding application of new knowledge, particularly when he is allowed time and opportunity to carry out properly planned investigations into special problems, which will often be variants of general and recognised problems that have already been investigated by other workers.

Finally, let no reader close this book with the belief that most of the metallurgical facts set out are of interest only to those who have been fortunate enough to have had a scientific training, or that the majority of the proposals put forward are impractical for any except large organisations. Producers of deep drawn or pressed products, whether on a large or a small scale, suppliers of sheet and strip, superintendents, manual workers, indeed all the "Students, Craftsmen and Intelligent Industrialists" to whom this book is dedicated, are asked to consider very carefully whether some portion of scientific knowledge—perchance some hints or suggestions gleaned from these pages—may with advantage be applied at once to *their* work, to *their* product or to *their* plant. If so, and in such measure as this application can be envisaged and attempted, the author's purpose will have been achieved.

THE NEED FOR DEFINITION OF TERMS

Now that the subject of deep drawing and pressing is discussed more often and ideas are exchanged more freely concerning the various kinds of operation which this general heading is assumed to include, it is becoming increasingly desirable that definitions be made and adhered to in all public discussion and even in private conversation. The ideas of different people as to what constitutes the essential difference between "pressing," "drawing" and "deep drawing" vary considerably, and indeed are often vague. Because of this, confusion occurs, and will continue to occur, until standard definitions are accepted and used.

Various conditions have been held to make a press operation one of "drawing." For example, it has been suggested that the wall of the shell must be "ironed" or thinned between the punch and die, as in tube-drawing, that compressive as well as tensile stresses must exist in the walls, or that the periphery of the blank must decrease in size; while in many shops a true drawing operation is spoken of as "pressing" when the depth of draw is small. It seems as if at least three distinct definitions are needed to avoid possible confusion.

One, to describe true deep-drawing, in which the periphery of the blank decreases in size and the walls of the shell are thinned by "ironing." These conditions obtain in the drawing of deep, parallel-sided cups, such as shell cases.

Two, to describe operations in which the periphery of the blank decreases but the walls of the shell are *not* thinned by "ironing," and their thickness—which in places may be greater than that of the original sheet—is determined entirely by the properties of the metal and the shape of the tools. This definition would cover a wide range of industrial press operations, including the shaping of automobile wings, but in some instances—for example, when thickening occurs at the corners of a rectangular shape—ironing might take place locally, thus confusing the clarity of this suggested definition.

Three, to describe operations in which the periphery of the blank is prevented from decreasing in size, and the desired shape is produced entirely by the extension of the area of sheet held by the clamping rings, as when an Erichsen test is made with the clamping rings screwed up tightly.

The formulation and acceptance of definitions approximating to those just outlined is needed badly; how this is to be accomplished, and accomplished in the shortest possible time, is uncertain unless some Institute or Committee takes upon itself the task of launching with some semblance of authority terms which have been decided by a committee of specialists to be the best available.

APPENDIX B

THE APPLICATION OF X-RAY EXAMINATION

General Considerations

The continued application of X-ray examination to the study of problems connected with deep drawing and pressing is one from which much valuable knowledge is certain to result. Apart from help in the elucidation of special problems not having general significance, the chief usefulness of X-ray examination may be considered from three aspects :—

(1) Fundamental research in the mode of crystal deformation under general conditions—as already attempted with some success by Gough and Wood[123] and other workers—and also under the special and very complicated conditions peculiar to deep drawing.

(2) The measurement in sheet metal of important properties such as the size—and perhaps the regularity of size—of the crystals ; the severity of " directionality," *i.e.*, of preferred orientation ; the perfection of annealing or conversely the amount of cold-rolling—as imposed, for example, during " temper-rolling " operations.

(3) The measurement, non-destructively, in any part of a deep-drawn article of the severity of deformation ; of the degree of residual, that is elastic, strain ; and, in annealed articles, of the completeness of annealing with respect to recrystallisation or to stress-relief.

It must be conceded that this list, comprising as it does items of the utmost importance, justifies the fullest possible use of X-rays in research work relating to deep drawing and pressing practice and also investigation to discover its field of application as a method for routine examination in works laboratories.

For a proper exposition of the fundamental principles underlying the examination of metals by means of X-rays, as well as for description and criticism of the particular methods and technique applicable to sheet metal, readers are referred to the already plentiful literature in which these subjects are discussed by acknowledged authorities. All that can be attempted here is to give the briefest possible description of the fundamental principles for the benefit of those who are as yet unacquainted with them, and to indicate, in rather greater detail, the nature of the information which can be obtained by operators equipped with suitable apparatus and possessed of varying amounts of specialised knowledge.

Method. Considering, first, fundamental principles, the peculiar value of X-rays is explained by the shortness of their wavelength, a value of the order of 10^{-8} cm.; that of light within the visible spectrum being of the order of 10^{-5} cm. As the wavelength of X-rays is of the same order as inter-atomic distances, X-rays are able to penetrate atomic aggregates when light, having a wavelength greater than the inter-atomic distances, is unable to do so. The depth to which X-rays of given power can penetrate is dependent upon the wavelength of the particular X-rays employed and upon the density or absorptive power of the metal into which they are directed. For crystallographic examination, reflection—or as it is termed "diffraction"—from the surface layers of atoms, not deep penetration, is desired; a fact which enables a long wavelength radiation and apparatus of low power to give most of the needed information.

The capacity of X-rays to penetrate solids is utilised without elaboration to obtain the familiar radiograph—or "shadowgraph"—pictures which reveal blowholes in castings and defects in welds; but, for the three methods of application to sheet metal which it is proposed to discuss here, the equally valuable property of *diffraction* has to be employed. If a beam of X-rays be directed into a metal specimen, the beam will be reflected as if it were a beam of light falling on a polished surface, but with two important differences. First, since the beam will penetrate the specimen instead of being totally reflected by its surface, it is possible for reflection to take place at successive planes of atoms in the space lattice of the crystal structure. Secondly, the intensity of the reflection will depend upon the closeness with which the atoms on the reflecting planes are packed and also upon the "Bragg condition," which states that reflection will take place only when

$$n\lambda = 2d \sin \theta$$

where n is an integer, λ is the wavelength of radiation employed, d is the space between the atomic planes, and θ is the angle between the incident beam and the planes at which reflection occurs. This condition is illustrated diagrammatically in Fig. 314. Actually this condition is nothing more than that at which the length of the path traversed by the X-ray beam between successive atomic planes is equal to one or more complete wavelengths: when it is not fulfilled, the emerging beams reflected from successive planes will not be "in step," and, as with ordinary light, darkness will result, owing to interference.

At present it is necessary to take photographs in order to obtain the desired information. If in the future it becomes possible to render the image visible on a fluorescent screen, as is already possible in certain other applications, the value of X-rays for routine examination will be very greatly enhanced. Even should fluorescent screens of greatly increased sensitivity become available, a powerful emission, necessitating expensive apparatus, would probably be essential: so it is fortunate that in actual practice the disadvantage of having to take photographs is not as serious as is often suggested. It must be remembered that even in metallographic examination, when an image can readily be examined visually, photomicrographs are frequently taken for purposes of record and detailed examination.

Apparatus. It is necessary to dispel the belief that X-ray examination entails the use of enormously expensive apparatus and profound and highly specialised knowledge on the part of those who use it. Outfits comprising the necessary generators, transformers and control gear, housed in a compact case, to operate small, shock-proof tubes

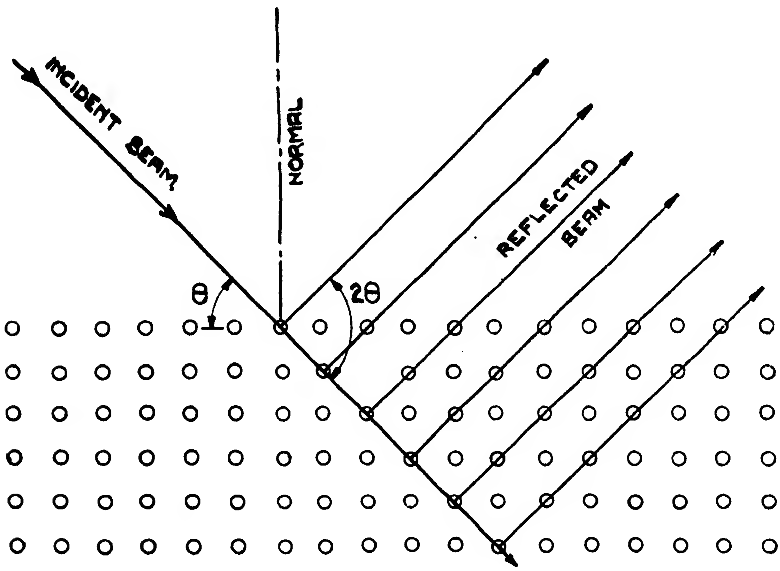
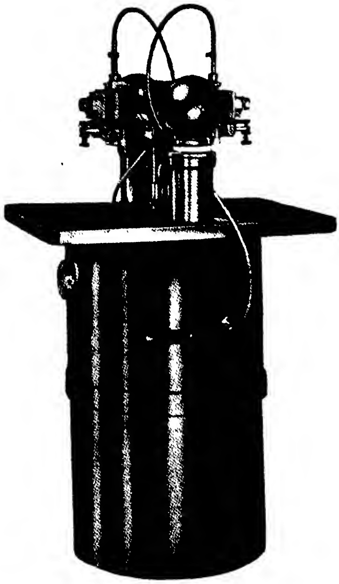


FIG. 314. Diagram illustrating principle of reflection of X-ray beam from planes of atoms.

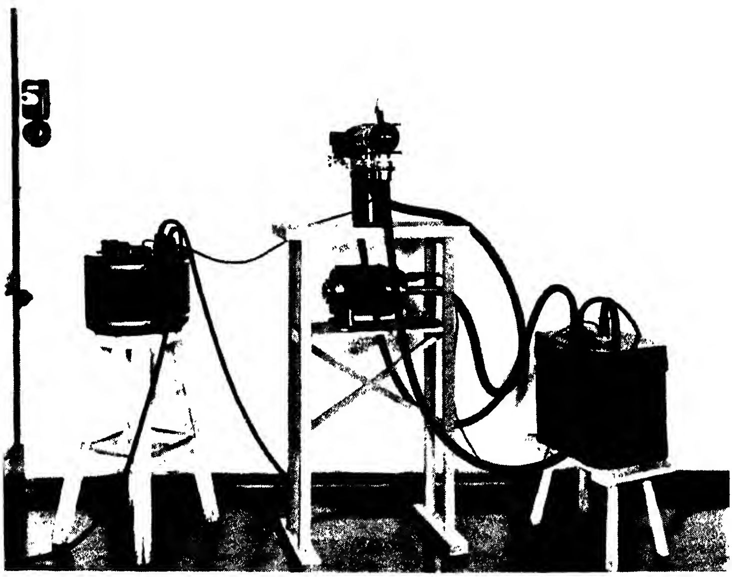
of adequate power for all normal investigations are now marketed at a relatively low figure. Fig. 315 shows a small self-contained bench unit designed for crystallographic examination. A more powerful unit, in which the X-ray tube is separate from the generator and adjustable in all directions, is shown in Fig. 316. This apparatus, which is self-contained and portable, can be used either for crystallographic investigation or for radiographic work and possesses, for this reason, a much wider field of application.

For a description of the methods and apparatus by means of which X-rays are produced, directed in a suitably concentrated manner on to the specimen, a portion of the reflected radiation collected and recorded on a conveniently disposed photographic film, as well as of the means adopted carefully to control and measure the angles of the



[*By courtesy of Philips Industrial X-ray Service.*

FIG. 315. Bench type X-ray unit suitable for crystallographic examination.



[*By courtesy of Philips Industrial X-ray Service.*

FIG. 316. Multi-purpose portable X-ray unit suitable for crystallographic examination (as shown) or for ordinary radiographic examination.

[*To face p.* 700.

beams, readers are referred to the many text-books in which these details are dealt with at length.

Operators. Turning from apparatus to those who operate it, modern equipment of the type described can be worked by any reasonably intelligent person. For fundamental research on the properties and mode of deformation of metals, considerable knowledge of crystal and atomic structure is, naturally, essential for the proper interpretation of results and also for the planning of determinations. Less profound knowledge is, however, adequate for the determination of much useful information concerning crystal size, degree of preferred orientation, degree of cold work and such like matters in sheet metal. For the actual taking of photographs, and for their comparison with standards, little specialised knowledge is necessary; so, once standards and methods of procedure have been worked out, routine examination by means of X-rays can be carried out by the junior members of a laboratory staff in a manner comparable with that adopted for spectrographic analysis.

The purposes for which X-ray examination can be applied most usefully in the deep drawing and pressing industry are the three enumerated at the beginning of this section (p. 663). For the sake of clarity, it is proposed to examine these three applications separately, yet it will be appreciated that each depends for its success upon the same technique and methods of interpretation of results.

Application to Fundamental Research

No detailed elaboration of the previous indication which has been given of the possible field of application of X-ray examination in the field of fundamental research—nor, indeed, of the value of the results which have been and will be obtained from it—seems necessary. A clearer conception of the methods by which deformation occurs and proceeds in metals is far from being of purely academic interest, because such knowledge may point the way to better methods and procedures in the shaping of metal sheet for industrial purposes, and may even establish in a more precise manner than is now possible the condition of various metals which will be most suited to suffer deformation by certain industrial processes. Up to the present the knowledge which has been gained concerning the deformation and recrystallisation of metals has come almost entirely from investigations which are of a general nature or related to some practice other than deep drawing and pressing; for this reason the concentrated application of X-ray study to deep-drawing problems would be most welcome and without doubt productive of much valuable help.

Loskiewicz,[124] in an examination described later, observed that the X-ray pattern given by sheet reduced a certain amount by cold-rolling differed from that given by the same sheet reduced a similar amount by deep drawing. This observation provides interesting confirmation of the suspected dissimilarity in the nature of the deformation produced by deformation in tensile testing, in which the sides and faces of the test specimen are free, and in actual deep drawing, in which the metal is confined on all sides ; a matter discussed in preceding chapters. It is likely that this fact explains the accepted and regrettable inadequacy of the tensile and other forms of test to predict in a complete manner the behaviour of sheet metal during deep drawing and pressing. Further investigation to determine the precise nature of this difference between the mode of deformation of the crystals under the two conditions would form a most valuable contribution to fundamental knowledge, and constitutes an excellent illustration both of the usefulness of X-ray examination applied to deep drawing and pressing problems and also of the very close relationship which exists between so-called purely academic knowledge and its practical application.

Further practical confirmation of the fact that the effect produced upon the crystals differs with various methods of plastic deformation is provided by the work of Beck,[125] who has shown that, when cold-worked aluminium sheet is annealed, the temperature of recrystallisation is lower with sheet which has been bent through a certain angle than in exactly similar sheet which, after having been bent through the same angle, is then bent back in the reverse direction to its original shape. This suggests that the total amount of plastic deformation measured in linear units is not necessarily related to the amount of residual strain left in the metal or to the latent energy stored in the crystals, both of which factors influence the temperature of recrystallisation and—perhaps of more importance industrially—must also influence the capacity of the metal to suffer further plastic deformation. In the instance just mentioned, it would appear as if the residual strain and latent energy were less in the crystals of the sheet which had been deformed the greater amount measured in linear units, a condition which, though probably obtaining only within a limited range of deformation, may yet be of considerable importance.

How closely this seemingly purely theoretical consideration is linked to every-day industrial practice will become evident when it is remembered that practical experience has shown that, when " reversed " methods of drawing are used, draws of greater depth can be accomplished before annealing becomes necessary than when ordinary methods of drawing are employed. " Reversed " drawing is the term applied to that method in which one or more draws are made in one direction, and then the shape so formed is pushed back through the plane of the original blank and drawing continued in the reverse direction to that in which the first draws were made.

The precise explanation of this observed fact in terms of crystal deformation will certainly be difficult, but it is certain that X-ray examination offers the most hopeful method of investigation. In no other way can the process of crystal deformation be revealed, or the amount of internal stress in individual crystals—as distinct from in the whole wall of a drawn shell—be estimated.

Because it is only recently that deep drawing and pressing problems have been studied from the theoretical aspect, this instance is typical of many in which the reason for the success of hitherto inexplicable practical "dodges" has been brought to light. Continued scientific study may, therefore, point the way to new methods of deep drawing and pressing which will be of great benefit industrially.

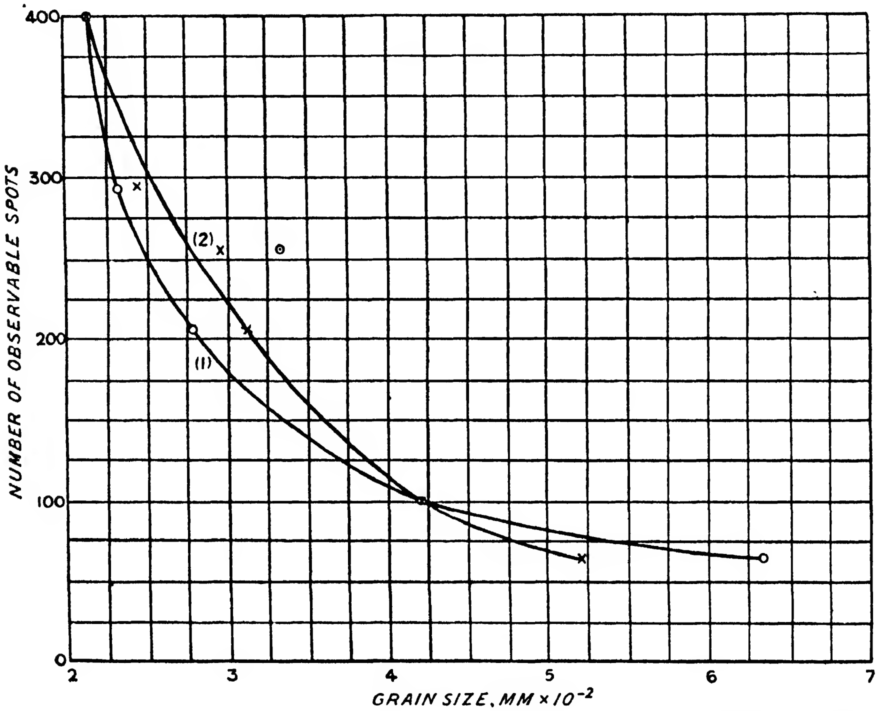
Application to Sheet Metal

Four distinct applications of X-ray examination merit consideration.

Measurement of Grain Size. This application, usefully summarised by Stephen and Barnes,[126] is one which has attracted the attention of a number of workers. Various methods have been proposed, for example, those owing to Czochralski and, of greater promise, to Shdanow,[127] which can only be used for very thin sheet and are therefore not very useful; to Glocker,[128] who showed that the sizes of the spots produced on a diffraction photograph are proportioned to the size of the crystals in the specimen; and to an elaboration of this due to Clark and Zimmer,[129] which involves the difficult task of measuring the size of diffraction spots.

The method proposed by Shdanow depends upon the fact that when a large number of crystals oriented at random are illuminated by monochromatic X-rays, a certain proportion will be in a position to reflect the incident beam in accordance with the equation already quoted. When the volume of crystalline aggregate irradiated and also the dimensions of the camera and X-ray system are known, the size of the crystals can be calculated from the number of reflections; but, in order to determine accurately the volume irradiated, Shdanow employed transmission pictures, and the method can therefore be applied only to very thin specimens.

Stephen and Barnes[126] have extended this principle to the reflection method, thereby rendering it applicable to thick specimens and making it more attractive for use under industrial conditions by virtue of the much shorter exposure required, and also of the fact that small areas in articles of any shape and size can be examined without having recourse to cutting out actual specimens and thereby destroying the article. Although from theoretical considerations two photographs seem necessary to enable an estimation of the grain size of any specimen to be made, Stephen and Barnes have shown that it is possible to obtain at least an empirical relationship between the number of spots on single photographs taken under standard conditions and the "average grain size" of a series of specimens. If this relationship be established for given conditions and expressed as a graph, the "average grain size" of any new specimen can be read off. Fig. 317 shows a graph prepared by these investigators for aluminium; in this the number



[Stephen and Barnes.

FIG. 317. Relationship between number of spots observable on an X-ray diffraction photograph and "average grain size" of aluminium sheet. The curves represent the number of spots plotted against "average grain size" determined by microscopical examination (curve 1) and X-ray examination (curve 2).

of spots is plotted against "average grain size" determined by microscopical examination (curve 1) and by X-ray examination (curve 2). It will be seen that the measure of agreement is certainly within the normal error obtaining in estimation by visual inspection of microspecimens, and the method would therefore seem to be of considerable value for the measurement of grain size in routine inspection.

The originators of the method state that for grain sizes larger than 5×10^{3} cm. the method is not very sensitive, but they claim that an accuracy of 10 per cent. can be obtained in the region down to 10^{3} cm., which covers a good proportion of the sheet metal used in deep drawing and pressing. Moreover, by inspection of the variation in the size of the spots on the X-ray picture it is possible to estimate the variation in size of crystals above and below the adjudged "average," and also to form an idea of the proportion of crystals outside a definite range of size. This application is important, because without it X-rays could not compete with microscopical examination.

Measurement of Degree of Deformation. The effect produced in metals by deformation being fundamentally one of lattice distortion, and X-rays being the only means of examination which can actually reveal the nature and magnitude—as distinct from the manifested effects—of lattice distortion, it follows that the value of X-rays for studying this very important phenomenon is unique. Readers who wish to study the various theories which have been proposed to explain the fundamental mechanism of deformation of metals are referred to the many scientific papers given by acknowledged authorities on this subject; all that can be attempted here is to indicate how X-rays can usefully be employed *under industrial conditions* to reveal severity of both elastic and plastic deformation in both rolled sheet and deep-drawn or pressed shapes.

Elastic Deformation. Elastic deformation of the crystal lattice produces a broadening, in a *radial* direction, of the reflection spots seen on an X-ray picture. Until recently it was thought that this radial broadening, termed "asterism," necessarily indicated elastic strain in the lattice. It is now definitely established[123,130] that asterism is not *necessarily* due to this cause, that a broadening of the spots can be produced solely by slight imperfections—often referred to as a mosaic structure—in crystals free from strain, and that extreme precision in X-ray technique is essential if true elastic strain of the lattice is to be revealed with certainty. For this reason the industrial application of X-rays for revealing elastic—as distinct from plastic—strain may be difficult when the amount of strain is small, although recent progress in this particular application is encouraging. On the other hand, when the degree of elastic strain is relatively large, X-rays provide a valuable non-destructive means for estimating the approximate degree of strain existent in a specimen, although it is not yet possible to measure the degree of strain in terms of stress per unit area except, possibly, by comparison with X-ray pictures obtained on similar specimens in which the stress is known.

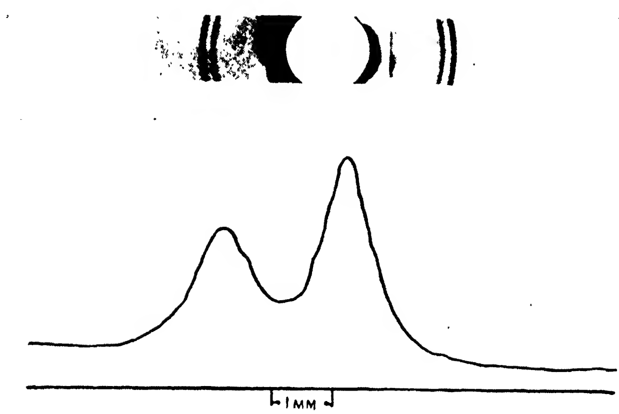
A brief description of the method of examination used by Norton[131] will serve to show a way in which the measurement of elastic strain can be attempted. In this method, characteristic radiation from an X-ray tube, which usually contains two wavelengths close together—such as the K-*alpha* doublet given by cobalt—is directed on to the surface of the specimen and reflected back in the usual manner to a film surrounding the collimator. With perfect crystal grains the resulting images, reflected from tiny atomic plane mirrors, would be sharp; with elastically-strained crystal grains the images, reflected from roughened or wavy mirror surfaces, would be blurred or broadened, and it is postulated that the amount of broadening is a measure of elastic strain.

As measurement of the peripheral or radial width of single diffraction spots is a very difficult task, it is usual to rotate the specimen so that the complete *locus* circles of all individual spots are filled up and superimposed one upon another. The width of the resulting uniform, aggregate *locus* circle, which can be measured with relative ease, is assumed to represent the average degree of strain in the irradiated portion of the specimen, which is usually from 2 to 5 sq. mm. in area. When the size of the crystals is very small, the diffraction circles may be sufficiently uniform and continuous to render rotation of the specimen superfluous; when, on the other hand, the size of the crystals is very large, measurement is difficult unless the diffraction circles are uniform: but rotation will produce *locus* circles of reasonably uniform intensity with many of the industrial metals. It is important to notice that, as it is the surface of the specimen which is examined, this surface must be prepared very carefully, and finally etched, to remove all traces of strain caused by cutting and preparation.

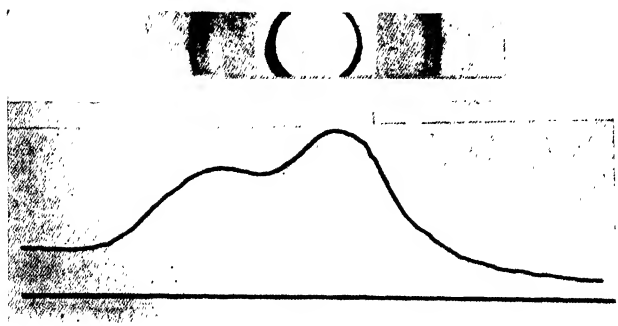
The width of the *locus* circles, which increases rapidly with increasing elastic strain in the crystals, is measured most conveniently with the aid of a densitometer, this being an instrument which records the blackening of the photographic film as a function of radial distance. A typical record obtained in this manner is shown in Fig. 318, and Norton suggests that the width of the lines in records of this nature be measured at a point midway along a vertical line dropped from the apex of the peak to a horizontal line representing the average background density. One of the difficulties associated with the measurement of the width of these lines is the overlapping of the adjacent twin circles, as shown in Fig. 318 (B), and Wood [132] has suggested a method of calculation based upon both lines of the doublet. Norton is of the opinion that widths can usually be measured to within an accuracy of 10 per cent.

The result of strain measurements made, by the method just described, on a number of specimens cut from a weld in mild steel which have been subsequently heated for two hours to the various stated temperatures and cooled slowly is shown in Fig. 319. In this graph the units termed "line breadth" denote the ratio of the half-breadth to the peak on the densitometer record, and indicate the average strain in the area of the specimen irradiated.

It must be understood that line-breadth values are purely arbitrary, and—apart from broadening attributable to elastic strain or imperfections in crystal structure—depend upon the size of the collimator and



A



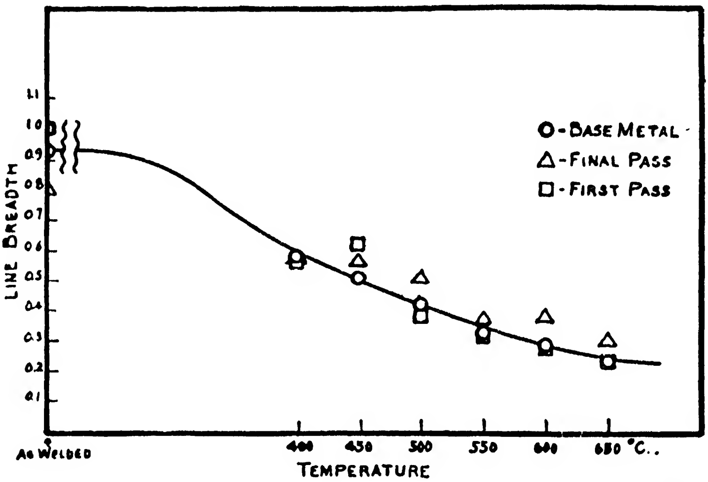
B

[*Norton.*

FIG. 318. X-ray diffraction photographs and corresponding densitometer records of diffraction rings (specimens rotated during exposure).
(A) Unstrained crystal grains.
(B) Strained crystal grains.

[*To face p.* 706.

the wavelength of the X-rays employed: for this reason they cannot be translated into definite values such as tons per square inch. Severity of strain can be estimated only by comparison, and the main use of the method in its present form seems to lie in its ability to reveal the *order* of the degree of elastic strain present in a specimen; that is whether it is large, moderate or very small. Results obtained under industrial conditions to reveal the order of the elastic strain present in deep drawn and pressed shapes, for example to show whether a stress-relieving treatment has been adequate, have not, as far as the author is aware, been published. There seems no reason why curves similar to those shown in Fig. 300 for a weld should not be obtained on any



[Norton.

Fig. 319. Curve showing relationship between line breadth and temperature of stress-relieving treatment on weld in steel.

desired area in a deep drawn or pressed shape, and why a single X-ray photograph should not tell men of experience whether a stress-relieving treatment has been carried out properly. If so, a most useful non-destructive method of examination becomes available to supplement the commonly-used destructive tests.

Plastic Deformation. Plastic deformation, which postulates a breaking up of the crystal grain into small "crystallites" each having a lattice structure which resembles that of the initial crystal but each differing very slightly from it in orientation, is revealed on an X-ray photograph as a broadening of the spots in a *circumferential* direction. As the amount of deformation proceeds, individual spots broaden to merge into their neighbours, thus producing the continuous circles or arcs which are characteristic of metal which has suffered a considerable amount of deformation. The progress of this merging can be seen in Fig. 320.

The reason why lattice deformation produces a broadening of diffraction spots will be readily appreciated if the atomic planes within an undistorted crystal are visualised as tiny plane mirrors, as indeed they are. These plane mirrors will reflect an impinging X-ray beam sharply; but, should imperfections—such as those caused by an internal mosiac structure—occur in the mirror surface, reflection will be less sharp. Should the mirrors be curved slightly—the apparent effect produced when the crystal breaks up into smaller crystallites having orientations slightly different from the original—the reflected spots will be elongated in one direction.

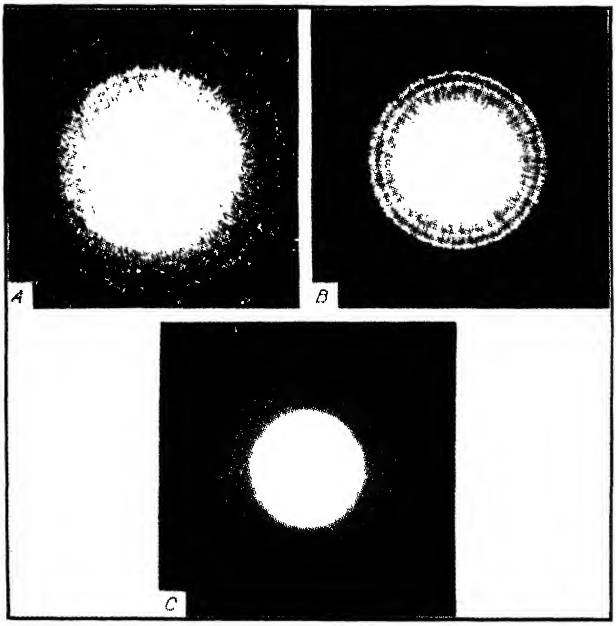
The sensitivity of the X-ray method is very great. Indeed, one of the most striking features of X-ray examination as applied to the study of cold-worked metals is the clear manner in which are revealed changes in crystal structure produced by small amounts of cold work. Visual inspection under the microscope, and even statistical grain counts, often fail to reveal any change in crystal structure after a reduction as great as 15 per cent.; frequently no distinct change can be observed after appreciably higher reductions. Using X-rays, the effect produced by a reduction amounting to 5 per cent. is very great, while the change associated with a reduction of 15 per cent. is even greater.

Fig. 320 shows the X-ray pictures obtained from normalised cold-rolled mild steel strip before and after 5 and 15 per cent. reductions in area. From these pictures it will be evident that reductions considerably less than 5 per cent. will be manifested clearly, and a useful method for the control of the "temper rolling"—amounting perhaps to only 1 per cent.—which is given to mild steel strip is at once suggested. In roller-levelling, an operation which flexes the sheet without producing any appreciable reduction in thickness, X-ray examination offers the only known method for indicating the amount of deformation imposed.

The extreme sensitivity of the X-ray method renders necessary the exercise of the very greatest care in handling specimens, because the least flexure of relatively undistorted specimens will cause an increase in distortion which will be recorded and perhaps attributed incorrectly to previous treatment.

Study of the Effect Produced by Annealing. Turning from the process of cold-working to that of annealing, it is possible to determine the temperatures at which re-crystallisation begins and ends, and also the influence of time and chemical composition, more accurately by means of X-rays than by microscopical examination.

As typical examples of this valuable application there may be cited the investigations of Trillat,[67] in which the difference in behaviour of 99 per cent. and 99·99 per cent. purity aluminium when annealed at various temperatures after cold rolling was studied, and of Goss,[24]



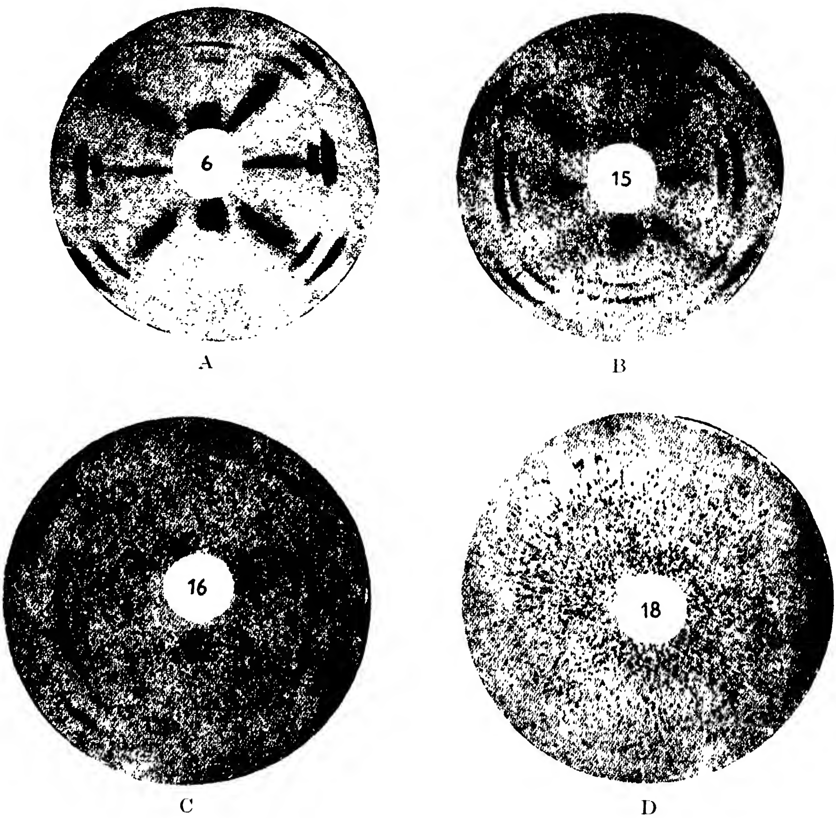
[*Goss.*

FIG. 320. X-ray diffraction photographs showing the influence of small amounts of cold reduction on normalised cold-rolled steel strip.

(*A*) Normalised specimen.
(*B*) After 5 per cent. reduction in area.
(*C*) After 15 per cent. reduction in area.

(Note. The radial asterism evident in *A* is due to an internal mosaic structure in the unstrained crystals, not to the existence of strain.)

[*To face p.* 708.



[*Trillat*.

FIG. 321. X-ray diffraction photographs showing the progress of recrystallisation of cold-rolled aluminium sheet.

(A) Cold-rolled sheet.
(B) Annealed five hours at 220° C.
(C) Annealed ten minutes at 250° C.
(D) Annealed ten minutes at 500° C.

[*To face p.* 709.

in which the recrystallisation of commercial deep-drawing quality steel sheet was examined. An important advantage of X-ray examination is that it reveals the nature of certain changes which, occurring before microscopically-visible recrystallisation begins, are responsible for observed differences in the physical properties of a metal.

Fig. 321 shows the kind of picture obtained in X-ray investigations of this nature. Fig. 321A shows the characteristic picture given by a severely cold-rolled sheet. The symmetrical, geometrical pattern is explained by the fact that plastic deformation of a crystalline aggregate produces slip on certain planes of the individual crystals accompanied by translation and rotation of the crystals, which try so to orient themselves that their slip or " glide " planes will lie in the direction of applied stress and, in so doing, become oriented symmetrically with respect to it. No change could be seen in the X-ray picture obtained after this specimen had been annealed for ten minutes at 220° C., but Fig. 321B shows the picture obtained after it had been kept at this temperature for five hours. Fig. 321C shows the effect of ten minutes at 250° C., and Fig. 321D the effect of ten minutes at 500° C. In this last picture signs of preferred orientation have practically disappeared, while the increase in size and decrease in number of the reflection spots show that considerable crystal growth has occurred.

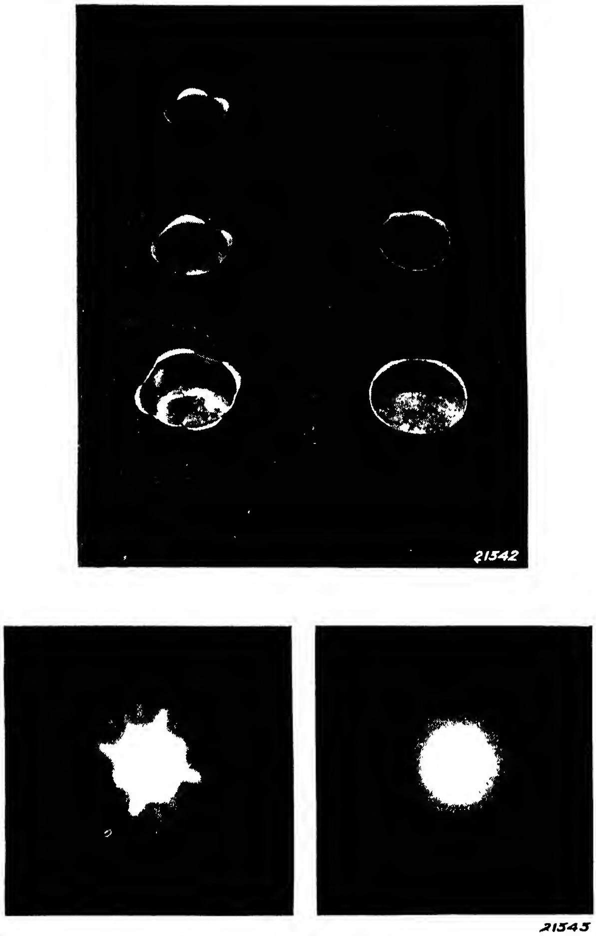
Measurement of "Directionality." Directionality or, more correctly, preferred orientation is shown on X-ray diffraction photographs as symmetrical geometric patterns which may appear as star-shaped images when the effect is pronounced—as in cold-drawn wire—or merely as small arcs of increased intensity in the diffraction rings when the effect is slight. Both forms of manifestation can be seen in Figs. 321A and 321B; in Fig. 321C preferred orientation is quite slight, and only faintly increased localised intensity is apparent on the diffraction circles. These symmetrical patterns, the manifestation of preferred orientation in the crystals comprising an aggregate, show that the effect of deformation of the aggregate has caused the crystals to fragment and rotate in such a manner that their slip planes tend to arrange themselves as far as is possible in the position most favourable to slip under the applied stress. In doing so they become oriented symmetrically to the direction of applied stress and, consequently, with respect to one another; hence the symmetrical patterns of their diffraction picture. The actual rotation of crystals subjected to stress has been proved and studied by observation of tensile specimens composed of a few large crystals.

In an earlier chapter the important influence exercised on the behaviour of sheet metal during deep drawing and pressing operations by the property commonly termed "directionality" has been discussed at some length, and the difficulty of measuring the degree of preferred orientation in a crystalline aggregate by means of microscopical examination has been explained. While it is true that the practical effect of directionality is revealed to some extent by the simple tear-length test or by a number of tensile tests, precise information concerning the actual degree of preferred orientation existing in any specimen, particularly when this information can be obtained without destruction of the specimen, would often be of great value in research investigations and also in the routine examination of sheet metal by both users and suppliers. For disclosing information of this nature X-ray examination stands supreme because it enables a measurement of the degree of preferred orientation to be obtained, often without destruction of a specimen, in a mere fraction of the time taken to obtain a less accurate indication by laborious statistical examination of microspecimens in the manner described in Chapter XIII.

An illustration of this application of X-ray examination is given in Fig. 322. The left-hand series of cups seen in the upper part of the illustration has been deep-drawn from chromium-iron sheet in which the crystals possessed a degree of preferred orientation ; the resulting formation of pronounced " ears " is clearly visible. The right-hand series has been drawn from similar sheet possessing practically no preferred orientation, and it will be seen that no ears have been formed. The X-ray photographs, shown in the lower part of Fig. 322, obtained from these two sheets demonstrates how clearly preferred orientation can be revealed by this method of examination.

Lloyd-Richards [133] has examined by means of X-rays some of the specimens used by Cook [112] in his instructive correlation of " directionality " in brass strip with microstructure, tensile properties and proclivity to form " ears " during deep drawing ; very definite confirmation of the existence and influence of preferred orientation was forthcoming and, by inference, the marked difference in the degree of preferred orientation produced in brass strip by various modifications of rolling-mill procedure was revealed.

Goss [34] has used X-ray examination to trace the effect of various conditions such as chemical composition, starting and finishing temperature of rolling, reduction per pass and roll diameter upon the degree of preferred orientation existent in hot-rolled strips of mild steel, nickel and austenitic steel. The practical importance of this able demonstration to producers of all kinds of deep drawing and pressing quality strip cannot be over-emphasised, for by no method other than X-ray examination could the influence of these factors have been studied so closely or on such a large scale ; the making of large numbers of statistical grain counts would, for example, have been quite impossible unless a veritable army of lynx-eyed observers could have been commandeered. It may be remarked, in passing, that this and similar investigations by means of X-ray examination reveal quite clearly the existence of preferred orientation in both hot-rolled and fully



[*By courtesy of Philips Technical Review.*

FIG. 322. *Top :* Cups drawn from chromium-iron sheet possessing (left) appreciable preferred orientation of its crystal structure, giving pronounced ear formation; and (right) practically no preferred orientation, giving no distinct ears.

Bottom : X-ray diffraction photographs of the sheets used for the cups illustrated above : (left) sheet exhibiting distinct preferred orientation; (right) sheet exhibiting practically no preferred orientation.

recrystallised strip when, in the light of past—and as it now transpires, incomplete—knowledge a truly "equi-ax" crystal structure might have been expected to exist.

It must always be remembered that a marked difference in the degree of preferred orientation is revealed between pictures taken with the X-ray beam directed normal to the thin edge of the strip at right angles to the direction of rolling and those taken with the beam directed normal to the flat surface; distinct preferred orientation is discernible in the first direction long before it becomes apparent in the second. This must be borne in mind when considering the results of investigations in which only the more usual direction of incidence, *i.e.*, normal to the flat surface of the strip, has been employed.

A very distinct difference usually occurs between X-ray pictures taken parallel to the surface of a sheet but, respectively, at right angles and parallel to the direction of rolling. This explains, and can be used to predict, the difference in tensile properties obtained in tests made in these two directions. Pictures taken with the X-ray beam directed at various angles lying between the 0 and 90 degree orientations to the direction of rolling would doubtless explain the peculiar differences in physical properties—described in Chapters XII and XIII—which are found to occur.

It is, then, established very definitely that X-ray examination offers a unique and ready means whereby suppliers can in the first place determine the sequence of mill operations which will produce the least degree of preferred orientation in the final sheet and, in the second place, check their product to ascertain whether the prescribed treatment is followed consistently. When, as is to be hoped, users show greater insistence on being given sheet possessing only a small degree of "directionality" attributable to preferred orientation in the crystal structure, routine X-ray examination may well come to be an important item in the checking of supplies.

Application to Deep Drawn or Pressed Articles

Using methods hitherto available, such as microscopical examination of sections or measurement of thickness or distances between lines scribed prior to deformation, it is seldom possible to form a clear idea of the amount of deformation suffered by sheet metal as a result of deep drawing. It is true that some idea may be gathered by the old methods as to the average deformation which has occurred over areas of considerable size in articles of simple shape, but the deformation in small and often important regions must still remain a matter for conjecture. By the use of X-rays it is possible to estimate the amount of deformation in any chosen spot more closely than has so far been possible, thus enabling the flow of metal to be visualised and hence the stages in multi-stage drawing operations to be apportioned more suitably. In this way the location of regions which have suffered a critical amount of deformation calculated to encourage abnormal crystal growth during subsequent annealing can be traced, thereby enabling the drawing procedure to be modified.

The possibility of using X-rays under industrial conditions to reveal the magnitude of residual elastic strain, and therefore internal stress, in deep drawn and pressed shapes has already been discussed. The main advantage of this application is that the test would be non-destructive; whereas existing methods, such as immersion in corrosive solutions or dimensional measurements made before and after stresses have been relieved by whole or partial cutting or machining of the article, destroy the specimen and can therefore be made only on occasional samples.

The value of X-ray examination for studying the progress of recrystallisation in cold-rolled sheet has already been illustrated; it will be evident that this application can be extended to deep drawn or pressed articles of any shape, and that the degree of recrystallisation and also the "average grain size" of the recrystallised structure can be ascertained in any small region without damaging the article in any way.

Loskiewicz[124] has described how X-ray examination is able to reveal the method of manufacture of deep-drawn articles. Given a brass cartridge case and a small piece of the sheet from which it was made, Loskiewicz was able to deduce both the severity of the draw imposed upon the sheet to form the cartridge case and also the annealing treatment which had been given to it during manufacture. Cases made to prescribed methods from brass sheet prepared to resemble the original sample as closely as possible gave exactly similar X-ray pictures, thus confirming the accuracy of the investigator's deductions. Although this particular application of X-ray examination may not be one which is needed often, it is instructive and, as in the instance described, of real value upon occasion.

Enough has been said to justify the claim made at the beginning of this section describing the application of X-ray examination to problems connected with deep drawing and pressing, namely, that the method offers considerable potential value both in the study of plastic deformation and also in the routine examination of sheet and deep-drawn shapes. Although pure research connected with the plastic deformation of metals will undoubtedly proceed without encouragement, the rapidity with which X-ray examination will come to be used on a practical scale in the deep drawing and pressing industry will depend upon the interest and enthusiasm evinced by the members of this industry.

APPENDIX C

PROTECTIVE ATMOSPHERES FOR ANNEALING FURNACES[1]

THE most important development in annealing—and for that matter in most kinds of heat-treatment—has been the industrial advent of so-called " bright annealing " achieved by the maintenance of a " protective " atmosphere within the annealing and cooling chambers. The choice of the term " bright annealing " was an unhappy one ; " clean annealing " would have been—and often is still—a more truthful term, and its adoption would have saved many controversies which have sometimes tended to obscure the very great benefits which the use of available methods and plant can give even though the condition of the work treated cannot truthfully be described as " bright " in the sense insisted on by purists. A point which is often given insufficient attention is that even when, owing to certain circumstances, a " bright " annealing plant does not even give " clean " annealed work, a slightly oxidised condition is but a small handicap, because with it a quick dip in pickling solution is all that is needed to give a smooth, bright surface ; whereas without the use of an even moderately efficient protective atmosphere, lengthy pickling, with consequent risk of pitting and other troubles, is needed to remove heavy scale which itself may have roughened the surface of the work.

The ideal protective atmosphere for use under industrial conditions should be :

(1) Non-reactive toward the metal being annealed. (With some metals elements other than oxygen—for example, sulphur—will react to give a discoloured surface and, sometimes, to cause injury to physical properties.)

(2) Cheap.

(3) Easily obtainable in convenient form or, alternatively, easily produced in the works of the user.

(4) Non-explosive.

(5) Non-toxic.

(6) Slightly reducing in nature so that any oxide present on work placed in the furnace is reduced.

Unfortunately, all these requirements are not easily met, yet atmospheres are available which satisfy some to a reasonable degree, and give a useful compromise between others, perhaps incompatible. In the early days of industrial " bright annealing " hydrogen was frequently used ; but, except in special instances where it is particularly suitable, its high cost—and also the explosion hazard in-

[1] Owing to numerous requests this section, which supplements the information given on page 683, has been added to the reprint of the second edition.

separable from its use—soon led to its abandonment. Atmospheres derived from "burnt" butane or propane were also used to some extent, although their cost was about the same as that of electrolytic hydrogen.

Atmospheres Derived from Ammonia. The next atmosphere to be developed on an industrial scale was one derived from ammonia, and, for many purposes, this remains the most efficient of any yet available. Ammonia is readily obtainable in liquid form compressed in cylinders in a very pure state, and to produce a protective atmosphere it is only necessary to dissociate or "crack" it into pure nitrogen and hydrogen, its constituent elements. This is usually done by passing the gas liberated from a storage cylinder over a catalyst contained in a tube heated electrically to a temperature of 540° to 550° C., giving a gas consisting of three parts of hydrogen to one of nitrogen according to the familiar equation

$$2NH_3 \rightleftharpoons N_2 + 3H_2.$$

This gas is very pure indeed and, which is of great importance, free from moisture. It is, probably, the most efficient protective atmosphere available on an industrial scale; but, although cheaper than electrolytic hydrogen, it is, unfortunately, expensive, and, like hydrogen, explosive when mixed with air. Considerable economy can be achieved by partially burning the cracked gas with a controlled proportion of air, thus converting most of the hydrogen into water which is then removed by passing the products of combustion through suitable drying units, such as a refrigerator to remove the bulk of the water, followed by a drier utilising either silica gel or activated alumina as the drying agent to reduce the moisture content to a very low value. By varying the proportion of air used in the combustion stage, the composition of the dried product can be varied from about 90 per cent. nitrogen plus 10 per cent. hydrogen (giving a reducing atmosphere) to something approaching 99 per cent. nitrogen plus 1 per cent. hydrogen (giving a highly inert atmosphere). This gas is non-explosive and non-toxic, two advantages of considerable importance industrially.

In furnaces of suitable design still further economy can be achieved by the incorporation of what is known as a "regenerative" system. In principle, this consists of circulating an atmosphere of "cracked" and "burnt" ammonia through a furnace by means of a pump, continuously purifying it and making up for loss with fresh gas. In practice, this is accomplished by passing the gas drawn from the annealing furnace through suitable filters to remove dust, oil vapour, and other unwanted substances, and then passing the filtered gas through the "ammonia-burning" unit at the same time introducing a sufficient quantity of fresh, dissociated-ammonia gas from the "cracking" unit to make up for losses incurred in the furnace. Providing that door leakage is reasonably small only about 10 per cent. of the gas passing through the furnace should be lost; hence this system shows a considerable saving over that in which the "cracked" and "burnt" gas is discharged to waste.

To summarise, ammonia, either "cracked" or "burnt-cracked-and-*thoroughly*-dried," is probably the best protective atmosphere available. It can be used on all the industrial metals, and, having regard to the excellent results achieved, its cost cannot be considered unreasonable unless a large proportion of the gas used is lost by leakage at the furnace doors. It is, however, not suitable for annealing alloys containing zinc in large-aperture furnaces because oxygen from the air is likely to enter the tunnel, de-zincify the metal and choke the filters of a "regenerative" system with oxidation products.

Atmospheres Derived from Town's Gas. In an effort to obtain a protective atmosphere less expensive than those derived from ammonia, a very large amount of development work has been done in attempts to produce a suitable atmosphere from ordinary town's gas. Having regard to the difficulties which have to be overcome, remarkable progress has been made. As a result, atmospheres are available which are satisfactory for the industrial annealing of many metals, and still further improvement, leading to increased cleanliness and to application to metals which now have to be annealed in other atmospheres, is to be expected. At the outset the fact that the composition of town's gas is variable complicates matters; but the greatest difficulties lie in the efficient removal of certain substances which are prejudicial to the bright-annealing of some, if not of all, metals. Of these substances, sulphur and carbon dioxide are the most important, for water can be removed without much difficulty when suitable precautions are taken.

The composition of ordinary town's gas usually lies within the following limits :—

Hydrogen	43–55 per cent.
Methane	25–35 ,, ,,
Carbon monoxide	5–11 ,, ,,
Unsaturated hydrocarbons	2·5–5 ,, ,,
Nitrogen	2–12 ,, ,,
Carbon dioxide	0–3 ,, ,,
Oxygen	0–1·5 ,, ,,
Sulphur	17–25 grains per 100 cubic feet.

In order to produce an atmosphere suitable for bright-annealing the gas has to be partially burnt with a controlled proportion of air, and then dried and purified to an extent determined by the particular metal to be annealed and the degree of "brightness" desired on the annealed work. The partial combustion of town's gas involves a number of chemical reactions, many of them reversible and influenced both by temperature and by the proportion of individual gases present. Readers interested in this aspect are referred to the many papers dealing with these reactions and to the many published charts claiming to represent, for example, the composition of the product as the ratio of town's gas/air is varied and the equilibrium of carbon dioxide/carbon monoxide mixtures at various temperatures. In the event of complete combustion the product would consist mainly of carbon dioxide with a smaller proportion of nitrogen and a little water vapour plus certain impurities. Partially burnt town's gas, as generally used, may contain up to 14 per cent. hydrogen, up to 12 per cent. carbon monoxide, a smaller percentage of carbon dioxide which will vary in proportion inversely with the percentage of carbon monoxide, together with a small percentage of methane and the usual impurities, the balance being nitrogen. A typical analysis of partly-burnt town's gas is :—

Carbon monoxide	10 per cent.
Carbon dioxide	6 ,, ,,
Hydrogen	14 ,, ,,
Oxygen	0·1 ,, ,,
Methane	0·5 ,, ,,
Water	0·1 ,, ,,
Nitrogen	Remainder.

Sometimes a richer product is used, but this tends to deposit carbon ; whereas with a product approximating to the composition just given this trouble is avoided. The proportion of water varies considerably in different plants, depending upon the efficiency of the drying units.

In order to obtain an efficient protective atmosphere, both the water and the sulphur contents of the burnt gas must be reduced to a very low percentage, and failure to achieve a satisfactorily low figure is usually responsible for the mediocre success sometimes achieved with atmospheres of this kind. Water can be removed by passing the gas through suitable driers containing some desiccating agent, such as silica gel or activated alumina ; but, as the quantities to be removed are large, pre-treatment by refrigeration is a precaution which, in the opinion of some authorities, is highly desirable. The chemical driers are usually duplicated so that, while one is working, the desiccating agent in the other can be regenerated by the simple process of passing hot air through it. These observations on the removal of water apply also to the drying of "burnt" ammonia gas already described.

The removal of sulphur is more difficult because this element is present in more than one form. Some exists as sulphur dioxide ; this is removed in the coolers, which for this reason have to be made to withstand the action of the resulting acid. Sulphur present as sulphuretted hydrogen is generally removed by passing the gas through towers containing "bog ore," a form of hydrated iron oxide, although purifiers utilising a nickel catalyst are sometimes used. Two purifiers are usually arranged in series, and it is essential that these be sufficiently large to deal with the maximum flow of gas ever likely to be passed through them and that the "bog ore" used to recharge them be sufficiently porous not to impede the flow of gas unduly.

Unfortunately, "bog ore" purifiers will *not* remove organic sulphur, which is present in the gas as carbon disulphide and complex compounds. Organic sulphur can be removed by "cracking," which consists in principle in passing the gas through an iron tube containing coarse iron swarf heated externally to a temperature which, although dependent upon the metal to be annealed, must always be appreciably in excess of that to which the gas will be heated in the particular annealing furnace in which it is to be used as a protective atmosphere. The iron tubes need frequent cleaning, and, as with driers, it is usual to have two units so that while the one is in service, the other can be cleaned without having to interrupt the working of the furnace. This "cracking" process also causes the decomposition of the methane and unsaturated hydrocarbons present, with a consequent slight increase in the percentage of hydrogen and carbon dioxide in the product, and produces a certain amount of carbon deposition depending upon the amount of moisture present.

When alloys contain chromium, manganese, silicon or aluminium, carbon dioxide must be eliminated, because in the presence of water vapour—which is usually present in the furnace even though in very small percentages—these metals will decompose carbon dioxide and will react with the oxygen thereby liberated. This also happens, though in rather less degree, with zinc; hence when really "bright" annealing of brass is desired carbon dioxide should be removed from a protective atmosphere of "burnt" town's gas.

Carbon dioxide can be removed by chemical methods, for example, by passing the gas containing it through scrubbing towers in which it meets a spray of aqueous diethenolamine or a related compound which has the property of dissolving carbon dioxide—and, incidentally, sulphuretted hydrogen—and of giving it up when heated.

This method, although efficient, is costly; so a less expensive method termed "double cracking" has been evolved to produce from partially burnt town's gas an atmosphere containing a very low percentage of carbon dioxide. The first stage in the process consists in the "cracking," de-sulphurising and drying of burnt town's gas as already described. After this the gas is passed through a unit heated to a temperature of 1,050° to 1,100° C. in which, owing to the absence of water vapour, the reaction proceeds from left to right in the following equation:—

$$CO_2 + H_2 \rightleftharpoons CO + H_2O.$$

After passing through a final chemical drier to remove the moisture produced by the reaction just mentioned, a protective atmosphere is available which for most purposes is as efficient as the much more expensive ones derived from ammonia.

Another refinement to improve the efficiency of atmospheres derived from burnt town's gas is a unit often termed a "stabiliser," which consists essentially of a tube containing charcoal heated externally to a temperature of about 1,000° C. By passing partly-burnt, dried town's gas through this, very nearly all the carbon dioxide is broken down into carbon monoxide in accordance with the following equation :—

$$C + CO_2 \rightleftharpoons 2CO.$$

The higher the temperature the more the equilibrium tends to move to the right, but in practice a temperature of 1,000° C. is not often exceeded because above this the cost of working and maintenance tends to become considerable, and the results achieved at this temperature are adequate for most purposes.

This outline gives some idea of the more important developments in the production of a cheap and efficient protective atmosphere from burnt town's gas. Enough has been said to show that even now it is a serious rival to the more expensive atmosphere derived from ammonia, and it is likely that fresh developments will increase its efficiency even more and will extend its field of useful application. Attention may be drawn to the fact that with any protective atmosphere the *bête noire* of surface decarburisation, so serious when steels of medium and high carbon content have to be heat-treated, is usually of no consequence in the annealing or normalising of the low-carbon steel handled in the press shop : a fortunate circumstance for which those concerned with deep drawing and pressing must be duly thankful.

Charcoal Gas. To conclude this review of the more common protective atmospheres used to achieve as nearly as possible truly "bright" annealing under industrial conditions, mention must be made of atmospheres derived from charcoal. These find extensive application in the "clean" heat-treatment of steel when it is important to avoid either carburisation or decarburisation of the surface of the work treated, and their application to the bright-annealing of both ferrous and non-ferrous metals should not be overlooked.

When air is passed over charcoal heated to a temperature of about 1,000° C. a series of reactions takes place as in the familiar "producer" used to produce a combustible gas from coal. These result in the formation of a gas consisting essentially of carbon monoxide and nitrogen, but containing a small percentage of carbon dioxide. Provided that sulphur is absent, nickel and cupro-nickel can be successfully bright-annealed in an atmosphere containing relatively high percentages of carbon dioxide and water vapour ; hence, charcoal gas would seem to be a suitable protective atmosphere for these particular metals.

It is unsafe to hazard a guess as to what new atmospheres, or what modifications of ones now in use, will be employed in the future to give "bright," or perhaps merely "clean," annealing. Cost is, obviously, a matter of major importance; yet too much emphasis ought not always to be placed upon this factor, and it should always be considered in relation to the kind of article to be annealed, the cost of pickling it and the harmfulness of severe oxidation and perhaps drastic pickling upon the appearance—and sometimes even upon the service performance—of the finished product. The size and shape of the articles to be annealed will have to be studied, because a large-aperture furnace will always tend to give large leakage losses and thus perhaps preclude the use of an expensive, as distinct from a relatively cheap, protective atmosphere. As a rule a furnace aperture higher than 8 inches will lead to heavy losses, although this generalisation will naturally be modified by the efficiency of whatever baffles, screens, flaps and other devices are fitted to minimise leakage. With batch-type furnaces a very cheap atmosphere is essential, because the whole furnace must be completely refilled with protective gas with each fresh charge of work.

No matter how efficient a protective atmosphere may be, and no matter how well a furnace be sealed, it is useless to expect clean work to emerge if the work charged into the furnace is covered with drawing lubricant. This essential condition is not always appreciated by users, and as a result the plant, and sometimes even the principle upon which it works, is falsely blamed for the unsatisfactory appearance of work annealed in it.

Even when the protective atmosphere is efficient, the furnace free from air leaks and the work free from lubricant the surface of the annealed work will be tarnished if it is discharged into the atmosphere at too high a temperature. Furnaces constructed by reputable makers usually have cooling chambers of sufficient length to meet ordinary needs, but if the user increases the speed of conveyors or uses metal of unusually heavy gauge there is a possibility that the discharge temperature may be sufficiently high to cause discolouration of what otherwise would have been a genuine "bright-annealed" surface. The following figures give a rough guide to the maximum temperature at which various metals should be allowed to emerge from a protective atmosphere if visible tarnishing is to be prevented :—

Copper	75° C.
Cupro-nickel	130° C.
Brass	140° C.
Mild steel	150° C.
Austenitic steel ("18/8")	200° C.
Nickel	400° C.

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D.D. and P. = Deep Drawing and Pressing.
Pressings = Deep-drawn or pressed articles.

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