THE

MECHANICAL WORKING OF STEEL

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"THE STRUCTURE OF STEEL SIMPLY EXPLAINED"
ETC.

WITH A FOREWORD

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FOREWORD

THE art of working metals has been practised from ancient times, and its first beginnings belong to those prehistoric days of which no records remain. The fine gold ornaments found in the tombs of Egypt's early civilization clearly indicate that the primitive methods of drawing and beating gold still practised in parts of Africa were known thousands of years ago. In the same continent can still be found primitive forges in which the anvil consists of a block of hardstone, the fire of charcoal, and the bellows a pair of goat skins worked by a sitting boy.

It has been reserved, however, to comparatively recent times for other means than the strong arm of man to be developed for the hot and cold working of metals.

During the last century, important and complementary developments have not only revolutionized the use of metals in industry, but also brought about changes in the industrial life of the world greater than in any previous century. Three of these can be briefly summarized as—

(i) Fundamental scientific discoveries, and the application of the scientific method to investigation and control;

(ii) Developments in the production of power; and

(iii) The mechanical working of metals.

The authors have, in previous volumes, shown how scientific methods have assisted in revealing the structure of steel and the control of its manufacture. In this volume they not only describe the remarkable developments that have taken place in the technique of the hot and cold working of metals, but in a simple way have attempted to discuss the structures produced by the various types of operations and how these can be modified to produce the best results. The importance of choosing the right type of material to be formed by any given process and for the tools used is also emphasized.

The problems that arise in the cold working and pressing of metals are of great importance in modern mass production.

These are discussed in relationship to the changes that occur due to overstraining and during heat treatment.

By a thorough appreciation of the stresses to which materials are subjected when deformed by hot and cold processes, and in their engineering applications, much can be done to ensure the orientation of the fibrous structure in the way best suited to meet the designer's demands.

As a first introduction to a subject of great and growing importance in modern industry, this work will no doubt prove useful to engineering and metallurgical students, to whom a knowledge of modern processes is important; to those who are responsible for those processes; and to designers who should be familiar not only with the elastic properties of materials generally assumed as the basis of design, but also with the plastic properties and how advantage can be taken of these to produce those forms which can most effectively resist the elastic conditions under which the materials are assumed to work.

F. C. LEA

PREFACE

THE success of our two previous books—and they really have been successful—has led us to add yet another to our series of technical simplifications. For this we make no apology.

Dr. Gregory and I have a common enemy, other than and distinct from the arch-enemy at present threatening our national existence. He is the man with "the little black book" tucked carefully away in his pocket, who secretes such knowledge as he possesses and guards it jealously, refusing to transmit one iota of his rule of thumb experience to those who need it, surrounding with an aura of mystery and terror the details of his craft. Seldom has he recognizable standing in his own sphere; you do not see or hear him cited as an authority. Possibly he isn't. A few hundred years ago he would have been a Rosicrucian or a witch doctor. To-day it is impossible to regard him as other than a hindrance to the war effort, which depends on swift mastery of production technique by new-comers to industry, and therefore on the readiness of practical men to teach and assist.

In writing this book we have been largely actuated by the desire to defeat these monopolistic tendencies.

In *Steel Manufacture Simply Explained* we finished with an account of the making of ingots and castings. It will be realized that most of the steel produced by the processes there described must be subjected to certain manipulative operations or methods of mechanical working, such as forging or rolling, before being fabricated into usable parts. These and other processes not merely reduce the cross-sectional area to that desired; they considerably improve the mechanical properties of the steel.

In this book an attempt is made to explain these manipulative processes as simply as possible. Forging, rolling, pressing, spinning, etc., are discussed in such a manner that even the layman may follow them. At the same time, it is assumed that the reader has read with some attention the previous two books—*The Structure of Steel* and *Steel Manufacture*—because reference is frequently made to points fully dealt with in those earlier works. Wherever necessary, however, summaries of these points are given, so that the reader's understanding of what is written may not be hindered or prevented by the need to refer to a different work.

We have explored and tried to explain simply for both layman and practising engineer the basis of numerous mechanical working processes, some of the detail of which is still hidden away in the "little black books" to which we have referred. This is not so easy as it sounds, and in one or two instances we have been compelled to go outside our own experience and summon to our aid expert authority, while reserving and exercising the right of rearrangement and simplification. Notably, we must thank Professor G. Cook and Dr. J. D. Jevons for valuable and generous help, acknowledged later in the appropriate places. We must also thank those firms and journals who have kindly lent illuminating illustrations. Useful help in the chapter on "Riveting" was given by Mr. F. C. Welch, of Messrs. Edgar Allen & Co. Ltd., and, as always, Mr. R. G. Woodward, a Director of that company, has kept a kindly but watchful eye on our work. Messrs. Edgar Allen & Co. Ltd., Sheffield, have generously given us permission to reproduce such of this material as has already appeared serially in their technical journal, *The Edgar Allen News*, and for this we are exceedingly grateful.

ERIC N. SIMONS

EYAM, 1942

CONTENTS

THE MECHANICAL WORKING OF STEEL

CHAPTER I

Forging

FORGING is the process by which steel or other metal is altered in shape or form as a result of being struck with a hammer or similar tool, or squeezed under a pneumatic press, generally when the steel is hot. Forging under the hammer is one of the most ancient of all the crafts associated with metals, and there is evidence that it was practised long before written records of human activities existed. It constitutes one branch of the hot-working of metals, but its importance is extreme and its economic value admitted. It is divisible into two main sections, hand forging and power or mechanical forging. In hand forging, the object to be struck is held by tongs and the hammer is wielded by human effort. The village blacksmith's work is a characteristic example of hand forging, where mild and medium carbon steels are fashioned to shape, but it may be mentioned that high-speed steel lathe and other cutting tools are frequently hand forged in present-day workshops.

In mechanical or power forging, the blow is struck by a hammer driven by steam or compressed air. In drop forging (see Chapter II), the hammer head and the die, or anvil, are so shaped that the desired form of the forging is readily obtained. Drop forging is particularly suitable for the manufacture of crankshafts, gear-blanks, etc., and is fully discussed later.

In order to understand the principles and practice of forging steel, it is necessary to know the purpose or purposes for which forging is employed, the metallurgical changes involved, and the means adopted to ensure the desired results. The purpose may be quickly summarized. It is to bring a solid mass of steel down to a certain required size and shape, in many instances as nearly as possible to those of the completed product, so as to leave the minimum of finishing operations, such as machining, in order to produce the completed part. For instance, forging and rolling produce blooms and billets from ingots, bars from blooms and billets, while drop forging produces shaped parts such as crankshafts, pinion and wheel blanks, etc.

What is sometimes regarded as a secondary object, but is really of primary importance, is to improve the quality of the steel by mechanical working. Hot-working refines the grain structure of the steel, and this refinement leads to enhanced toughness.* A typical example of forging designed to improve the quality of steel is "double shear" steel,† where the second forging operation is carried out solely for the purpose of yielding a better and denser structure.

We may now turn our attention to the metallurgical phenomena associated with forging. As certain facts are common to all forms of the hot-working of steel, it will be as well to indicate these at the outset, and it will then only be necessary to refer to them briefly when dealing with other forms of hot-working in later chapters.

The solid block of steel to be hot-worked must first of all be reheated to, and soaked at (i.e. heated right through its mass, which takes a certain time), the correct temperature. Generally, the first hot-working temperatures are between 1000° and 1250° C., the actual temperature being determined by such factors as the quality or chemical composition of the steel, and the size and extent of the first reduction in cross-sectional area desired, etc.

Small ingots, particularly those of the alloy steel types (high-speed, stainless, heat-resisting, etc.), are usually allowed to go cold and are then reheated to the desired temperatures for forging. Larger ingots, however, of the type for constructional purposes, are more often transferred, while still hot,

* For an explanation of this, the reader is referred to *The Structure of Steel*, by the present authors.

† The making of double shear steel has been fully described in *Steel Manufacture Simply Explained.*

from the ingot-moulds into soaking pits or reheating furnaces before being hot-rolled. This practice has much to commend it, since it not merely conserves heat and thus reduces heating costs, but also greatly reduces the tendency to develop cracks.

When steel, whether ingot, bloom, billet or bar, is reheated to the proper hot-working temperature, its structure consists of a mass of relatively large crystals. If the steel were cooled down without hot-working, this coarsely crystalline structure would persist and the steel would be lacking in ductility and toughness. Steel as cast, in the form of either ingots or castings, suffers from these weaknesses, and for this reason most steel castings need to be annealed before being placed into service. By annealing, the crystal grain-size of the steel is reduced. Moreover, the ductility is improved by purely thermal means as a consequence of the steels being reheated to a temperature just above its critical range, i.e. the range of temperature at which definite structural changes occur in the steel.

To toughen steel to the maximum extent and impart to it the maximum ductility, mechanical hot-working by forging or rolling is a necessary preliminary to such later processes as annealing and normalizing. Hot-working produces grain-refinement by force, as it were, and smashes up the larger into smaller crystals. If, however, the temperature at which mechanical work is *finished* is too high, the crystal-size is larger than when the work is finished at a temperature just above or below its upper critical temperature. The anticipated toughness and ductility may not then be obtained. It must be realized, therefore, that *both* the temperature at which hot-work is begun and the final temperature when it is discontinued are of paramount importance to the properties of steel. When the steel is heated to too high a temperature, and is almost on the verge of melting, it is said to be *burnt*, which means that incipient melting may have begun on the outside layers. This is accompanied by oxide formation along the crystal boundaries, and the plasticity of the hot metal is then so impaired that cracks readily develop during later mechanical treatment by forging and rolling. Overheating, or burning, may indeed result in a crumbling or disintegration of the steel during the hot-working process.

At the other extreme, if the final temperature of rolling is too low, this may also result in a hot-worked product full of stresses, and the production of material lacking in ductility. The stresses thus set up may then give rise to distortion or even cracking during later heat-treatment.

The control of both the starting and finishing temperatures for any form of hot mechanical working is therefore of vital importance. The upper and lower temperature limits between which a steel can be properly worked constitute its *hot-working range* and this, as already indicated, is not fixed, but varies according to the composition of the steel and the amount of reduction required.

It must be borne in mind, however, that hot-working within the accepted range of temperature will not of itself always yield a satisfactory product. In most instances, though there are exceptions, it is usual to subject the steel after hot-working to some form of heat-treatment designed to put it into the best structural condition. Even when hot-worked under almost ideal conditions, the steel is in a condition of internal strain, and the mischief is that these strains are not always evenly distributed. This unequal distribution of internal strain may result in distortion during machining or during reheating for hardening, and in this respect the temperature at which hot-working is finished is vital. The lower the finishing temperature, particularly if below the lower critical point, the greater the internal strain. It is for these reasons that many hot-worked steels are normalized or annealed in order to get rid of internal strains before machining. Metallurgists agree that the lower the finishing temperature, so long as this is not below the lower critical point, the more refined will be the structure of the steel, i.e. the smaller will be the crystals of which it is composed. If the sole consideration were lowness of finishing temperature, the matter would be relatively easy. Other factors than one theoretically ideal temperature have, however, to be taken into account, such as the mass of the steel, its form, the particular kind of hot work to which it will be subjected, and the like. In general, the bigger the mass to be hot-worked down to a specified size, and the more complicated the shape to be dealt with, the higher will be the finishing temperature, in consequence of the need of adequate plasticity during the early stages of working. This means that later heat-treatment processes play a greater part than when smaller and less complicated shapes are dealt with. The smaller the size and the simpler the form, the nearer can the finishing temperature go to the lower limit of hot-working. Moreover, it is definitely

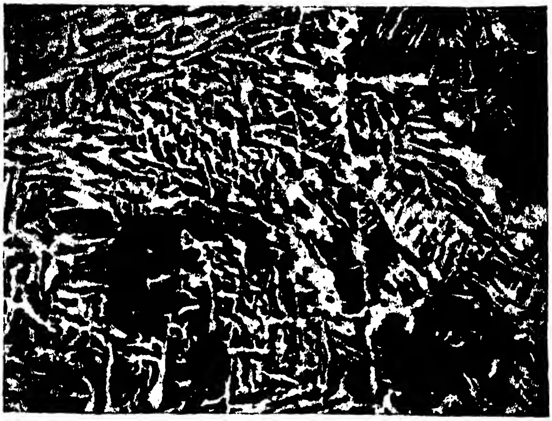


FIG. 1. 3·5 PER CENT NICKEL STEEL IN CAST STATE
Mag. × 250. Note heterogeneity of structure.

easier to control this finishing temperature. Less internal work is then required during the final heat-treatment process.

The higher carbon steels containing, say, more than 1·0 per cent of carbon are put into the best condition by finishing the hot-work at or near to the lower critical point. The famous swords of Damascus were produced by giving successive heatings and light forgings at the critical and even at sub-critical temperatures.* This created a highly distorted structure of the free cementite in "wavy" form, so that an exceptionally sharp and strong sword was produced.

Some idea of the changes wrought by forging and rolling is indicated in Figs. 1, 2, 3, 4, and 5, taken from *Metallurgy* (Gregory) by permission of Blackie & Co., Ltd.

Having thus dealt with certain structural alterations induced by the hot-working of steel, we must now pay some attention

* For a full explanation of these terms see *The Structure of Steel.*

to the actual behaviour of the metal itself when forged. In this chapter we are not concerned with the squeezing action of the hydraulic press (see Chapter VII), but with the impacting

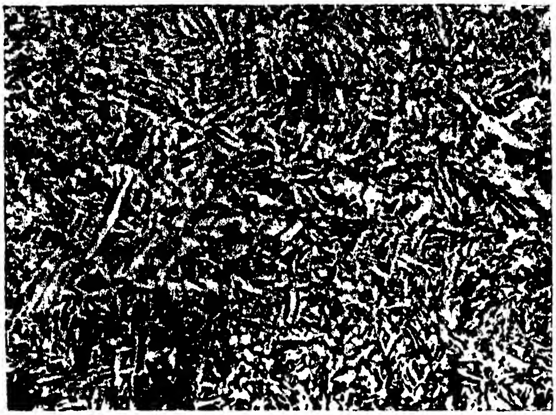


FIG. 2. SAME STEEL AS FIG. 1, BUT IN FORGED CONDITION
Mag. × 250. Structure finer and more homogeneous.

FIG. 3. RAZOR STEEL CONTAINING 1·3 PER CENT C. IN CAST CONDITION

FIG. 4. SAME STEEL AS FIG. 3, BUT IN FORGED CONDITION

action of forging proper. Under the hammer, the latter exerts its greatest effect at the moment of impact, its power lessening quickly as the energy of the blow is passed on to the steel and absorbed in changing its form.

What happens when steel is struck by a forging tool of the impact type? It flows and spreads in much the same way as a mass of butter spreads when allowed to fall from a height upon a flat surface. The impact causes it to spread evenly in all directions. The object of forging is, however, to produce not a formless mass of this kind, but a formed mass of recognizable and desired contours. It is necessary, therefore, to canalize this tendency to flow under impact, to dam it up, as it were, here, and release it there, so that the flow is only in the required directions. It must be realized that the flow is not a continuous but an intermittent movement, whose rhythm is given by that of the repeated hammer blows

FIG. 5. 1·3 PER CENT C. STEEL FORGED AND THEN ROLLED: LONGITUDINAL SECTION

Mag. × 100. Cementite and Pearlite.

The "canal" along which the steel is forced to flow is represented by the shape of the forging tools, or dies. In forging a steel ingot down to "bloom" or "billet" form, the operation is relatively simple, since the existing form of the ingot section is more or less retained; all that is required is an elongation and a reduction in cross-sectional area. The steel is therefore hammered on its sides and periodically turned over, by which means it is forced to flow outwards along its length. If, however, the work is applied to two opposite sides only, the effect is to cause spreading and produce a flat "cake."

The above effects can be readily demonstrated by means of a square stick of "plasticine." If squeezed alternately on each pair of opposite faces it will rapidly elongate, whereas if continuously pressed on the same pair of opposite faces it will become flattened and yield a form comparable with a steel plate.

The phenomena of plastic flow in hot-worked steel are, however, not quite so simple as suggested by this experiment. A fact to be remembered is that steel, under impact, behaves in a similar way to electricity, i.e. it follows the line of least resistance.

According to Naujoks and Fabel (*Forging Handbook*, p. 107), impact pressure on a cylinder produces an even flow of metal in all directions. Theoretically, this should result in a cylinder of identical form, but of increased section and reduced height. Actually, however, there is friction between die and cylinder faces; also the hot cylinder ends cool more quickly than the

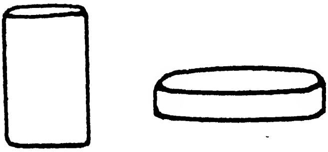


FIG. 6
(THEORETICAL)

FIG. 7
(PRACTICAL)

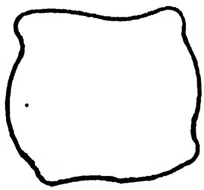


FIG. 8

interior of the cylinder, because in contact with the cold dies of the forging machine. Finally, the metal at these ends is slower to flow outwards (because less plastic) than the metal in the centre. The pressure results eventually, therefore, not in a smaller and perfectly formed cylinder, but in a barrel-shaped piece. These points are indicated in Figs. 6 and 7.

If a piece of square section is being forged, the metal will flow outwards at the sides, maximum flow taking place midway between the corners. Forging down a square block on two faces only, therefore, does not produce a perfectly rectangular cross-section, but a "bastard" cross-section of the form shown in Fig. 8.

If the effect of the impact penetrates to the centre of the forged billet, even when the rectangular cross-section is retained throughout by alternate blows on each pair of opposite faces, the ends of the billet are definitely rounded, as indicated in Fig. 9.

If, however, the blows are relatively light, as in forging large sections, the effect is mainly confined to the surface layers and

FIG. 9

does not penetrate to the interior, with the consequence that the ends of the billets are of the form indicated in Fig. 10.

On the other hand, when the forging is conducted under a steam or pneumatic press, which maintains a steady pressure and kneads the metal like dough, the ends of the forged blooms

FIG. 10

and billets again have the form shown in Fig. 9. The appearance of the ends, in large forgings, is indeed a clear indication whether the original ingot has been hammered or pressed. Pressing will, of course, be dealt with later.

From what has been stated, it will be clear that metal, when subjected to impact, or squeezed, always endeavours to assume a roughly circular form, and the direction of flow is invariably towards the narrow sides or at those points nearest the centre of the mass.

The above facts are not merely of academic importance; they govern the actual practice of forging, as will be seen.

The preliminary stage of forging is known as *cogging*. This operation is designed specifically for the production of blooms and billets, and to improve the grain structure of the steel. In many instances the cogged blooms (and billets) are subjected to a subsequent re-rolling. After cogging comes the *cutting* or *slicing* to length of the forged bloom or billet. The bloom or billet is next drawn or forged down so as to reduce its section and increase its length.

Another forging operation is known as *up-ending* or *upsetting*. This consists in forging the piece of steel in such a direction that the blow or pressure is along its major axis. In this way the length of the piece is decreased and its diameter increased. Upsetting will be further considered in Chapter III.

Setting down is the term applied to the operation of decreasing the cross-sectional area of any particular part of a forging.

There are other forging operations, such as piercing, punching, boring, trepanning, and expanding, but these will be considered later (see page 33).

A distinction must be made here, however, between hammer forging and drop forging. At the moment we are concerned solely with hammer forging. Drop forging, a method of manufacturing a large number of identically shaped parts, will be fully discussed in Chapter II.

Hammer forging is more often used in those operations concerned with steels of high carbon content, highly-alloyed steels such as stainless steel for cutlery, high-speed steel and tool steels generally, nickel-chromium steels of high quality, etc.

Furthermore, hammer forging is generally adopted where the parts required as forgings have an intricate form or comprise thin or unsymmetrical sections. It has some advantage also as a preliminary to drop forging, taking the steel mass and roughing it out to some extent in advance of the actual drop forging. This is a procedure employed when the dies of the drop-forging machine are not wide enough or have inadequate space.

Sometimes the number of forged parts desired may be so small as not to warrant the cost of making special dies, or the particular form may be better given by the hammer than by the die.

Another use for hammer forging is as a later stage in drop forging, particularly when a forging with a long shank or shaft is required. This can readily be drawn down by the hammer, so obviating the necessity and cost of supplying long dies. Again, it is occasionally employed for reducing stock metal down to smaller dimensions, especially when costly steels, such as many of those produced by the crucible and high-frequency electric furnace processes, are concerned. Where only small numbers of the forgings in these steels are ordered at a time, it pays to buy bigger stock and forge down as

Fig. 11. Hammer Forging of Steel

required rather than stock a large number of small sizes in not very considerable amounts, especially where delivery of small sizes is difficult.

Hammer forgings range from small parts weighing ounces only to large masses weighing several tons. While most forgings are machined to size when required for accurate components of a piece of plant, skill to-day is such that many need only a minimum of machining and some none. Working to comparatively fine limits is achieved in numerous works. Typical hammer forgings include axles, bars, bolts, bushes, crankshafts, collars, die blocks, hooks, levers, nuts, rams, rings, rolls, shear blades, springs, spindles, shafts, trunnions, valves, wrenches, and yokes.

We will now turn to the actual appliances and machinery needed for efficient hammer forging. A furnace in which to heat up the steel to the requisite temperature is, of course, an indispensable adjunct, but the question of furnace control, design, and operation is outside the scope of this book. The essential requirement is, of course, the hammer itself. This is driven by either steam or compressed air. Much of the work is done with special forging tools, such as swages. (See page 15.)

These hammers are divisible into two main types, the single-acting and the double-acting. They consist of a die block or anvil of steel embedded in the foundations and a steel hammer moving in guides and striking down upon it vertically, this hammer being attached to one end of a steel rod. The other end of this rod is fastened to a piston working in a cylinder. When the motive power is employed merely to lift the hammer, allowing its fall to be due to gravity alone, the hammer is called *single-acting*. When steam or air pressure is employed to add to the power of the downward blow, the hammer is *double-acting*. The power of the hammer is always based on the actual weight of the striking mass or tup and rod combined. Thus, a ten-ton hammer is one whose tup and rod weigh ten tons.

A *cogging hammer* is one employed for forging ingots into blooms.

In addition to a hammer, mechanical appliances for cutting up the steel into lengths suitable for manipulation under the

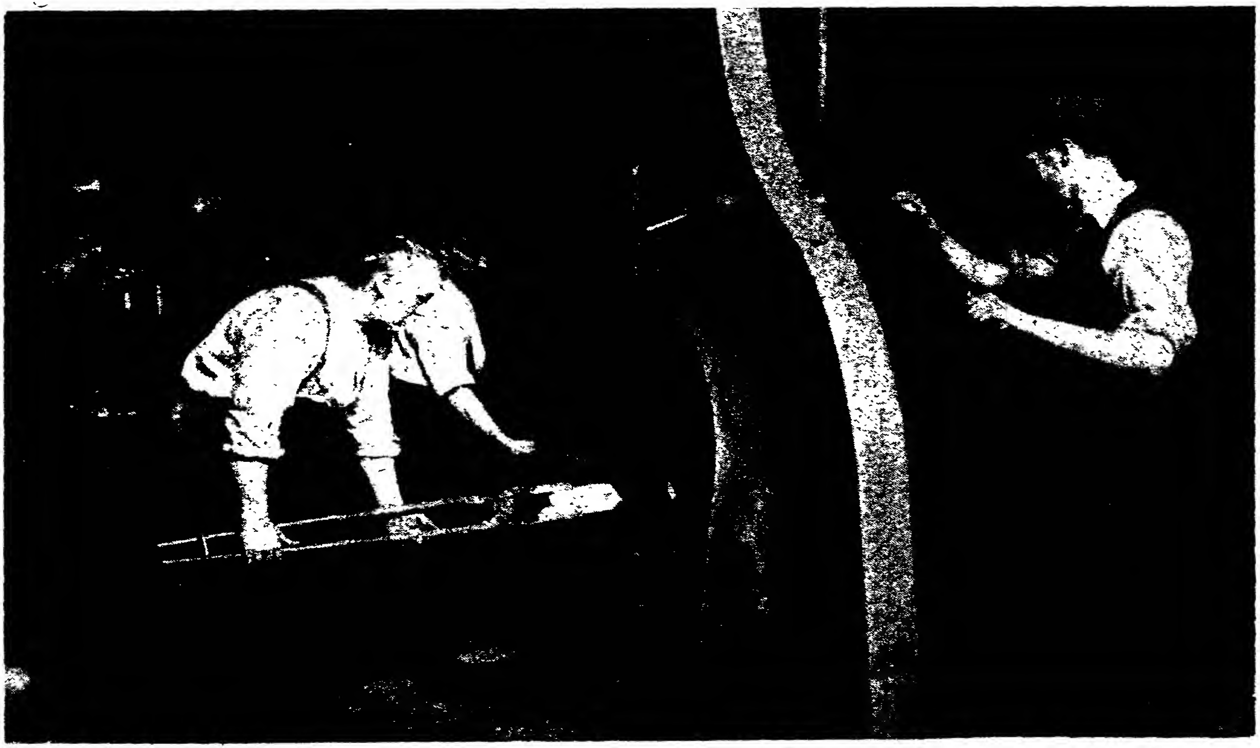


Fig. 12. Another View of the Hammer Forging of Steel

hammer may be necessary. Power-operated shears and circular sawing machines are examples.

During the heating of an ingot, bloom, or billet, a *scale* forms on its surface due to oxidation (the combination under heat of the oxygen of the atmosphere and the iron of the steel to yield the magnetic oxide, Fe_3O_4). Some of this scale may be scraped off with special scraping tools before the forging or other hot-working, and most of it flakes off and falls away during the process. It will be readily understood, however, that as the scale falls away, the exposed surface of the hot steel again becomes coated with a new scale, whose thickness is exceedingly small compared with that on the surface of the ingot, bloom, or billet when withdrawn from the reheating furnace. It will be seen, therefore, that all hot-worked steel is covered with a film of oxide or scale and, in some instances, the whole of the first oxide formed during heating may not fall away during the mechanical treatment, but may be knocked, pressed, or rolled into the surface of the steel, giving rise to the defect known as *pitting*.

Pitting and other surface defects, notably seams (which are elongated blowholes), rokes, etc., are best revealed by the process known as *pickling*.

Pickling is a means of removing scale by immersion of the part in a tank containing an acid, either sulphuric (vitriol), hydrochloric (spirits of salt), or, for stainless steels, mixtures of hydrochloric and nitric acids. These acids are diluted with water before being used for pickling. The acid eats away or loosens the adherent and undesirable oxide surface. The shot-blast and the tumbler are other methods of cleaning forgings by ridding them of the adherent scale. In the one, a jet of "chilled" iron shot (or sometimes sand, as in the sand-blast) is directed on to the forgings at high pressure and scours them. In the other, they are placed in a rotating barrel or other receptacle and the consequent friction of the articles against each other and the barrel walls rubs or knocks away the adherent scaly film. Sometimes steel balls or "stars" are introduced into the barrel to increase and expedite the scale removal.

Even when the scale is wholly removed from a pitted surface, the surface of the forged or rolled product may be so uneven that it becomes unsuitable for the particular purpose intended, as where the pickled surface is that of the finished article. On the other hand, if the scaly surface is not removed by pickling, particularly when pitted, difficulty may be experienced during later machining, since the scale may give rise to unexpectedly hard patches which damage or unduly wear the tool nose.

Finally there are the *smithing tools*, such as punches, swages, swage blocks, mandrels and vee-blocks, knives, pegs, and tongs, and the range of dies and tools for specific operations. The punches are for producing holes under the hammer. *Swages* are a form of dies for giving a required form to a forging. They comprise a lower piece fitting into or on the anvil and an upper piece held by the smith. Between these two pieces the steel is worked into its desired form. They are sometimes called top and bottom tools. The swage block is a rectangular cast-steel block perforated in the centre by a number of holes, both round and square. This receives the forging that has to be given a shoulder. The edges of the block are grooved in different sectional forms so as to be able to deal with forgings larger than the ordinary bottom swages will take.

Mandrels are round metal rods upon which nuts, sleeves and rings are finished to shape. *Knives* are flat forged steel-edged tools for cutting down the hot steel into shorter lengths after forging. *Pegs* are tools for reducing the steel to size during forging. *Tongs* are, of course, for gripping the hot steel and manipulating it.

Transportation of the forgings from furnace to hammer, and suspension during forging, are usually by hand unless they are over two cwt., in which case jib cranes for medium-sized pieces and overhead cranes for specially big forgings may be required.

Pressing is the only means of dealing with large ingots and forgings. Even with the heaviest hammer available, the interior of the forging may not be worked to the desired extent, and, indeed, if the section is very large, may be entirely unaffected. Big guns and large hollow forgings generally, such as large high-pressure vessels, are fashioned under the hydraulic or pneumatic press. From these observations it must not be assumed that the press is not used for the ordinary forging of smaller masses into blooms and billets. On the contrary, thousands of tons of steel ingots are reduced to these forms by means of the press. Pressing is dealt with in Chapters VII and VIII.

CHAPTER II

Drop Forging

Drop forging is a process used when a considerable number of identical parts that are not simple in shape are required. It comprises forging or stamping a suitable piece of hot steel between dies under a hammer, mechanically operated. The die is in two halves, a lower and an upper. The lower die is affixed to the anvil block. The upper is attached to the hammer itself, and goes up and down with it. If the part being forged is not too complicated, one set of dies may prove adequate, but if more intricate parts are desired, two or more sets may be needed, one set for roughing and one for finishing. When the two halves of the die meet, some of the metal will be squeezed out by the pressure between the edges of the dies, and will constitute a thin "fin" or "fash" at the sides of the part. This has to be removed. There are two ways of doing this. One is to revolve circular stock in the dies through a small arc, alternating between every few blows, so that the fin is eliminated on formation. The other is to knock the forging through a die pierced with a hole of identical form, so that the fin is stripped off and left behind.

The drop-forging process, though simple to all appearance, is much more complex than might be supposed from this brief description. Practice differs considerably; American drop-forging methods, for example, are very different from British. Some of the general phenomena of forging have been dealt with in the previous chapter. Such notes as are given here relate mainly to drop forging. Nevertheless, it will be as well to read both chapters for a full understanding of the subject.

In drop forging, the first requirement is an adequate piece of metal or "stock." If there is too much metal, there will be undue waste in the form of an excessive fin, which has to be cut off and serves only as scrap for re-melting.

Another drawback to an excessive amount of stock is that more time and effort are needed to produce a forging of the correct dimensions, not only because more metal has to be forced out of the dies, but also because the metal forced out, which is invariably colder than the mass of the metal, having been in contact with the relatively cold die faces, takes many more blows to bring it down to size. These additional blows will, as the fin hardens in cooling, cause cracks, which may ultimately spread to the forging itself. In those instances in which a more than usually large supply of metal is desirable, dies are designed with recesses to absorb the surplus.

If there is only a bare sufficiency of metal, three possibilities arise. First, the metal may be completely absorbed by the die impressions, with no surplus to be forced out as a fin. Secondly, the operator may find it exceedingly troublesome to manipulate the piece in such a way that the die impression will, on the descent of the hammer, be wholly filled with metal. Thirdly, the metal, or part of it, may be trapped between the die faces, and fail to reach the impressions. In this instance, the forging will be unsatisfactory because these impressions will not be completely filled and the proper shape of the forging not be obtained, particularly as the trapped metal will keep the dies from coming properly together. If there is no surplus metal to be forced out as a side fin, there will be no supply of hot plastic material to absorb part of the hammer blow and mitigate its severity. This blow will then fall entirely on the hardened faces of the dies themselves. The steel of which the dies are made is not designed to withstand such heavy impact, and is, furthermore, relatively cold. Great stresses of this type inevitably result, therefore, in the break-down of the dies through cracking, chipping, or complete fracture of their hardened faces.

If there is insufficient metal, the die impressions will not be completely filled, the piece will be only partly forged, and there will again be no surplus metal to act as a pad between the die faces, which will therefore clash against one another with harmful results. It must be stressed that a slight surplus of metal is essential to form the protective fin, which, flowing in every direction as a result of the successive blows, not only interposes its plastic layer between the two hardened die faces and prevents them from striking each other, but also equalizes the force of the blow so that it does not fall upon only one small area of the die face. One other advantage of the fin is that it ensures complete filling of the die impressions with metal, and as it is squeezed out under pressure, packs this metal firmly and uniformly, so that the forging eventually produced possesses the required structural properties, as will be seen.

We have indicated the importance of the right amount of metal or "stock." Equally important is the proper manipulation of this stock. Drop forgings differ greatly in form, some being relatively simple and capable of production straight from the stock. Others are intricate and call for numerous and complex operations. It is not usual for the piece to be *increased* in any one dimension by drop forging, and the stock should, for this reason, never be smaller in cross-section than will provide adequate metal for making the greatest cross-sectional dimension of the finished part, for the reasons explained in the following pages.

The stock is usually in the form of bars or billets, and certain preliminary forging work is often done upon it to put it into the best possible form for drop forging. There is a definite advantage in so arranging operations that the metal is not compelled to go too much against its grain, so to speak, when driven by impact into the different recesses and impressions of the die. In other words, the direction of the flow of the metal under the hammer into these recesses should as far as possible coincide with the natural flow of metal in a plastic condition when under impact, and particularly from the thick sections to the thin. The stock, therefore, when necessary, is shaped and prepared so that, on final drop-stamping, the metal flows into the recesses and grooves as if down previously prepared channels aiding rather than impeding its progress. It is not compelled to climb obstacles, so to speak, nor is it thrust more than is essential out of its natural path, as a wayfarer might be thrust out of a main road into an undesired alleyway by the terrific pressure of an advancing or expanding crowd. We shall say more on this point later.

Not every drop forging needs these advance operations on the stock. The simpler and comparatively symmetrical parts, such as discs, flat and bevel gear-blanks whose bosses are shallow, and also certain pipe fittings, can be made straight from the stock in bar or billet form, but in such instances the metal or "stock" must usually be of suitable size and weight for making one forging only at a time. While output is lowered by this method when the forgings are only small or of medium dimensions, this is not of great consequence unless the quantity required is large, while there is a saving because the dies used will be less costly than those necessary if speed of production is the main requirement. Furthermore, where the drop forgings are bigger, it is doubtful if greater production would be achieved by advance operations.

The economy of making these simpler forgings directly from the single piece of stock lies in the fact that no part of the bar or billet has to be forged into a narrower projection to enable tongs to hold the material tightly while forging, and therefore a proportion of the material is saved. This is a particularly serious item when the steel used is a high-priced alloy steel. On the other hand, the absence of this hold for the tongs slows up the work, and consequently reduces production. Each individual forging will therefore cost more to make, and the manufacturer has to balance the two factors one against another, and decide whether it is more economical to drop-forge straight from the stock or to forge a tong-hold and shape the material to suit the job. Some forgings, even though simple, must, in any event, have their stock prepared for drop forging.

We have referred to the flow of the metal under impact pressure. This follows certain laws that can be readily understood, especially if Figs. 13, 14, and 15 are examined. Fig. 13 shows the forging blank about to be stamped between the dies *A* and *B*. Fig. 14 shows an intermediate stage in the operation. It will be seen that the blank (shaded) has spread sideways and partly flowed into the impression of the bottom die *B*, but in comparison only a small proportion of the metal has moved into the upper recess of die *A*. Fig. 15 shows the completed forging operation. It will be observed from this that some of the metal has been forced by pressure into the cavities to the right and left formed by the coming together of corresponding recesses in dies *A* and *B*. This metal will constitute the fin of the completed forgings, and as its section is not great, it cools quickly, hardens, and so (by its resistance) prevents further metal from flowing in its wake. Debarred from further lateral progress, the metal is thus compelled to seek an outlet in a different direction, and is forced into the upper recess in die *A*.

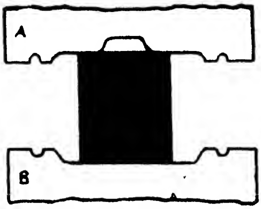


FIG. 13

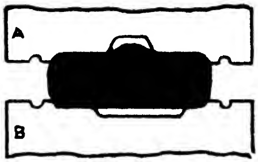


FIG. 14

FIG. 15

This it completely fills, thereby giving the desired final form to the drop forging.

In forming the stock for drop forging, as has been pointed out, an attempt is made to shape it in such a way that the steel can travel or flow from the thicker sections to the thinner, since the reverse of this is difficult to achieve. Similarly, it is sought to distribute the fash or fin uniformly by manipulation during the operation to avoid certain stresses set up when a large mass of surplus metal confined to one small area of the forging cools, and therefore contracts, in advance of the remainder. It should be borne in mind, also, that metal in a plastic state flows in the direction of minimum resistance. Opposition to plastic flow is usually greater where the surfaces of the steel and the dies come into contact. Without dwelling on the various methods of shaping the stock, which are governed by the form, number, and quality of the drop forgings, let us turn to an equally, if not more, important aspect of plastic flow.

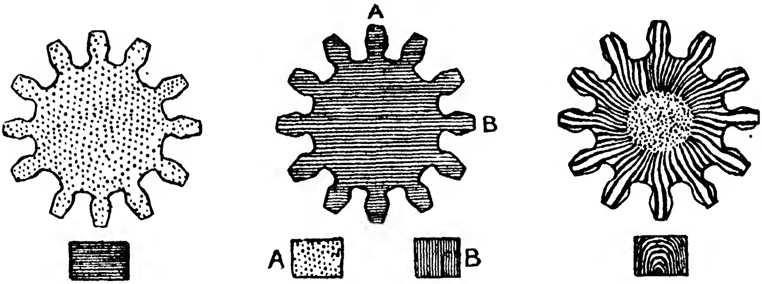
As will be appreciated by readers of *The Structure of Steel*,

steel is a crystalline substance. A piece of cast steel fractured, and examined under the microscope, reveals a structure in which the crystals of the metal are distributed, undeformed by mechanical working, throughout the piece. Their distribution is indeterminate, like that of a casual crowd gathered in a public square. There will be no marked difference in strength between one part of the casting and another, and theoretically a stress applied at any point will meet with approximately equal resistance, as would be the case if the assembly in the square were charged at any point by the police.

When, however, a piece of cast steel is mechanically worked by rolling or forging, as happens to a bar or billet intended for use as stock in drop forging, the crystals of the steel are deformed by elongation in the direction in which the mechanically produced stresses have been applied. In other words, they are themselves crushed and squeezed into a particular form and direction. The type of structure thus produced is termed *fibre*, and experiments have conclusively proved that steel is more resistant when stresses are applied *across the direction of its fibres* than when applied *in the direction of its fibres.* In these circumstances, with certain types of drop forgings, it is desirable that the stresses ultimately to be encountered in the finished part should be such that they are approximately at right angles to the fibre or grain of the steel. This can often be arranged by careful design and manipulation, as will shortly be seen.

The difference in strength between steel in which the stresses are along the grain or fibre as compared with across is considerable when shock, vibration, and impact are concerned, though less noticeable where pulling or tensile stresses are concerned (only 2–5 per cent in this latter instance).

Further, the way in which the structural fibre runs plays an important part in later operations after the forging has been made. For example, if a drop stamping has to be heat-treated, there is always a risk of distortion if the fibre is badly disposed. Without going too deeply into the matter it may be stated that the coefficient of expansion of steel, i.e. the rate at which the steel is known to expand when heated, varies according to the direction its axis makes with the grain or fibre. Further, as a consequence of fibre, a given piece of steel may be longer or shorter after being reheated than previously, so that one effect of imperfectly arranged fibre is to set up unequal stresses in different parts of the forging after it has cooled down. The heat-treating operation, designed to put the forging into proper structural condition for its purpose, may release some of these stresses but introduce others. The interplay of these unbalanced



Longitudinal sections of teeth.

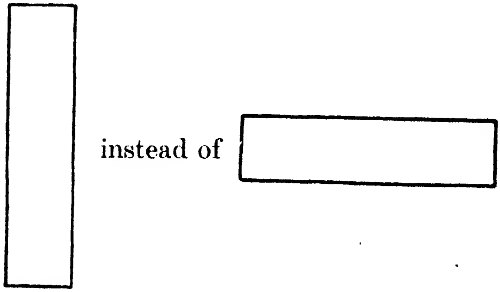
Gear made from round bar. | Gear made from flat bar. | Gear made from up-ended bar.

Fig. 16. Showing "Fibre" in Teeth of Gears made by Different Methods

(From "Metallurgy," by E. Gregory, by courtesy of Blackie & Co. Ltd.)

stresses, pulling at the metal too strongly here and not strongly enough there, so to speak, results in a warped part.

While in certain types of drop-forged parts the direction of the fibre is not of great consequence, and in others the form of the forging allows the fibre to run naturally in the proper way, there are large numbers in which a careful consideration of fibre direction has to be made beforehand. For example, one may take a flat steel bar to be drop-forged into the form of a gear wheel of small size. If the bar is simply placed under the hammer thus: , the fibres will run laterally. When teeth are cut in the gear, they will then have some fibres running longitudinally, some running diagonally, and others again running horizontally. (See Fig. 16.) Following out the remarks made earlier, to the effect that a stress is met more successfully when the stress is across fibres, it will be obvious that as the stresses a gear wheel has to meet consist mostly of a pressure across the teeth, the first and second examples will not be so satisfactory as the third, and may fail in service. To overcome these inequalities of tooth strength, it is usual to cut from the flat steel bar enough material to make one gear wheel, and then turn this up on end for drop forging, i.e.



This makes a radical difference to the lie of the fibres, which will be as in Fig. 16 (p. 23). When the teeth are made from this type of forging the fibre will run from tip to root of every tooth, and so a gear of uniform strength will be obtained. A point to be borne in mind is that not only is the *direction* of the fibres important, but also their position *vis-à-vis* one another. If a gear-blank were machined straight from a flat bar without forging, the fibre would be found running in the correct direction, but such a gear would not be so strong as one up-ended and drop-forged in the manner indicated. The reason is that the fibres, though parallel with one another and running the right way, are not in any way linked up. On the other hand, the fibres in the up-ended gear blank are forced by the pressure into intimate and interlocking contact. The difference in resistance to pressure or stress is that between a body of men all separate, and a body of men with arms linked.

The instance we have quoted is a simple one. In more complex forgings greater thought is necessary, and to achieve this, much skill will be called for on the part of both designer and operator.

One other feature of the fibre of a drop forging calls for mention. The reader will appreciate that when a piece is cut from a bar, the fibres of that piece are severed. These severed fibres at the ends of the piece are known as end fibres. A severed fibre is obviously not so strong as a whole one, so that the position of these end fibres in the finished part will affect the strength at these points. Hence they must be kept, as far as possible, away from the points of greatest stress, where the maximum strength is required. Moreover, it is desirable that during the actual forging operations as few fibres as possible should be cut or torn, and if this cannot be altogether avoided, their position should be such that in the finished part they do not constitute zones of potential weakness. Research has shown that cut or torn fibres have often been responsible for the break-down of a drop-forged part in use.

The importance of fibre direction should by now be apparent, and although it may be possible to produce drop forgings more cheaply by ignoring fibre flow in relation to the finished part, the result can seldom be as satisfactory to the user.

There remains yet one further aspect of this subject, namely, the influence of the actual steels used on the flow of the plastic metal. The different steels all have their special forging characteristics; some being much more plastic at forging temperatures than others. Low carbon steels, for example, with, say, 0·2 per cent carbon, are easily drop-forged within a wide temperature range, so that they can be readily manipulated and a large number of reheatings is not necessary. As the carbon percentage in the steel increases, the plasticity of the metal declines, and the range of temperature within which forging can be carried out narrows. With the introduction of alloying elements, the plasticity of the steel decreases, i.e. its "stiffness," or resistance is greater than that of a carbon steel, even at elevated temperatures. Thus the high-chromium (above 12 per cent) stainless steels, the "18—8" austenitic corrosion-resisting steels, the high-speed steels, etc., are not nearly so plastic as "carbon" steels at temperatures above a red heat and, moreover, the ranges of temperature within which alloy steels may be forged or worked are considerably narrower. The consequences are that not only is greater care in manipulation necessary, but also reheatings become more numerous. This will explain part of the high cost of forged parts made from these steels, since the difficulties outlined involve not only a longer time in forging and reheating for forging, with their attendant expense, but also, as a rule, more powerful hammers and dies of special quality, to withstand the severe service.

The effect of higher carbon percentage is to increase working difficulties and lessen the plasticity of the metal, so that whereas with a low-carbon or soft steel it is relatively simple to fill quite deep recesses in the die with adequate material by only a few simple forging operations, a high-carbon steel requires extra operations or greater power to produce the same result.

It is not within the scope of this book to describe the manufacture of the dies themselves, but some notes should be included on the steels for, and on the phenomena attending the use of, dies. The dies are made of a steel suitable to the material being drop-forged and the intricacy of the die. Modern practice in Great Britain and America is to use, for ordinary drop forging dies, a nickel-chromium-molybdenum steel, such as A.100 (approximately 2·5 per cent nickel, 0·5 per cent molybdenum, 0·6 per cent chromium—recommended by Edgar Allen & Co. Ltd.). Where the work does not call for an alloy steel of this quality, e.g. for short runs and flat die work, a carbon tool steel with 0·6 per cent carbon and of suitable temper (i.e. hardness) can be employed. On the other hand, for certain forgings, where the temperatures at which the work is carried out are higher, and in forging machine and upsetting work (dealt with in Chapter III), a steel containing from 8–9 per cent of tungsten, with chromium (2·5–3·25 per cent) and vanadium (0·4–0·6 per cent) has been found satisfactory for the die blocks. This has often been described as an "*inverted*" *high-speed steel*. There are, of course, numerous other compositions, all of which have their advocates, but those mentioned above constitute the three main varieties. Cheap and poor quality steels should be avoided for these purposes.

In course of time, dies become worn. Apart from faulty working leading to fracture, etc., as previously explained, wear will take place principally as a result of abrasion caused by the movement of the metal into the recesses of the die. The extent of this abrasion will be governed largely by the quality of the steel. The harder and more resistant the steel being worked is to plastic deformation, the greater will be the wear. Wear is also caused by the heat of the metal resting in the bottom die, and the longer these two surfaces remain in contact the greater will be the extent of this wear. Drop forgings made from the single piece of stock with no hold forged for the tongs cause greater wear than those provided with a hold, because the hot piece cannot be raised from the bottom die between the hammer blows. In consequence this die is brought to a temperature that, even if it does not carry the steel to the point at which its structure changes considerably for the worse, definitely lessens its wear-resistance. Again, this inability to raise the piece out of the die means that the oxidation-scale formed on its surface cannot be removed, and each successive blow thereafter will force these hard flakes of scale into the die recesses, thus heightening the wear, and, incidentally, spoiling the finish of the forgings.

Another cause of wear is inadequate control of furnace temperature, leading to an insufficiently or unevenly heated piece of stock, or, alternatively, an overheated piece. In the first instance the stock will be less plastic and will consequently need more work, which means more die wear, and will also itself be harder on the dies. In the second instance, there will be much greater surface oxidation of the metal, leading to excessive scale, which, as we have seen, is a continual source of wear. Improper design of the dies will also heighten wear, since it will mean a larger number of stages to produce the finished part than is altogether necessary, and increased operations inevitably mean increased wear. Frequent removal and refitting of the dies, as when only short runs are required, is also a source of die wear. So, too, is carelessness in manipulation or slackness in use and care of the tools on the part of the operator, as when excessive or insufficient lubrication of the die recesses is given.

We will now turn to the actual stages of making a drop forging. These comprise, as stated, preliminary or roughing out and finishing operations. In between these a middle stage may be necessary, the blocking out stage. The preliminary work can be divided into edging, fulling, drawing, and bending.

An *edging* die consists of an upper and lower half, which, when in contact, leave an oval recess (see Fig. 17). By this means the steel is firmly imprisoned above and below, but can still move sideways, at each end. At the close of the operation,

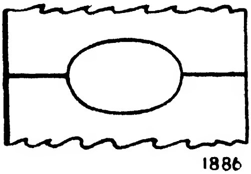


Fig. 17

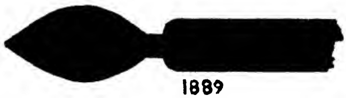


Fig. 18

the stock bar is compressed to a narrow neck at one end, which swells out again to an almost pineapple-shaped mass, a trifle thicker in section at its widest point than the bar itself (see Fig. 18). The object of this operation is to produce a certain

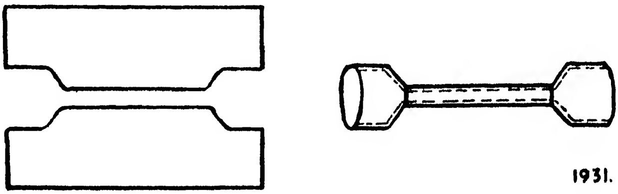


Fig. 19

form most favourable to the later operations, as previously explained.

Fulling, on the other hand, instead of creating a bulbous section at one end of the stock, modifies the process and drives the plastic steel away from the centre and towards the extremities of the die. A typical fulling die is shown in Fig. 19. Here,

Fig. 20

as will be seen, the recesses for the metal are at each end of the die, with the result that the stock bar will be compressed in the middle, i.e. reduced in cross-section (see Fig. 20). Sometimes both operations are carried out on the same bar, as in the manufacture of connecting rods.

Drawing is a form of fulling by means of which the bar is made smaller in cross-section at one end only, not between two ends, as in Fig. 21.

Bending in the drop-forging sense is a later operation than the others, and is employed when the stock has to be formed

Fig. 21

asymmetrically to prepare it for the forging of the finished part. See Fig. 22 for a characteristic example. The phenomena of bending in general are fully dealt with in Chapter IX, and need not be considered here.

Reference has been made to an intermediate blocking-out stage. This becomes necessary when the drop forging is so

Fig. 22

complicated that even the preliminary forging work carried out on the stock will not enable the finished part to be produced by the ordinary finishing operations alone. Sharp variations in cross-section, intricate recesses, awkward convolutions, projections, and other impediments to the ready flow of the steel into the die impression, make it necessary to interpose this intermediate operation.

Blocking-out gives to the forging what is virtually the final shape, with the exception that abrupt angles, holes, and awkward changes in cross-section are nicely rounded off instead of being left sharp, the metal being then favourably placed for the final finishing work, but not subjected to the severe stresses that would be occasioned by a drastic forcing into the difficult shape at one operation. Blocking-out lessens die wear, since less strain will be thrown on the finishing dies. It can also be used as a sole preliminary operation in certain instances, as when the part is simple but has sharp changes in cross-section.

We now come to the finishing operation, which is merely the summation of what has gone before, the dies having the final shape required and giving the part the form that will henceforward remain unaltered, except for the removal of the fin, unless some special later operation of a different character is required, as in forming the throws of crankshafts. There is no need to dwell, therefore, upon the finishing work, since most of the requirements for making this effective are implicit in what has been written.

The cutting off of the fin is a power-press operation involving the use of a punching tool of identical form with the forging, the entire fin being trimmed off at one operation. This work is normally carried out while the part is still hot, though on occasion it may be done after the steel has cooled. Forgings are then pickled, i.e. immersed in a bath of dilute sulphuric or hydrochloric acid to remove the adherent scale, tumbled or sand-blasted to rid them of rust and to give them a good surface finish, and heat-treated (normalized) to remove the stresses set up by the drop-forging operations. Tumbling, or rumbling, is a process for cleaning metal parts by placing them in a hollow revolving cylinder or drum. Their clashing against one another cleans them. Further final cleaning (and sometimes a hardening and tempering treatment) follows. The explanation of normalizing and tempering will be found in *The Structure of Steel*.

There remains but to discuss the types of hammers employed for drop forging. Only the essentials will be mentioned here. The reader requiring information of more detailed character should refer to standard works on the subject.

Drop hammers are "steam," "air" or "board" drop according to the motive-power employed. They comprise an anvil, upon which repose and to which are attached the frames; a head, connected with the frame tops and serving for the transmission of the power; and a tup or ram by means of which the forging blow is delivered. The dies are fastened to the ram and to the anvil cap, which is a steel block fixed between the bottom die and the anvil, to minimize wear of the latter. This block can easily be taken out and machined up when its surface is worn. The anvil's removal would be much

FIG. 23. ERIE DROP HAMMER INSTALLED IN A BRITISH FACTORY

Total weight 470 tons, anvil weight 360 tons, total weight of falling parts, including tup, die, piston, and rod, 29 tons. This is the largest steam drop hammer in the world, but is not used for steels.

(*Photo by courtesy of "Metallurgia" and High Speed Steel Alloys, Ltd.*)

more difficult, as it is bolted down to foundations, or possibly embedded in them. In "steam drop" and "air drop" hammers, steam or air under pressure constitute the motive power. In the "board drop" type, the forging blow is struck by the force of gravity, and power is only employed for the purpose of raising the tup for a fresh blow. While the steam and air hammers can strike blows of varying power, the board drop can only vary its blow if the height of the tup's fall is suitably adjusted. It cannot strike light and heavy blows alternately in quick succession without special adjustment.

There is still to be considered that type of forging known as "upsetting," and this will form the subject of the following chapter.

CHAPTER III

"Upsetting," "Heading," or Machine Forging

THUS far, in previous chapters, we have dealt with straightforward plain hammer forging without the use of machined dies, and with drop forging in which dies are used. Upsetting, or machine forging, is a third form of forging by which large numbers of forgings are made. At first, the machine employed was designed for forming the heads of bolts by the upsetting

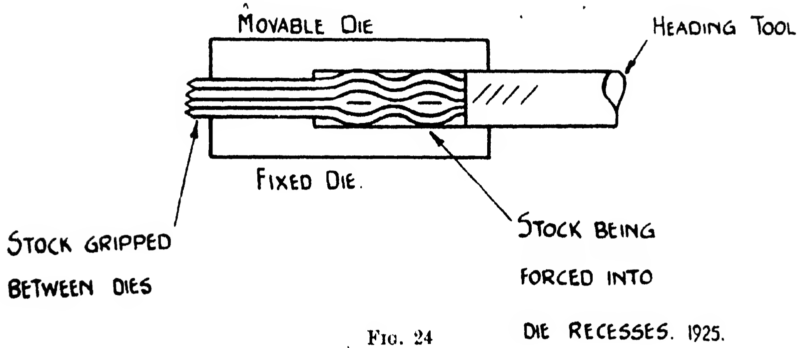


FIG. 24

method, which consists of enlarging the cross-section of a piece of hot or cold metal at one end by the repeated striking or pressing of that end upon the anvil. (It is sometimes called "jumping up.") Later, it was improved and developed, and new uses found for it. The machine itself comprises a massive steel body containing two dies, one fixed and one movable. The piece to be forged is placed on the fixed die, and the machine set in operation. This brings up the movable die, which firmly holds the stock against the fixed die. A heading tool, i.e. a tool for shaping the head of a forging, then slides forward and pushes against the stock which it forces into the die recesses. (See Fig. 24.)

The movable die then withdraws to its original position. Should more than one stroke or "pass" be needed to complete the forging, the stock is transferred to the next die position.

If the forging is complete after the first pass, it is withdrawn, and may be sheared or punched off the bar at once.

Typical products of the forging machine are bolts, nails, cap screws, etc. As with drop forging, the metal will flow in the direction of minimum resistance, but the force causing the flow is not a sharp and sudden blow, as with drop forging, when the energy acquired by the ram or tup as a result of its descent is at once transmitted to and absorbed by the plastic metal, after which this energy is almost completely expended, and both ram and metal come to rest. The upsetting machine does not strike a sharp blow of this type, but gives *a powerful, continuing and increasing thrust,* the momentum of which is strongest at its finish. It does with one thrust what would probably take two or more blows with the drop hammer. Additional strokes or thrusts ("passes," "blows," or "shots" as they are technically named) are only required when the forging has to pass through more than one set of dies.

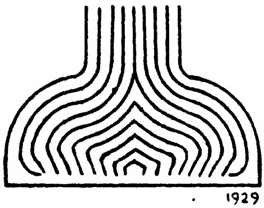


FIG. 25

In the previous chapter we stressed the importance of the direction of the grain fibre to the strength of the forging when made under the drop hammer. Fibre-direction is equally important in upsetting or machine forging, although the conditions are somewhat different.

At first sight, it may be thought that a forging "upset" in the machine is subjected to what are essentially compression stresses. This is true regarding the metal in the interior, but since the cross-section is increased during the process, this means that the outer layers or "fibres" are stretched and elongated. It is this tension or stretching which is responsible for the opening-up of seams and rokes during upsetting, and for this reason the surface condition of the steel becomes a matter of paramount importance. The process of upsetting smashes up the crystals of which the steel is composed, and its grain, or fibre, is made to follow the contours of the die, as indicated in Fig. 25.

As will be imagined, this process demands stock totally free from flaws, and especially from those types of flaws known as "seams" or "rokes." These are the equivalent of cracks on the surface of the piece of metal, formed during rolling. They are usually caused by blowholes (bubbles of imprisoned gas), under or on the skin, which have become oxidized, or by cracks in the surface of the ingot. Obviously, if a seam or roke runs longitudinally along a bar and this bar is then upset, the effect of the compressional force will be to enlarge and open the crack and finally the metal will burst, thus ruining the part.

Some time ago three rules for upset forging were formulated by Mr. E. R. Frost, an American authority. It is of importance that these should be understood, and they are therefore given here, in a revised form consistent with the object of this book, which is to explain such details with the utmost simplicity.

1. The maximum length of unsupported metal that can be upset in one blow is three times the bar's diameter. Thus, a bar 1 in. in diameter can only have about 3 in. of its length successfully upset, unless some special support is given to the metal. The reason for this limitation is that any additional length will result in a harmful buckling up of the bar. In practice, manufacturers work to twice or, at the most, 2½ times the diameter of the bar.

2. Where the length of unsupported metal is not greater than three times the bar's diameter, the maximum enlargement of cross-section obtainable with one blow in upsetting is 1½ times the diameter. Thus, a bar 1 in. in diameter can have a head 1½ in. dia. formed on it with one blow. In practice, 1·3 times the bar diameter is the usual limit for upsetting. Neglect of this rule again leads to buckling and distortion.

3. Where the length of unsupported metal is necessarily *greater* than three times the bar diameter, but the upset not more than 1½ times the bar diameter, not more than one bar diameter of the metal must extend unsupported beyond the die face. Thus, if the length of a 1 in. bar required to be upset is 6 in., and the amount of cross-section enlargement is 1½ in., not more than 1 in. in length must extend beyond the die face without support. (See *X* on Fig. 26.) If this rule is violated, buckling will inevitably occur, ruining the part.

The number of blows required to complete an upset forging varies with the type of forging and the economic conditions governing its manufacture. From a minimum of one to a maximum of five is the normal range. Where four or five passes are required, it is probable that the first and possibly the second will comprise preparatory work on the bar to get it into the correct place for the final blows. The last blow often concludes the process of forcing the steel into the die recesses and at the same time severs it from the stock bar by a punching

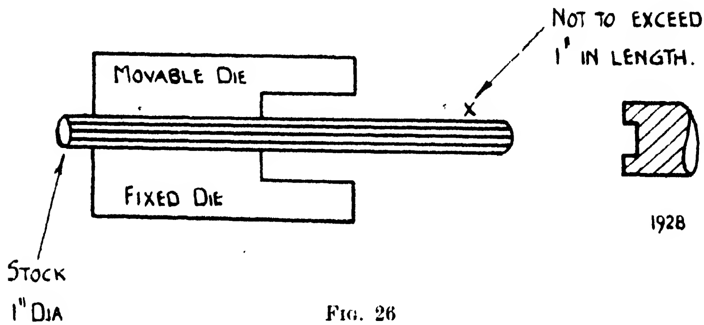


FIG. 26

operation. As to the different methods adopted for different types of upset forgings, these are best studied in the practical handbooks on the subject. They are too detailed and technical to be dealt with in this book.

Before we leave the subject, however, we must turn to one branch, not the least important, of machine forging not hitherto dealt with. This is deep piercing, which consists in producing a hollowed-out forging, not by cutting or boring out from the solid on the lathe, but by driving a punching tool into the central mass of the metal while at the same time forcing the displaced steel into the particular form required by the part. The advantage this method has over drop forging and then machining out the centre of the piece is threefold: (*a*) the forgings are better; (*b*) there is a saving in time and money, since machining is a slower process than machine forging and costs more; (*c*) it is possible to produce parts equally strong but of less weight. As the plastic flow of the metal is in the same direction as the thrust of the punching tool, there is no excessive abrasion of the punch or the dies.

In deep piercing, the stock must be of a diameter proportionate to the cross-section of the forging, while there must be adequate room in the recesses of the die for the metal driven out by the punching tool to find an outlet. An example of deep piercing is shown in Fig. 27. There are points to watch in this

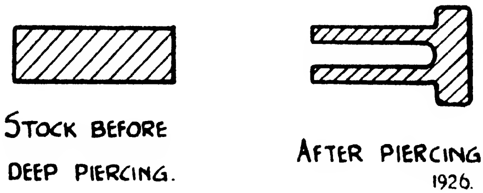


FIG. 27

work just as in upsetting. To try to produce too deep a hole with one thrust of the machine is almost certain to cause buckling, and the same rules as to length of unsupported metal apply. The dies must be properly designed to ensure the best results, and furthermore, the punching tools must also be correctly formed. Practice has shown that an included angle of more than 60° is inadvisable for these tools, except in special circumstances, as when a shearing operation is being carried out at the same time, and the end of the forging has to be made square by the punch. An included angle is that shown in the diagram (Fig. 28). It is the angle "included" or enclosed between the two diagonal lines forming the point of the tool, i.e. by the angle *ABC*.

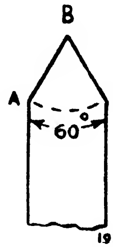


FIG. 28

Reference has been made above to the carrying out of shearing at the same time as the deep piercing. This is a newer method, which reduces the number of operations required by the older methods. In it the blade that does the shearing serves also as a backing for the forging operation and is movable. This new method enables more forgings to be produced in a given time, since fewer operations are needed and because the bigger stock bars keep hotter than they otherwise would and so need fewer reheatings.

It must be pointed out in conclusion that the forging machine is also used in conjunction with the drop hammer to make certain types of parts in which both methods are needed. It is additionally used in preparing certain parts for a later drop-forging operation. For example, the collar may be upset on a valve stem, the end of the stem being afterwards drop-forged.

CHAPTER IV

Cold Heading

COLD heading can be regarded as a form of upsetting (see Chapter III), but whereas ordinary upsetting is mainly a hot-working process, cold heading is, as the term implies, an upsetting process carried out on cold material. It was originally applied to the making of nails, rivets, bolts, and the like, from wire, the applied pressure forcing the wire into dies to give the form of the heads, hence the term "heading." In recent years its scope has, however, widened enormously, as will be seen, and it can broadly be said to serve for the production of those parts with a head diameter substantially greater than the shank or main body.

It may be asked why, since hot heading is a recognized commercial process, cold heading should be necessary. The reason is twofold. In the first place, as with cold rolling, cold heading produces a product with a superior shank surface, i.e. one not so rough, closer to form, and without oxidation scale. Secondly, the introduction of new metals and alloys capable of being worked without failure at little or nothing above ordinary room temperatures owing to their high malleability, has enabled more use to be made of a cold process than if it had been confined solely to one class of product.

The cold-heading process itself is in principle identical with upsetting (see Chapter III). There are two main methods. In the one, a single thrust or blow suffices to form the part. In the other, more than one blow is employed. The method employed has an effect on the amount of upsetting, i.e. the amount of material that can be squeezed or thrust into the die-recess forming the head. This amount is usually expressed in diameters, i.e. the length of the stock that can be upset is divided by its diameter, to give so many "diameters" of upsetting. For example, if a rod 4 mm. diameter can be upset to 12 mm., the amount of upsetting is expressed as 3 diameters.

The exact amount of upsetting is determined not only by the method employed, but also by the hardness or softness of the material, soft steel obviously being more easily cold headed than hard. Special dies and skilful manufacturing practice can extend the amount of cold heading, and by judicious annealing of the stock a further increase is made possible.

We will now consider the process itself. The mechanism employed for cold heading comprises a pair of cylindrical rolls into which the steel rod or bar to be cold headed is fed; a knife, mechanically operated, for severing the rod into suitable lengths; a means of mechanically transferring the cut rod or bar to the heading dies; and the heading punch and dies themselves. The dies are usually fixed, i.e. stationary, and the punches are thrust backwards and forwards by a reciprocating (i.e. back and forth moving) head. The number of thrusts or strokes of the punch required to complete the part can be one, two, or three, according to the type of heading machine employed.

Most cold heading is done by double-stroke machines. The first thrust gives to the part a bulbous or conical head-form, and the second forms a round head of the required depth. If a bolt is being cold headed to give a hexagonal or square head, it is usual to perform a second operation, the round-headed bolt being fed by hand, or sometimes by simple mechanical means, into trimming dies, which give it the final form.

The heading dies can be either solid or split, the former being used for the shorter parts, which are mechanically knocked out of them at the completion of the second or finishing stroke. When long parts are being headed, split dies are used, since there is a risk that they would "seize" or stick in a solid die. Solid dies are, however, being marketed that are claimed to be capable of heading parts with shanks 10 diameters long, without fear of sticking.

The "split" or "open" dies are divided vertically into two steel blocks with semi-circular grooves machined in each of the four faces. As the blocks are reversible when worn, they will give much longer life than solid dies, all that is necessary being to match the new grooves. The split dies are opened a little at the end of the finishing stroke, so that the part can easily be ejected.

Into the differences between the various types of cold-heading machines we do not propose to go. These differences govern such matters as the way in which the rod is cut into working lengths, the method of moving the punches, the means adopted for ejecting the finished part, and the arrangement of the various reciprocating parts. These details are all to be obtained from the catalogues of the various makers.

The types of steel suitable for and capable of being cold-headed range from low-carbon steel up to stainless, but in general there is a limit of 0·50 (which should not be exceeded) to the carbon percentage. 3·5 per cent nickel steel, nickel-chromium alloy steel, 18/8 austenitic chromium-nickel, and 25/12 chromium-nickel stainless steels, have all been and are still being successfully cold-headed. Other steels used are the "straight" (i.e. not containing other alloys) chromium steels.

Whether or not cold heading is used in preference to hot forging depends in the main on the price of the raw material, i.e. whether the cold drawn steel required costs so much more than the hot rolled steel for forging as to make cold heading uneconomical. Other limiting conditions are the capacity of the plant, the length of run (i.e. the number of identical parts to be produced), and the cost of putting down any plant not already existing in order to produce a part not previously cold-headed. There is also a limit of size. The maximum diameter appears to be $1\frac{1}{2}$ in., but in general 1 in. is the usual working limit for the steel to be cold-headed, and the maximum shank length in this diameter is about 9 in.

Considerable care has to be exercised in the choice of steels for cold heading. Much depends on what is required of the part itself. Such considerations lie outside the scope of this work. It is sufficient to say that where toughness is the main requirement, the lower carbon steels are used. Where hardness is the principal need, higher carbon steels are chosen. As the carbon percentage in a cold-heading steel rises, it is often desirable, and on occasion essential, to treat the stock in advance, as with cold drawing (see Chapter XI), in order to give it certain properties that will facilitate the operation.

There are three such types of treatment, namely, *processing*, *normalizing*, and *spheroidizing*.*

Processing is simply an annealing treatment given immediately before the last slight reduction in diameter in the wire mill. Annealing is a softening process which produces a more malleable steel with a brighter surface finish than is obtainable by the normal wire-drawing process.

Normalizing is a heat-treatment process to which steel rods are subjected in advance of their being drawn into wire. According to the type of steel, they are heated up to a suitable temperature and then allowed to cool in still air. This softens them and refines their grain or crystal structure.

Spheroidizing is another type of heat-treatment. In this the steel is held for some time within a temperature range just below the critical range (i.e. the range of temperature between the extreme points of which important structural modifications of the steel occur or, alternatively, just below and just within it in high-carbon steels). The carbide of iron in the steel then separates into spheroids, beads, or globules. This treatment gives a specific type of structure suitable for the difficult types of cold heading.

These various treatments bring into prominence the entire subject of grain size, and a few notes may for the sake of explicitness be given here. It is known that the grain size of steel has considerable influence on its general properties. In cold heading, a steel with fine grain (i.e. whose structure is built up of small crystals) is generally chosen when there is a risk of distortion in heat-treatment, and where the possibility of fracture in the finished part when put into use is serious. On the other hand, a steel with coarse grain flows more readily when struck by the punch, especially if correctly heat-treated.

In general fine-grained steels are used for cold heading parts above $\frac{7}{16}$ in. diameter and for the higher carbon steels. Coarse-grained steels are used for parts below $\frac{7}{16}$ in. diameter, and for carbon percentages below 0·40. The above remarks apply to the plain carbon steels. Where it is proposed to use one of the alloy steels it is customary for the cold-heading process user

* For a full consideration of these treatments the reader is referred to *The Structure of Steel.*

to co-operate with the steel-maker in choosing the right steel for the work and the right preliminary heat-treatment for the steel.

Quite apart from the three advance treatments described, it may be necessary or desirable to give the finished part itself a heat-treatment. Annealing to relieve stresses set up by the cold heading, normalizing to improve grain structure, tempering to relieve heading stresses, are all employed, and sometimes a complete heat-treatment comprising heating above the critical range, quenching in oil or water, and tempering to a required hardness, is given. This is usually where high physical properties, e.g. resistance to impact, high tensile strength, hardness, and ability to withstand fatigue, are called for in the cold-headed part. Case-hardening is also used for parts requiring wear resistance.

The steels of which the dies themselves are made are usually of two qualities, a carbon vanadium steel or a carbon tool steel. Typical analyses are as follows—

	Per cent Carbon	Per cent Vanadium	Per cent Manganese	Per cent Silicon
Carbon Vanadium Steel	0·95–1·0	0·2–0·3	0·25–0·35	0·2–0·3
Carbon Tool Steel .	0·95–1·0	—	0·2–0·3	0·15–0·3

The heat-treatment given to the steel in making the dies is of great importance, and in this respect the die-maker usually consults the tool steel manufacturer if he is in doubt. Typical parts manufactured by the cold heading process include bolts, rivets, valve-spring retainers, commutator segments, drum plugs, screws, studs, etc.

Cold heading is, in reality, a severe form of treatment, and on this account the steel must be free from surface defects such as seams, as otherwise these open out during the process.

CHAPTER V

Rolling

ROLLING is one of the main processes by which steel is mechanically reduced in section. The steel ingot, billet, bloom, or slab is heated in a furnace to a suitable temperature, varying with the type of steel to be rolled, and then passed between two revolving cylindrical pieces of metal known as *rolls*. These are power-driven in opposite directions and carried by a heavy cast-iron supporting framework, known as the *housing*, resting on solid and strong foundations to ensure complete rigidity. Each independent complete set of rolls with its housing constitutes a *stand*, and two or more stands constitute a *train* of rolls. For the rolling of slabs, plates, and sheets the rolls are essentially plane cylinders but are grooved for the rolling of blooms, billets, bars, and sections. For these reasons, rolling mills are generally divided into the following categories: (*a*) cogging mills, (*b*) plate mills, (*c*) sheet mills, (*d*) bar mills, (*e*) rod and wire mills.

When blooms and billets are re-heated and rolled in a different mill the operation is known as re-rolling.

The power of the engine or motor is transmitted to the rolls by pinions (i.e. helical or toothed gears) and connecting spindles or universal joints, the entire combination of the rolls, framework, and gearing constituting the rolling mill.

Rolling is a much less costly operation than forging and for the great majority of purposes yields eminently satisfactory results, so that it is for this reason that enormous quantities of steel are rolled to the required section straight from the ingot.

Before discussing the effect of rolling on the structural characteristics of the steel, however, we must return to the mechanical considerations..

ROLLS

The rolls between which the hot steel is passed are nearly always cast to the approximate form desired and then machined

FIG. 29. 12 IN. FOUR-HIGH ROD MILL

(Photo by courtesy of The Sheffield Forge & Rolling Mills Co. Ltd.)

down to the precise dimensions. The rolls for hot rolling are almost invariably of cast iron (either sand or chill cast) or steel of special composition, i.e. containing alloying elements. (See also the notes on page 60.)

Sand-cast or "grain" rolls are made by pouring the molten cast iron into ordinary sand moulds, followed by relatively slow cooling and even, in some instances, by annealing the slowly cooled castings. Sand-cast rolls are normally employed for the first reductions, i.e. the first rolling down (sometimes known as "roughing"), or where it is not essential for the rolled product to possess a high degree of smoothness on the surface, i.e. where a particularly good surface finish is not required. Sand-cast or "grain" rolls remove adherent scale more readily than chilled rolls, particularly when water-cooling of the rolls or flushing of the surface of the rolled product by means of water jets is out of the question. It is for this reason that in the train of rolls constituting a sheet or thin plate mill, the first pair of rolls are of the soft grain type and the last pair are chilled rolls.

When the rolls themselves are continuously water-cooled, they are, as a rule, slightly convex.

A complete classification of the kinds of rolls used is difficult since this depends on the quality of the steel, the desired size and shape of the section of the rolled product, etc., but some indication of the types of rolls commonly employed follows.

For plates and sheets, as already indicated, chilled cast-iron or alloy steel rolls are commonly employed where a smooth surface is required. Incidentally, a *chilled* high-quality cast-iron roll is made by casting it into a mould provided with pieces of cold iron or steel, termed "chills," inserted flush with the mould surface. These chills serve two purposes. They first ensure an even rate of contraction, or "shrinkage" as it is called, in the metal as it cools, and they furthermore produce an extremely hard surface, owing to the retention of most of the carbon in the combined state. The chills inserted in the mould rapidly conduct the heat from the surfaces of the cast metal, and the accelerated rate of cooling prevents the formation of graphite that would normally occur (with slower cooling), so that practically the whole of the carbon in the surface layers is retained in the form of the intensely hard carbide of iron, having the chemical formula Fe_3C. This same constituent is the major constituent of the "alloy" steel rolls employed in both hot and cold rolling.

Steel rolled with "chilled" iron or alloy steel rolls has a hard and smooth surface.

For heavy rolling, i.e. where considerable reductions in section are carried out at a single operation, alloy irons and steels are being employed, especially for cold rolling. Cold-rolls are considered in greater detail in Chapter VI.

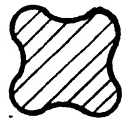


FIG. 30

The roll itself comprises a central part, termed the *barrel*, which is the portion actually responsible for reducing the section of the piece or forming its shape. At each end of the barrel is a *neck* or journal, supported on *bearings*. The fillets or radiused parts connecting the barrels with the necks are termed *shoulders*. The bearings supporting the journals are kept in place by means of *chocks* or *chucks*. The actual bearings are made of various materials, according to the nature and type of the mill. Thus, white metal alloys, brass or bronze, fibre and plastic bearings of the "bakelite" type, are employed, the lubricating agent being varied to suit the particular kind of bearing used. With metal bearings special greases such as "Tecalemit" are used, and even mutton fat is still employed in certain mills. For high-speed reversing mills the lubricant is forced into the bearing under pressure, and the same applies to fibre and plastic bearings where water under high pressure constitutes the lubricating agent.

Graphite and colloidal graphite solutions are also used for purposes of lubrication, and in some mills roller and ball-bearings are employed.

In a mill consisting of a series of stands, the power is transmitted from one set of rolls to the other by means of *coupling boxes*. The extremities of the rolls are known as *wobblers* and have the cruciform cross-section shown in Fig. 30. Externally the coupling boxes are plain cylinders but their internal shape is that of the exterior of the wobblers.

In a single-stand mill such as a cogging mill it is now usual to employ *universal couplings* or joints for the transmission of the power to the rolls. Such mills run more smoothly and efficiently.

When coupling boxes are used, these are arranged to constitute the weakest link in the mill train, so that if the mill is overstressed, fracture takes place in the coupling boxes rather than in the rolls themselves.

The roll barrels, as has already been indicated, are either plain cylinders or furnished with *grooves* and corresponding elevated portions termed *collars*. The hot steel is passed through these grooves and so given the required form, since the grooves have already the master form that the pressure of the rolls forces the steel to acquire. Each passage of the piece of steel between the rolls is called a *pass* or *gate*. A pass may therefore be defined as the opening between a pair of rolls formed by corresponding collars. A *closed pass* (or "box" pass) is formed by the groove in one roll, having a collar on each side, into which fits the raised parts of the other roll, which is then described as the "former." An *open pass* consists of a groove without adjacent collars. Passes are designated according to the sections they produce. Thus we have the *Gothic* pass (like a double Gothic arch) (see Fig. 34, page 62), the *diamond* pass, the *oval* pass, the *bellied* pass, etc.

A *live pass* is one where the steel is actually mechanically worked and a *dead pass* when the steel is passed from one side to the other of the rolls without any alteration in cross-section. Thus with a two-high (i.e. two-roll) non-reversing mill, when the piece is returned to the original side over the top roll without being mechanically worked, this is known as a dead pass.

The pressure on the hot steel during rolling is controlled by reducing the distance between the rolls. On top of the housings are situated the housing caps, through which pass the housing screws. These screws force down the top roll and keep it in its proper position. The principle is much the same as that of the ordinary household mangle. In some mills, particularly for thin sections, the rotation of the screws is accomplished by a hand-operated lever known as a *spanner*, but in many modern mills it is achieved by means of mechanical or electrical control. A large dial, something like a clock, is situated above the

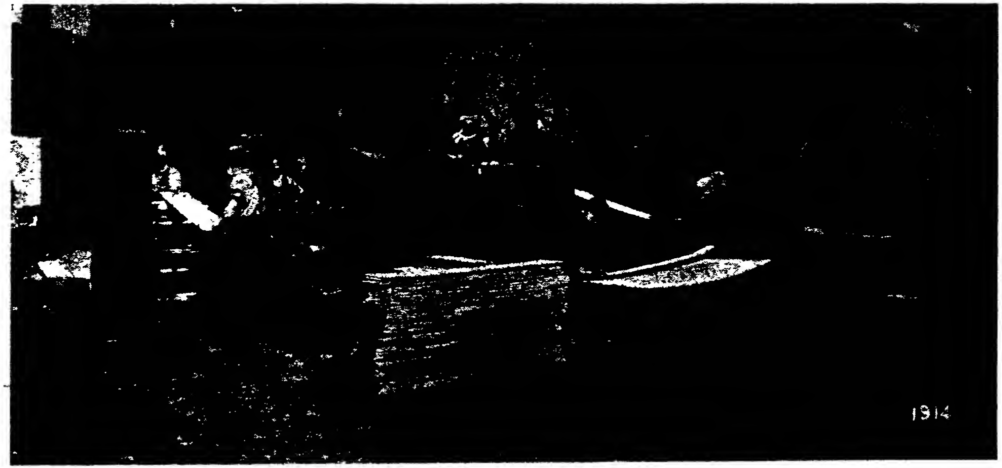


FIG. 31. ELECTRIC SHEET MILL

(Photo by courtesy of The Sheffield Forge & Rolling Mills Co. Ltd.)

housing, and the extent of the reduction in cross section indicated by a large pointer.

It should also be mentioned that the *pinions* are the gears that transmit the power to the rolls from the engine or motor driving them. The pinions are supported in a separate *pinion housing*. When the rolls are driven directly from the engine shaft by means of a casting or forging known as a *crab*, the mill is said to be *direct-driven*. If gears are interposed to reduce or increase the speeds of the rolls, the mill is described as *gear-driven*.

When the pieces being rolled are only of small dimensions, they can be manipulated by hand, as is the case with sheets and bars. The larger pieces, such as ingots, blooms and slabs, have to be dealt with mechanically by a *manipulator*.

These larger pieces of hot steel are made to travel forward towards the rolls of the actual mill by a series of "floor" rolls or rollers. Those rolls not mechanically driven, but merely rotated as a consequence of the velocity and passage of the hot billet, bloom, or ingot over them, are known as *idle rolls*. *Live rolls* for this purpose are those actually driven by either mechanical or electrical means. A similar series of rolls is situated on the other side of the mill so that the steel can be passed backwards and forwards and finally transported to the desired point.

Another important point is the extent of reduction in cross-section at one pass or *draught*, as it is called. This depends on the actual cross-sectional shape and, in particular, on the chemical composition of the steel being rolled, as well as its temperature. Thus, at similar temperatures, alloy steels are "stiffer" (i.e. they have a less degree of plasticity) than ordinary "carbon" steels, and therefore a greater draught can be given to ordinary carbon steels than to those of the high-speed tool or "stainless" types. Nickel, chromium, tungsten, molybdenum, etc., all have the effect of stiffening hot steel.

The *entering angle* or *angle of contact* (i.e. the angle between the longitudinal axis of the ingot, billet, or bloom and the tangent of the roll at the point of contact) is a matter of great importance and must be less than 30°, since otherwise the rolls will not "bite" and the steel will not pass through them. In order to facilitate the entry of the steel into the aperture between the rolls, the latter are frequently chipped out at regular intervals on their surfaces. Such rolls are called *roughing*, *ragging*, or *cogging rolls* and generally are chipped in such a way that shallow depressions or "hollows" are formed across them. The marking of ragging or roughing marks is a most important matter, since if these marks are too sharp and deep, they may possibly lead to "spells" in the final rolled product (see page 61).

It is not always appreciated that in rolling something more is done than merely gripping and squeezing the hot steel. In consequence of the reduction in cross-section the steel leaves the rolls at a faster rate than it enters them, so that it is actually to some extent "squirted" through the rolls. The thickness of section, the roll diameter, and the extent of the reduction all have their influence on this increase in speed. The increase in velocity of the emergent metal has to be taken seriously into consideration when a series of reductions is being carried out in successive operations in continuous mills, because it governs the relative speeds of each of the following sets of rolls. In continuous rolling mills, a number of sets of rolls or "stands" are placed one in front of the other, tandem-fashion, whence arises the term *tandem mill*, and their several speeds of revolution have to be carefully calculated so as to ensure proper completion of the sequence of rolling operations. Hence the need to consider the extent of the "squirting" effect. As an example, let us consider a series of four "stands," each one reducing the section by one-fourth. If the first set of rolls revolve at 60 revolutions per minute, the subsequent rolls need to be driven at speeds of 80, 100, and 125 r.p.m. respectively so as to cope with the accelerated speed of the steel as it leaves each set of rolls.

Rolls are not always set horizontally. They can be, and indeed sometimes are, mounted vertically.

The effect of horizontal rolling with plain cylindrical rolls is to diminish the thickness and *slightly* increase the width of the section. Vertical rolling, on the other hand, reduces width and slightly increases thickness. Hence, if both dimensions have to be reduced the roller may have to use both vertical and horizontal rolling. Alternatively, he can repeatedly turn the piece through an angle of 90° in order to produce the required cross-section. At present, the latter method is the one commonly employed.

It must not be assumed from what has been written thus far that a rolling mill is a simple fixed entity. Rolling mills are of numerous kinds, and can be grouped, according to Tiemann, into four main classifications: (*a*) mills depending on the position and rotation of the rolls; (*b*) mills depending on the arrangement of the stands; (*c*) mills for special products in which little reduction takes place; and (*d*) mills based on the character of their product.

Each of these groups is again sub-divisible into numerous classes, according to the number of rolls in a stand (ranging from two to as many as seven, and classed as "two-high," "three-high," and "cluster" rolls); whether the mill is reversible or not; whether the rolls are fixed or adjustable; whether the stands are placed end to end, which is termed a "train" of rolls, or one behind the other in series, or a combination of both; whether there is much reduction or otherwise; and whether the mill produces rough, semi-finished, or finished products. Into these complexities there is no need for us to go, and the interested reader can pursue the subject for himself in the various technical handbooks. We may, however, penetrate a little farther into the nomenclature of these mills. First, let us consider how rolling mills derive their "size" as exemplified by the term "16-inch bar-mill."

A rolling mill's "size-description," in bar mills, is theoretically governed by the *pitch diameter*. This is the distance between the axes of the finishing rolls. In actual practice, however, it is based on the distance between the pinion centres. This is because the rolls themselves in a given mill may vary in dimensions as a result of their being machined down from time to time to level up their worn surfaces. This, naturally, reduces their diameter. Hence, a 16-inch bar mill is one in which the distance from the centre of the pinion at one end to the centre of the pinion below or above it measures 16 in. In general, the smaller the "size" of the mill, the smaller are the roll diameters, and the faster the rolling speeds.

In a given mill, bars of different sizes can be rolled, but there are restrictions. Thus, as already indicated, if the dimensions of the billet are large compared with the diameters of the rolls, i.e. the entering angle exceeds 30°, the steel will not pass through the rolls. In other words, each particular mill has its own particular range of sizes which can be produced from it, although some overlapping of sizes is possible in different mills.

In plate mills, the "size-description" generally refers to the actual length of the roll barrel. It might be thought, therefore, that this length indicates the maximum width of the plate (or sheet) that can be produced from the mill. Actually, however, plates of this width can never be obtained, and the width is always less than the length of the barrel of the roll.

Incidentally, in rolling plates the slab is first rolled so that its *length* is that of the *width* of the plate finally required; the slab is then turned through 90° and rolled until the required thickness is attained. This is known as *cross-rolling* and improves the quality and structure of the steel. It is a curious and interesting fact that in the rolling of plates and sheets the deformation is essentially in a longitudinal direction, i.e. in the direction of its length. A certain increase or "spread" in the width does take place, but this is a matter of inches only compared with several feet in the increase in the length. With plates, the two inches at either side are usually cut off as scrap.

A "*two-high*" *mill* is one in which two rolls are mounted one above the other, whereas a "*three-high*" *mill* has three rolls thus mounted.

In two-high mills, the rolls revolve in opposite directions. In old-fashioned mills, the rolls were invariably *non-reversible*, so that before a second "live" pass could be made, the product had to be brought back to the front (over the top roll, i.e. given a "dead" pass) and re-passed through the rolls on the same side. This obviously involved a loss of heat, time, and effort, as well as of metal, which oxidized as it cooled, forming a scale of much less economic value. For these reasons, *reversible mills* have been developed, so that the product can be rolled again on the "reverse" or return journey.

In three-high mills, the hot steel is passed through the lower rolls and returned or brought back through the upper rolls, or vice versa. None of the rolls is then reversing, this being unnecessary since the lower and upper pairs of rolls move the plate or bar in opposite directions.

In three-high plate mills, a platform consisting of live rollers that can be elevated or lowered at will is used to pass the steel between either the upper or the lower pair of rolls.

The *draught*, or actual percentage reduction in cross-section at each pass, varies according to the nature of the steel, its original cross-sectional area, and the shape of the section. The first draughts when rolling ingots must be "light," since at this stage the steel is somewhat tender. Roll design also plays a most important part in controlling the permissible amount of reduction in cross-sectional area at each pass.

When bars are rolled from billets, the reduction at each pass may vary between 10 and 40 per cent, the greater reductions being possible as the diameter or cross-sectional area becomes less. In the rolling of wire rods, a reduction of as much as 50 per cent at each pass is possible by alternating between a diamond and an oval pass.

In the rolling of plates the draught at each pass usually varies between $12\frac{1}{2}$ and 25 per cent.

Types of Sections

Rolling is carried out on both hot and cold metal. It not only produces bars from ingots and billets, and sheets and plates from slabs, but also produces a wide range of rolled sections. As many as forty principal sections are rolled, as shown in Fig. 32.

When the ingots to be rolled are of large dimensions, or alternatively when the finished product is small, it is customary to employ two separate mills, one for roughing down and the other for finishing. Mills whose primary purposes are to produce blooms (rectangular pieces of cross-sectional area greater than about 36 sq. in.), billets (rectangular pieces with a cross-sectional area from 9 to 36 sq. in.), slabs (rectangular pieces of cross-sectional area not below 16 sq. in., and of width at least double the thickness), and sheet bars (small slabs) are usually termed *cogging mills*, although a distinction

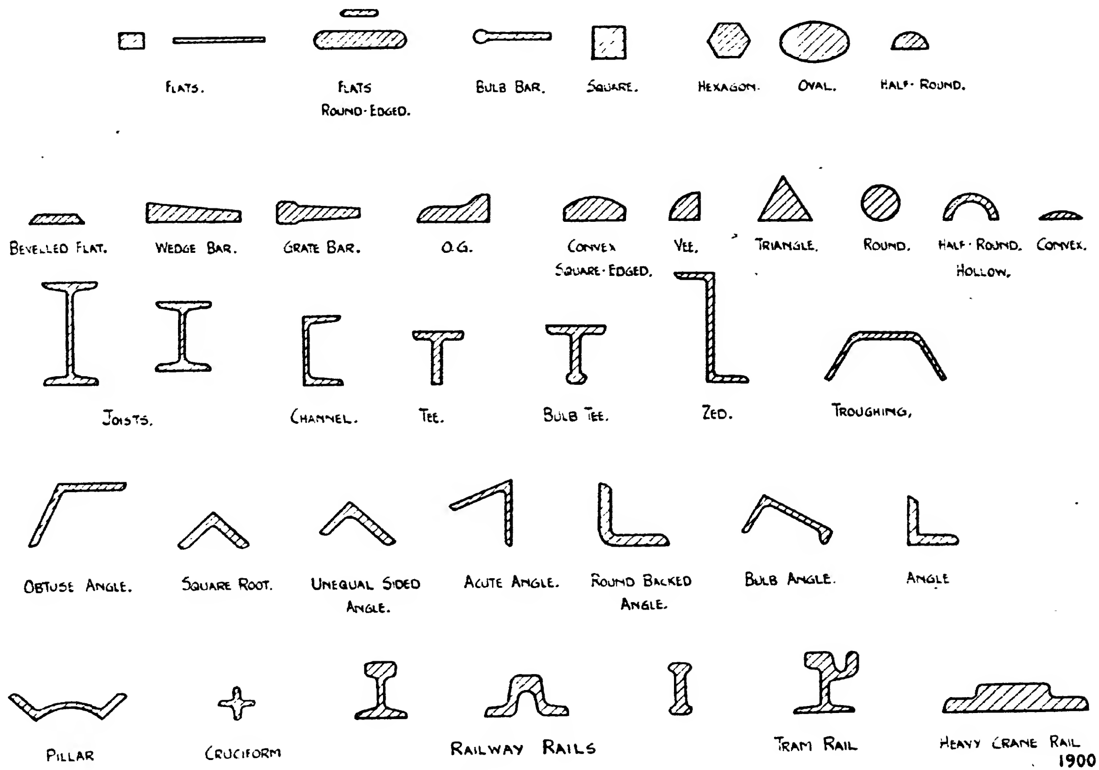


FIG. 32. PRINCIPAL ROLLED SECTIONS

is frequently made by describing them as "billet" or "slab" mills according to the shapes of the final rolled products. This type of mill is usually two-high (but sometimes three-high) and the rolls range from 30 to 54 in. diameter, and will take an ingot weighing from 35 cwt. to 130 cwt. or more, and measuring 14 in. square and upwards. A 14-in. square ingot can readily be reduced by these rolls to a bloom or billet less than 6 in. square. The successive grooves of the rolls are not identical in shape. The first and largest groove, through which a "billet" ingot is first passed, is rectangular or box-shaped. (See Fig. 33.)

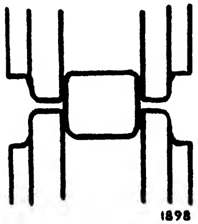


Fig. 33

When the ingot has passed through this, the upper roll is lowered and a second pass made through this or the next size of groove. The ingot is then turned through an angle of 90° and rolled again. This turning 90° may be repeated until the last groove is reached. Different shapes of grooves are required for different types of bloom or product, and for square sections the penultimate pass is often diamond-shaped.

Continuous Rolling

Small billets and slabs are also rolled in continuous mills. The rolls of these are from 12 to 16 in. in diameter, and there are several stands of two-high, non-reversing rolls set one behind the other and revolving at progressively faster rates. In these high-speed continuous mills, when the rolled bars are often travelling at a speed of 6 to 8 ft. a second, the length of the material on emergence from the final stand is so great that if the cutting up were left until the rolling were finished, the length of floor space required would be enormous and uneconomical.

In consequence, the steel is cut into lengths automatically, as it comes away, by means of shears. These are either flying shears or rotary shears. The flying shears are worked by a trigger set for the required length. As soon as the end of the emerging rod or bar strikes this, the trigger is sprung and an upper shearing blade comes down to sever off the required length. The blade is then thrust outward in order that it may not impede the progress of the next length. These shears are often steam-operated, but the more recent rotary shears are driven by electricity. In these there are two rolls, each of which carries a shearing blade. These rolls revolve at different speeds adapted to each other and to the speed of the moving length of steel in such a way that they close up at the correct intervals and sever off the proper length. There are many other types of rotary shears used for cutting up cold plates into circular shapes.

In some wire and rod mills this difficulty is partly overcome by causing the metal to serpentine backwards and forwards in the shape of a letter S as it travels through adjoining stands of rolls, and in wire mills it is conveyed to a rotating drum which coils the steel as it emerges from the final pass.

Plate and Sheet Mills

The formative mills for finished products comprise the plate mills and shape mills for heavy sections, and bar or "merchant" mills for smaller sections. In this country many plate mills are two-high and reversing, although, as in the United States, three-high and non-reversing mills are used. In Great Britain two stands of rolls are frequently employed, one for roughing and one for finishing, as against one in the three-high mill, which fulfils both purposes.

The tandem or continuous plate and bar mill has replaced these in some of the larger firms in both countries. Plate mills of the normal type will roll anything from ¼ in. to approx. 2 in. thick. The mills for rolling armour plate are of much more formidable type, capable of dealing with enormous masses of metal. Their rolls are from ten to fourteen feet in length and from three to four feet in diameter. They are usually of two-high reversing type, and employ plain rolls. Grain rolls are used for the earlier and "chilled" iron rolls for the final passes.

Sheet mills deal with thin plates or sheets not more than ¼ in. thick. Their rolls are seldom more than 30 in. in diameter and are usually of chilled cast iron. They are generally two-high and non-reversing. This may seem paradoxical in view of what has been said concerning waste of time and labour. In this instance, however, the waste is less evident, owing to the method of working. In these mills a man stands at each side. One takes a sheet as it emerges from the rolls and then passes it over the top to his mate.

Slab and Strip Mills

Strip mills are smaller than plate or sheet mills and are employed in the production of thin and narrow strips or ribbons of steel intended for various purposes, e.g. steel rules, barrel-hoops, safety razor blades, and the like. In Great Britain they are usually two-high and continuous. The Americans, though using the continuous type for large-scale production, favour the three-high non-reversing mill for ordinary work.

Thin sheet or strip ranging from 12 to 60 in. wide and down to 16-gauge or even a little thinner can be produced in these mills. The strip so produced in hot mills is frequently rolled still thinner in a "cold" rolling mill.

Slab mills are really heavy plate mills with rolls about 30 in. in diameter and are of the two-high reversing type. The slabs produced in them are generally rolled into plates in another mill. In rolling slabs from an ingot, *"edging" passes* are frequently given to the hot steel. After several passes of the ingot backwards and forwards through the rolls, the hot piece is turned on its edge and then passed two or more times through a groove formed between the ends of the rolls. These edging passes, which serve several important purposes, may be repeated at a later stage during the rolling. In the first place, edging passes preserve the rectangularity of the slab by minimizing the concavity or hollowness of its edges, and thus improve the amount of usable material. Edging is also of great importance in that it breaks off most of the oxide of iron, or scale, first adhering to the ingot's surfaces. If this scale is not removed, it will be rolled *into* the surface of the slab or plate, and may give rise to the defect known as *pitting*.

The avoidance of pitted surfaces in rolled slabs and plates is a major problem for the steel-maker. In the first place, the heating conditions within the furnace in which the pieces are heated have to be carefully controlled in order to produce a scale of the right type. During rolling, "besom" twigs are often thrown on to the surface of the slab or plate as it enters the rolls. This results in a series of minor explosions which break the scale away from the steel. Flushing of the surfaces with powerful jets of water as the hot steel leaves the rolls serves a similar purpose. The throwing on of handfuls of ordinary salt (sodium chloride, NaCl) during rolling has been strongly advocated, and is practised in several mills, but from experience the authors are of opinion that this method is not nearly so effective as the other methods described.

Merchant mills are those in which small finished or semi-finished sections are rolled.

Shape mills are those in which, as a result of successive passes, sections such as beams, channels, rails, etc., are produced. These obviously need grooved rolls, and the forms and proportions of the grooves need to be carefully designed to bring about the gradual reduction in cross-section. Great skill and experience are necessary both in designing and operating the rolls, and problems arise that bear directly on the structure and behaviour of the steel being rolled. These problems will be dealt with later to some extent.

These mills often comprise several stands of three-high rolls in one or more trains, although the finishing passes are frequently through two-high stands. A mill of this type may consist of three stands: the first stand is roughing, the second section-forming, and the third rolling the finished section. When rolling flanged sections, the section-forming and finishing rolls generally consist of alloy cast iron or steel so that the collars may successfully withstand the increased pressure thrust upon them.

Two adjuncts of importance from the mechanical point of view must be mentioned. The first is what is known as a *manipulator*. This, for a three-high plate mill, may consist of a movable platform or framework comprising a series of reversible rollers which convey the hot steel backwards and forwards to or from the rolls. By raising this platform or table the plate of steel may be passed between either the upper or lower pair of rolls of the mill.

In two-high cogging mills, manipulators that operate between the fixed horizontal roller table are used to turn the hot metal on to its edges and, in a billet mill, from one groove to the next. These manipulators consist essentially of mechanically-operated fingers set at right angles to each other or a pair of grips which move the steel to any desired position. In some bar mills, the manipulator consists of a movable chute which conveys the rolled section from one stand to another.

A second adjunct is the *guides*, used in bar and section mills. These generally comprise two metal plates or sections, set either apart or close together, between which the hot steel is passed just before it enters the rolls. By this means the passage of the steel through the correct opening or pass is ensured. In some mills automatic or movable guides are used to transfer the steel from one stand of rolls to another.

The *cramp-bar*, which carries the guides, is also used to ensure that the entrance of the steel into the rolls is in a horizontal direction, and in many mills the cramp-bar itself may actually be regarded as a "guide."

The term *guards* is applied to the metal parts which guide the steel in the proper direction as it emerges from the rolls. Without such precautions, there is a grave risk that the steel will coil itself around the upper roll instead of being driven forward in a horizontal direction, a fault included in the term "cobbling."

In reversing mills, the guides and guards are of similar form, so that in these circumstances the two terms are interchangeable—a guide may become a guard and vice versa.

In some instances, hanging guards are employed, particularly when rolling steel which is "stiff," i.e. resistant, at all temperatures, e.g. stainless steel. The lower part of such a guard is fastened to a bar that runs athwart the rolls whilst the upper part is suspended by another such bar maintained in position by a counterweight.

Rolls for Cold Rolling

In cold rolling (see Chapter VI) three types of roll have been used. Chilled iron rolls, the original type, have a surface "scleroscope hardness" between 50 and 65.* The main defect of chilled rolls of this type is a tendency for pieces to flake off (or "spall"), and generally if spalling does occur the roll is afterwards useless. Each time the surface of the roll becomes worn or irregular, it must be machined or ground, thus reducing the diameter of the roll so that the thickness of the chilled or hardened portion (or skin) becomes successively thinner. Finally it becomes so thin that it breaks down.

For hot-rolled sheet and strip, chilled rolls are admirable, producing an extremely clean surface, and for the preliminary stages of cold rolling are still used with satisfactory results. An additional advantage is that they are soft enough to be "trued-up," i.e. machined or ground, in position, without its being necessary to take them out.

The next type are the forged alloy steel rolls, generally containing high proportions of chromium and having a hardness of approximately 100 scleroscope. They have a highly satisfactory surface, probably better than that of any other type, and the successive grindings do not in any way impair this, owing to the structural homogeneity of the steel. On the other hand, each change of job means that they have to be taken out and ground. Forged steel rolls are essential in the modern four-high and "cluster" mills (a cluster mill comprises seven rolls, three small, with two larger below and two above), but experience has shown that these mills do not produce to full advantage unless a preparatory rolling of the strip in a two-high or other mill of similar dimensions is given.

The latest type are the cast (chilled) steel rolls. These have a hardness of 50 to 60 scleroscope and have the great advantage that, as the result of the alloying elements in their composition, they work-harden during use. This means that the surface becomes harder as the result of use, a phenomenon explained in *The Structure of Steel*. A cast "alloy" steel roll will produce better results after a few weeks' use than when first employed. These rolls are principally used for the intermediate stages of

* The scleroscope for testing hardness is an instrument consisting essentially of a small hammer with a diamond point allowed to fall freely in a glass tube marked with fine lines to show divisions on a graduated scale. The height of the drop is constant, and the level to which the hammer rebounds then becomes a measure of the hardness of the iron or steel.

rolling and for finishing the thicker materials. They can be trued-up (i.e. ground) in position, and this is an advantage in the type of work for which they are used, which often makes it necessary to correct irregular surfaces left by hot rolling. They are, however, quite unsuitable for thin material, for which forged steel rolls are better. They do not break down on the surface, as chilled iron rolls do, and they cost less than forged steel rolls for work where the highest degree of finish is not required.

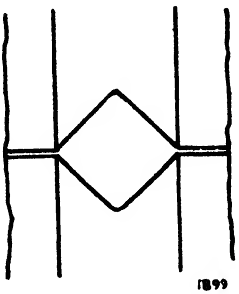


Fig. 34. Gothic Pass

The actual proportion of use in a cold rolling mill would be 70 per cent forged steel rolls, 20 per cent cast steel, and 10 per cent chilled iron.

Roughing and Finishing

Rolls for forming finished sections are, as has been seen, of two classes: roughing and finishing. The roughing rolls are very much nearer to the finished section than the cogging rolls referred to on page 54, but they are intended to roll a wide range of sections so that they will require the minimum number of changes. Taking out and changing rolls is an expense to be avoided if at all possible. This is why small lots of a particular section may take a long time in delivery, since if the rolls are not in at the time, the order must wait till enough orders have accumulated to make it worth while to change the rolls.

Finishing rolls must be changed for each different section, except in special circumstances, as when the webbed portion of a rolled section has to have a slight variation in thickness given to it. (The web of a section is the main vertical plate connecting the top and bottom flanges.)

Rolling Sections

Except for round bars, etc., steel sections, when rolled, are completely enclosed by the rolls. The groove in the bottom roll is bordered by collars rather deeper than the enclosed bar. These collars enter into corresponding grooves in the top roll, and the steel is imprisoned between them. It goes through a series of these grooves, being reduced in area and extended in length at each pass. As each groove is traversed, a slight "fin" of metal is formed at the sides of the piece where a small portion of the steel is squeezed out between the edges of the grooves. This is obliterated in the next pass and a fresh fin formed, until in the final finishing pass the extent of the reduction is very small, a finish of the surface being the main result.

In rolling sections, the metal does not spread sideways to any great extent, so that it is advantageous to reduce entirely or mostly in the vertical plane. Some sections, such as joists, tees, and rails, present difficulties in this respect. Experience and skill based on long practice have to be employed in overcoming these. Fig. 35 shows stages in the production of a steel girder section, the left-hand column showing the successive passes through the roughing, and the right-hand those through the finishing, rolls. In rolling sections, extra work is thrust upon the collars, and it is for this reason that alloy iron or steel rolls are generally employed.

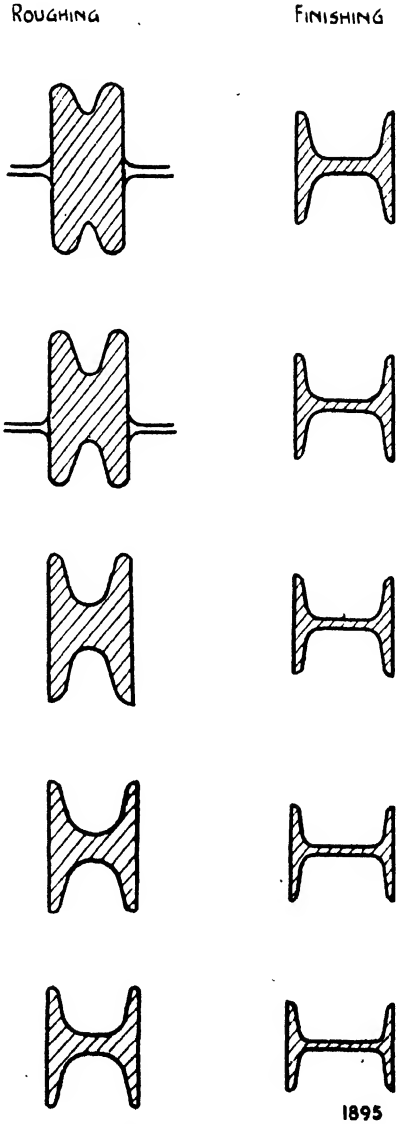


FIG. 35. STAGES IN THE PRODUCTION OF A STEEL GIRDER SECTION

Deep groovings and heavy sideways thrusts on the rolls are avoided in rolling angle sections. In rolling channels, and similar difficult sections, a happy mean has to be struck between the demands of economy and the technical difficulties involved. Economy calls for as few passes as possible, to save expense. The rolling operations involve, however, the severe thrusting and pulling of the steel in varying directions. If dangerous stresses, resulting possibly in badly strained material, are to be avoided, the reduction must be as easy as is practicable, which means as large a number of passes as is reasonable. The balance between the two conflicting demands is maintained by the skill of those to whom the work is entrusted.

The thickness of rolled sections is easily changed without its being necessary to change the rolls by altering the distance between the roll centres, which is done by screwing down the upper roll.

The reduction at each pass, i.e. the draught, varies according to the roll design, but is generally between 10 and 40 per cent.

Effects of Rolling

We may now consider briefly the effects of rolling upon steel. The question may arise in the reader's mind: Since steel is cast into ingots for rolling, why not cast it at once into the shape or section required? The answer is that cast steel sections used as they came out of the melting shop or the foundry would generally not be sufficiently strong and tough. It is certainly true that many thousands of tons of steel castings, having such intricate shapes that they could only be fashioned to shape in any other way with great difficulty (and, incidentally, at great cost), if at all, are used for multifarious purposes after they have been annealed. Annealing alone, however, will not induce the toughness and strength of "wrought" steel.

Again, in some steels, such as "rimming" steel (an incompletely deoxidized steel, normally containing less than 0·25 per cent carbon and having certain special characteristics), the gases liberated during solidification or freezing give rise to the formation of gas-cavities or blowholes in the solid metal.

During rolling, however, these blowholes, if they do not exist in the actual ingot skin, are welded up, and the steel thereby made more compact and dense. Further, the actual surface of a rolled product is much superior to that of the cast metal. By heating the steel and rolling it within the proper temperature limits, the work put upon it serves to refine its structure and strengthen it. (The earlier chapter on "Forging" should be carefully read in this connection.) On the other hand, there are certain sections, such as manganese steel tramway points and crossings, that are not rolled, but cast quite successfully as a result of the steel-founder's skill and experience, the steel in the cast condition being adequate for its work.

The rolling of solid steel ingots into sections at temperatures between yellowish-white (about 1250° C.) and dull red (below 900° C.) involving great reductions in transverse dimensions, necessarily sets up internal stresses and strains, especially when these reductions are carried out in two directions at right angles to each other. One effect of these internal strains is to raise the yield-point and ultimate tensile strength of the steel.

As an ingot of steel solidifies, certain tree-like formations of crystals are created in it, known as *dendrites*, and these branching congregations of crystals with their tangled structure ensnare many impurities and prevent them from rising to the top, where they can be lopped off in the discarded head, and from travelling centripetally to the centre of the ingot and segregating there. Rolling does not entirely obliterate these dendrites. It elongates and distorts them. The impure particles trapped in their tangled branches are drawn out into fine threads, and as the material cools, the excess iron (ferrite), or, if the carbon content is high enough, the excess carbide of iron (cementite), is deposited about these thread-like impurities. A section of rolled steel examined under the microscope would reveal all the various crystalline structures in a highly elongated form, the elongation being in the direction of rolling.

The manner in which the impurities are disposed and the character of the crystalline structures formed make a great difference to the characteristics of the steel, as will be seen from Fig. 36. From this diagram it will be seen that although certain properties (tensile strength and ability to elongate

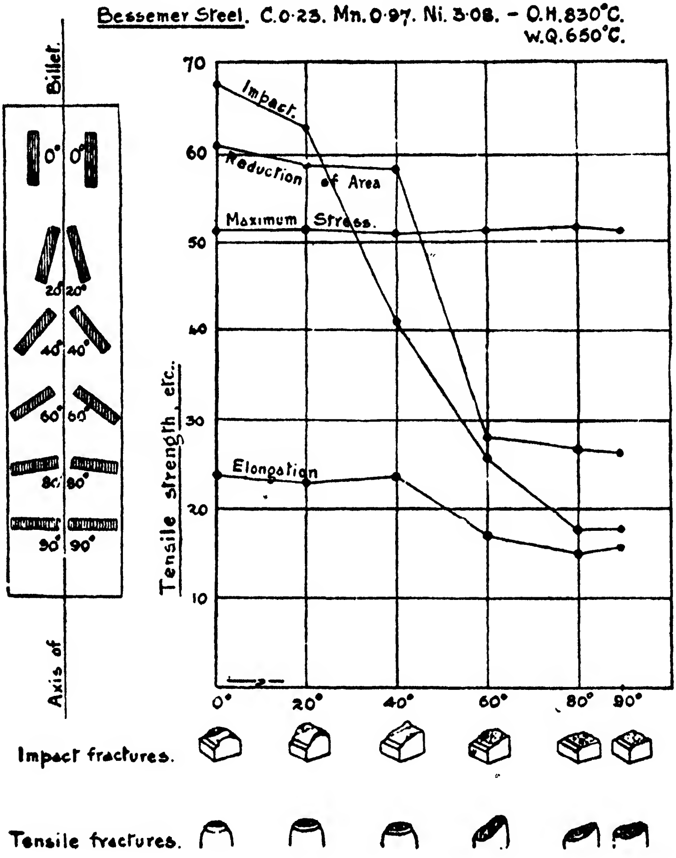


FIG. 36. INFLUENCE OF SLAG LINES, ETC., ON STEEL

Showing their effect in relation to the direction of stress (Brearley).

(Taken from Gregory's "Metallurgy" by courtesy of Blackie & Co. Ltd.)

without fracture) remain relatively unchanged, others vary greatly. The higher the temperature at which the ingot is cast, the greater the variations. Hence, if uniformity of structure and properties is desired, it is important to cast the steel at its correct casting temperature.

Economics of Rolling

Rolling is a quicker process than forging or drawing through a die. It also uses less power, and is, in consequence, the most economical of the three methods of reducing the section of a piece; the other methods are employed only when rolling cannot be done, as when the piece is excessively large or extremely small in cross-section, and when the cross-section undergoes considerable fluctuation in different parts of the length of the piece. Where the cross-section is very large, the number of pieces required is usually so small that it would not pay to make an enormous rolling-mill and its appurtenances specially for their production. Large shafts for marine engines are an instance. Very small cross-sectional material, such as wire, is more readily reduced by pulling it through a tapered hole in a die, which brings down its cross-sectional area much quicker than would a transit through rolls, the straight pull on the wire by the grippers being much more powerful than the "squirting" and elongating effect of rolling. (See Chapter XI.)

Because of the cheapness of rolling, engineers seek wherever possible to design their parts so that they can be rolled, which means that they must be straight and of uniform cross-section. Thus, railway rails are rolled, whereas otherwise they might be made of varying section, the parts over and supported by the ties being thinner and shallower than those between them. Pieces not of uniform cross-section throughout their length are not suitable for rolling, because the cross-section in a rolled piece is governed by the size of the roll opening or pass, which is constant.

Certain faults sometimes arise during the hot rolling of steel. Thus, cracks may develop during the cooling or reheating of the steel ingots; during rolling, these open up and are eventually converted into elongated *rokes* in the finished billets or bars. If the original ingot skin contains "blowholes,"* these are elongated into *seams* (or reeds), which may be regarded as shallow rokes. There is this difference, however. Rokes are generally isolated defects and do not necessarily exist on all sides of the rolled sections, and may be confined to only a

* See *Steel Manufacture Simply Explained.*

portion of the billets and bars rolled from the same cast of steel. On the other hand, when seaminess does occur, the whole cast is affected, generally on all sides of the rolled sections.

Collaring is the term applied when the hot steel does not properly enter the intended groove in the rolls. This may result in a cutting and overlapping of the surface of the steel, giving rise to the formation of what is really a double skin.

Cobbling is the general term applied when, on the one hand, the hot piece is not finished to the proper size or shape or, on the other, becomes wrapped around the roll.

If roughing marks are too deep, or of improper design, in the roughing rolls this may give rise to what are described as *shelly* or *spelly surfaces.*

From what has been stated, it will be evident that the greatest care in designing the rolls, heating the ingots or other pieces to be rolled, and during the actual rolling itself, is needed in order to avoid such defects.

In many instances, rolling is not the final hot mechanical working operation, and rolled blooms, billets, and bars are often forged, drop-forged, or up-ended afterwards in order to induce the most favourable structure or grain in the steel. These points have been dealt with in earlier chapters.

CHAPTER VI

Cold Rolling

WE have dealt in Chapter V with the general principles governing the rolling of steel. Similarly, in Chapter IV, we have indicated the reasons for cold working a metal as against hot working. These reasons apply equally to cold rolling as against hot rolling, namely, special size-accuracy, a clean, smooth, or bright surface finish, better physical properties for certain purposes, and readier machining. Nevertheless, it must not be assumed that so far as bars are concerned cold rolling is the principal process employed where these advantages are desirable. Cold drawing is by far the more usual procedure, and cold rolling to-day is mainly confined to wide flat bars, to sheets, and to strip.

It involves "rolling at temperatures sufficiently low to result in essentially no change due to annealing of the deformed structures resulting from the reduction of gauge by rolling" (Hayes and Burns). This undoubtedly accurate definition is, however, hardly clear enough for our purpose. More simply stated, it means this: When steel is hot rolled, the strained crystalline structure momentarily produced by the deformation involved does not remain unaltered. Almost immediately, the heat retained in the hot steel causes it to recrystallize, resulting in a semi-annealing or softening effect, which modifies the structure and to a large extent relieves the strains set up during rolling. It must not be assumed that this self-semi-annealing completely gets rid of rolling strains. It does not; for these strains to be completely eliminated a proper annealing or normalizing treatment must be given to the steel.

When steel is *cold* rolled, however, the strained structure remains completely. Internal heat is generated during cold rolling, but is dissipated so rapidly that the temperature of the steel as a whole is not much higher than atmospheric. Indeed, one theory to account for the increased hardness brought about by cold-work is that the internal heat generated raises the steel above its critical point and that the dissipation of heat is so rapid that, in effect, the steel is quenched, and that the hard micro-constituent, martensite, is produced in consequence. Some support of this theory is given by the fact that cold-worked steel loses its hardness when later tempered or annealed.

It will be evident, therefore, that the difference between cold and hot rolling is essentially a structural one. Some authorities mistakenly assumed that *hot rolling* implied working the steel *above* the transformation temperature range, and *cold rolling*, working it *below* these temperature ranges. It has been found, however, that even at temperatures well under the lower transformation point, a semi-annealing action and, in consequence, a modified structure, results. On the other hand, with certain steels, such as the austenitic "stainless" steels of the 18/8 chromium-nickel type, even when the final rolling is conducted in the region of 800° C. the material, so far as its structure and general properties are concerned, is in reality cold-worked, and to soften 18/8 satisfactorily it must be reheated to and cooled from about 1100° C.

For the above reasons it has been necessary for us to define the term "cold rolling" more accurately and in relation to the steel's final structural condition rather than to its working temperature.

By far the greater tonnage of cold-rolled steel is in the form of sheets or strip, and although some bars are cold rolled, as already indicated, we shall confine this chapter mainly to these more usual forms of cold-rolled material.

The steel, into whatever form it is to be rolled, has first to be freed from scale, as in cold drawing, and passed through rolls a suitable number of times to secure the desired reduction.

The raw material is sheet steel which has been produced by hot rolling, and is normally over 0·104 in. (12 gauge) in thickness. The hot rolling will have left on the strip an oxidation scale which, as in cold drawing, is removed by pickling. It is essential that *no* scale shall be left on the material, as otherwise there is considerable risk that it will be rolled *into* the steel, thereby impairing the surface, lowering the mechanical strength of the steel, and increasing its liability to pit-corrosion, i.e. the formation of "pits" or hollows in the surface where corrosion* has either already occurred or where corrosion can begin to take place. Incidentally, the latest practice is to wash and filter the air entering the cold-rolling shop, so that no floating particles of gritty matter can be worked accidentally into the surface of the steel.

When the pickling process has been completed, the low carbon steel can be rolled at once, but the higher carbon steels must first be softened by a proper annealing treatment. We shall, however, deal first with the actual rolling operation.

Tandem mills, single-stand reversing mills, "Steckel" mills, and cold sheet mills are the four main types of rolling mills employed. In the chapter on "Rolling" these types have been defined, but as the "Steckel" mill was not described in detail, further notes explaining the principle of this mill are given later.

Whichever type of mill is used depends mainly on its respective advantages. The tandem mill is least employed because it needs a good deal of floor space, is an expensive mill to put down, and does not allow of quick changes of section, while the number of passes the material can receive is fixed and limited. Moreover, this mill does not give as close a control of dimensions as the other mills. On the other hand, it has a high output and a low cost of operation.

The single-stand reversing mill is more economical in the first two respects, gives greater gauge (i.e. sheet or strip thickness) control, and furthermore, provides a wider variation in the number of passes that can be made.

The Steckel mill comprises two small working rolls and two large supporting rolls. Its distinctive feature as compared with other mills is that these four rolls are "idle," i.e. they are not revolving *power-driven* rolls. They are employed for producing the very thinnest strip, and this is drawn backwards and forwards through them by large reels placed one on each side of the mill, these reels themselves being power-driven.

This mill is not high in first cost. It allows of a reasonable variation in the number of passes and does not require extensive floor space. On the other hand, although it can, if necessary,

* The mechanism of corrosion is explained in *The Structure of Steel.*

be used for rolling nickel-chromium austenitic stainless steels, high carbon steels, etc., it has nothing like so great an output as the other types of mill. Moreover, as the ends of each coil on the reels have to be scrapped, since they cannot be taken through the rolls, there is an additional disadvantage in the waste of metal and money thereby represented.

The cold sheet mill is designed for use where coils of strip are not available. It has a high capacity but will not produce a dead flat sheet, and involves a fairly high scrap loss, since the ends of each sheet have to be trimmed off.

Before cold rolling, the strains set up during the deformation by hot rolling of the higher carbon steels have to be removed by an annealing process, which consists of heating the steel to a suitable temperature in a closed cast-iron box containing cast-iron turnings or drillings. This sealing up in a box is intended to protect the surface of the pickled steel from the oxidation that would take place if the heating were carried out in the open air, or in an open furnace. The object of the cast-iron borings is to prevent oxidation by the air within the closed box; the cast iron, being rich in carbon and other elements, is oxidized first so that oxidation of the steel's surface is minimized, even if not entirely prevented. The material is maintained at the correct annealing temperature for about four hours and then allowed to cool down to room temperature. The entire process is called "box-annealing," as distinct from ordinary "open" annealing.

The effects of cold rolling on the structure and physical properties of the steel are largely equivalent to those of cold drawing. The tensile strength rises sharply up to a reduction of about 10 to 15 per cent of the cross-sectional area, and then, with greater reductions, remains more or less the same. The yield point rises in a similar way, although rather more steeply, as does the Rockwell (or Vickers) hardness. Curiously enough, the yield point may afterwards drop to a minimum value, although it may again rise rapidly after 10 per cent reduction. The elongation per cent values, as might be expected, gradually fall, but recover after about 16 per cent reduction in cross-section, and actually rise afterwards up to 60 per cent reduction.

The above properties depend on the actual annealing temperature employed, so that the importance of the accurate control of this temperature cannot be over-estimated. The higher the annealing temperature, the lower are the final tensile strength, yield point, and Rockwell or other hardness values of the cold-rolled steel. The elongation per cent increases, after a sharp fall at about 5 per cent reduction, and climbs steadily up to 60 per cent reduction.

Summing up, we may say that cold rolling raises the elastic limit, yield point, tensile strength, and hardness, but lowers the ductility, as expressed by the elongation per cent. The extent to which these changes occur depends mainly on the extent of the reduction, and to some degree on the annealing temperature.

Another test commonly applied to cold-rolled steel is the Erichsen cupping test. This is an excellent test to indicate the *drawability* of sheet and strip, and consists in producing a bulge in the material by means of a dome-shaped die which is slowly forced into the metal under the influence of a hand-controlled ram until fracture occurs. The depth of the dome at the moment that this fracture occurs is then read off in millimetres and the value thus obtained is taken as a measure of the drawability and quality of the strip. Of course, the Erichsen values vary with the thickness of the steel under test. In the usual Erichsen test the strip is free to move and adjust itself as the deformation proceeds and the bulge is formed, but in the modified (No. 2 test) Erichsen the sheet or strip is gripped and held firmly between dies during the time that the bulge is being formed. This latter test is obviously much more severe than the usual Erichsen test, and some authorities regard the difference in drawing depth, i.e. the difference between the depths of the bulges produced by both methods, as a more true indication of the drawability or deep-pressing qualities of the steel under test. There seems little doubt that much practical information can be derived from a comparison of the behaviour of the metal under the above two sets of conditions.

After cold rolling, strip steel is often heat-treated (i.e. hardened and tempered) so as to produce certain specific physical and mechanical properties. This changes the structure of the steel in such a way as to remove completely the effects of cold rolling. This heat-treatment of sheet and strip is often a delicate and difficult operation, the essence of which is the avoidance of both distortion and decarburization of the surface of the steel. Decarburization, or decarbonization as it is sometimes called, means that carbon is removed, by combination with oxygen, from the steel's surface layers, and as carbon gives the steel its hardness, the result is a "soft skin" which the purchaser does not desire. The detailed description of the various means adopted to prevent decarburization, e.g. limited heating period, electric heating, controlled atmosphere, etc., is outside the scope of this work.

As cold-rolled steel has to undergo several passes before it is rolled down to finished size, it is usually advisable not to reduce the cross-section too severely at any one pass, and with alloy steels, in particular, it may be necessary to anneal (soften) the steel after each pass. This involves heating up to the appropriate high temperature, with the risk of further decarburization. When excessive decarburization occurs as a consequence of repeated reheatings, the steel is sometimes more severely rolled at the next pass to obtain the necessary hardness, but this practice is unsatisfactory as it produces a steel not always dependable.

Stainless steels of the chromium-nickel "austenitic"* type have frequently to be softened at intermediate stages before they can be reduced to the required thickness by cold rolling, a consequence of their somewhat abnormal capacity to harden when subjected to cold-deformation. In many instances, austenitic stainless sheet and strip are supplied in the cold-rolled condition, especially when specified minimum values for the "proof-stress" and tensile strength must be exceeded. It must be borne in mind, however, that cold rolling tends to influence adversely the corrosion-resistance of such steels. The maximum resistance to corrosion can then only be obtained by *softening* the steel by reheating it to a temperature of about 1100° C., followed by cooling of the sheet or strip in the air, or even by quenching.

* For an explanation of this see *The Structure of Steel*.

CHAPTER VII

Pressing

Pressing is an operation akin to machine forging in that it forms the stock to shape by means of a steady squeeze or pressure rather than by a sharp blow. On the other hand, the equipment differs considerably, and the stock also differs, thick solid slabs or pieces being used instead of bars, while the pressure is exerted downwards (i.e. vertically) and not horizontally, as in the forging machine. The plant employed is either a mechanical press, if the pressings to be produced are of comparatively small or medium dimensions, and of the softer metals, e.g. copper, brass, etc.; or a hydraulic press for larger pressings. The mechanical press ranges from 200 to 2000 tons capacity. It uses a bottom die, on which the stock is placed in readiness for the downward pressure, and if this bottom die is stationary, i.e. is not divisible into fixed and movable parts (as in the forging machine dies), the press is known as single-acting, because one vertical stroke constitutes the operation.

If, on the other hand, the press employs not only a downward stroke but also an additional motion which brings a movable die up to a fixed die before the downward stroke is completed, it is known as double-acting, and is, in effect, a forging machine stood on end, so to speak, i.e. one that acts vertically instead of horizontally.

The hydraulic press has a much wider range of dimensions than the mechanical press, and will produce shaped parts of a size that no steam forging hammer can attempt, such as the huge propeller shafts for the great modern liners *Queen Elizabeth* and *Queen Mary*. From 200 to over 15,000 tons is the range of these enormous presses. They employ what is virtually the incompressibility of water and its consequent transference of applied pressure in order to achieve a tremendous effect with only a small expenditure of power. The pressure is given to the water or other fluid by pistons operated by steam or water power. If water is employed, motor-driven pumps are used to provide the pressure. By the water this pressure is transmitted to a pressing area, consisting of a solid tup or ram actuated by a plunger which acts upon the steel to be shaped or compressed. The pressure exerted by a steam-operated hydraulic press is controlled by gearing, which shuts off the steam at a point in the downward movement regulated by the situation of the hand control lever. In this way the speed with which the steel is pressed is completely governed by the speed of motion of this lever, and the work can be brought to a dead stop by stopping the lever movement. Thus, there is perfect control of the press, an invaluable asset when such work as bending or cutting off is being carried out. As the operator stands, he can read off from a graduated scale, along which a pointer moves, the distance between the dies. This pointer is affixed to the head of the press (i.e. that portion carrying the upper die), and by its means he can work to predetermined dimensions.

In some presses there are two control levers instead of one, the operations of the press being divided and each lever controlling one part. It is a moot point which system is superior.

The mechanical forging press is, as stated, mainly used for the smallest types of pressings or forgings, e.g. those not above 30 lb. in weight, and is most effective with the non-ferrous metals. The hydraulic press is used for the very largest forgings as well as for special types of forgings of smaller size. This press does not employ fixed and movable or "split" dies but solid dies, or, as in dealing with large steel ingots to be pressed into smaller billets or blooms, special shaping and cutting tools.

The mechanical press is not so well adapted for dealing with steels as with the softer metals, but it can be, and is, used where the pressings required are uncomplicated in form, of roughly symmetrical type, and able to be pressed in one operation (i.e. one thrust or blow) for each step. The reason is that steels, being harder, are less responsive to the squeezing action (as contrasted with the impacting action of the drop hammer or steam hammer), and do not flow so readily into intricate die impressions under this type of pressure.

Fig. 37 shows a geared column press suitable for cutting heavy stock and other operations requiring long and steady

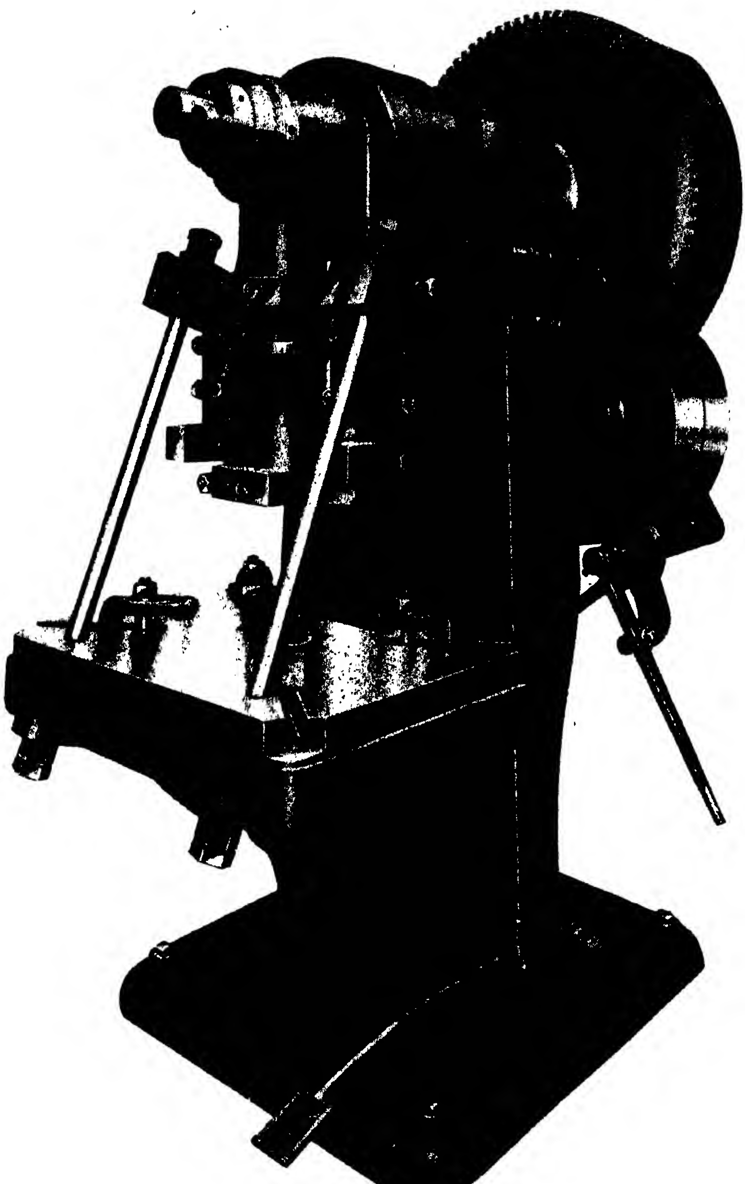


Fig. 37. Column Punching Press
(*Photo by courtesy of Messrs. Sweeney & Blocksedge (Power Presses), Ltd., Birmingham.*)

movement of the punch. The design combines great strength and rigidity with convenience in handling dies and materials. The gears are machine cut. The shafts are of forged steel.

Mechanical presses use slabs or "chunks" of metal of the correct dimensions. These are heated in suitable furnaces to the proper temperature for pressing, which is governed by the type of steel concerned. The piece is then placed in the lower die and subjected to the first thrust or squeeze of the machine. The steel is forced by the pressure to flow into the die impressions.

Where a high output is desired, certain types of pressings can be made by employing two preliminary impressions and a finishing impression, only one squeeze being required for each impression. The first impression is set at the front end of the dies; the second is in line with it and a proper distance back; and the third, i.e. the finishing, impression is also in line and immediately behind the second. The stock taken from the furnace is then passed through the press, and with each thrust or squeeze the three impressions are carried out on three portions of the stock, the stock being moved forward one impression per squeeze.

The hydraulic press will forge steel ingots ranging in section from 12 to 70 in. and over. It does not produce so rapidly and cheaply when used for smaller work as the steam hammer, which means that ingots up to 12 to 14 in. are best forged by the latter. From 12 to 24 in. ingot size their rate of production and economy seem to be about equal. From 24 in. onwards the advantage is with the hydraulic press. Apart from the difference in their action (squeezing as against impact) on the metal, there is not much difference between the two methods in application and practice.

The actual distance covered by the upper die of the smaller hydraulic presses as it descends until it comes to rest on the bottom die ranges from 24 to 72 in. according to the size of the press, and the actual distance throughout which it will exert pressure on the steel adequate to the work required ranges from 4 to 7 in. This, of course, represents the distance from the first contact with the metal to the end of the working thrust. This, again, is according to the size of the machine. These figures are for presses ranging from 300 to 5000 tons. With the larger presses from 5000 to 15,000 tons, the distance over which working pressure can be exerted will

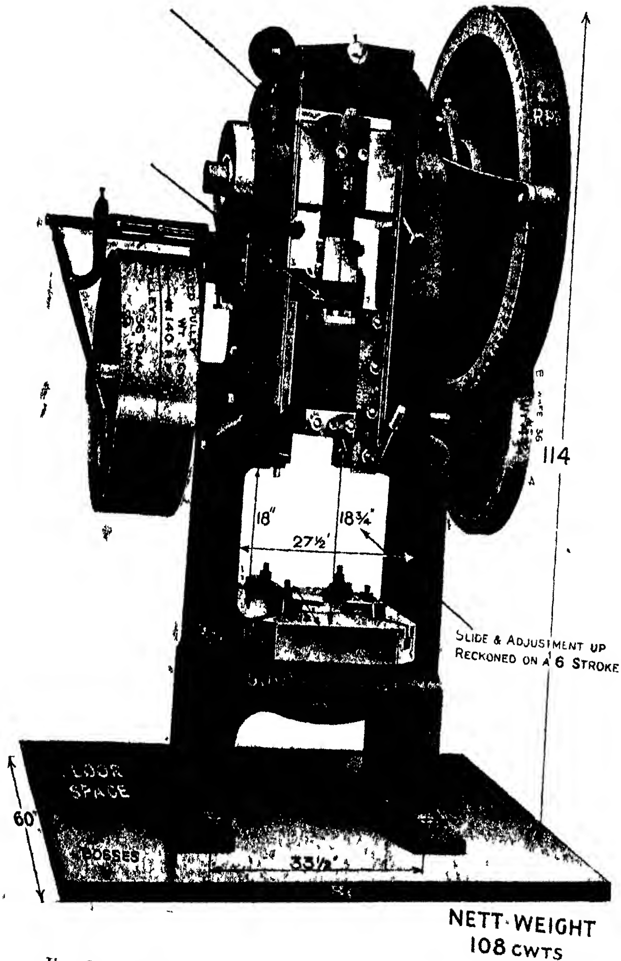


FIG. 38. 120 TON PRESS FOR STEEL AND HOT AND COLD BRASS
(*Photo by courtesy of Messrs Sweeney & Blocksedge (Power Presses), Ltd Birmingham.*)

be governed by the actual needs of the work, and the press will in many instances be specially designed to give the working distance required.

The grain structure of forgings produced by pressing in the hydraulic press will not differ essentially in type from that produced by other methods, the same general principles operating here also. The flow-lines of the fibres will correspond to the disposition of the part in regard to the operating pressure. For long pieces, such as shafts, the fibres will run longitudinally. Where slab-like stock pieces are employed, the same type of structure can be achieved as by upsetting.

The pressure the dies and other tools used in pressing are called upon to withstand depends largely on the type of operation, and whether it is carried out on hot or cold metal. For hot pressing, the usual range of pressures is from 14 to 34 tons per square inch, and for cold pressing, from 50 to 100. In hot working, lower pressures can be employed by proper care in heating the stock to the best possible working temperature, as recommended by the manufacturers. The maximum working pressure required is calculated by multiplication of the area over which contact extends at its greatest point by the yield point of the steel. The yield point of steel is dealt with in *The Structure of Steel*, but it may be described as the point at which metal ceases to be perfectly elastic, and is expressed in terms of the tons per square inch of pressure required to bring the material to this point. In normalized and annealed steels the yield point is generally assumed to be the same in compression as in tension, but there is generally a difference with cold-drawn or cold-rolled steels.

Fig. 38 shows another type of press of cast iron, which exerts 120 tons pressure. These presses are used mainly on the cold pressing of steel and also on hot and cold brasses, while they are also suitable for clipping the fins from die or drop forgings. For this last-mentioned work, open space is needed round the press, and the column type is preferred with the flywheel out of the way at the back of the machine. In comparison with cold pressing, however, relatively little hot pressing of steel is done. Cold pressing is dealt with in Chapter VIII.

CHAPTER VIII

Cold Pressing

In the previous chapter the discussion confined itself mainly to hot pressing. In cold pressing, the material or part to be pressed is not first raised to a suitable temperature in order to soften it, but is worked at ordinary temperatures. Unquestionably a most arduous form of pressing, it demands attention because of its profound and characteristic effects on the steel itself.

To form a part by cold pressing calls for a pressure whose extent is governed by the area of the surface over which it is to be applied; by the plasticity or stiffness of the material; and by the amount of deformation to be done. The plasticity or resistance of steel is not a static or fixed quantity. It varies, and the variation is governed by the carbon content or alloy content, the amount of previous work done upon the steel, and the extent to which the metal is free to flow under pressure.

Steel is not normally a highly porous material. It is generally dense and homogeneous, a solid mass of "grains" or "crystals." Consequently, if pressed, it does not lose volume to any serious extent, as does a sponge. The particles displaced have to find an outlet in an unstressed direction. In other words, pushed in at one point they must push out at another. The narrower or more closely constricted their outlet, the greater is the resistance to the press and consequently the severer the task of the operator and his tools.

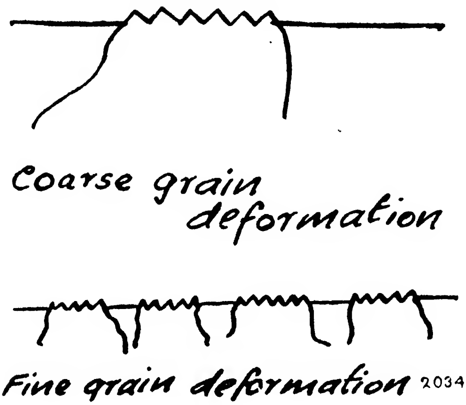
It has been said that steel does not lose volume when pressed, and this is reasonably correct in everyday practice. There is, however, a slight decrease in density, i.e. increase in volume, calculable by formulae and due, it is believed, to a distortion of the geometrical arrangement of the atoms of which the steel is composed. Careful measurement has shown that the maximum permanent increase in volume or decrease in density brought about by cold-deformation is about 0·3 per cent only.

In *The Structure of Steel* it was explained that, up to a certain point, steel behaves as a perfectly elastic body, and when the pressure is removed, this elasticity causes the atoms to resume their original positions and groupings, and the steel regains its original volume, as does a rubber sponge when no longer squeezed in the hand. (The reader must not take this comparison too literally, as steel is generally not full of holes containing air or any other gas cavities.) Beyond this point, however, the steel is permanently deformed to some extent so that not all the atoms are able to regain their original positions, with the consequence that the steel is internally strained. It is this internal strain that results in pressed steel being harder and having lower electrical conductivity than normalized steel. Indeed, by normalizing, the original hardness (or, rather, softness), tensile strength, and electrical conductivity may be restored.

Cold pressing, because of the severe strain it imposes on dies and plant, cannot be employed on all metals and alloys indiscriminately. Some of them are far too hard. To be suitable for this operation a metal or alloy must possess sufficient ductility. So far as steels for cold pressing are concerned, their carbon contents are generally relatively low, and the most widely employed steels were, at one time, "dead-soft" steels containing between 0·10 and 0·15 per cent of carbon. This is because carbon raises the tensile strength and hardness of steel, but lowers its ductility, so that generally a deeper pressing or "draw" becomes possible, the lower the steel's carbon content. Even to-day, the most intricate pressings are usually made from very low carbon steels. At the same time, however, it can be stated that enormous numbers of cold pressings are now produced from steels containing up to 0·45 per cent of carbon. Naturally the depth of draw at one operation is generally less than when dead-soft steel is being pressed, but when the steel is subjected to intermediate normalizings and annealings, it is possible to fabricate somewhat intricate pressings from these higher carbon steels. In some instances, simple pressings may be formed in a single operation and placed in service without further treatment other than a final machining. In all instances the severity and sequence of the pressing operations are determined by the carbon and manganese contents and the condition of the steel. When the carbon content exceeds 0·20 per cent, the steel may be subjected to one of the following treatments before being pressed to shape: (*a*) normalizing; (*b*) annealing; and (*c*) spheroidizing or sub-critical annealing. Some reference was made to these earlier in this work, but the following additional explanation is now given.

Normalizing consists in heating the steel to a temperature above its critical range, i.e. above its upper critical point, and then cooling it, after withdrawal from the furnace, in still air. In true annealing, after reheating to a temperature above the critical range, the steel is cooled down slowly in the furnace. Annealing yields a softer but coarser structure than normalizing, and it is a curious fact that whereas the two treatments may give elongation per cent values of the same order and, indeed, exactly alike, superior reduction of area per cent values are generally obtained by normalizing. The tensile test-piece fractures then tend more towards the "cup-and-cone" variety. The inference from these facts is that properly normalized steel is more amenable to local deformation by cold work than annealed steel, a matter of considerable importance in connection with cold pressing and cold working in general.

Spheroidizing consists in a prolonged heating of the steel at a temperature below its lower critical point, generally about 670°–680° C. At these temperatures, the carbide of iron in the steel becomes "balled-up" or spheroidized as a consequence of the influence of surface-tension forces, instead of existing in the form of layers or plates in normalized and annealed steels. In consequence, the structure of the steel consists essentially of minute globules of carbide of iron embedded in a matrix of almost pure soft iron. There is little doubt that such a structure is capable of withstanding considerable deformation by cold work, and for cold rolling is most desirable. For cold pressing, however, it has been shown that normalizing only, which is a quicker and more economical process, yields highly satisfactory results, which are better than those obtained from annealed steels. This statement may appear paradoxical in view of the fact that the grain size of a normalized steel is smaller than that of an annealed steel. A fine-grained steel, i.e. one with crystals of small size, is usually (though not invariably) harder than a coarser-grained steel of the same chemical composition, so it might be expected that an annealed steel would yield or press more easily than the same steel in the normalized condition. Ease of pressing is, however, not the sole consideration, and in cold pressing the appearance of the surface of the pressing is of paramount importance. This is, indeed, one of the great advantages claimed for cold pressing over hot pressing



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in regard to the surfaces of parts not afterwards machined. In cold pressing, the size of the grains or crystals has a noticeable effect on the surface of the product. When the crystal grains are large, the final pressed surface may be rough—something like the skin of an orange—an effect to be avoided wherever possible. The cause of this roughness will be better understood if *The Structure of Steel* has been previously read and assimilated, but for the benefit of those who have not read this work we give the following brief simple explanation, which, although not exact, will, it is hoped, give the reader some idea of the changes involved. When cold steel is plastically or permanently deformed, as in bending or pressing, the deformation occurs by a process of slipping of the atoms along the crystal planes of the crystals of which it is composed, in much the same way as books in a pile slide over each other when pushed from one side. But the crystal planes of neighbouring crystals lie in different directions, so that when a stress or "push" is applied in a given direction, slip most readily occurs in those crystals

P.G. Mark	Nomenclature	CHEMICAL COMPOSITION					Condition in which supplied	TYPICAL TESTS		TYPICAL APPLICATIONS
		C.	Si. (max.)	S. (max.)	P. (max.)	Mn.		Tensile strength tons/sq. in.	Elongn. % in 4 in	
101.	Dead-soft Steel	·07/·12	·10	·05	·05	·40/·70	N* at 910°C A* ,, 910°C	24·6 23·5	41 44	General cold-pressing work for automobiles, colliery equipment, miscellaneous hardware, etc.
102	Special dead-killed, dead-soft Steel	·07/·12	·04	·04	·04	·35/·60	N ,, 910°C A ,, 910°C	25·3 24·8	35 41	Difficult cold-pressings such as wire-wheel hub shells, sumps, clutch-housings, tapered disc wheels, etc., thimble tubes for boilers, etc.
102A 102B	·10/·15 Carbon Steel ·15/·20 ,, ,,	·10/·15 ·15/·20	·15 ·15	·05 ·05	·05 ·05	·40/·70 ·40/·70	N ,, 900°C A ,, 900°C N ,, 890°C A ,, 890°C	25·9 25·6 28·8 27·5	36 37 33 34	Automobile parts not highly stressed, seamless hardware, barrows, elevator buckets, gear-cases, ballistic heads for shells, etc.
103	·20/·25 ,, ,,	·20/·25	·15	·05	·05	·40/·70	N ,, 880°C A ,, 880°C S* ,, 680°C	31·5 30·0 25·5	28 30 33	Chassis frames, tapered disc wheels, centre-locking hub shells, brake-drums, axle and brake-housings for automobiles, aircraft parts, etc.
104	·25/·30 ,, ,,	·25/·30	·20	·05	·05	·40/·70	N ,, 870°C A ,, 870°C S ,, 680°C	34·0 32·0 27·5	28 32 35	The most popular steel for cold-pressed brake-drums, axle-housings, etc., for automobiles.
105	·30/·35 ,, ,,	·30/·35	·20	·05	·05	·40/·70	A ,, 860°C S ,, 680°C	35·4 29·3	26 32	Brake-drums, centre-locking hub shells, and other high-tensile pressings for automobiles.
106	·35/·45 ,, ,,	·35/·45	·20	·05	·05	·40/·80	A ,, 850°C S ,, 680°C	36·8 30·2	25 30	Higher-tensile brake-drums for heavy commercial vehicles, brake-drum liners for aircraft, etc.
107	·20 Carbon High Manganese Steel	·18/·23	·20	·05	·05	1·4/1·7	A ,, 880°C	38·9	21	High-tensile chassis frames, brake-drums, etc., of improved rigidity, and/or wearing properties.

* N—normalized; A—annealed; S—spheroidized.

whose cleavage or gliding planes run most parallel with the direction of the stress, i.e. these crystals are really deformed to a greater extent than their neighbours. When the crystal size is large, this deformation will tend to be more "patchy" than in a finer-grained steel consisting of a larger number of crystals of smaller size. In effect, when the crystals are small, the changes are more "averaged out" than with coarsely grained steel. From a sub-microscopic viewpoint (see illustration on page 84) we may represent the conditions during pressing.

Another important point to be considered, however, is that the smaller the crystal size or grain, the stronger or harder is the steel. Thus a greater stress is imposed on the machine and dies required to produce a given amount of deformation. Indeed, if the grain size or structure is very fine, it may crack or fracture during the pressing operation. Thus, on the one hand there is the demand for a ductile steel (which implies larger crystals), and on the other hand for a fine-grained steel (which implies smaller crystals and consequent greater difficulty in pressing). These conflicting demands necessarily involve a compromise, and the steel manufacturer provides a material with a grain structure to give a reasonable degree of surface smoothness in the pressed condition, while not being so hard as to give rise to difficulties during the actual pressing operation.

The advantages gained by smoothness of surface are (*a*) when the product must be finally polished, the cost of polishing will be less because there will be less preparatory work needed, and (*b*) painting, lacquering, plating, or cellulose spraying are more easily effected and yield more pleasing and satisfactory surfaces.

In the table facing this page, reproduced by kind permission of the Park Gate Iron & Steel Co. Ltd., are shown some of the properties and applications of their steels for cold pressings.

We have now to turn our attention to a phenomenon peculiar to metals and alloys (including steels) of the ductile type when subjected to deformation in the cold by such operations as cold drawing, cold rolling, and cold pressing. One result of such treatment, as in cold pressing, is to "work-harden" the material (see *The Structure of Steel*). This phenomenon has also been explained in earlier chapters, however, and should be well enough known to need no further description. One essential feature to be dealt with here is that sometimes this work-hardening effect due to the cold pressing of ductile steel is not uniform. Some parts, usually in the form of zones or ribbons, are unequally work-hardened, and the result is apparent in the form of a surface-disfigurement or linear pattern, known as a *stretcher-strain.* Such zones or bands may vary in hardness, according to the amount of deformation carried out, by as much as 5 per cent. These stretcher-strains are thought to occur in the region of the yield point, and are due to the irregular behaviour of adjacent parts of the steel within this region. The practical disadvantage of these markings is their serious influence on the finished cellulosed or sprayed surfaces of such bodies as motor-car wings, etc. To eliminate the effects of stretcher-strains, filing, grinding, and polishing operations would be needed, and these are both costly and laborious operations.

The chief method adopted to minimize this trouble is to pass the sheets through a levelling or flattening machine, consisting of a number of staggered rolls which lightly cold work the steel. Sometimes, also, a slight stretching of the sheet is carried out at the same time. Assuming that the steel is suitable in all other respects, it will not unevenly work-harden and yield stretcher-strains so long as the true pressing operation is not unduly delayed, i.e. say, not beyond 24 hours. If too long an interval expires between the levelling and stretching of the sheet and the final pressing, the effect of the preliminary slight cold working disappears and the steel reverts to its original condition. For this reason, makers of steel sheets intended for cold pressing usually send their products in the softened state when the purchaser's works are a considerable distance away. The purchaser then does the levelling and stretching in order that a minimum time shall ensue between these operations and the final pressing operation.

Another important phenomenon in connection with cold-worked steel in general, and of cold-rolled or cold-pressed steel in particular, is that of *ageing.* This is a generic term applied to the changes in mechanical and physical properties that take place when steel in different conditions is allowed to stand, either at ordinary atmospheric temperatures or at more elevated temperatures, say up to 300° C., for prolonged periods of time. The general effect is to increase the hardness of the steel at the expense of its ductility and impact values. When the phenomenon relates to the changes that occur in quenched steel, it is described as *quench-ageing*, and when applied to the alteration in properties with time of cold-worked steel, as *strain-ageing*, and this is the phenomenon with which we are immediately concerned. It has been shown, however, that steels susceptible to quench-ageing are also susceptible to strain-ageing. This increase in hardness and lowering of ductility is almost as if the steel grows prematurely old, so to speak, and can be rejuvenated only if its original properties are restored. This rejuvenation is achieved by a softening or annealing treatment, which consists of heating the steel to about 670° C., followed by slow cooling.

The question of finding steels that will not "age" when cold-worked and stored has been a subject of much experiment and research. There is no doubt that strain-ageing is intimately connected with the development of stretcher-strains, and the problem is most acute in "partly" deoxidized steels of the so-called "rimming" type. Fully deoxidized or "killed" steels are not nearly so prone to the effects of strain-ageing as rimming steel, although it is of interest to note that some boiler-plate failures have been attributed, in part, to the effects of strain-ageing, due to cold-punching, of the areas around rivet holes. In pressings, the effects of strain-ageing and the formation of stretcher-strains have caused much trouble in the past, but these difficulties have now largely disappeared in consequence of the researches carried out in the steelworks' laboratories.

It may be asked: "What is the cause of ageing?" In metallurgical language the cause is "the precipitation of sub-microscopic particles of carbide of iron, and perhaps also of nitride of iron, from ferrite solid solutions," this precipitation being accompanied by a straining of the space-lattice of the fundamental iron crystal units or cells. Readers of *The Structure of Steel* will have little difficulty in grasping what is meant by these statements.

During cold working, it is assumed that sufficient "internal" heat is generated momentarily to cause the iron to dissolve more carbide of iron than when in the undeformed or "ordinary" condition. Since the temperature of the cold-worked steel as a whole, immediately after being deformed, is at little above the atmospheric, it follows that this *additional* amount of carbide is retained in solid solution in the ferrite. This in itself increases the steel's hardness, but it is obviously an unstable condition of affairs, and the tendency is, with time, for the ferrite gradually to "throw out" or precipitate the excess carbide of iron (cementite) in the form of sub-microscopic or "discrete" particles. This precipitation, however, because it takes place at ordinary temperatures when the steel is internally hard and rigid, results in a distortion of the space-lattice of the iron units, and this straining of its lattice further increases the hardness and lowers the ductility of the steel. When the steel is afterwards reheated to some elevated temperature, as that of a red heat, say between 600° and 700° C., the internal (and external) rigidity is so decreased that the displaced iron atoms are able to regain their normal positions. In consequence, the hardening effects due to cold working and "ageing" disappear, and the steel regains its original properties, i.e. it becomes more plastic and ductile. It is for this reason that when steel is subjected to multiple pressing operations, as in the production of deep or intricately shaped pressings, intermediate softenings or normalizings are necessary before the article is fabricated to the required shape. This simple explanation of strain-ageing may, perhaps, be open to criticism, but it will suffice to give the reader some idea of the mechanism of the process.

Ductile types of corrosion-resisting steels are being increasingly employed for cold pressings, such as in the manufacture of hypodermic surgical needles and for stainless steel tubes and pressings. Though requiring more care than mild carbon steels, they do not present insuperable difficulties. The main problem is the rapidity with which these steels work-harden when cold-deformed. This adds to the wear on the dies, and many intermediate softenings and annealings may become necessary. The actual softening temperature depends on the type of steel being dealt with. Thus, for a stainless steel of the "straight" chromium type, such as is used for surgical needles, cutlery, etc., containing about 0·30 per cent carbon and 13 per cent of chromium, where final hardness is a prime consideration, the softening temperature is about 750° C., but for the low carbon "austenitic" stainless steels of the 18 per cent chromium–8 per cent nickel type, air-cooling or even water-quenching from temperatures above 1000° C. is necessary. It will be evident that the pressing operations, as well as the heat-treatment operations, are modified to meet the special difficulties occasioned in the fabrication of stainless steels.

In making deep pressings it is essential that there should be proper and sufficient lubrication of the dies in order to reduce the amount of die wear and also to prevent scratching or damage of the surface of the pressed part. This scratching is caused when the die surface and the pressed metal "seize" or "bind" together. Not only is this seizing bad for the surface of the steel, but it may also cause the bursting of the pressed product, and may even stop the press.

The mechanical aspects of the subject have been fairly well covered in the chapter on hot pressing, and apart from the greater severity of the operations, there is little difference in the methods, but the range of cold-pressing operations is naturally somewhat less wide.

The great advantages of cold pressing over hot pressing are that a cold-pressed article is more accurate to shape and is generally more rigid, while for certain purposes the enhanced hardness due to work-hardening is decidedly beneficial.

CHAPTER IX

Bending

BENDING steel by deforming it is not the simple operation it may seem. There are no fewer than nine different possible ways of bending, as follows: (1) spinning; (2) hammering the steel up to a previously shaped forming tool, i.e. a tool giving form; (3) bending the steel about a fixed pin or former; (4) bending it about a pin or former between walls; (5) folding it over a fixed bar or plate or over itself; (6) holding one end firmly in a swivelling vice and stopping the free end from turning by the aid of a fixed stop; (7) wrapping the steel about a revolving forming tool or mandrel, i.e. a cylindrical rod or spindle; (8) forcing the steel between fixed points or walls; (9) rolling.

With rolling we have already dealt in a previous chapter, but as certain types of rolls, known as bending rolls, are specifically designed for bending rather than for reducing the steel in section, they will be dealt with here. Spinning will be considered later.

Bending is applied to give a specific form to steel so as to fit it for a particular part or purpose. It is hardly necessary to give examples, but a few may be mentioned, e.g. bars, pipes, and U-bolts, which are bent to shape; plates and sheets, which are given a curvilinear form, as in forming tube mill ore-grinding shells, i.e. their cylindrical revolving bodies, boiler drums, and strips, angles, tee sections, such as pit-arches, channels, and girders, which are also bent to form. One could give numerous other examples.

It is, however, of value to know the utility and special applications of the nine methods outlined, not all of which are applied to steel. Spinning is employed for making curved vessels and lids of circular form from flat discs of thin sheet steel. (See Chapter XIV.) Motor-car hub caps, for example, have been spun from stainless steel sheet. The cold pressing of steel plates for motor-car brake-drums and wheels also comes into the category of bending to shape. (See Chapter VIII.)

Hammering of the type mentioned under (2) is principally employed in fashioning formed coils of various kinds. Pipes, bolts, and bars of round or square section are usually bent about a fixed pin or former, as are steel strips bent on the flat,

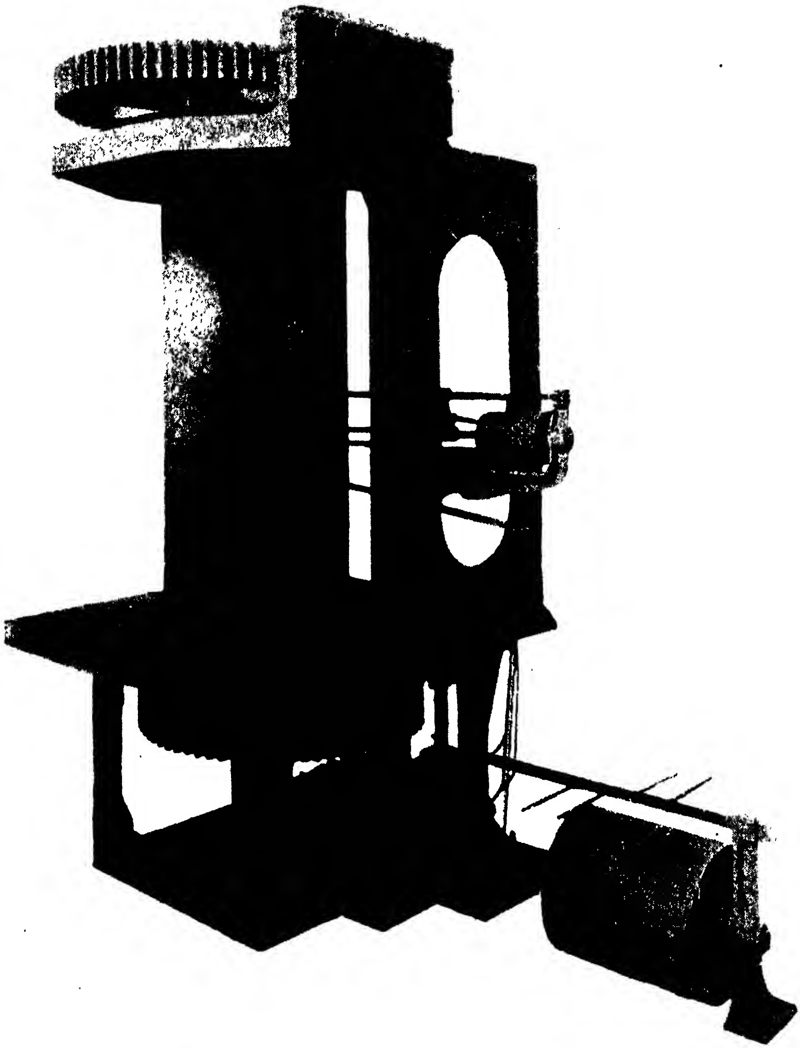

FIG. 39. VERTICAL PLATE BENDING MACHINE

(By courtesy of Messrs. Crosthwaite Furnaces & Scriven Machine Tools, Ltd., Leeds.)

i.e. not on the edge, when it is necessary to form a definite radius thus  at the elbow of the bend. On the other hand, if no radius, but a sharp angle  is needed, these strips are gripped in the adjustable jaws of a vice and bent about a bending block as required, the sharp edge of the block giving the sharp angle required. Folding over a fixed bar or plate is adopted when it is desired to produce a curled edge on a thin sheet or plate, or to fold the sheet upon itself. Wrapping about a mandrel is the method used for winding steel wire springs of round or square section, and for continuous coils of square or flat section, though these latter are seldom of steel.

Fig. 39 shows a four-roll type vertical plate bending rolls. This type of machine is preferred by makers of horizontal boilers. It is identical in principle with the horizontal type of machine, and can also be obtained with three rolls instead of four. The great advantage of the vertical form is that large plates can be handled more easily, particularly when working near the ends. The four-roll machine will make complete circles, bending up the ends equally with the centre portion of a plate, and for this purpose it is necessary to bring the ends to the centre line between the two centre nipping rolls. Power adjustment of the bending rolls is necessary. Belt, reversing motor or clutch drives are fitted according to circumstances.

Fig. 40 shows a large horizontal power bending and straightening machine, with a working load of 360 tons. This machine has a fabricated steel body, carrying a screw-adjusted central hammer at one end, and a wide slide with hammers adjustable up to 6 ft. 6 in. centres at the other. This slide has a reciprocating motion, i.e. it moves backwards and forwards. The machine is usually driven by an electric motor. A special safety device prevents any serious overload and damage. This safety device consists of a heavy forged steel plate, which keeps the nut in position, and is supported by two specially heat-treated steel breaking bolts. This material has a very high elastic limit* in relation to the breaking load, and gives practically perfect safety.

* See *The Structure of Steel.*

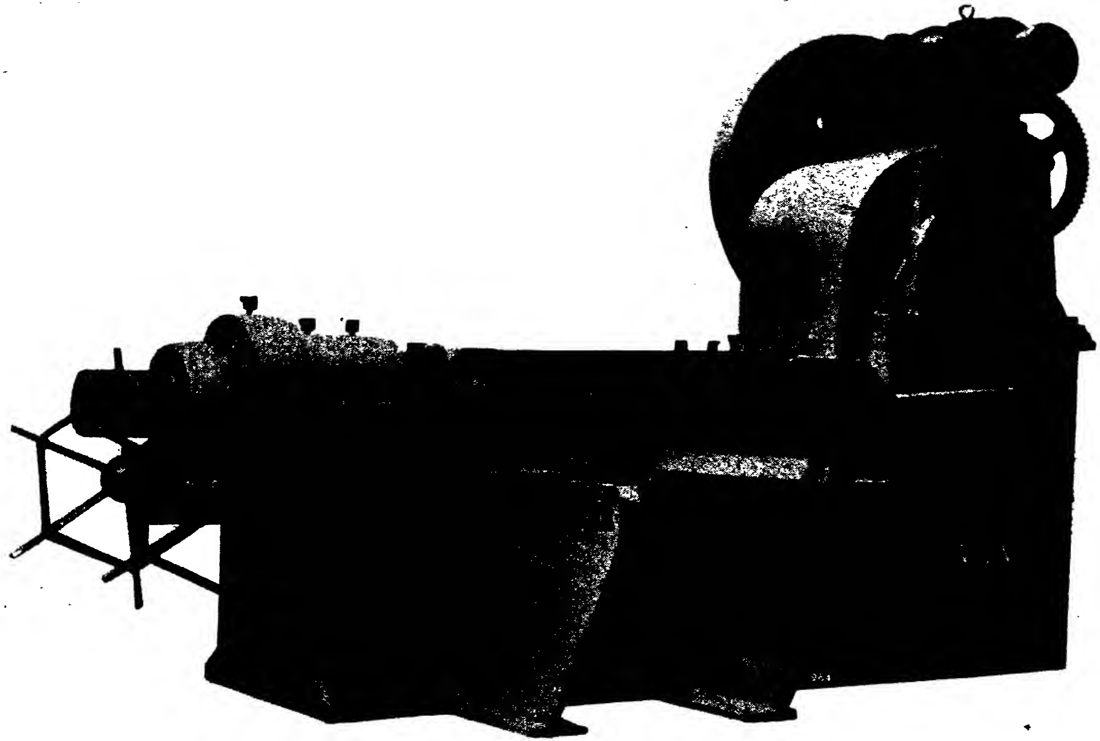

FIG. 40. BENDING MACHINE

(By courtesy of Messrs. Crosthwaite Furnaces & Scriven Machine Tools, Ltd., Leeds.)

Forcing between fixed points or walls is adopted for bending flat strip steel by the exertion of mechanical pressure, the steel being given its form by dies. This necessitates the use of either a hand or a power press. Dies are blocks of iron or steel in which a shape has been hollowed out. They are sometimes in one piece; sometimes they comprise top and bottom halves, fastened together. Into these hollowed or tooled out shapes the steel is forced by pressure, and so acquires the desired form.

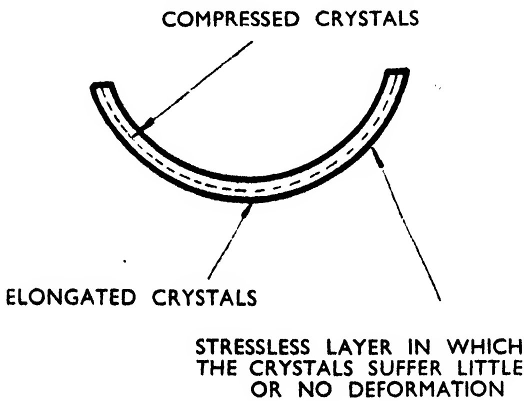

Fig. 41.

Rolling, in so far as it is designed to bend the steel, is used for forming tube mill drums or shells; for making corrugated sheets for constructional use; and for bending angles, bars, or plates to curves of specific radii.

Which process shall be used for any specific job is governed to a large extent by the form, dimensions, and type of steel used, and by the availability of any particular bending tool or machine.

It should be borne in mind that bending steel is virtually a forging operation. The bent part or piece is physically changed as a result, and this change may, and generally does, considerably alter its strength. Thus, if an ordinary straight bar is bent to a right angle, the crystals of the steel at the angle of the bend undergo physical alteration. Some of them—those on the outer surface—are drawn out lengthwise; some—those at the centre—stay as they were at first; others again—on the inner surface—are squeezed or crushed. (See Fig. 41.) This means that within the area of bending and during the bending operation a series of different and opposing stresses is set up within the steel. There are tensional stresses, compressional stresses, and areas in which no deformation occurs. Furthermore, the larger the section of the bent bar, the more extensively are the crystals stretched or compressed (see later in this chapter). To reduce the harmful effect of these stresses it is often desirable to heat the steel first to soften it, and this also makes the operation easier.

Bending may thus be carried out either hot or cold. Which method is chosen depends mainly on the composition and type of steel. In general, steels high in carbon are bent hot; annealed steels can often be bent cold, because they are already in a relatively soft condition. Annealing is a softening form of heat-treatment given to certain steels, and is fully explained in *The Structure of Steel* by the present authors.

A fact to be borne in mind in designing tools for bending steel is that cold steel is perfectly elastic up to a certain point, i.e. when force is exerted upon it, it recovers, reverts to its original form; e.g. if pulled, it springs back like elastic (though, of course, much less noticeably) unless the pull is so powerful as to stretch the steel beyond its "elastic limit," i.e. beyond the point at which it will recover, just as rubber, if pulled too hard, will stretch beyond recovery and tear or break. In bending, the elasticity of the steel causes it to spring back to some extent after the bending operation. For example, if a piece of steel were being bent by dies to a right angle (90°), and the dies were themselves designed to a dead accurate right angle, the piece after the operation would not be exactly right-angled as on p. 92, but obtuse-angled, thus:  This is because the steel, having been forced to a right-angled bend, has, as soon as the pressure is removed, sprung back a little. Obviously, then, if an accurate right-angled bend is desired, the dies must be designed to an angle rather less than a right angle. The exact angle can only be fixed in relation to the type and size of the steel, as the extent of its elasticity and the consequent partial recovery of shape vary with different steels. Soft mild (i.e. low carbon) steel will not spring back so far as good-quality spring steel. The recovery will also be less when the bending operation is carried out on hot steel than when on cold. Another point to be remembered is that some steels, e.g. spring steel, will, even in the hot state if bent, spring back a little as they cool, unless steps are taken to avoid this, e.g. by slow cooling.

The temperature to which the steel is raised for the carrying out of the hot bending operation varies, again with the type of steel, and the manufacturer should always be consulted on this point if doubt exists. The temperature of the steel largely governs the ultimate strength of the bent product, and also governs the number of degrees the steel will spring back. In heating the steel, localization of heat at the area to be bent should be avoided. The wider the area over which the steel is heated, the more evenly will the stresses be distributed during eventual cooling. The hotter the steel becomes, the greater its plasticity, and therefore the greater the ease with which its section is reduced under pressure. Thus, it is advisable that the maximum heat should be as close as possible to the angle or elbow of the bend. Otherwise there may be an unequal elongation of parts of the finished product, one side being reduced in cross-section, and therefore elongated, to a greater extent than the other, as, for example, in a U-bolt, in which one leg would then come out longer than the other, which, of course, is to be avoided.

Fig. 42 shows 26 ft. × $\frac{3}{4}$ in. pipe-bending rolls. This is a large four-roll type of plate-bending machine for producing tubes. The four-roller principle enables perfect tubes to be bent in readiness for riveting or welding. The two centre rolls are driven from a continuously running motor, and the necessary accurate control of the plate when bending up the edges is given by an ingenious mechanism, while the speed for the body of the tube is also adequately provided. The two side and the lower centre rollers are adjusted by a continuously running motor similarly driven, which acts as a safety device. The side rollers can be raised or lowered at each end to correct the run of the plate or to bend conical tubes.

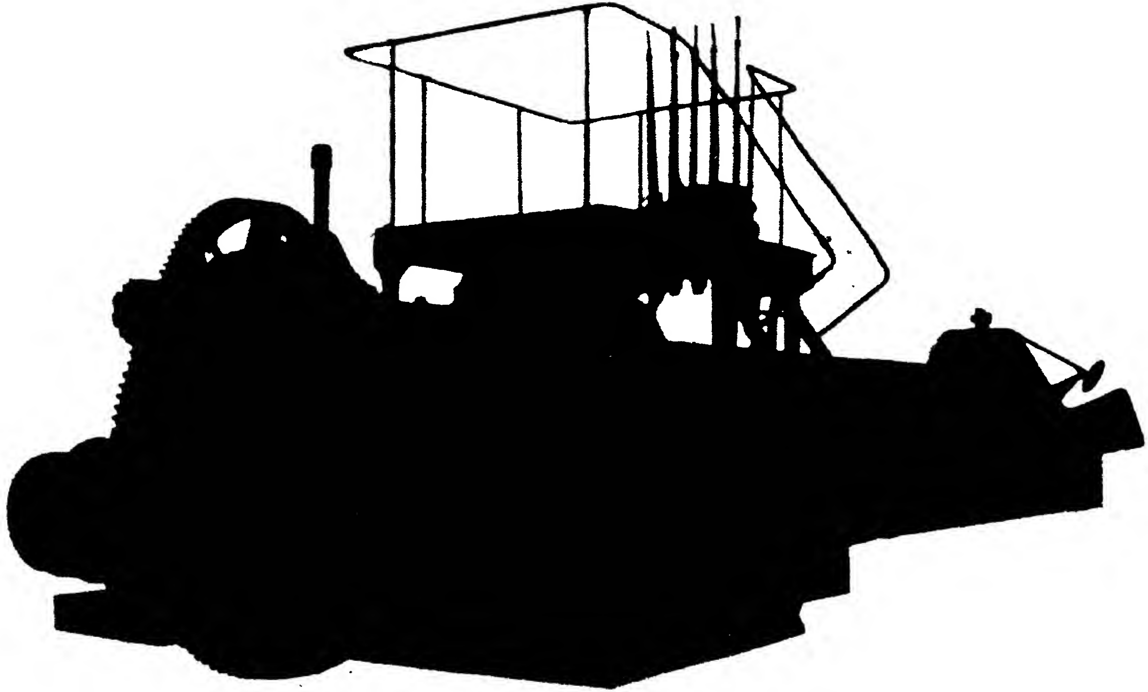

Fig. 42. Four-roll Bending Machine

(By courtesy of Messrs. Crosthwaite Furnaces & Scriven Machine Tools, Ltd., Leeds.)

Fig. 43 shows a hydraulic flanging, bending, and forming machine. This is of extremely simple design, having a strong bed plate, carrying vertical guides for the moving beam. This beam is operated by hydraulic cylinders, and can be brought down either parallel with the bed or at an angle, as required. Flanging, curving, or general forming work can be done by means of suitable dies. The machine can be worked from hydraulic mains or by means of a self-contained pump. Gear-driven machines having the same general characteristics are also made.

The steel should always be heated to the temperature recommended, as the steel-maker has found this the most suitable for preventing fracture at the points deformed and stressed to the greatest extent. The heating should be uniform and thorough. Irregular heating nearly always means irregular bends.

Hot steel can be bent through a greater angle at one operation than cold steel; approximately twice as much, in fact. Whether bending cold or hot, the greater the angle through which the steel is bent, the more severe will be the effect upon the steel, the outer edges of which will be stretched to an extent, on occasion, equal to double its original length.

In bending steel tubes or pipes, the opposing stresses set up at the bend angle may, if measures are not taken to prevent it, cause collapse or flattening. These measures comprise inserting a packing substance within the tube to act as a support for the walls, or alternatively using an external device for bending, so fashioned that the convexity of the tube fits into a corresponding concavity in the bending instrument, thus reducing the liability to flatten or collapse. The packing material is often sand, which is rammed in tightly until it fills the tube, after which the ends are sealed to prevent it from falling out. Resin or lead is sometimes used, but lead (or one of its alloys) is the main filling material for the smaller tubes or steel pipes. Another supporting method that has its advocates is a well-fitting coil spring fitted inside the tube or pipe. This is lubricated to facilitate withdrawal, and its insertion and withdrawal usually involve a mechanical operation.

After the tubes have been heated for bending, the outer

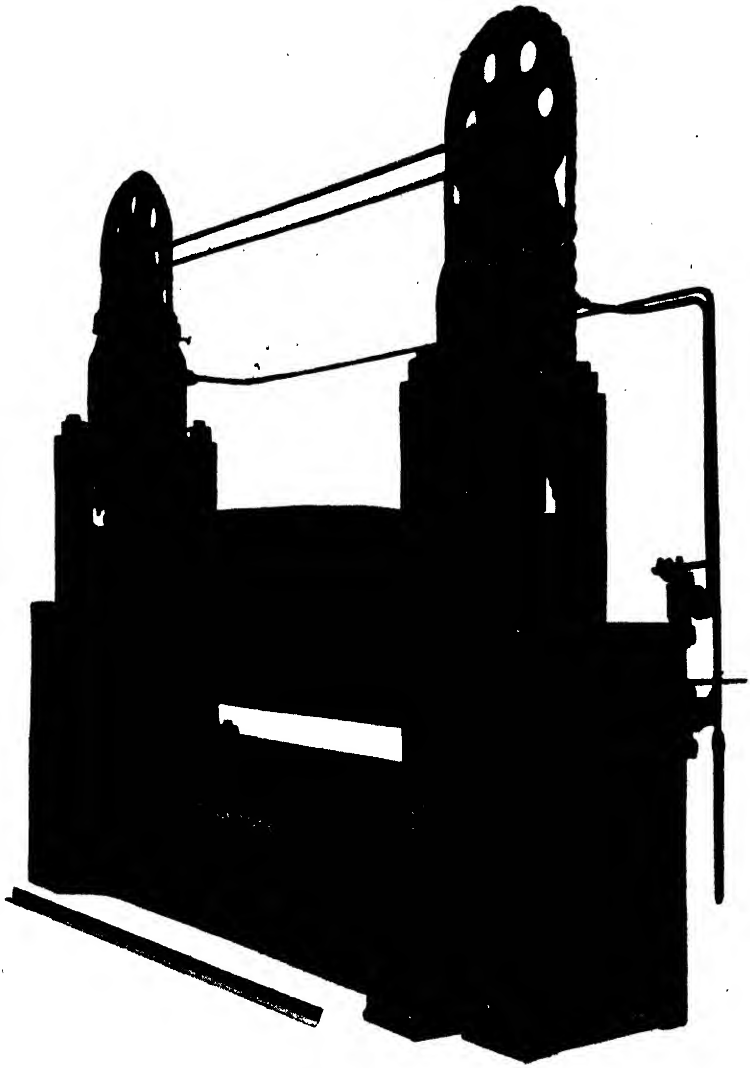

FIG. 43. HYDRAULIC FLANGING MACHINE
(*By courtesy of Messrs. Crosthwaite Furnaces & Scriven Machine Tools, Ltd., Leeds.*)

surface is sometimes cooled with water. This reduces the cross-section or diameter of the pipe to some extent by shrinkage or contraction, so that better support is obtained from the packing material by reason of the tighter fit. Uncooled pipe, on the other hand, slightly increases in cross-section during heating, so that on bending less support is had from the filling substance as a result of the looser fit.

Another type of supporting device is the internal mandrel, which may be either a simple rod of cylindrical form inserted in the tube and fitting tightly, or a series of metal balls partly connected and partly free-moving; or a formed mandrel specially designed for a particular job.

Fig. 44

The extent to which a pipe or tube can be safely bent is largely dependent on the thickness of the wall and the type of steel. In general, the thinner this wall, the greater the angle through which the tube can be bent.

Rolls for bending large plates, as for tube mill shells or cylinders, will take steel plates 1½ in. thick and 20 ft. long, and bend them into a tube 7 ft. in diameter or larger. Plates ¼ in. thick can be rolled into cylinders 4 ft. in diameter and larger. The plates are bent in the cold state, being passed between an upper single roll and two lower rolls, the distance between upper and lower rolls being adjustable, as is also the speed at which the rolls revolve. The diameter of a typical roll for this work is 31 in. and its weight is 21 tons, a 150 h.p. motor being needed to supply driving power.

Much skill is required to ensure that when the cylinder emerges from the rolls it is almost truly circular, especially at the ends of the plate, where these have to be joined by riveting or welding. If care is not exercised in handling, a "step" may result at the end of the tube at the point where the two ends of the plate meet when rolled. (See Fig. 44.)

The large capacity of plate-bending rolls for heavy material makes it possible to manufacture a tube mill shell or cylindrical body such as a boiler drum of, say, 20 ft. nominal length. This means that there are no joints on the circumference and only one or two longitudinal joints, which makes a very strong

Fig. 45. Tube Mill Plate Going Through Bending Rolls

design. For larger cylinders of, say, 8 ft. × 45 ft. nominal size, a suitable arrangement of plates would be a centre section 20 ft. in length, built up of two plates to the round, with two longitudinal joints and two end sections, each of one plate, to the round, and 12 ft. 6 in. long. The single longitudinal joints of the end sections would be staggered to each other (i.e. arranged slantwise or in zig-zag fashion) and also to the two longitudinal joints of the centre section.

There are, of course, many other machines and appliances for the bending of metal, not all of which can be dealt with here. We will, however, give a brief outline of the more familiar types, such as bar-folders, brakes, draw-benches, and the like.

The bar-folder is an appliance worked as a rule by hand. This seizes the metal and bends or folds it back over itself to the requisite degree. It is employed on steel of "light" gauge, i.e. of thin section.

The brake is a power-operated machine of the press type. It is provided with a die of vee shape, the vee angle being one of 90°. This die runs the full length of the press, and the machine is so planned that it will enable numerous combinations of bends to be made. These are carried out one at a time, and the steel sheet or strip on which the bends are carried out has to be shorter than the die. Steel furniture and steel required for ornamental or architectural purposes, as in the trimming of doors and the roofing of buildings, are usually bent in this way.

The draw-bench is another die-using machine, and is employed for the mass production of a special single form from straight steel strip. Such steel bends as those required for mouldings, steel window sashes and trims, are usually carried out in these machines.

Heavier bends are carried out in bulldozers or hydraulic presses. These are presses of horizontal type, the pressure of which is applied over a wide area. This makes them specially suitable for the job-bending of bars of heavy section, rails, rolled sections, etc. They have a considerably greater extent of operating space than an ordinary press possesses. The work is generally carried out on hot steel, and the results achieved are largely governed by the careful preliminary heating of the steel and the skill of the operator in handling it.

The hydraulic press is a machine in which the virtual incompressibility of water and its pressure are employed in order to obtain a tremendous effect without a great expenditure of power. It includes the pressing area, actuated by a plunger or ram (i.e. a piston and piston head) moving in a water-tight cylinder, and a force pump which provides the pressure. This pressure is then applied to a wide range of bending operations. To make the employment of hydraulic or other types of power presses economical, a large quantity of parts for bending is required.

The large number of methods of bending, and the different and multifarious types of bends, as well as the complications of design due to the necessity of guarding against "spring-back" of the steel, are impossible to describe in a simplification such as this, and demand a detailed study of more highly technical handbooks, particularly of those dealing with the individual dies.

It is sometimes profitable to bend sheet or strip steel edgewise instead of on the flat.

In many bent parts or products it is necessary that holes should be punched, and it should be borne in mind that in certain instances this punching operation should follow and not precede the bending. The reason is that in bending there may be a slight alteration in the dimensions of the material, which would throw out the position of any previously punched holes. There might, for example, be a slight spread of the steel, or a variation in thickness. Again, in bending, a change in the mechanical strength of the steel as a result of the operation might lead to cracking or tearing of the metal between or at the edges of the holes. On the other hand, many discs are supplied with holes punched through, which discs are later pressed into brake drums. Both methods are, therefore, used, i.e. the punching of holes both before and after bending to shape.

One point sometimes overlooked in connection with the bending of steel shells or tubes is that, when a bend is made, the steel on the outer surface of the bend is under tension, and therefore the greater or sharper the bend the more these outer layers stretch. The steel on the inner surface, on the other hand, is compressed, and the greater the bend, the greater is the amount of compression. It is because of this that a sharp bend lengthens the outer layers but compresses the inner walls of a tube so that the metal required to give this additional length is forced out of the bend, leaving the wall thinner at that point. The more acute the angle of bend, the thinner the wall at the bend.

Thanks are due to Messrs. Crosthwaite Furnaces & Scriven Machine Tools, Ltd., Leeds, for details of the machines illustrated, and for the majority of the photographs illustrating this chapter.

CHAPTER X

Extrusion

EXTRUSION is a process whose commercial application to steel is of relatively recent date, though it has been used for many years in connection with non-ferrous alloys of low melting point, e.g. lead and bronze alloys. Steel has a high melting point, and is therefore more difficult to extrude, as will be seen.

The process itself has been defined as "the application to a relatively massive billet or blank of sufficient pressure to cause the metal to flow through a restricted orifice, thereby forming a greatly elongated section of uniform but, relatively, less massive volume." This definition is clear enough to require no further amplification. Extrusion is analogous to cold drawing (see Chapter XI) with the differences that the metal is *pushed*, not *pulled*, through the hole in the die, and the process is conducted at an elevated temperature.

As stated above, the extrusion of steel is difficult because steel has high mechanical strength and considerable resistance to deformation at the temperatures normally employed for the hot extrusion of the low-melting-point alloys. Up to the present, the principal commercial application of the process is in the manufacture of stainless and seamless steel tubing, presses of from 200 to 2000 tons capacity being employed, together with hydraulic draw-benches of 75 to 300 tons capacity. Extrusion is also employed for the manufacture of chromium steel valves, which are afterwards finished by grinding without previous machining. How far extrusion can be still further developed as a steel-working method depends mainly on whether or not tool steels or materials can be found for extrusion tools capable of standing up to the work. Furthermore, if such tool steels are produced, it will be found necessary to re-design both the tools themselves and the power presses, so that they will withstand the vastly greater pressures necessary, and also the much higher temperatures at which alone the extrusion of steel is possible.

In the manufacture of stainless steel tubes in America, pressure is obtained from a hydraulic press, but in the extrusion of steels for valves, mechanical presses are sometimes used. In Germany and Japan the new Mannesmann process is employed and is described later. Some additional notes on the extrusion of valves will also be given.

Although the application of extrusion to steel is at present limited, the probability of its further development is sufficient reason for outlining the methods employed, bearing in mind that considerable modification of these will doubtless be necessary for each new application. As the cold extrusion process is hardly likely to be used, we shall not deal with it here. Hot extrusion comprises the heating of the steel until it is sufficiently plastic to be pressed through the die. The amount of pressure needed will depend upon the kind of steel, the temperature, the dimensions of the billet, rod, or piece, and the number of sections per die. Variation in the speed of extrusion will also be considerable. The presses may be either hydraulic or mechanical, according to the pressure required, and either vertical or horizontal. The hydraulic press is the more usual, because it possesses greater flexibility and compactness, and less liability to injury caused by incorrect or careless use.

The manufacture of seamless steel tubes of small diameter by the extrusion process was first developed in Germany at the Mannesmann works, and in 1937 had already become fully commercial, over 4000 tons of tubes being produced monthly. The process is similar in general outline to normal extrusion processes. The solid steel billet is heated to 1250° C., and placed in a container. By means of a mandrel it is then pierced, i.e. a hole is made in the solid billet by mechanically forcing the punch or mandrel through it. The hollow billet is then extruded through a die by means of a *mechanical* vertical extrusion press.

The hydraulic press is, as previously indicated, used mainly in the United States for the extrusion of stainless steel tubes, but in Germany and Japan the mechanical press is preferred. Certain advantages are claimed for it. In the first place, as the temperature of the hot steel billet is relatively high, and the pressure required great, it is vital that the extruding dies should be in contact with the hot metal, and subjected to the immense pressure, for as brief a period as possible. The mechanical press alone gives the requisite high stroke-speeds.

FIG. 46. MECHANICAL VERTICAL EXTRUSION PRESS WITH SIZING AND DESCALING ROLLS IN THE FOREGROUND

The mechanical press gives an output of two billets a minute, but only three to four seconds are actually spent in contact with the dies. The brevity of the actual extrusion process means that there is little heat-loss due to radiation and conduction, so that, if desired, it is possible to transfer the extruded tubes straight to a reducing mill. It is stated that by the Mannesmann process tubes from $\frac{3}{8}$ in. to $\frac{3}{4}$ in. with normal wall thicknesses and in lengths up to 65 ft. are produced in one heat.

It is also possible to use the cheapest steel, e.g. basic Bessemer steel, by substituting the mechanical process for the hydraulic. Deformation occurs under all-round pressure, resulting generally in the welding up and closing of any defects

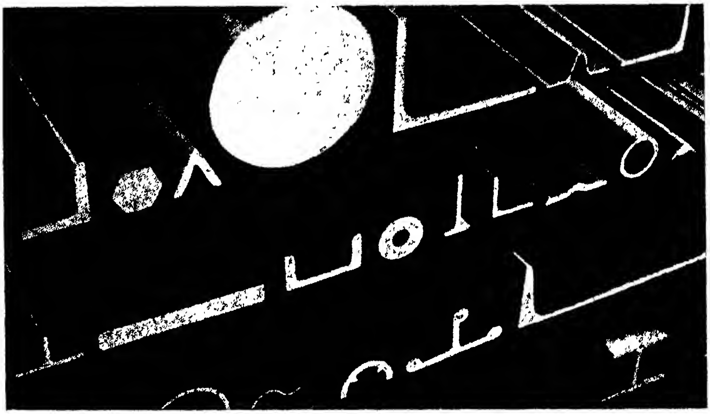

FIG. 47. VARIOUS EXTRUDED SHAPES

such as blowholes and cracks. The reverse happens in cross rolling, where the defects are opened out and extended. Hence the advantage of extrusion.

The amount of deformation is slight, and as it is feasible to work within a narrow range of temperatures, the stainless and other alloy steels not readily manipulated can be quite successfully worked by this method.

We shall now describe the Mannesmann process in greater detail. The first stage in the process comprises the provision by the steel-maker of long steel bars. These are nicked to the required lengths, and fractured at the nicks in a special machine, giving a short piece or *slug* of steel, which is heated up to 1250° C. in a suitable furnace and then passed quickly through a descaling mill comprising a set of rolls which, by their action, remove the oxidation scale resulting from the heating operation, and at the same time render the piece properly cylindrical.

After having been descaled, the short bar is then transferred to the mechanical extrusion press, which is of vertical type.

When the bars leave the machine in which they are broken to length, they naturally have rough ends. These have to be

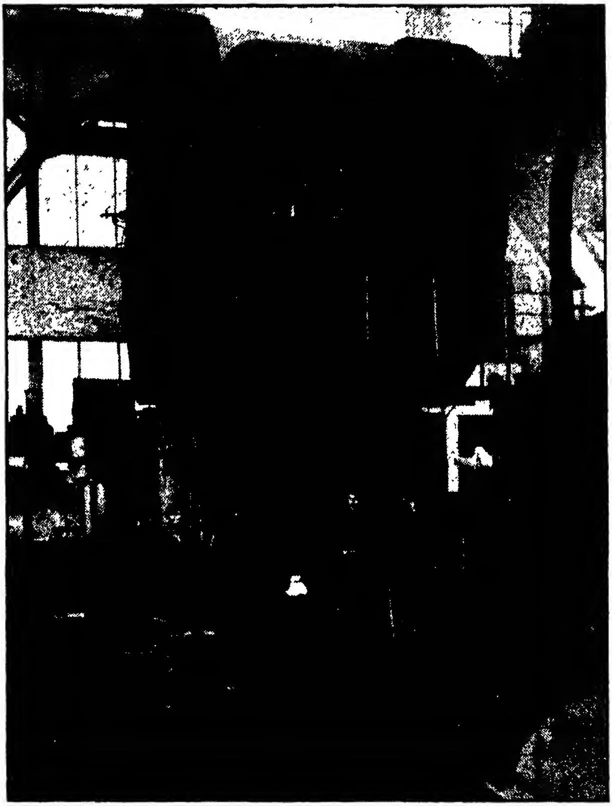

FIG. 48. INSERTION OF HOT SOLID BILLET INTO PIERCING CONTAINER BEFORE EXTRUSION

made regular, which is achieved by pressing them flat, as the first stage in the mechanical operations. Simultaneously, the pieces are thrust by pressure into a hollow receptacle or container. Here they are compressed until they completely fill the container. Thus a short billet or piece of steel is produced.

This is pierced by a punch or mandrel. The tube thus formed is then forced over the punch and through a matrix or die. This takes only from two to three seconds. The tube-maker is then left with a tube up to 40 ft. in length of the diameter required at that stage. One end of this tube will consist of a short solid piece (left on the leading end). This is cut off by a circular saw. The tube is then inserted in a rolling mill comprising a set of successive rolls. These reduce the tube to the desired ultimate diameter and wall thickness.

From the rolls the tubes travel on a moving cooling rack to an automatic machine, which screws their ends, i.e. puts a screw thread or series of spiral grooves on them.

In making chromium steel valves at the Chevrolet automobile works, the steel is cast into ingot moulds, the ingots obtained being then forged or rolled into bar form. The analysis of a typical steel is 0·40–0·50 per cent carbon; 0·30–0·50 per cent manganese; 3·00–3·50 per cent silicon; 8–10 per cent chromium; 0·025 per cent sulphur and phosphorus. Blanks about 1¼ in. dia. × 15/16 in. long are cut from the bars, previously heated to 815° C., by shears, which sever four bars at once. These blanks are then cleaned in a tumbling barrel, i.e. they are rolled or tumbled about together in a rotating metal drum, which action cleans them from scale. The blanks are then reheated in a gas-fired furnace for a short period to 1100° C. The hot steel is placed straight into the first die and the valve stem is extruded by means of a punch. Rectangular slots are then punched in the stem. The result is a smooth stem approximating closely to the required dimensions. After extrusion, the "fash" or surplus metal is cut off the end of the stem and the valves are again tumbled, i.e. they are inserted in a revolving steel barrel or drum, and by clashing against each other and the walls of the barrel, remove much adherent dirt and scale, reheated to about 700° C., and cut to exact length in a punch press.

The dies used are of high-speed steel, as are the punches. Lubrication is plentifully employed. The extruded valves are finally rolled in a roll threader, i.e. given a screw thread by rolling in threading dies, and bench-straightened, after which they are annealed at 800° C.

In the American process as practised by the Bethlehem Steel

Fig. 49. Heating Furnace (*on the left*); Descaling Rolls (*in centre foreground*); Mechanical Piercing and Extruding Press (*in centre background*)

Co., the steel bars or billets for extrusion are nicked and broken to length by means of the oxy-acetylene torch and a press. The steels to which extrusion has been applied here include nickel-chromium, chromium-molybdenum, nickel-chromium-molybdenum, medium carbon-manganese, and other alloy steels, as well as ordinary carbon steels. Preheating of the stock is carried out in a furnace at temperatures ranging from 1150°–1260° C. Heating is carried out at a slower rate for alloy steels than for carbon steels.

When hot enough, the stock is placed in a die in a hydraulic press and pierced by a punch. After this operation, the hollowed out pressing is transferred to a draw-bench of horizontal type. It is slipped over a long mandrel and the hydraulic cylinder of the machine then forces or extrudes it through a range of drawing rings, or dies of annular (ring-like) form. These reduce the wall thickness of the tube while increasing its length, and though sometimes made of grey cast iron rich in graphite, are more usually of a suitable hardened and tempered die steel.

The tubes are annealed at suitable temperatures after extrusion, and sometimes additional heat-treatment is given if essential. This is often carried out after the tube or part has been machined. Typical examples of extruded steel parts are cylinder sleeves for aircraft engines; pipe cross forgings; trunk pistons for locomotive boosters; steam trap bodies, saddle flanges, pump sleeves, pins and box end tool joints, pinion crankshafts for auxiliary locomotives, etc.

This chapter would be incomplete without reference to the "pneumatic-hydraulic" steel extrusion press invented by Stanley W. Sparks. This proposes to employ the sudden explosive force of air pressure in a 14,000 ton extrusion press. The object is to shorten the extrusion time considerably, and hence the duration of contact between the hot metal and the parts of the press—a time of 5 secs. is suggested. The machine itself employs air and water pressure. Hydraulic pumps serve water vessels, which are in turn coupled to air containers. The water is made to force air into the air vessels; this is repeated until the air cylinders have become fully charged with compressed air. Extrusion is performed by opening the appropriate valves, when the air suddenly expands against the water, which

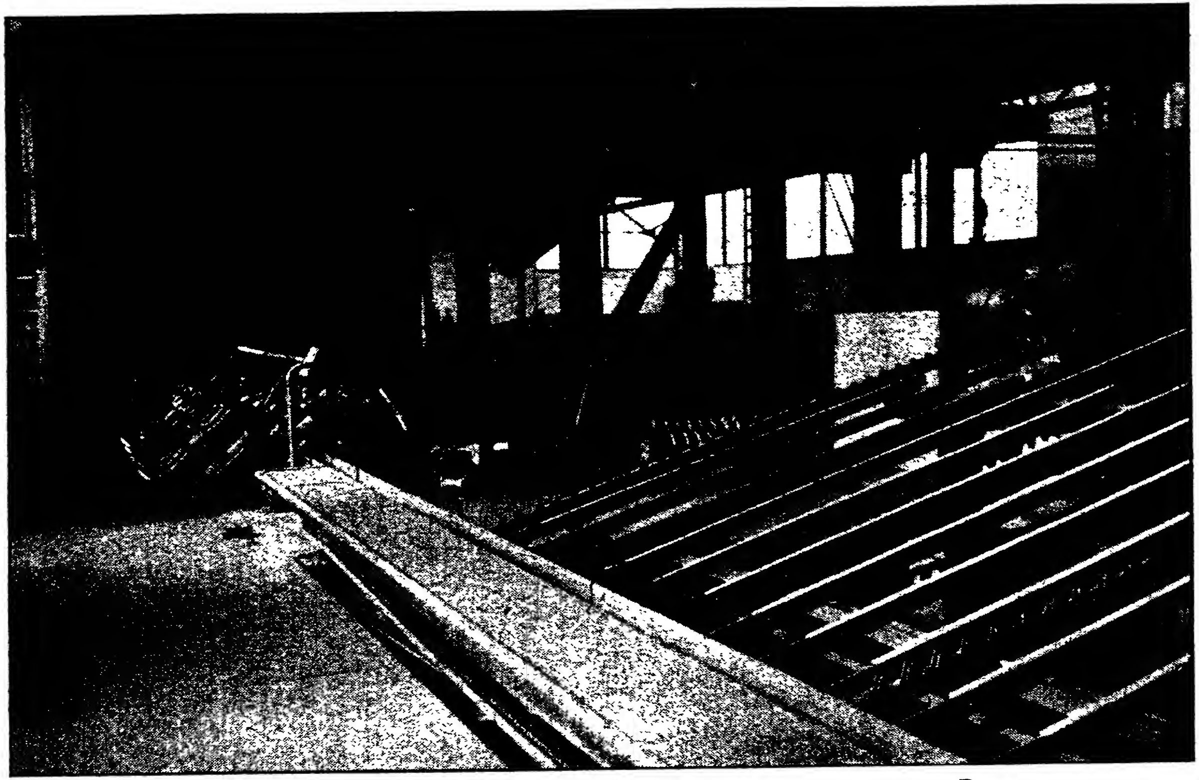

FIG. 50. GENERAL VIEW OF REDUCING MILL AND TRAVELLING COOLING RACK

in turn exerts pressure against the extruding ram or thrusting rod. Additional pneumatic and hydraulic cylinders are used to provide a return motion for the ram.

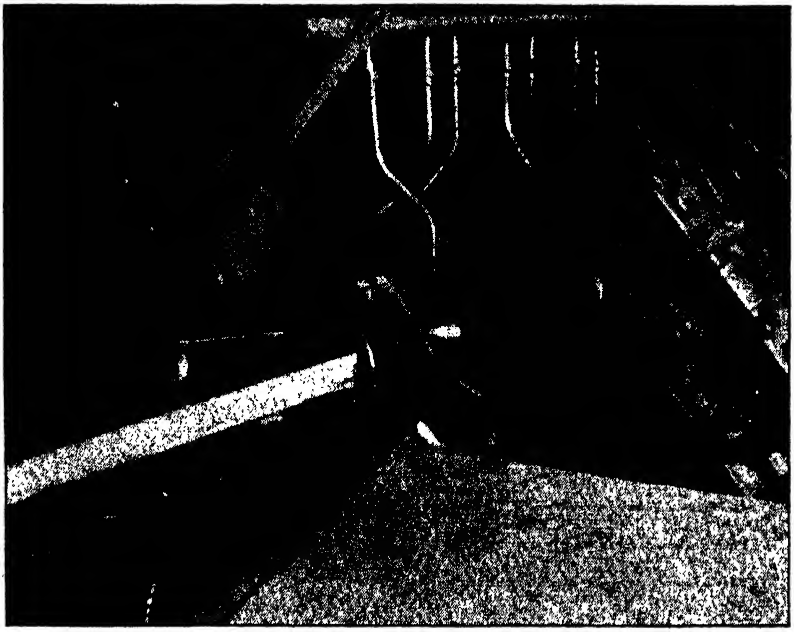

FIG. 51. CLOSE-UP OF DELIVERY END OF REDUCING MILL

An important feature of extruding processes in general is that the grain or flow of the metal lies in a direction best suited to withstand imposed stresses in service.

The authors acknowledge gratefully the loan of illustrations by *Iron and Steel*, London.

CHAPTER XI

Cold Drawing

COLD drawing is a method of reducing the section of unheated steel rods, bars, or coils by stretching or lengthening them. It is not an easy process, and it is reasonable to ask why it should be adopted when, as is evident, hot metal is so much more plastic and yielding. The answer is that cold-worked steel, whether rolled or drawn, has certain advantages over hot-worked. In the first place its dimensions can be more accurately controlled. Secondly, it can be given a smooth and bright finish. In addition its typical physical properties, which will be discussed later, have certain advantages; finally, it is more readily machinable.

Cold rolling is dealt with in Chapter VI. In the present chapter we are concerned only with cold drawing of bars, wire, and seamless tubing, taking bar-drawing first. Cold drawing is carried out on bars previously rolled in the hot state or, when wire is required, on coils specially prepared. It is important to note that a hot-rolled bar which is afterwards to be cold-drawn must be of first quality, as otherwise the cold-drawn material may prove defective. If, for example, the rolled bar is "piped" (i.e. contains an extensive central elongated cavity or pipe), seamed (i.e. carrying a streak or streaks of unsound metal on the surface), badly pock-marked or "pitted" by scale, internally blowholed (i.e. full of gas cavities), or contains segregated impurities in its structure, the cold-drawing operation will exaggerate these defects, and the result will be inequalities of surface, fluctuations in dimension and shape, and even fracture in drawing. The presence of hard scabs on the surface of the bar may wear the drawing dies excessively or even cause them more serious injury.

The first step before the actual cold drawing is a pickling operation.

PICKLING

Pickling, as we have seen in *Steel Manufacture*, is a method of detaching from the surface of hot-worked or freshly cast steel the scale formed by oxidation during hot-working and cooling down. This scale is not only a serious blemish on the appearance of the metal, but also a hindrance to the cold-drawing operation, since it chokes up the dies. It also badly abrades the steel being drawn, and may spoil the dies themselves.

The principle of the method is to steep the stock in a tank or bath of 3–8 per cent dilute "vitriol" or sulphuric acid (sometimes hydrochloric acid is used) containing an *inhibitor*. An inhibitor is an organic substance (e.g. pyridine or some similar nitrogen-bearing compound) whose inclusion lessens the loss of metal, due to acid corrosion, and the consequent acid consumption by setting up a reaction between the inhibitor and the acid. By using a proper inhibitor the action of the acid is made somewhat more gentle, and pitting of the surface by the acid, due to accelerated local attack, is minimized.

The acid solution in the pickling bath or tank is not cold, because cold acid is not nearly so active as warm or hot acid in removing the scale. Pickling is essentially a chemical process, and the chemical reactions involved take place much more readily at higher temperatures. The solution is therefore heated to about 65° to 70° C. When the scale is thick, its removal is effected less by chemical than by mechanical means, a surprising fact until we grasp the explanation. The essential constituent of the oxide film or scale to be removed is the ferrosoferric or magnetic oxide, having the formula Fe_3O_4.

In actual fact, its chemical composition is almost identical with that of Swedish magnetite ore.* In the pickling bath, the scale may not dissolve to any great extent, but in some way the acid manages to work its way underneath it.

There it finds a material more congenial to attack in the form of the steel itself. Having outflanked the Maginot line of scale, so to speak, the acid rapidly attacks the underlying metal so that ferrous sulphate (a chemical combination of iron, sulphur, and oxygen having the formula $FeSO_4$) is formed, hydrogen gas being freed at the same time, as represented by the following chemical equation—

$$\underset{\text{(i.e. the iron in the steel)}}{Fe} + \underset{\text{(sulphuric acid)}}{H_2SO_4} = \underset{\text{(ferrous sulphate)}}{FeSO_4} + \underset{\text{(hydrogen gas)}}{H_2}$$

* See *Steel Manufacture Simply Explained*.

The liberated hydrogen gas is released under considerable pressure, and blows off the adherent scale above it, so that it is detached and sinks to the floor of the tank, whence it is cleared from time to time.

In addition to the temperature and strength of the acid solution, the time given up to the pickling of a piece or coil of stock is important. This time must not be too short, or the scale will not have been completely removed. It must not be too long, or acid corrosion of the surface of the steel will have been carried too far, and serious pitting or surface attack will have occurred, apart from the obvious waste of acid and time.

With steel wire, in particular, too long a period of immersion may result in excessive "acid" or "pickling" brittleness, a form of embrittlement due to occluded (imprisoned) hydrogen along the grain or crystal boundaries, caused by the action of the acid, which seriously weakens the structure and ductility of the steel. This "pickling brittleness" is a very real thing but, fortunately, is only temporary, so that it disappears entirely when the steel is allowed to stand for some days, and in a few hours when the steel is heated or "baked" at temperatures between the boiling point of water (100° C.) and 150° C.

Here it may be as well to point out the danger associated with the pickling of hardened steel, which involves a grave risk of the development of cracks.

The exact time-period for pickling cannot be laid down, and is a matter for the skilled men entrusted with the work. The type of steel to be pickled, the strength of the solution and its age (i.e. whether it is fresh or has been used before), the character of the scale, the bath temperature, the dimensions of the bar or coil, have all to be taken into account.

When the steel has remained in the solution for an adequate period, it must be washed in water, under pressure. This is to eliminate the acid left on its surface, as this would still further attack the metal. Even so, water jets alone will not clear away every trace of acid, so that as a further precaution against surface pitting and corrosion, the steel is plunged into milk of lime (i.e. an emulsified mixture of slaked lime and water) or in slaked lime itself. This lime neutralizes any residual acid, but it does something more. It dries on the bars, and it is claimed that it serves as a lubricant during the cold-drawing operation, thus lessening the abrasion on the drawing dies. When the lime emulsion is used it is usually heated to a temperature of about 80° C. and its consistency is governed by the thickness of the lime coating required.

The Draw-bench

The bar is now ready for the actual cold-drawing operation. This comprises the mechanical pulling, tugging, or drawing of the steel through the hole in the die.

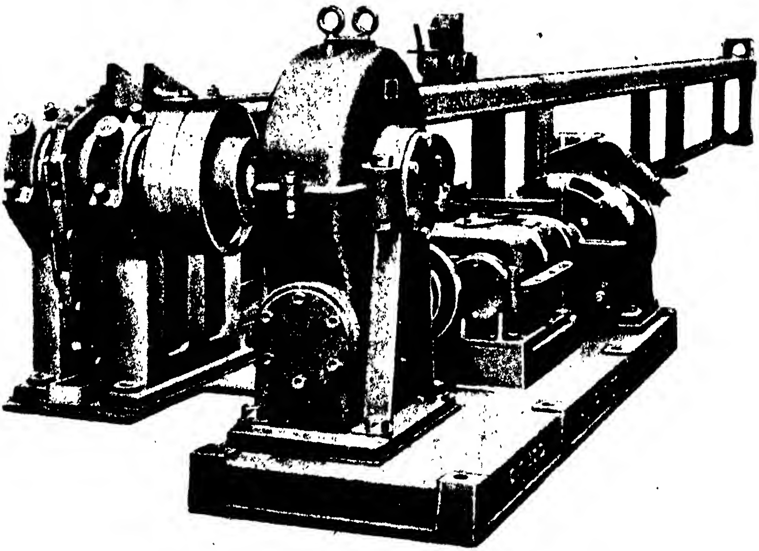

Fig. 52. Single Draw-bench and 25 h.p. Drive
(By courtesy of Fisher Humphries & Co., Ltd., Pershore.)

The machine used is known as a draw-bench. For drawing steel rods or wire it consists of a draw-plate (sometimes described as a "wortle plate"), i.e. the metal die-plate containing the tapered hole or holes through which the steel bar or rod is pulled; a driving mechanism, usually a variable-speed electric motor; a "pointing head," i.e. a gripping mechanism that seizes the material and pushes it a little way through the dies; and a "pulling head" which then grips this protruding end and completes the operation by pulling or drawing the material right through.

To explain this in greater detail, the motor transmits power through gearing to a "sprocket." A sprocket is a chain wheel furnished with projections or teeth along its rim. These are so

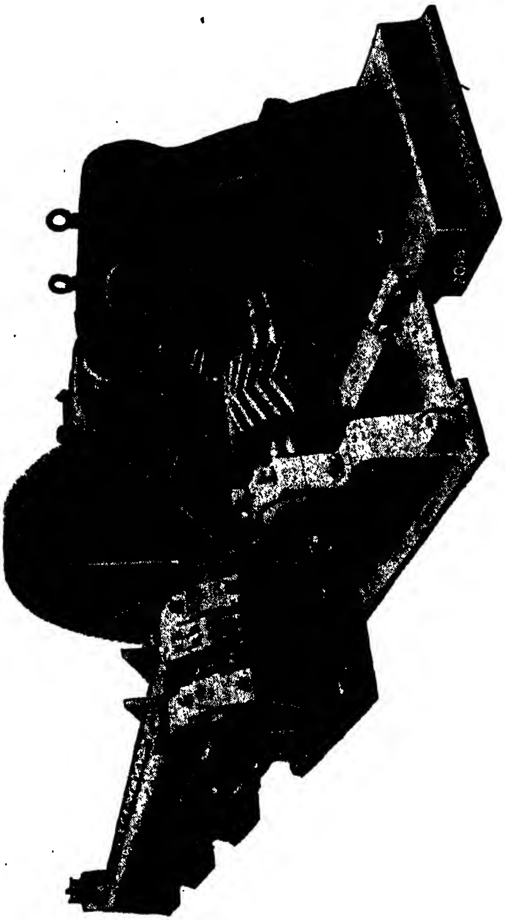

FIG. 53. SINGLE DRAW-BENCH AND 60 H.P. DRIVE
(By courtesy of Fisher Humphries & Co., Ltd., Pershore.)

"pitched" (i.e. spaced out) that they enter the recesses of flat link or pitch chains and either carry the chain along as they revolve or are themselves carried round by it. The sprocket wheel of a bicycle chain is an excellent example.

In cold drawing, this sprocket wheel drives an "endless" chain which runs the full length (30 to 75 feet) of the draw-bench. The other end of this chain passes over another sprocket wheel, which in this instance does not drive but is driven, i.e. it is an "idle sprocket." This idle sprocket is attached to a shaft on which are arranged a number of cams. (Cams are projections on a wheel or axle transmitting variable reciprocal motion to a piece of mechanism.) In this way the power of the drive is transmitted to the pointing head, which comprises wedge-like grips so disposed that the greater the resistance of the dies, the firmer is the grip on the bars.

The pulling part of the mechanism, i.e. the draw-head, is furnished with jaws which clamp on to the protruding bar. This bar is supported on a carriage as it is drawn through the die, and the carriage itself is hooked on to the endless chain, whose forward movement, due to the driving sprocket, provides the power for the pulling operation.

Pointing the Bar

There is another method adopted for the first stage of the process, which consists not in forcing the bar by a pushing mechanism through the hole in the die, but in giving the end of the bar to be drawn a point, so that it can penetrate the die easily, and sufficiently to be gripped by the draw-head carriage jaws. Pointing is carried out in two different ways, one mechanical and the other chemical.

The first is a type of forging by the aid of "swages" (see the chapter on "Forging") in a rotary machine. This reduces the cross-section of the bar by approximately $\frac{1}{16}$ in. over a length of 6 to 8 in. from its extremity. The second is by a process known as "over-pickling," which, as its name implies, is an extension of the pickling process. The bars are placed vertically in little pickling tanks, about 6 to 8 in. only being actually immersed in the hot dilute sulphuric acid which is, however, of much higher concentration (i.e. stronger) than that employed for the ordinary pickling, and is at first about 50 per cent, although this concentration rapidly weakens as the process goes on. The acid eats away about $\frac{1}{8}$ in. of the cross-section; this method is usually adopted when the shape or section of

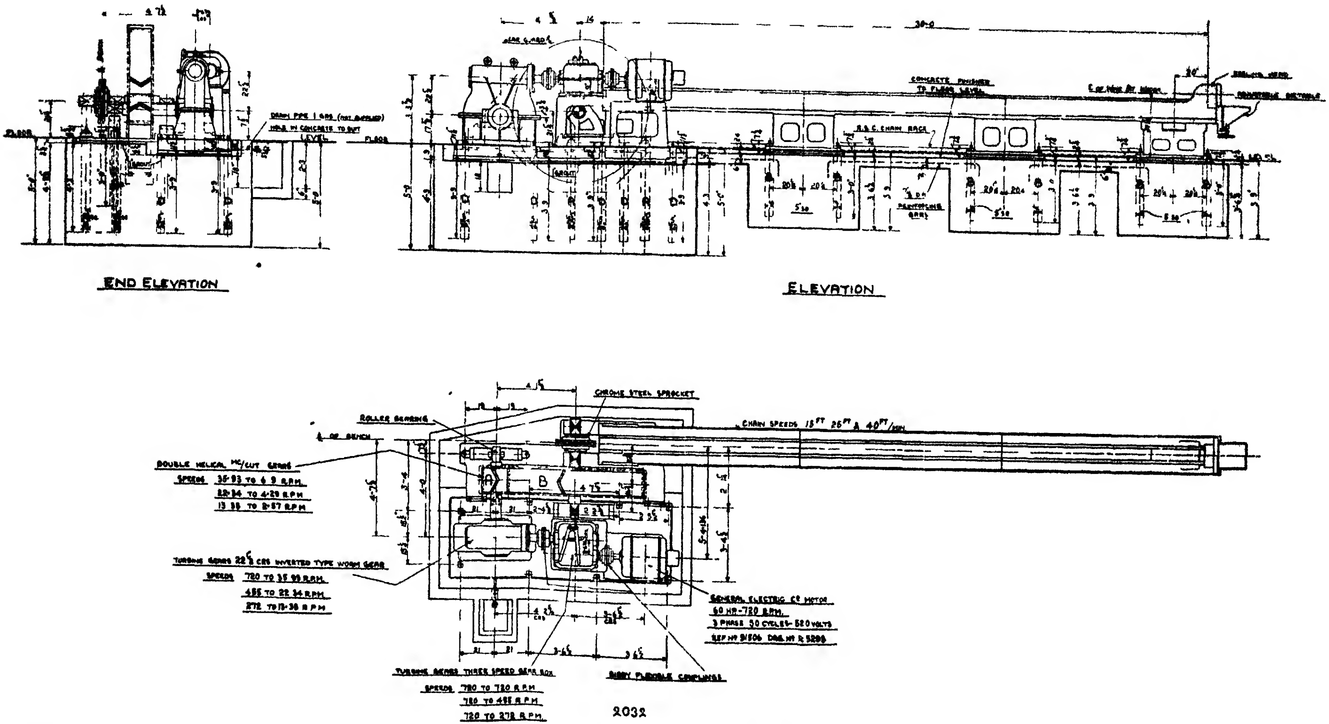

FIG. 54. GENERAL ARRANGEMENT OF SINGLE DRAW-BENCH

the bar is such that it cannot be pointed by forging and cannot be forced through the die by a pointing head.

Lubrication

The next important point is lubrication. This is already partly achieved by the film of lime that has dried upon the bar, but this film alone is insufficient. A box containing some form of grease is usually set before the die, and the bar passes through this on its way to the hole.

An alternative method is to use soluble oil impinging from a jet on the steel as it prepares to enter the die. Other types of lubricating media are also employed. The value of lubrication lies in the improvement of the cold-drawn surface it produces, and the economy it effects in preserving the dies as well as facilitating the drawing.

Speed

How quickly steel is "drawn down" is governed by the kind of machine used, the methods employed, the dimensions and form of the material, the degree of finish required, the kind and composition of the steel, and the extent of reduction or "draught." The speed of drawing varies from 40 to 100 linear feet a minute, taking the average run of material in a typical plant, but if the range is extended to cover special sections and wire, the effective speeds vary between 9 and 600 linear feet per minute. The maximum number of bars that can be drawn simultaneously is four, but this is only possible with suitable machinery, material, and dimensions.

The amount by which the diameter (or width across flats in hexagons) of the bar is reduced during cold drawing is generally $\frac{1}{16}$ in. or $\frac{1}{32}$ in., although heavier or lighter draws are given on occasion.

Straightening

The bars having been drawn, they will now need a further operation to render them fully suitable for use. This is straightening. The cold drawing sets up strains in the material that may cause a certain amount of distortion, varying with the skill and care of the operator. These slight irregularities of alignment have to be removed by mechanical means.

The type of machine used depends on the section. Thus, the larger-diametered round bars are passed between the rolls of a special straightening machine, which has cross rolls functioning in somewhat the same manner as in reeling.* One of these rolls is concave and one plain. The bar is inserted horizontally, and the pressure of the rolls, adjusted beforehand, serves to straighten it as it passes through. The rolls also have a burnishing effect, which gives a slight polish to the bars. All *cold*-finishing processes tend to burnish or polish the surface.

Round bars of smaller dimensions, e.g. for drill rods and wire, are also rolled straight, but in this instance, unless they are required polished, the rolls are a series of upper and lower staggered plain rolls set horizontally.

Square, flat, hexagonal, octagonal, and other difficult sections may be either rolled by the same machine as with the smaller rounds; hand straightened; or dealt with by another type of straightening machine employing a power-driven head situated midway between two blocks, which form two points of resistance on the same principle as bending rolls (which have been dealt with in the chapter on "Bending").

This head is on the opposite side of the bar to be straightened, the bar itself being laid against the blocks. The head is thrust forward or backward by a cam or eccentric, and being pressed against the bar, straightens it according to the relative positions of the blocks and the amount of pressure brought to bear upon the iron. The machine can also be used for bending. (An eccentric is a piece of mechanism designed to convert the rotary motion of a shaft into a reciprocating—backwards and forwards—rectilinear motion.) After this the bars are cut to length, protected against rust by "slushing," i.e. coating with oil, inspected, and ultimately dispatched to their destination.

The table on p. 123 gives some indication of the influence of cold drawing on the mechanical properties of steel.

WIRE-DRAWING

We will now consider the drawing of wire in so far as it differs from the drawing of bars. We have indicated that the raw material, which, for steel wire, consists of a coil obtained

* See *Steel Manufacture Simply Explained.*

EFFECT OF BRIGHT DRAWING ON THE MECHANICAL PROPERTIES OF A FREE-CUTTING STEEL

MECHANICAL PROPERTIES

Chemical Composition		Hot-rolled Bar		Bright-drawn Bar
Carbon .	0·12 per cent	Yield point* .	16·8 tons/sq. in.	26·0 tons/sq. in.
Silicon .	0·005 ,,	Maximum stress*	24·8 ,,	26·8 ,,
Sulphur .	0·234 ,,	Elongation% (2 in.)*	34%	22%
Phosphorus	0·030 ,,	Reduction of area* %	57%	54%
Manganese	0·850 ,,	Izod impact values*	58 ft./lb.	37 ft./lb.

* For an explanation of these terms see *The Structure of Steel.*

by hot rolling from a steel ingot or billet, should be of high quality. The dimensions of the rods for wire-drawing range from 0·212 in. diameter up to 1 in., though still smaller wire rod has been produced by hot rolling. Given the need to produce wire of a certain thickness, the size of rod chosen as raw material is the smallest that will give the desired result. In Great Britain coils are of approximately 10 to 300 lb. in weight, according to the steel used and the class of mill. An average coil diameter is 30 in. for an average coil weight of 120 lb.

The pickling of these coils need not be so stringent as that of rods or bars. In the first place the scale to be eliminated is not so thick and does not cling so firmly. Secondly, the surface of the steel is smoother, so that the acid will not have to bite so deeply to get under the scale. On the other hand, every particle of scale must be removed, which is not quite so important with bars; but this can be achieved without an excessive acid attack. Cold hydrochloric or sulphuric acid is the usual pickling medium, but the best is a solution of ferrous chloride or sulphate and hydrochloric acid or sulphuric acid. The coils must not be tightly bound. Finally, for the highest quality wires, where acid brittleness is to be feared or pitting would weaken the strength of the product, pickling is supplemented by banging machines, which means that the coil is not wholly immersed in the bath, but has its scale partly removed by mechanical rapping or "banging."

The principle of wire-drawing is simple. It is that involved in pulling a shoelace through the hole in a shoe, with the difference that there is a *permanent* reduction of diameter. The wire is the lace, and the hole in the shoe corresponds to the hole in the die through which the wire is pulled. This hole is tapered, i.e. the hole by which the wire enters is of larger diameter than that by which it emerges. In plan, therefore, as Fig. 55 shows, it presents the appearance of a truncated cone, an appearance exaggerated in the diagram to convey the meaning. The extent of the tapering depends on the quality of the material being drawn and on the desired reduction in diameter per operation. In general the semi-angle of the taper ranges from 4 to 12°. The taper is seldom perfect, because a short parallel section occurs at the emerging end in most instances, especially when the steel is hard. This is designed to prevent the powerful pull from breaking the edge of the die at the exit, which breakage is known as "pulling out."

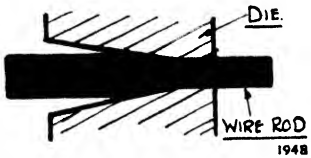

FIG. 55. EXAGGERATED VIEW OF DRAWING DIE

Without at the moment discussing the dies through which the wire is drawn, we will consider first the mechanical differences between bar-drawing and wire-drawing. The principal one is that the wire, instead of being gripped as it emerges and pulled on to a long draw-bench or carriage, is gripped as it comes out of the hole in the die and wound about a revolving barrel or drum.

SINGLE-HOLING

There are two methods of wire-drawing, namely, single-holing and continuous wire-drawing. Single-holing is the method adopted for manufacturing wire of fairly thick section (though even here it is falling out of use), and for producing special types of wire that call for extreme care in their manufacture. Single-holing means that the wire is drawn through only one hole before being wound on to the drum or "block," as it is termed.

To describe the operation in greater detail, the drum or block is mounted on a vertical shaft, driven usually by electric motor direct or through gearing. It measures from 22 to 28 in. in diameter and is given a taper from bottom to top, while there is a shelf or ledge at the bottom to prevent the wire from slipping off the block. After a few revolutions have begun to coil the wire, the tapered form causes the next loops or "turns" to slide upwards, and they rest easily without scraping over one another, which might lead to indentation or excoriation of the surface of the underlying turns. The taper also facilitates withdrawal of the coil from the block at the end of the drawing process.

The wire to be drawn is, like the bars for cold drawing, pointed to enable a small portion to be fed into the hole in the die and project beyond it. This pointing is carried out by filing, heating the end of the wire to soften it and then tugging it through, or by means of small mechanically-operated pointing rolls.

The die or "draw-plate" possesses about eighteen holes, any one of which can be used according to the reduction desired, and is firmly secured to the draw-bench. As the pointed wire emerges from the hole in the die through which it has been passed, it is gripped by tongs fastened either to a chain or to a wire rope operated by a capstan designed to pull the wire rapidly through. Before the main drawing operation is performed, a preliminary short pull is given, so as to produce a sample piece of wire for examination with gauges to verify its shape and dimensions. When passed, the wire is freed from the tongs and fastened to a small vice on the upper edge of the revolving drum or "block"; the drum is set in motion; and the operation completed. Methods may vary slightly with the type of mechanism used or the kind and dimensions of wire being drawn, but in the main this description holds good.

Continuous Wire-drawing

In wire-drawing by the continuous process, the wire is not drawn through a single hole and wound, then drawn again and rewound, if more than one pass is necessary. All the successive die-holes are passed through before the wire is fully wound on to the drum. Since with each passage the wire becomes thinner, it also becomes longer, and this extra length has to be dealt with. One could not leave it lying about, so to speak, or it would become inextricably entangled, clog the machines, and generally become a nuisance.

The difficulty is overcome by different methods according to the type of machine used, but the most effective, which has removed some of the drawbacks of former machines, appears to be to interpose separate blocks between each die on which the wire is coiled before passing on. Each block is revolved at a faster rate than its predecessors, as in continuous rolling, and a surplus of wire is allowed to collect on each in order to prevent slipping, which would scrape and injure the surface of the wire.

Though single-holing is still employed and has its uses and advantages, the modern tendency is increasingly towards continuous drawing, which, although it involves more time in threading up the machines, gives greater speed and output and requires much less labour.

Drawing Dies

To discuss in detail the manufacture of and materials for wire dies would require far more space than can be given here. Nevertheless, since the die or draw-plate (another trade term used is "wortle-plate") is, after all, the key to successful wire drawing, it would be wrong to omit all mention of it from this chapter.

There are two schools of thought in regard to die preparation. The one considers it the duty of the skilled operator both to prepare his own dies and to use them; the other regards the work of wire-die preparation as a skilled job to be done by trained die-makers doing nothing else, the actual drawing being done by a less skilled or differently-skilled type of worker.

The former is the more usual British practice; the latter, as might be expected, is American. The authors do not venture an opinion as to the better method, though a coldly rational analysis of the problem would suggest that on the whole the American practice is likely to be more efficient, since the skilled die-maker is kept at his specialized job, the skilled wire-drawer at his, and neither wastes time.

Die Materials

For the dies themselves, chilled cast iron, *forged* carbon tool steel, chromium steel, tungsten steel, and molybdenum steel all have their advocates. Chilled cast iron is mainly designed for producing the lower qualities and thicker sections. Carbon steel (1·6 per cent C. or over) is more favoured in this country and on the Continent because of its ability to be forged, and because, being malleable, it can be hammered in such a way as to close up any holes enlarged by use to less than their original size—a highly skilled manual operation known as "battering"—and then by use of a reamer (a hole-enlarging tool not unlike a drill) restoring them to their proper dimensions.

The alloy steels, owing to their greater heat- and abrasion-resistance and hardness, are superior to the chilled cast-iron and carbon steel dies, but as they are higher in first cost, their use will be largely governed by the type of wire and similar economic considerations.

Tungsten Carbide Dies

The most important development of recent years has been the introduction of tungsten carbide for wire-drawing dies. This material is of almost diamond-like hardness, and in certain aspects is ideal for the purpose. It is usually supplied in the form of a rough pierced cylindrical pellet, which is then enclosed in a metal casing or housing. The hole roughly pierced through this pellet is then opened out and finish-ground to size.

The disadvantages of tungsten carbide dies are few—

(*a*) Higher first cost.

(*b*) The holes cannot be hammered up and reamered back to their original size when worn, but must be opened out to the next size larger.

(*c*) A tendency to flake, i.e. for portions to chip off, due either to careless use or to fluctuations in wire-temperature setting up internal stresses.

As against this, their advantages are—

(*a*) Lower consumption of power (in the region of 30 per cent), due to less friction.

(*b*) Longer life between resettings.

(*c*) Better surface finish given to the wire.

The standard carbide pellets range from 9 mm. dia. and 6 mm. in length to 32 mm. dia. and 30 mm. long. Fig. 56 shows how the pellets are mounted and Fig. 57 shows a rough pierced pellet.

While the use of these dies is not yet world-wide, the probability is that they will be increasingly employed, except,

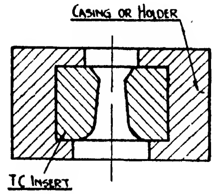

FIG. 56. SKETCH SHOWING HOW PELLETS ARE MOUNTED

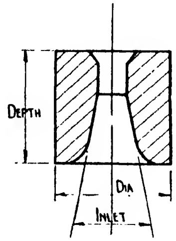

FIG. 57. ROUGH PIERCED PELLET

perhaps, for the more drastic reductions, such as those involved in bringing the rods for wire-drawing down to the first wire size.

The essential requirements of a die are smoothness of surface, accuracy of form, wear resistance, hardness, and correct

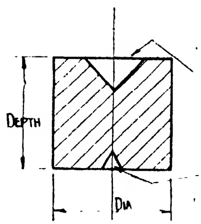

FIG. 58. ROUGH CENTRED PELLET WITH INLET AND OUTLET CONE

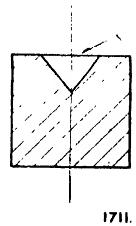

FIG. 59. ROUGH CENTRED PELLET WITH INLET CONE ONLY

design. This last factor is mainly a question of the angle of the taper, which must be suited to the size of wire and kind of steel. While this angle will not make a great difference to the quality of the material, it will considerably affect the consumption of power and the period of service obtained from the draw-plate. A steep angle gives a greater reduction, but

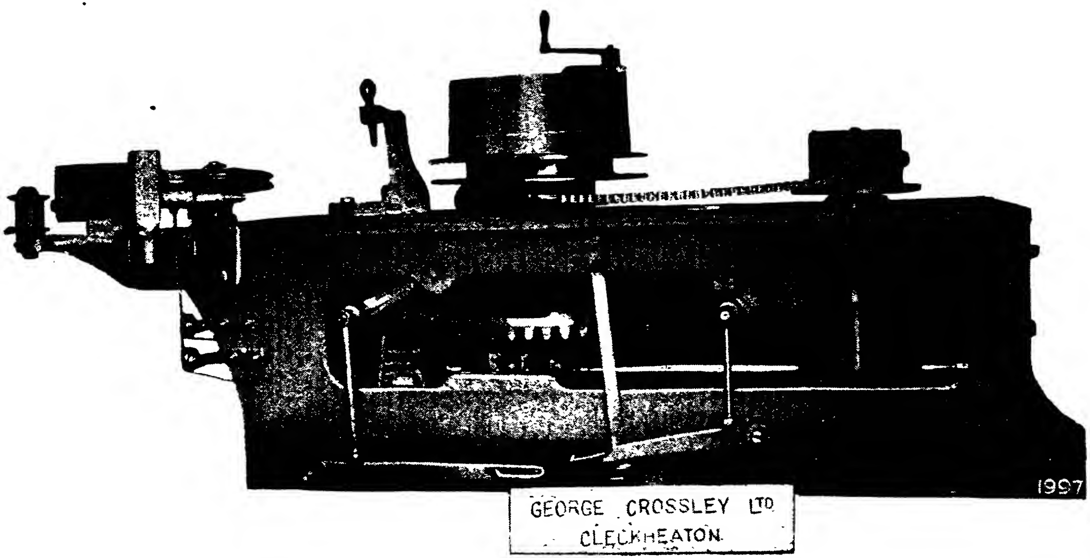

FIG. 60. CONTINUOUS WIRE-DRAWING BLOCK, 22 IN. DIA.
(Photo by courtesy of Messrs. George Crossley, Ltd., Cleckheaton.)

increases the risk of die-breakage ("pulling out") due to the severe pull necessary, a risk varying, of course, with the hardness of the steel being drawn.

It should also be mentioned that "diamond" dies are sometimes employed for the drawing of very fine wire (i.e. wire of very small diameter).

Fig. 60 shows a continuous wire-drawing block, 22 in. dia., arranged for single- or two-hole drawing high carbon or mild steel wire No. 5 S.W.G. (Standard Wire Gauge) down to 16 S.W.G. It is built with heavy cast-iron frames, and one complete machine has an approximate weight of 56 cwt. The horse-power required to drive the block is 25. The block and capstan pull-in gear are built so that they can be started or stopped independently of each other, the capstan gear being placed in a position such that the wire can be pulled through the die a good length before being well wrapped round the block, and the end fastened in the vice before starting up the machine. The speed of the block is usually arranged according to the size and class of wire being drawn.

Fig. 61 shows a wire-galvanizing frame arranged for pulling any gauge and number of wires up to twelve from the swifts or stands through a complete wire galvanizing plant. The winding frame is supplied with twelve blocks, 22 in. dia. (six down each side), and is of cast iron. These winding frames can be built to suit any number of blocks on each side, and are usually designed so that any fixed speed can be obtained by moving a small hand wheel on the variable speed gear, and clutch handle. All the blocks have a speed of 1 r.p.m. with any variation up to 23 r.p.m. The complete bench requires 5 h.p., and measures 24 ft. 2 in. long by 9 ft. wide.

Fig. 62 shows a wire-patenting frame arranged for pulling any gauge and number of wires up to sixteen from the swifts or stands through a complete wire-patenting furnace. The winding frame has sixteen blocks 24 in. dia. (eight down each side), and is of cast iron. It is built to suit any number of blocks on each side, and is usually designed so that any fixed speed for all the blocks can be obtained by moving a small hand wheel on the variable speed gear, and clutch handle. All the blocks have a speed of $\frac{1}{8}$ r.p.m. with any variation up to 4 r.p.m., or suitable speeds

FIG. 61. LARGE WIRE-GALVANIZING BLOCKS
(*Photo by courtesy of Messrs. George Crossley, Ltd., Cleckheaton.*)

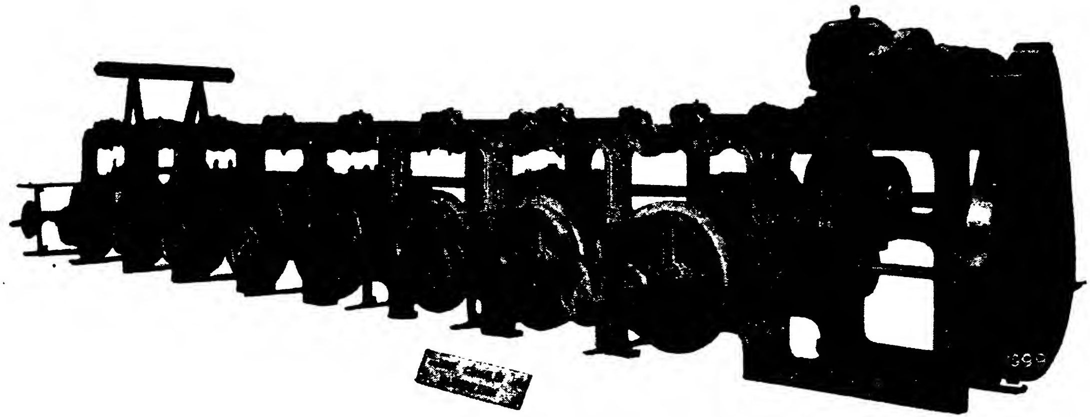

Fig. 62. Large Wire-patenting Blocks

(Photo by courtesy of Messrs. George Crossley, Ltd., Cleckheaton.)

by arrangement. 5 h.p. are required by the complete bench, which measures 28 ft. long by 6 ft. 8 in. wide.

Fig. 63 shows an extra-strong thick wire-drawing block, 22 in. dia., arranged for single-hole drawing mild steel wire ⅝ in. dia. or high-carbon steel wire ½ in. dia. down to smaller diameters or section wires. It is built with heavy cast-iron frames, and has an approximate weight complete of 3 tons 15 cwt. The block and capstan are built so that they can be started or stopped independently of each other, and the wire can be pulled straight through the die a good length, so that it can be well wrapped round the block and fastened in the vice before the machine is started up. The blocks are usually arranged to revolve at different speeds according to the size and class of material being drawn.

Fig. 64 shows a (heavy duty) single-hole machine. This machine is primarily intended for reducing hard steel and alloy rods from ½ in. dia. or equal sectional areas. It is a slow or medium unit for the reduction of high-grade steels that have to be drawn to specification. The machine is provided with double reduction gears, drawing block of 24 in. or 22 in. dia., and independent power pull-in equipment for threading the first length of wire through the die.

The main driving shaft is extended at the inlet end and fitted with a powerful friction clutch, the pan of which is grooved for "V" belt drive to the motor. The die-holder is water-cooled for use with round synthetic dies or, alternatively, a plate holder is supplied for drawing sections. The machine constitutes a robust unit for hard service.

Fig. 65 shows a non-slip wire-drawing machine of circular type, expressly designed for drawing medium and small gauges of iron and steel wire by the non-slip method. Instead of the drawing blocks being disposed in a straight line, the main framework of the machine is constructed in the form of a circular box.

The top section of this box accommodates the blocks, which follow each other to make an approximate circle. This form of construction occupies less floor space than the straight type of machine. There are two sizes of these machines. The larger takes a maximum inlet wire of approximately 0·1 in. dia.—

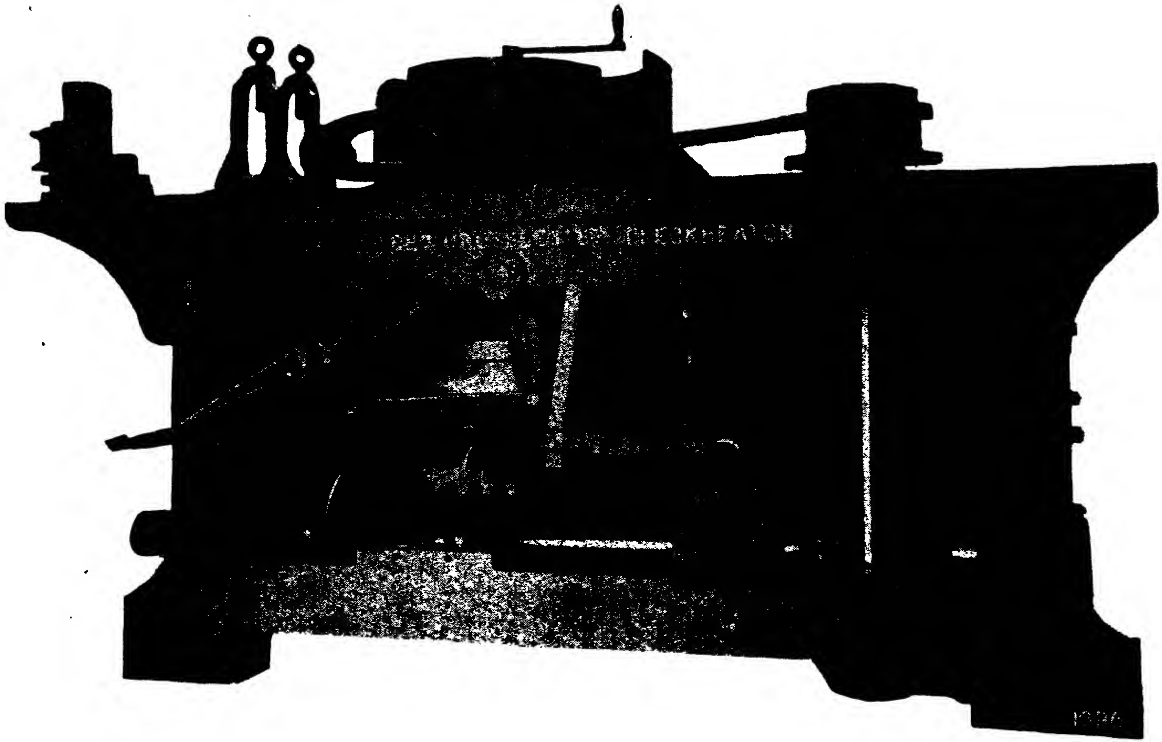

Fig. 63. Extra-strong Thick Wire-drawing Block
(Photo by courtesy of Messrs. George Crossley, Ltd., Cleckheaton.)

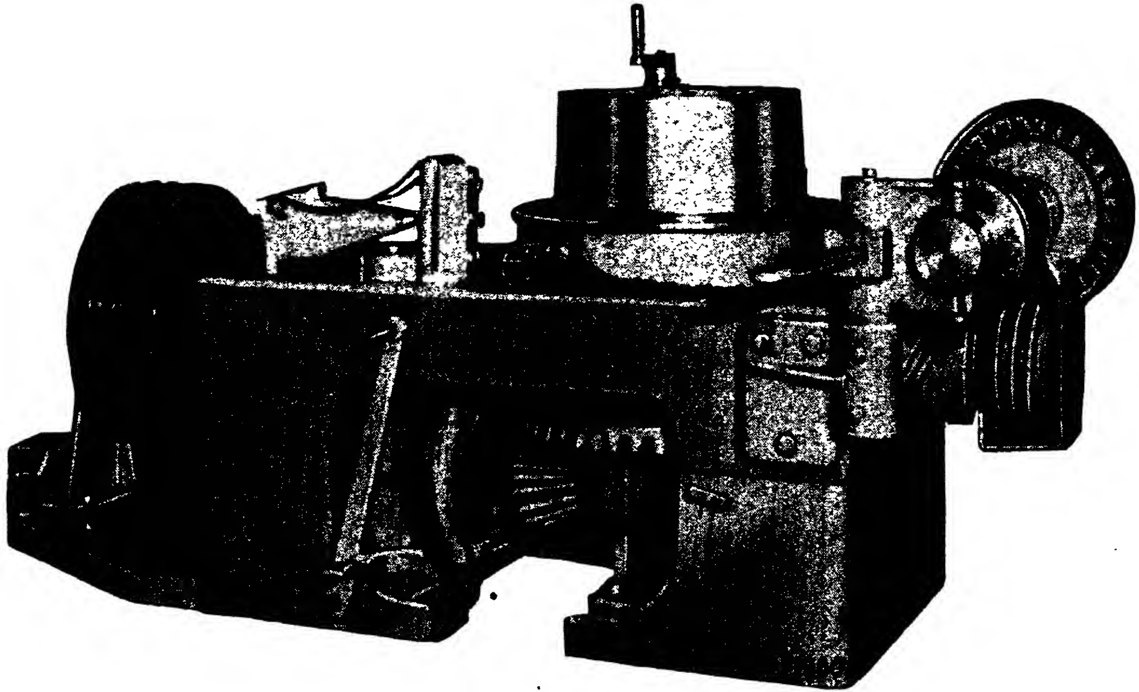

FIG. 64. BARCRO (HEAVY DUTY) SINGLE-HOLE MACHINE

(Photo by courtesy of Messrs. Barron & Crowther, Ltd., Preston.)

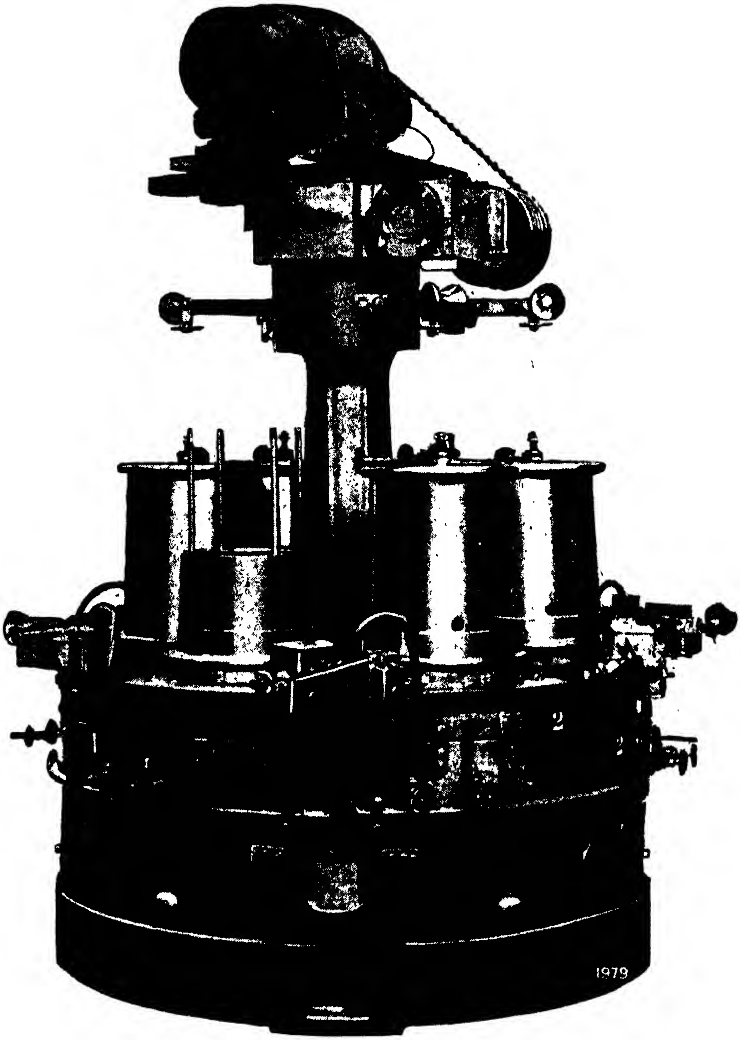

FIG. 65. NON-SLIP WIRE-DRAWING MACHINE OF CIRCULAR TYPE
(By courtesy of Messrs. Barron & Crowther, Ltd., Preston.)

12·5–13·0 S.W.G.—and may be fitted with 12 in. or 10 in. dia. blocks. The smaller takes a maximum inlet wire of 0·06 in. dia.—16–17 S.W.G.—with 8 in. dia. blocks. The drawing blocks in the heavier machine have provision for water-cooling, but as the smaller machines do not deal with the finer gauges of wire, these are not provided with water-cooling chambers.

Reduction Problems

In drawing wire it has to be borne in mind that the problem is not simply one of reduction to size. What is of equal importance is the physical condition of the wire when drawn. Only the practical expert needs to consider the various systems of draughting designed to manufacture wire of specified size and form with or without a given toughness and strength. The authors do not propose to discuss these in detail. All that is necessary is to point out that the amount of reduction per pass can be heavy, light, or medium, according to the type of plant and the methods employed. Only steels of highly ductile character can be heavily reduced at a single pass, while the hardest materials have to be given, perhaps, only one light pass at a time, after each of which they have to be softened by annealing. This is because the friction of the drawing process induces "work-hardening" (a hardness effect explained in *The Structure of Steel*). A point to be remembered, also, is that gradual reduction is not always productive of a more satisfactory wire, for reasons not always fully clear to metallurgists, nor is it merely a matter of reducing the draught as the wire hardens. The operator has to control the drawing so that the structure of the wire is satisfactory at every pass, a highly complex problem governed as yet by no formal rules, and one into which research continues. Generally, it may be stated that the first pass is the most critical so that the first draughting or reduction is usually less than occurs in later passes.

Lubrication

As in drawing steel rods, lubrication is necessary in drawing wire, to reduce friction and so minimize power consumption, and to eliminate fracture of the wire caused by its sticking or "binding" in the die-hole. The steel rods or coils are first given a film of iron hydroxide (or else of some soft metal, e.g. copper, or even tin), which is applied after or during the pickling; this, together with the lime coating left on after the pickling operation, serves as a first lubricant. Dry soap is the lubricant proper then used, the wire passing through specially shaped bags containing this before it enters the die. This is known as dry lubrication. Wet lubrication, though little used to-day, has an increasing number of advocates. It comprises the employment of liquid lubricants heated up to improve their lubricating power. Wet lubrication is claimed to give a better surface finish and consequent fatigue resistance, and, by lowering the frictional heat of the wire, toughens it to some extent.

In the wet lubricating process, the wire, after acid cleaning, is immersed in a dilute solution of copper or tin sulphate, or a mixture of both, depending on the colour desired. The coils are then removed and placed in a vat of fermented liquor made from rye meal and yeast with water, from which they are drawn wet, with the liquor serving as a lubricant. The metallic coating of copper or copper and tin requires no other lubricant than this liquor; but the percentage of reduction per draught must be less than with dry drawing.

Effects of Cold Drawing

It now remains to examine the effects of cold drawing, taking bars and wire successively. On bars, the operation produces a smooth, bright surface finish with no scale. Round bars, owing to the burnishing effect of the straightening rolls, are usually brighter than other sections. The advantage of this finish is that when the steel is machined, the absence of hard scaly patches reduces the wear on the edges of cutting tools, as well as keeping the coolants used from receiving particles of detached scale that might ultimately damage lathe or other machine-tool parts. Cold-drawn bars are largely employed for shafts and machined parts, especially when the completed product preserves either the whole or some part of the original bar surface. Thus, enormous quantities of bright-drawn bars are used for nuts and bolts, and for parts to be case-hardened. Another advantage obtained from bright drawing is that the machinability of the steel is much improved. This may appear strange, in view of the fact that the steel's hardness is increased, but it is nevertheless true, and applies particularly to the high-sulphur free-cutting steels now made in such large quantities and used for purposes undreamed-of not many years ago.

Cold drawing produces bars much closer to the required dimensions than will hot rolling, but the most striking feature is the remarkable alteration in physical properties that takes place in the steel after the operation. Summarized, this comprises a rise in tensile strength and yield point, the latter increase predominating; an increase in hardness and resistance to fatigue; and a diminution in elongation, reduction of area, and Izod impact values.

Some idea of these changes for cold-drawn bars was given in the table on p. 123, and they are further illustrated by the following data (extracted from Gregory's *Metallurgy*) relating to a steel wire containing 0·16 per cent carbon and 0·68 per cent manganese.

Condition	Yield Point	Tensile Strength	Elongation (2 in.)	Reduction of Area	Izod Impact
	tons/sq. in.	tons/sq. in.	per cent	per cent	ft./lb.
Hot-rolled . . .	20·0	28·6	38·0	70·0	96
Cold-drawn 13·5% reduction in section .	29·0	34·6	24·5	60·2	50
Cold-drawn 24·5% reduction . . .	38·1	40·6	13·6	54·8	35

The outstanding feature is the increase in the yield point, and in some instances this may be little lower than the tensile strength.

It must be pointed out that these changes are not mere surface effects due, perhaps, to friction, but affect the entire section of the steel. Nor is the surface of the bar "scraped off" by cold drawing, as has been supposed by the non-metallurgical mind. Another interesting point is that, unlike forging, cold-drawing bars does not materially alter the "fibre" or grain-elongation. Wire-drawing on the other hand does considerably affect the grain-structure.

Plastic Flow of Wire

In considering the effect of cold drawing on wire, we must hark back to the subject of plastic flow, dealt with in earlier chapters on other methods of mechanically working steel. When wire is being drawn, this plastic flow, its form and character are of maximum significance.

Uniformity of flow throughout the section is the great essential, and it must not be forgotten that the type of flow experienced in wire-drawing differs considerably from that experienced when steel is given a straight simple pull, as in the tensile testing machine (described in *The Structure of Steel*), or *forced*, i.e. *pushed* through a die, as in extrusion, which was dealt with in Chapter X. In wire-drawing two forces are at work: one is the straight pull of the revolving drum or "block"; the other, the enclosing pressure of the die. Whereas in a straight pull the central portion flows faster than the circumferential, so that the interior grains are more elongated than the exterior, in wire-drawing the die pressure balances the straight pull, the one tending to elongate the outer crystals, the other elongating the inner crystals. In this way a desirably uniform flow is obtained. As the wire to be drawn increases in thickness, however, the die pressure predominates over the direct pull, so that ultimately, with the thicker sections, the greater flow takes place at the circumference, the smaller at the core, which is the exact opposite of what happens with a direct tensile pull.

Cold drawing of wire produces a tougher and more resilient metal, which offers progressively greater resistance to additional plastic flow, and is therefore harder than the original material. This hardness varies in accordance with the extent of the drawing and the ultimate strength. The tensile strength of wire is greatly improved, and 0·85 per cent carbon steel wires have been made with strengths of up to 250 tons per sq. in. The ultimate tensile strength depends on the percentage of carbon in the steel, the size of the wire, and the amount of cold drawing done. (It must be borne in mind, however, that there is a limit to the amount of cold work that steel or other metals will stand, and it does not follow that to go on drawing a wire indefinitely will necessarily increase its tenacity or toughness.) There is a point at which the material becomes "overdrawn" and consequently brittle, due to a structural break-down caused by the repeated workings. It is as if the wire became "tired." The exact point of overdrawing is not easy to determine and must be left to the discretion of the practical drawer.

Ductility is reduced in wire by cold drawing and the percentage of elongation is lowered. Such other effects as the operation has on steel wire are so complex and so variable with the size, type, method of manufacture and testing, and extent of reduction, of the wire, as to be incapable of brief summarization here. Their interest is primarily for the specialized user and need not concern us. Nor shall we deal with the different ways in which wire is prepared for the market, e.g. tinning, galvanizing, etc., all of which lie outside the scope of this work. Instead, we will pass on to the cold drawing of seamless tubes. In this connection the reader should refer also to the chapter on "Extrusion."

Cold Tube-Drawing

The principle of drawing tubes is the same as for bars and wires; namely, the end of the rough tube is pointed, passed through the hole of a die, and pulled through a series of these dies or holes until the right amount of reduction is secured. There is one important difference. Where there is a possibility that the walls of the tube might not be strong enough to stand up to the operation, or it is essential that the internal diameter shall be accurate to a given dimension, a cylindrical rod or mandrel is inserted to support the tube walls and preserve the form of the tube.

Pointing the Tubes

The rough tubing to be drawn is produced by a hot process in a tube mill, and is termed a "billet," the size of which is dependent, of course, on the dimensions of the finished tubing required. This billet is cut up into suitable short lengths. It is then pointed with the aid of the forging hammer or press, or by swages between revolving hammer dies, for the billets of smaller dimensions. This pointing may have to be repeated if the first point proves too large to be passed through the smaller die orifices as the reduction proceeds. As with wire, the diminutions of cross-section lead to an increase of length. This cannot be dealt with, except in tubes of very small dimensions, by wrapping the tubing about a "block" or drum, so that when the length threatens to become unmanageable the tube has to be severed. The cut ends are then given a point, so that they can be passed through the succeeding dies. A common practice is to punch a hole towards the pointed end while pointing is being carried out. One purpose of this is to enable the pickling solution to enter the interior more easily, and also at a following stage the drawing lubricant.

Tube Pickling and Lubrication

As suggested above, a pickling operation is necessary here also. Dilute 5 per cent sulphuric or hydrochloric acid is employed. Scale has to be removed from both the internal and the external tube surfaces, as otherwise much injury may be done to dies, mandrels, and finished tubing. The pickled material is well washed, then dried or "baked" by being heated up for a period in a suitable furnace. This drying process also serves to prevent and even eliminate any structural brittleness caused by the hydrogen liberated in the pickling.

Lubrication is achieved either by steeping the billet in a suitable mixture (e.g. palm oil and tallow), or by power-pumped oil in advance of drawing. (Metal coatings, e.g. tin, copper, and lead, are sometimes used, but are expensive both to apply and remove.)

The billet is now ready to be drawn, and three methods are extant: (*a*) drawing with no mandrel inserted in the billet; (*b*) drawing with a short fixed mandrel; (*c*) drawing with a long moving mandrel. In detail, these three are explained as under.

Drawing without Mandrel

Technically known as "sinking," this method is employed when it is not essential that the internal diameter shall be dead accurate, or where a smooth surface finish internally is unnecessary. It can be used, also, for tubing with walls of great thickness as compared with the diameter. Internal lubrication is not employed and the amount of reduction at each passage through the die is from 20–35 per cent.

Drawing with Fixed Mandrel

In this method the plug or mandrel, which is short in length and made from a special steel, is affixed to a longer rod or thin bar in such a way that its "business end" is on a level with the die. The other end of the rod is secured to the rear end of the drawing machine or bench, and its length can be adjusted if required. The rod allows the mandrel to be drawn backwards and to one side, which allows the tube billet to be "threaded" over it. It is then drawn as with bars.

This method gives accuracy of internal diameter and wall thickness, but has the disadvantage that there is inevitably severe friction between tube walls, die, and mandrel, and it is the extent of this that determines how much reduction can be effected at each pass. It is only suitable for tubes above ¼ in. dia., as below this the mandrel cannot easily be fastened to the rod, while the frictional resistance becomes disproportionately high owing to the larger surface area of the tube wall as compared to the sectional area of the rod, which latter area governs the ability of the steel to resist the mechanical pull. The mandrel does not go through the die.

A normal range of reduction per pass by this method is 30–40 per cent.

Drawing with Moving Mandrel

In this method the mandrel is its own rod, so to speak, since it comprises a long hardened alloy steel rod or a wire of cold-drawn type, often pianoforte wire quality. This rod is, however, not fastened to the draw-bench at one end, but is placed within the tube and goes through the die with it as if both were one. This means there is considerably less frictional resistance than with the second method. On the other hand, after the tube is drawn, the mandrel has to be taken out of the tube by one or other of various mechanical methods, which involves the expense of additional plant. These methods are based on the principle that if the *tube* is made a trifle larger in diameter, the mandrel can readily be withdrawn from it. They comprise reverse rolling through grooved rolls, spiral rolling through straightening rolls, moving through revolving swaging dies, and other similar operations.

In addition to less friction, the moving mandrel method reduces wear on the surface of the mandrel, which can therefore be made from a less resistant and expensive material. Reduced friction means less heating up locally caused by friction. There is also a lubricating effect due to the fact that as the portion of the mandrel which passes through the die moves at a higher speed than that which has still to pass through, the internal walls of the tube as they pass through the die encounter a continually new surface.

This method is chiefly employed for tubes below ¼ in. dia. and for medium sizes above this where the thinness of the tube walls would lead to injury by friction if a fixed mandrel were used. The method is not employed for tubes of large diameter, because of the heaviness of the mandrels necessary, the difficulty of handling them, and furthermore, the difficulty of obtaining them with adequate hardness and straightness.

At this point we may mention the method of producing "hollow" drill steel. The drills made from this material, used mainly for drilling rock in the diamond mines of South Africa, must contain a hollow cylindrical cavity so that the actual drilling edges of the tool may be kept cool by passing cold water through them. For this purpose, the modern method is to insert an "austenitic" manganese steel* rod into the core of a pierced billet. During later re-rolling the dimensions of *both* the billet and the manganese steel insert are reduced. Finally, the circular manganese steel rod is withdrawn, leaving a hollow tube, as it were, of the steel intended for drills. The relative ease with which the manganese steel core can be withdrawn from the drill steel itself is due essentially to their differences in expansibility. This difference results in a contraction between the manganese steel rod and the inner walls of the drill steel and thus facilitates withdrawal.

* This steel contains about 1 per cent of carbon and 13–14 per cent of manganese.

Mechanism and Speed

The draw-bench mechanism for tube-drawing is on the same principle as that for drawing rods and bars, except that the carriage of the bench is from 40 to 60 ft. in length, while a hydraulically operated piston is sometimes used in place of an endless chain with a drawhead because of its greater speed, readier adaptation to automatic working, and minimization of noise. The actual rate of drawing depends on the dimensions of the tube, and on the quality of the steel, as well as on the lubricating medium used. From 10 to 60 ft. a minute represents the range in normal practice.

Die Materials

Tube-drawing dies call for extreme skill and long experience in their design, because the right proportions between tube diameter and thickness of wall are not attained by chance. The materials used to-day are chiefly tungsten steels (containing about 3·5 per cent tungsten); nitrided tool steels (i.e. tool steels containing high proportions of both chromium and aluminium which have been given a special surface—or "case-hardening" treatment—by a process known as "nitriding," comprising heating them at a temperature of about 500° C. in an atmosphere of heated ammonia gas); and tungsten carbide dies. The intricate and largely individual subject of die design is outside the scope of this work and must be studied elsewhere.

CHAPTER XII

Thread Rolling

THREAD rolling is a relatively recent process. It is essentially a method of producing the threads on such objects as screws, bolts, screw caps and the like, by rolling under pressure. The older method was to machine them out of the bar or piece with taps, or with stocks and dies, which are tools provided with special cutting teeth for this purpose, the latter being held in a "stock" or box provided with lever handles. In ordinary screw cutting the tap, die, or chaser is held in the lathe slide rest and caused to travel in a lengthwise direction to an exact and measured distance for each revolution of the lathe, the "traverse" or travel being effected by means of a guide screw and change wheels. A chaser is a comb-like steel tool whose cutting edge is the counterpart of a screw section. It may be "internal" for cutting inside threads or "external" for outside threads. The guide screw referred to is the "leading" screw which runs longitudinally in front of the bed of a self-acting lathe, its pitch, i.e. the spacing between the tips or bottoms of its threads, being the first factor in cutting screws. The change wheels are gear wheels of "fine" (i.e. narrow) pitch whose function is the transmission of motion from the mandrel or shaft of a lathe head to the guide screw, for the cutting of screws of various pitches. The wheels are interchangeable, both on the mandrel, the guide screw, and the intermediate stud; hence their name.

It will thus be seen that screw cutting is a machining operation, and, strictly as such, does not come within the scope of this work. Thread rolling, however, is a mechanical working process in which the requisite threads are pressed or rolled into the metal by a roller or roll. The parts to be threaded by this method are caused to revolve, then compelled to make contact with the rollers, to which the required pitch and form of screw threads have previously been given. Certain benefits are derived from this process. For example, since no metal has to be machined off or gouged out, so to speak, to form the threads, there is a considerable saving in material when compared with "headed" bolts, which are machined from the solid. Furthermore, the pressure brings about a degree of cold working of the metallic surface of the parts, and so improves their mechanical properties.

For bolts subjected to fairly heavy stresses, a relatively low

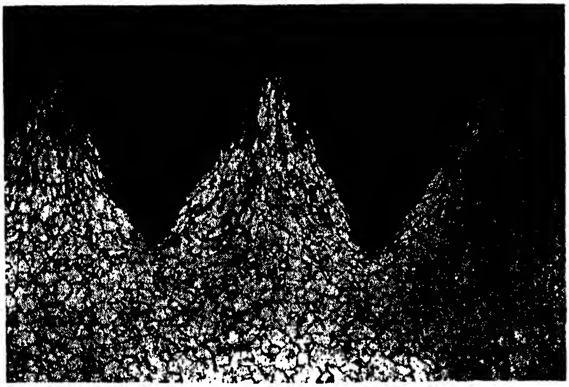

FIG. 66. ROLLED THREAD IN LOW SULPHUR, LOW PHOSPHORUS STEEL, FREE FROM MARKED DIRECTIONALITY. × 50

sulphur and low phosphorus steel is generally employed. The bars are moderately cold-drawn, the head formed by upsetting, and the thread rolled on to the original diameter. Machined bolts, on the other hand, are frequently made from a high-sulphur free-cutting steel, cold-drawn to 30 to 40 tons tensile strength. The tensile strength of the core of the headed and thread-rolled bolt is, therefore, often less than that of the machined bolt, although the thread itself is actually cold-worked to a tensile strength of a similar order to that of cold-drawn free-cutting steel rod. The advantages claimed from threading, using the lower sulphur steel, are (1) superior toughness, (2) the relative absence of non-metallic streaks, such as manganese sulphide, parallel to the imposed stresses, which tend to facilitate stripping of the thread, and (3) that what original directional grain-flow, segregation and non-metallic matter exist are converted by thread rolling into such configurations that the tendency to stripping is enormously resisted. The latter advantage is not only obtained over machined free-cutting steels, but also over machined bars of ordinary sulphur contents, always assuming, of course, that the steels possess similar "core" strengths. The reason for this is apparent from the photo-micrographs shown in Figs. 66 and

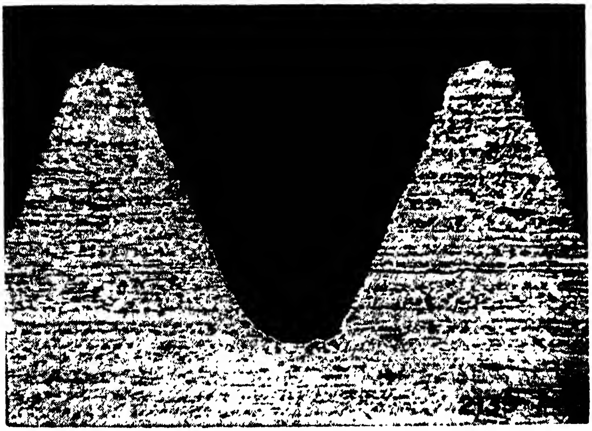

FIG. 67. MACHINED THREAD IN A FREE-CUTTING STEEL. × 50

67. In Fig. 67 it will be seen that the grain-flow is at right angles to the teeth of the screw; and the laminated structure, so typical of mild and medium carbon steels rolled under most commercial conditions, constitutes a potential source of weakness in regard to stripping. Fig. 66 shows, on the other hand, that by thread rolling, the grain or crystal flow follows the contour of the threads. Such a disposition of the grain offers the maximum resistance to stripping, since it is generally recognized that steel, like wood, is stronger across the grain than with it.

It should be mentioned that there is nothing to prevent free-cutting steels from being subjected to thread rolling, but it must be borne in mind that the facility with which such steels can be machined at high peripheral speeds is their outstanding and most useful characteristic.

When screwed parts are to be produced from thin sheet metal, such as in the production of screw-cap electric lamp sockets, screw cutting is often impossible and thread rolling is the only way of producing the threaded part. Again, some of the softer metals used for such parts, e.g. aluminium and "alpha" brass (yellow brass with 70 per cent copper, 30 per cent zinc), are very difficult to screw-cut with a smooth finish

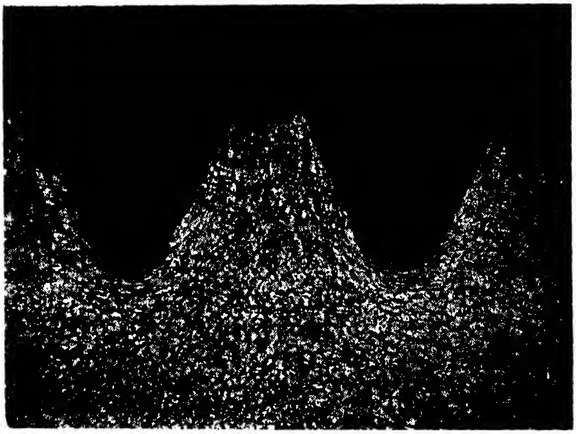

FIG. 68. ROLLED THREAD IN LOW SULPHUR, LOW PHOSPHORUS STEEL, HAVING DEFECTIVE SHAPE. × 50

under almost any conditions; hence another advantage of thread rolling.

Thread rolling can be done in lathes, automatic screw machines, or in special machines for the purpose. Lathes are only used for special threads, e.g. in very long parts that cannot be made on a special machine or would cost too much to make in that way. Automatic screw-cutting machines are frequently used for thread rolling. Special machines are usually employed when particular types of threads have to be rolled on. For example, bolts and screws are threaded in a special machine by means of two suitable dies, one stationary, the other movable, and moving in a plane parallel to the axis of the work. About 30 to 100 parts a minute can be threaded in these machines.

In thread rolling, it is important to see that the blank to be threaded is of correct diameter, though there are no specific formulae by which this can be determined in advance. In general it can be laid down that too small a blank gives a badly developed thread of insufficient size, whereas too large a blank gives an oversize thread which is often rough.

Incorrect machine setting, perhaps aggravated by incorrect size of wire, produces defective rolled threads, which cannot

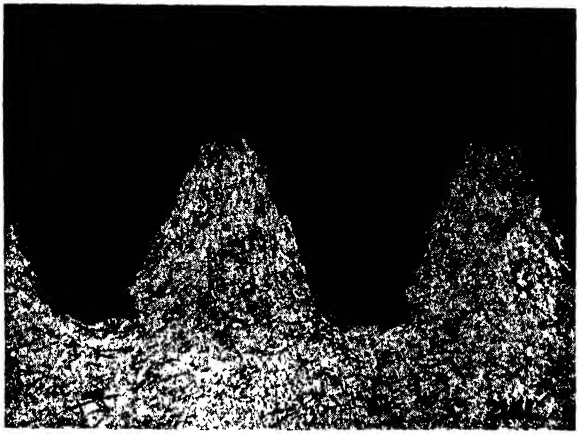

FIG. 69. ROLLED THREAD IN LOW SULPHUR, LOW PHOSPHORUS STEEL, HAVING DEFECTIVE SHAPE AT ROOT. × 50

always be detected by mere visual inspection or examination. Examples of these defects are shown in Figs. 68 and 69, where the etched sections have been magnified 50 times.

The types of thread produced by this method are not standardized to any one system, and numbers of different systems are employed. As a rule, in making threads on lamp sockets, caps, tubes, etc., the shell diameter is greater than the pitch diameter. The shaft or arbor size approximates very nearly to that of the blank, which means that the shell can just fit on to the arbor. The roller size is ascertained by deducting the single depth of thread from the pitch diameter and multiplying by a factor (sometimes as high as 12, but more often about 4). The arbor and roller are mated by means of gears, and the roller will have either one, two, three, or four threads, according to the factor employed; e.g. if two is the multiplying factor, the roll will have two threads.

The shells are usually fed by automatic means into the thread-rolling machine, and discharged in a similar manner. There are no definite speeds, since every job is different and must be considered on its merits.

The authors gratefully acknowledge the assistance given to them by Dr. J. Dudley Jevons, Ph.D., B.Sc., A.I.C., in the compilation of this chapter, and his loan of illustrations.

CHAPTER XIII

Knurling

KNURLING is an operation employing a roller or rollers to impress a design in a solid or hollow metal article. The rollers are forced against the work as it revolves. The actual design is carried by the rollers themselves, and is embossed upon them. The specific reason for using a knurled surface is to

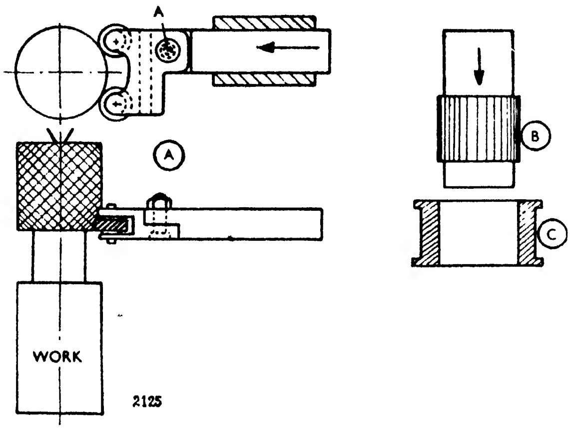

FIG. 70

make a part easier to handle, or to enable the user to dispense with the keying or screwing of light cylinder-shaped pieces together.

Knurling is done in one or other of three types of machine tools, namely, the lathe, the automatic screw machine, and the special knurling machine. The operation itself comprises the impressing of a number of right- and left-hand thin grooves in the steel by means of a knurling tool, as shown in Fig. 70. The job is secured between lathe centres—which are the hardened conical points between which the work is suspended—and driven by a carrier in the normal manner. A carrier is a looped or heart-shaped iron or steel forging, or a steel casting, made to slip over a piece of metal rod which has to be turned between the dead centres of a lathe. It is tightened upon the rod by an adjusting screw, and is itself driven by a short projecting pin affixed either to a face or catch plate. Its function is to impart rotation to the work. The knurling tool is fixed in the tool post. This is a circular post attached to the top of a slide rest for the clamping down of cutting tools. It is pierced with a rectangular hole, through which the tool is slid and clamped with a set screw passing down from above. Tool posts are used only on small lathes, the lathes of larger size being provided with screwed studs and nuts and cross-bars, or with a triangular or rectangular shaped form of clamp. The slide rest consists of a saddle and two slides, the latter moved by hand screws, the saddle by hand or by rack and pinion or by means of a lead screw. These move in a rectilinear direction and act as a guide or steady. Each of the rollers can pivot about the bolt and rest easily against the part being knurled.

A good deal of pressure is employed to compel the knurling rollers to impress the design on the part, so that ample lubrication is essential. In the early days one roller was used, forced towards the job, but this proved unsatisfactory, because unless the part was short and rigid, it was impossible for it to withstand the severe pressure required to produce a sharp and well-formed impression. Consequently one roller is seldom employed in present-day knurling. Two rollers are preferred, and these are so arranged that they are separated from each other by a pre-established distance which is somewhat less than the diameter of the job before it is knurled. In this way the pressure on the part is balanced and does not injure it, while the rollers can be set at any required angle.

The pressure to which the rollers are subjected forces them into the job, and since they are furnished with left- and right-hand grooves respectively, of diamond form, the fine grooves shown in Fig. 71 are produced. The knurling action is not limited to this type of impression. Coarse, medium, and fine serrations can be produced by an adjustment of the knurl helix angle, or angle of inclination of the threads or grooves.

On occasion as many as six rollers are attached to a single holder, thereby enabling the operator to employ any pair he wishes. For the production of knurled surfaces on concave or convex parts, rollers of concave or convex form can be used.

The lathe is only used for knurling when the number of parts to be dealt with is small, or when knurling is combined with spinning. It is possible to knurl with a hand tool akin to the spinning tool, or, as indicated earlier, the tool can be mounted in a tool post and held against the work. For this type of work the roller is generally about 2 in. in diameter, and is of hardened steel.

The automatic screw machine carries the knurling tool either in a turret—which is a thick perforated disc or circular

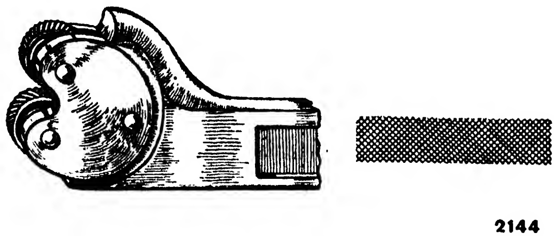

FIG. 71

tool holder, capable of holding a number of tools at once and, by pivoting round, bringing any of them into action—or on one of the cross-feed attachments. Alternatively it may be a swing tool.

Where the number of parts to be knurled is large, a special knurling machine usually proves advantageous. In such machines a vital factor is the design of the arbor or spindle and the pattern rolls, though this factor is not to be ignored when using the automatic screw machine or the lathe. It should be remembered, however, that whereas, when knurling by lathe, the operator is able to see when the pattern is not matching as the knurled part rotates, he cannot do this with an automatic. Thus, if the knurling tool is of the wrong dimension for the job, the result will be an uneven or weakly impressed pattern, because the job will rotate more than once during the operation.

Where the work is hollow, the arbor and roller are geared together to ensure correct mating or matching. The arbor is inserted in the hollow bore of the part to be knurled, and it carries the "male" or projecting impression on it. It must, therefore, be just small enough to fit into and be readily withdrawn from the hollow portion of the work. In this type of knurling operation the roller carries the female, i.e. the incised or recessed, impression. Automatic feeding is quite often employed, so that the whole of the work is done automatically.

Where the part to be knurled is only short, it is not essential that a longitudinal traverse motion should be employed.

Straight grooves running along the axis of the part, as at *B* in Fig. 70, can be produced by knurling, and these grooves are frequently employed as a means of connecting two parts intended to mate, the *B* portion when hardened being driven into the portion *C* of Fig. 70. In this way a quick and economical union of the two pieces is effected.

A typical application of knurling is to the edge of the head of an adjusting screw. In a sense knurling can be regarded as the modern equivalent of "milling," as on the edge of a silver coin in this country. Some knurling is done on shell bodies, and the surfaces of feed rollers are also knurled so as to give the essential friction for feeding different commodities along, as in automatic packing machinery. The handles of gauges and other tools are frequently knurled.

CHAPTER XIV

Spinning

SPINNING is an older form of mechanical working than pressing and stamping, which have to a considerable degree replaced it. It originated in France, Sweden, and Germany, and may be described as the forming or shaping of a revolving metallic disc on a lathe over a former called a *chuck*, by means of the pressure of a special former known as a spinning tool.

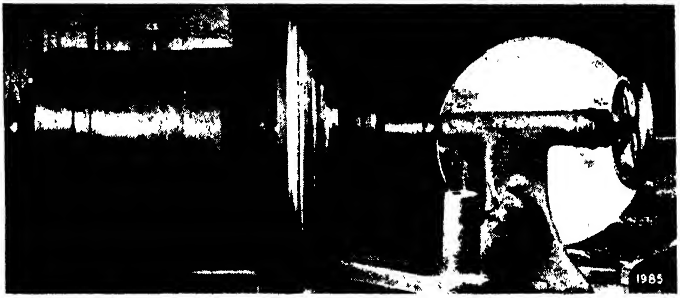

FIG. 72. SMALL SPINNING LATHE WITH MAPLE PATTERN (BLOCK) ATTACHED TO SPINDLE

As stated, spinning has had to give way in some respects to pressing and stamping, but it is still in vogue, and for certain types of work is the most effective and economical process. For example, with complicated parts, on shorter runs (e.g. below 100,000) it is a cheaper method than either stamping or pressing, which need expensive dies and machinery. Again, in numerous instances, spinning is the only process that will produce the desired form in one piece, without any need for soldering or riveting, as would probably be necessary for pressing or stamping. There is thus a gain in both strength and appearance if the piece is spun.

Steel, being relatively hard, is a much more severe problem to the metal spinner than the softer materials such as copper or brass. Nevertheless, it is spun commercially, though its spinning is of fairly recent introduction. The most important advance of late is the successful spinning of stainless steel. We have explained in earlier chapters the difficulties inherent in the working of the austenitic stainless steels due to their marked work-hardening properties. Work-hardening for a long time made the spinning of the 18—8 stainless steels impracticable, until an improvement in the ductility of these materials by variation of their compositions solved the problem. Not only

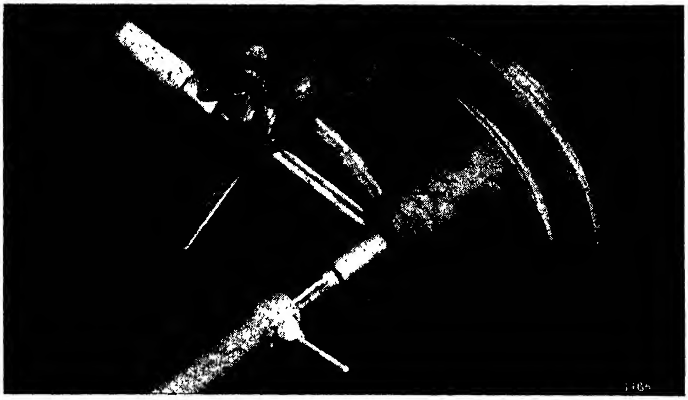

FIG. 73. OPERATOR PREPARES TO SPIN BLANK CLAMPED AGAINST BLOCK. BOTH REVOLVE AT 2,600 R.P.M.

can more complicated forms be given to stainless steel to-day by spinning than were possible two years or so ago, but much larger stainless steel spinnings can be produced. The extension of the range is from the 36 in. diameter of a few years ago to the 90 in. of to-day, which latter size is itself not regarded as a maximum for the future.

We will now consider the process in greater detail. The former or chuck is made to the required internal form of the complete product, and is mounted on the stationary spindle of a lathe. The blank, which is a circular disc of sheet steel, is likewise fixed on the spindle and clamped, while the lathe is still at rest, against the *block*, *pattern*, *chuck*, or *former*, to use the numerous terms employed for the shaped wooden pattern. The disc is lubricated with laundry soap or sheep's tallow. Both chuck and disc are then caused to revolve at a spindle speed of, for example, 600 r.p.m. A suitable metal spinning tool, generally a long blunt steel rod, is then pressed against the disc, using the blunt end. The disc is thus forced over the chuck or pattern and takes its shape. The spinning tool is

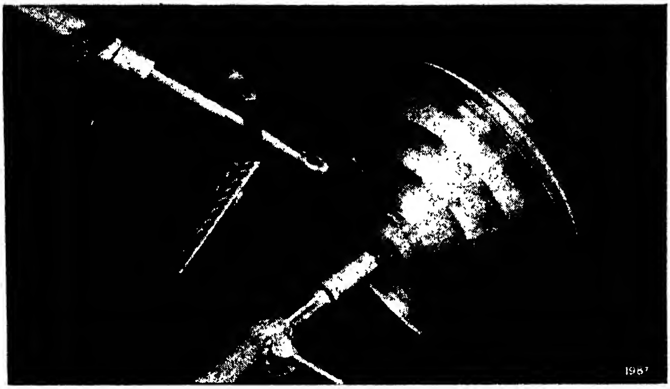

FIG. 74. THE OPERATOR PRESSES THE TOOL AGAINST THE METAL AND IT ASSUMES THE SHAPE OF THE BLOCK

sometimes operated by hand, the pressure being partly obtained by leverage, using a pinion, the lathe rest as a fulcrum.

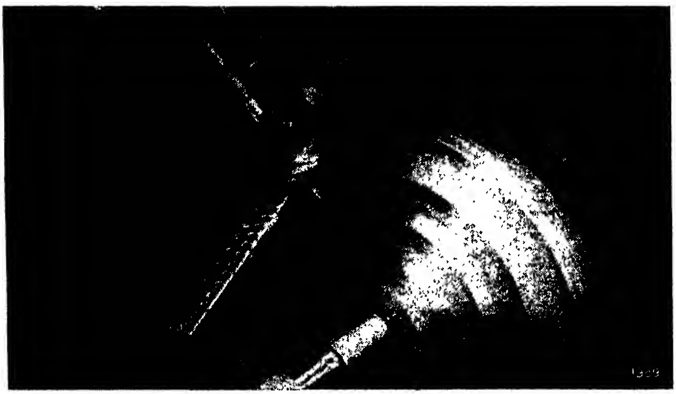

FIG. 75. THE OPERATOR BEADS DURING SPINNING. BEADING IS SMOOTH, WELL-ROUNDED AND CLEAN CUT

Sometimes the spinning tool is of roller type carried on what is described as a compound slide.

When the disc has been pressed to the required shape by skilfully working the tool forward or backward from centre to circumference of the disc, and vice versa, it has to be subjected to certain finishing operations. These comprise *trimming*, *curling* and *beading*. Trimming is the making even and regular of the ragged edges of the spun disc, the cause of which is discussed later. Curling is the operation of curling over the edges to form a rim. Beading is the forming of a "bead" or moulding, possibly for ornamental purposes, on the spinning.

Fig. 76. The Operator Prepares the Outer Edge for Trimming

These three operations call for special tools. When the work is done, the finished product is removed from the former, inspected for accuracy, and is then ready for use, since it will require virtually no polishing, the spinning operations themselves having imparted a high surface polish to the steel.

Sometimes spinning is employed as an auxiliary to pressing in making certain sheet steel products. The pressings, particularly drawn shells or cups for household articles, may need curling, beading, bulging, tapering, or necking operations for which spinning is highly suitable. Again, wrinkles or small furrowings of the surface of parts produced by dies can often be removed by spinning.

Some consideration must now be paid to the phenomena associated with the spinning process. The steel is inevitably subjected to tensional stresses at certain angles and corners, and is therefore stretched and reduced in cross-section. If its ductility is inadequate, trouble such as cracking and fracture at these stressed points may occur. This, however, is not the

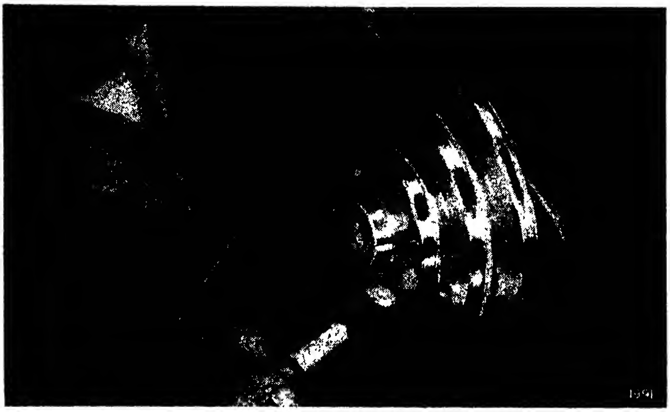

FIG. 77. THE COMPLETE SPINNING IS REMOVED

only phenomenon encountered. There is a progressive thickening of the steel towards the outer circumference of the spun

FIG. 78. FINAL INSPECTION FOR ACCURACY

product. It will be realized that the larger the diameter reduction of the blank by spinning, the greater will be the shift of metal towards the outer edge. Ultimately a point must be reached at which the thickness at the edge will be greater than can be tolerated, while the thinning at the centre may be excessive. Hence there must be a physical limit to the extent of reduction of diameter by spinning a revolving blank, since there is no way of completely preventing this increase in thickness, and the only means of overcoming it is to smooth or iron it out by hand spinning. This, however, involves several

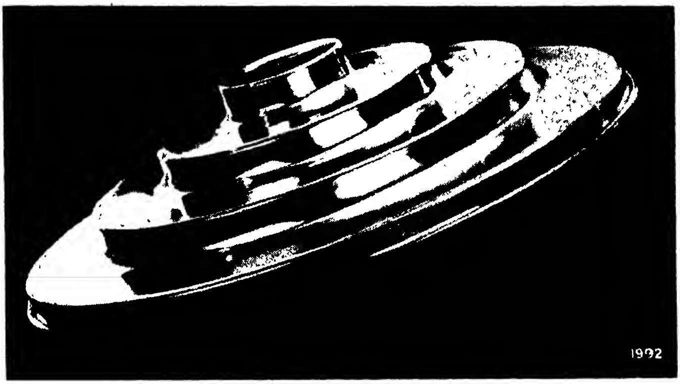

FIG. 79. THE COMPLETED COVER WHICH REQUIRES PRACTICALLY NO POLISHING

softenings or annealings of the steel, and is thus a tedious and expensive matter.

The principal lesson to be learned from this phenomenon is that the deeper the spinning, i.e. the more the diameter of the original disc is to be reduced, the thicker the steel must be at the outset, so as to allow of the shift of metal without serious thinning at the centre.

It must be also realized that the movement of the steel under the spinning pressure may not be uniform. The tool action may give rise to an expansion here or a shrinkage there, and an increase in cross-section at certain parts, as explained. The steel from which the blank has been made is usually rolled sheet steel, and will have a distinct grain, or alignment of crystals, in the main direction of rolling. According to whether the spinning tool is working with or against the grain will the metal behave; e.g. it will stretch more with the grain than against it. This means that the edge of the spun product will not have an even unbroken finish, as would be the case if the metal movement were uniform, but will be ragged and uneven, and because metal is being coaxed towards the outer edge at the same time as the diameter is being reduced, the surplus will tend to cause wrinkles or radial corrugations at the circumference which grow bigger and, if not eliminated, will set up vibration or chatter of the disc and produce cracks due to

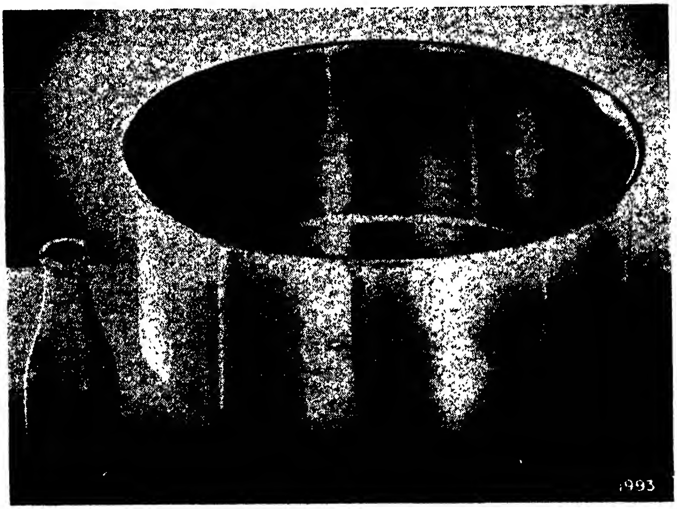

FIG. 80. A TANK FOR A BOTTLE-FILLING MACHINE, SPUN FROM 16 GAUGE 18/8 STAINLESS STEEL

fatigue. Skill in spinning can, however, partly prevent these wrinkles and also an excessive circumferential thickening.

One way of doing this is to reverse the normal procedure of working from the centre outwards, and instead to work from the edge inwards. This tends to move the metal back towards the centre, and thus promotes uniformity of thickness. Wrinkling can be prevented by avoiding excessive pressure of the tool against the work during spinning. Another point of importance is to avoid holding the spinning tool for too long a time on the same place, which may result in excessive work-hardening to such an extent that annealing of the steel is necessary before further work can be done.

The ragged edges of the spun product have to be removed by trimming, as stated.

The speed of revolution of the work is variable, according to the thickness and type of steel and the diameter of the blank. For mild steel, from 300–600 r.p.m. spindle speed is the range for the general run of work.

It must not be assumed that all spinning jobs are capable of accomplishment in one operation. It is only the simplest forms

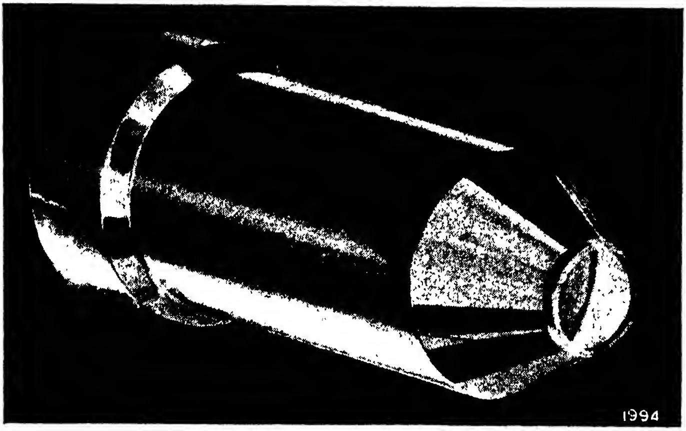

FIG. 81. A DIESEL ENGINE INJECTOR SLEEVE 0·109 IN. THICK, PRODUCED BY SPINNING

and the shallowest spinnings that require no intermediate annealings. The remainder will, as a result of work-hardening, inevitably require annealing before further spinning can be done. Pickling is usually carried out after each annealing operation, in order to remove scale formed by oxidation of the steel in the annealing furnace. Washing and drying follow, after which the next stage of spinning can be carried out.

The "former" or pattern is of softer woods, such as beech or birch, if the run is only short, i.e. if only a relatively small number of spinnings is to be made from it. For long runs, a hard wood such as "lignum vitæ," or even a cast-iron and steel former, is employed. Steel is employed principally when the spinning comprises sharp angles and grooves, which must not readily lose their shape. Sometimes a metal shell is spun, and fixed to the wooden former, the combined wood and metal chuck then serving as a former for the rest of the run. For long runs on deeply spun parts, it is common practice to provide a range of formers, each carrying the spinning operation to a point at which re-annealing of the steel becomes necessary, after which a new former embodying the form to be given by the next stage of spinning is used. This considerably lessens

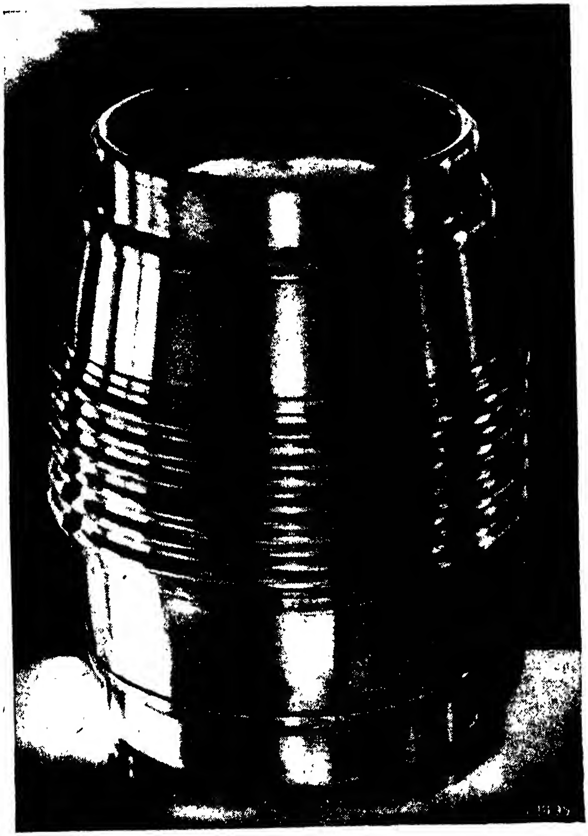

FIG. 82. A MINIATURE SCALE MODEL OF A STEEL BEER BARREL—AN EXACT COPY OF THE FINISHED SPUN PRODUCT

the extent of skill demanded. Sectional formers, i.e. formers built up of sections joined firmly together, are often used for finishing operations on drawn shells.

The tools used in spinning are too numerous and too specialized to be described here. Many are designed exclusively for the particular work in hand. In general, they comprise blunt, beading, and cutting tools. It is important in spinning to reduce friction as much as possible, and to ensure this the tools are made as smooth as possible at the hardened working end,

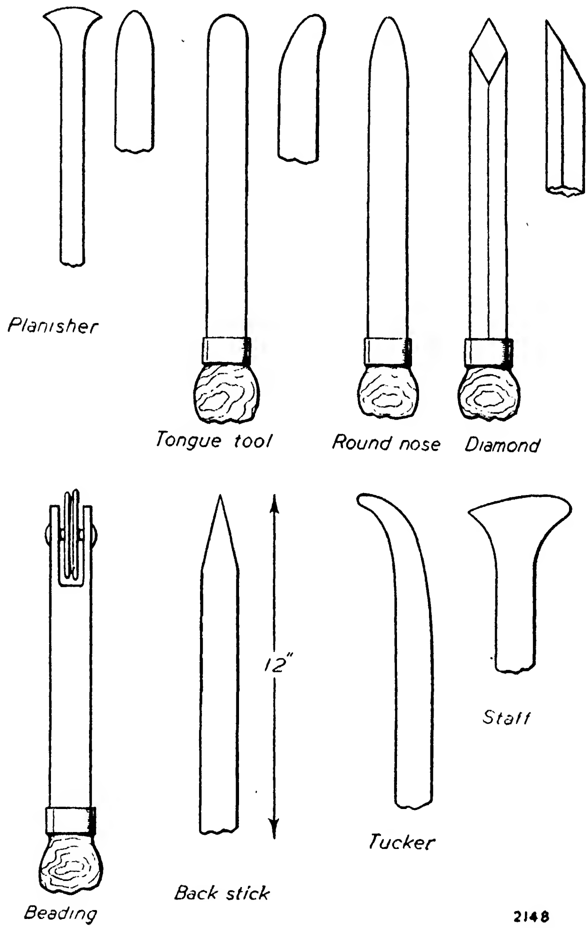

FIG. 83. SPINNING TOOLS

the shank being left rough. In this way there is little danger of fracture during use. After hardening, the tool end is again given a mirror polish to ensure smoothness and in order to minimize friction. The tools are of fair dimensions, owing to the heavy pressure and leverage employed. A typical tool measures, for example, 18 in. long by $\frac{3}{4}$ in. dia., and is placed in a wooden holder or handle which is itself $1\frac{1}{2}$ in. dia. by 24 in. long. The tools are usually made from a good-quality tool steel. Fig. 83 shows typical shapes. For spinning steel, however, bronze tools are employed.

One other aspect of spinning must be mentioned. It is used as a means of assembly. For example, a ball thrust bearing consists of two ball races and a ball retainer which are held together by a cup-shaped sheet metal cap. The races and retainer are inserted in the cap, the open end of which is then closed down firmly by the pressure applied by a spinning tool on to the bevelled corner of one of the races.

Examples of the products made by the spinning process range over many industries, and include stainless steel aeroplane engine cowls; seamless vessels for the food industries, e.g. covers for filling and capping machines used by dairies for bottling milk; steel beer barrels; automobile hub caps; diesel engine injector sleeves; and cylindrical and spherical forms for architectural ornament.

Any cylindrical form, even complete spheres, can be spun. Manufacturers of stampings are also using the process as a method, both effective and economical, of making samples for approval by their customers before proceeding to make the costly finished dies for stamping production.

The Authors' thanks are due to the Editor of *The Iron Age* for loan of the photographs illustrating this chapter,

CHAPTER XV

Riveting

A RIVET is defined as "a double-headed bolt-like solid fastening, employed for securing plates together in a permanent manner, the tail of the rivet being hammered over in place." Rivets are mainly employed where shearing stresses rather than purely tensile stresses are encountered. They grip in part as a result of their contraction on cooling, which causes them to seize the plates and hold them together, and in part by the frictional resistance imposed by the tendency of the plates to slip. It is this combination of two forces acting at right angles to each other that gives rise to shear stresses, since it should be clear that any expansion of the plates produces a tensile stress in the rivets at right angles to the frictional stress. Rivets are generally inserted and hammered or squeezed down while in the red-hot condition, though cold riveting is also common, as will be seen later. The rivet is heated to lower the resistance of the steel to pressure so that it will flow readily without the exertion of undue power. As a rule rivets do not exceed 6 in. in length for hot riveting, though any rivet over 4 in. between the head and tail may fracture at the head as a result of excessive contraction. Cold riveting is sometimes employed for rivets of undue length, and usually for the smaller rivets.

Whether hot or cold riveting should be adopted is a matter that cannot be decided offhand. In general, hot riveting gives a tighter fit because of the flow of the metal into the hole into which it is thrust and packed. Cold riveting is more convenient because there is no heating equipment to be maintained or transported to the job, while it is better for those steels whose structure may be detrimentally affected by heating. In addition, cold riveting is essential for the smaller rivets, because these would lose their heat by radiation far too quickly, and would be cold before they were in place and the heads formed, with the possibility of fracture as a result of being worked during what is known as the "blue brittle" range (about

300° C.). High carbon and high tensile steel rivets are best cold riveted unless special electrical methods are adopted. Case-hardened steël rivets can be hot riveted, because the hardened case spreads out by the shaping of the heads.

It should be borne in mind that the decision as to which of the methods of riveting described is to be adopted depends on the mechanical strength and reliability of the joint obtained; the potential speed; the convenience of the method in relation to the factory or shop lay-out; the cost per unit article; and the cost in plant expenditure.

A point to be remembered is that riveting should be carried out with the minimum pressure that will achieve the desired object. It is possible to reduce the tightness of the fit by excess of pressure, as a result of work-hardening of the steel and springiness resulting from this. The danger of breakage due to excessive pressure must also be borne in mind.

The rivet head is that part first shaped, not that turned over by the operation of riveting, which is termed the "tail." Heads can be segmental, i.e. shaped like the segment of a sphere, nearly a hemisphere; ellipsoidal, i.e. of elliptical shape; pan, i.e. like an inverted pan  ; snap or cup, i.e. semi-

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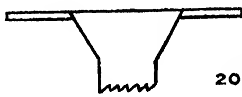
circular or cup-shaped; and countersunk  2088

i.e. with heads lying flush with the surface of the plate they secure.

Riveting itself is the turning over or clenching of the rivet heads. The finishing form is given to the head by the snap, a tool whose form is the exact reverse of the rivet. At one time it was a supremely important process in mechanical engineering, but of recent years welding has encroached more and more upon it as a means of uniting steel plates. Nevertheless, it has not been, nor is it likely to be, completely superseded. Originally a hand operation, it is now almost invariably mechanical. It is fundamentally a pressure operation, even when carried out by hammering, which is only pressure applied for a brief period and repeated many times.

It goes without saying that the strength of the riveted joint depends on the material of which the rivet is made and the manner in which the operation is carried out. In former days rivets were made from a soft iron of ductile character possessing a tensile strength or maximum stress of about 23 tons per sq. in. and an elongation of 25 per cent on two inches. To-day, however, steel has largely replaced iron because of its greater strength. The material used is a steel of relatively low carbon percentage with a tensile strength of above 25 tons per sq. in. and an elongation of 30 per cent on two inches. Steels of higher carbon content are sometimes employed where greater strength is required. Low carbon stainless steels are also used for rivets, but need different treatment as compared with the normal mild steel rivets. Iron rivets are now used only in hand riveting, which is employed for difficult corners and positions where the riveting machine cannot be utilized. The steel should withstand being bent in the cold state to a curve whose internal diameter equals that of the rivet itself. Quick hammering or squeezing is essential, and overheating or burning must be avoided at all costs. Some of the smaller rivets are hollow for easy closure, since they spread quickly under pressure, but these are not very strong and are used only for jobs where high mechanical strength is not desired.

Machine riveting is technically better than hand because (1) it causes the rivet to fit more tightly in the hole; (2) this tighter fit enables the rivet to support a greater degree of shearing stress;* (3) it closes the riveted plates together, and since every rivet is subjected to identical pressure, with little risk of loosely fitting rivets; (4) there is less risk of cracking, because the rivet is more speedily driven home; therefore the blows are not struck on steel that has become too cold, as may happen in hand riveting. Economically it is better, because cheaper, than hand work. Care must be taken, however, not to remove the pressure as soon as the rivet is formed, or the spring of the plate due to its resistance to cold work may stretch the rivet while it is still soft enough to respond to such stretching.

* Shearing stress, as explained, is the stress imposed upon a body subjected to two forces, one in a direction parallel with its section, and the other at right angles.

The holes into which the rivets are to be driven should be drilled to the required size to ensure exact fitting, and not punched, followed by enlargement to correct size with a tool known as a reamer. This is in order to avoid the damage done by punching, which distorts the structure of the steel in the region of the hole. Cold punching causes localized distortion of the steel's structure and consequent work-hardening. During later hot riveting, the stresses set up by work-hardening may not be relieved uniformly, with the result that cracks are developed around the holes. Although reamering out after punching relieves some of the localized stresses and strains caused, it still remains true that drilled holes are better.

Most riveting is done on boiler shells, and on the shells of rotary kilns, rotary dryers, washers, coolers, tube mills, and the like. The mechanical method adopted may be either hydraulic, pneumatic, or electric.

The hydraulic riveting machine is in essence a hydraulic press (see Chapter VII), embodying a die fixed near the end of a strong cast-iron or steel pillar. This takes the thrust of a movable cup or snap-headed die, the rivet lying between the two. The rivet is gently squeezed home with far less noise than is customary in hand and hand pneumatic riveting, in which a succession of rapid blows is struck. A variation of pressure can be made to conform to the dimensions of different sizes of rivets. The number of rivets inserted per hour is governed mainly by their location and the local conditions. Pressures up to 75 tons are exerted by these presses.

The following is a good average rate of riveting on tube mills, dryers, and similar classes of work.

Size of Rivets	Rivets per Hour	
	Pneumatic	Hydraulic
3/8 in.	90	
1/2 in.	·85	
5/8 in.	70	
3/4 in.	60	50
7/8 in.	40	50
1 in.	35	50
1 1/8 in.	30	50
1 1/4 in.	25	50
1 3/8 in.	20	50

One form of pneumatic riveter is operated by compressed air carried to the point of use in tubes or pipes. The rivet is heated in a portable forge or furnace, seized with tongs having long narrow jaws, and placed in position in the hole by one operator, the "rivet boy," while the riveter brings the pressure

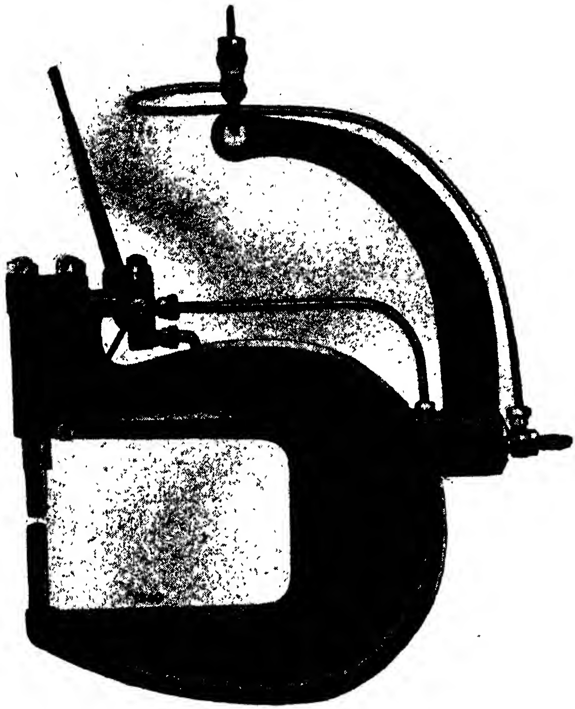


FIG. 84. A PORTABLE HYDRAULIC RIVETER OF "BEAR TYPE"
(Photo by courtesy of Henry Berry & Co., Ltd., Leeds)

ram of the pneumatic machine into line with it. By manipulating a lever a valve is opened in the valve chest, the rectangular box into which the compressed air is admitted. The air allowed to enter by this valve presses, as a result of its expansion, vigorously against the piston, which it pushes forward. The motion of the piston is transferred by an arrangement of toggle levers (see below) to a plunger or piston carrying a screw ram, to whose extremity is affixed the heading-cup, i.e.

the cup-shaped tool or die for forming the rivet head. The stroke is quick at the outset and slower as it progresses, the rivet being gently but firmly pressed home. The pressure is maintained for approximately a quarter of a minute to allow the rivet to cool. The pressure applied by this form of riveting machine is about 30 tons at the end of the stroke, though the pressure on the piston itself is only from 80 to 100 lb.

(Toggle levers comprise two lever arms at an angle to one another and hinged at the centre. The end of one is free to move. The end of the other is hinged on a fixed pivot. The endeavour to straighten the levers, i.e. to put them in line with one another, results in the exertion of great pressure at the ends. If he desires to pursue this further, the reader should consult some elementary book on applied mechanics.

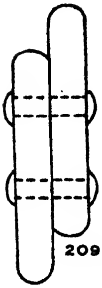
The hand pneumatic riveting machine employs compressed air at from 60 to 100 lb. pressure. Admission of the air is regulated by a thumb lever. The machine has a reciprocating piston which hammers rapidly on the end of the rivet snap or die and closes the tail of the rivet over. The rivet is supported by either a dolly or a pneumatic holder-up. A dolly consists of a round iron bar provided with a head, either flat or concave (i.e. cup-shaped). The dimensions, form, and angle of inclination of the bar vary with the dimensions and form of the rivets and their position in relation to the job. The holder-up comprises a cylinder, inside which is a piston. This thrusts against the rivet head at the same time as the ram is knocking down the tail, after which it remains stationarily pressed against the rivet while the closing is being completed. About 700 blows a minute are struck. Rivets up to $1\frac{3}{8}$ in. diameter can be dealt with by these machines, which have a capacity of from 90 to 120 rivets an hour and a stroke up to 9 in. Pneumatic riveting forms the rivet head with much lower breakage risk than methods employing direct pressure, and gives a tighter fitting rivet than the roller method described later. It will, moreover, rivet harder steels than any other process.

There are also electric riveting machines of portable type in which a piston is horizontally advanced by an electric motor by means of speed-reducing gear, so as to compress oil on the upper surface of the vertical ram to a pressure of 2 tons per sq. in. A resulting pressure of 32 tons per sq. in. on the first is then exerted. Another electrical process is carried out by means of the spot-welding machine, which electrically heats the rivet and forms its head by mechanical pressure, as in spot welding. This gives a much tighter fit, the rivet being made more plastic than in a cold riveting process, and is more convenient than the ordinary hand riveting process.

There is still another method, known as roller riveting, employed where the head of the rivet cannot be shaped by a single blow or by pressure on a shaped snap. A typical instance is small rivets, where the pressure or blow needed to form the head in one stroke would break or distort the rivet. In this method pressure is applied to revolving rollers formed to the profile or shape of the rivet head required. In this way, pressure is concentrated on a line across the head in course of formation, and the steel is made to flow locally. There is virtually no expansion of the rivet shank, only the metal of the head being locally spread. Hence the shank must be an accurate fit in the holes before riveting by this method is begun. This method does not give quite so tightly fitting a rivet, but is useful for delicate riveting work, since it needs only a low pressure, and the risk of breaking the rivets is less than with other processes.

Pneumatic riveting is in some respects better than hydraulic. In cold climates difficulties occur when the water in the hydraulic system freezes, while wear may result in leakage. Hydraulic riveting is, however, more uniform in its pressure, and for this reason is superior.

The method of arranging the rivets should avoid subjecting any portion to exceptional stress, and should not only give a tight joint, but also allow satisfactory work in the riveting. If the rivets are pitched too wide, i.e. set too wide apart, the plates may spring up between them, which will prevent the effective carrying out of later operations. If the rivets are set too close to one another, the extent of effective steel plate section is too drastically reduced. When the riveting machine exerts its pressure, the result may be distortion of the plate owing to the lack of adequate stiffness or strength, and the result will be imperfectly tight joints, causing leakage if the job be a containing vessel of some sort.



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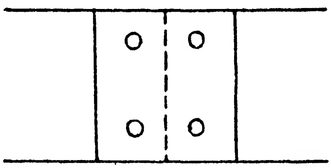
It is impossible to give precise rules for the strength of riveted plates, which is governed by such widely differing factors as the method of making the rivet holes, the accuracy and positioning of the holes, the quality of the steel for both rivet and plate, the character of the stresses to which the plates are subject, and the type of joint adopted, e.g. "lap" or "butt," "single" or "double."

Lap joints are those made by the overlapping of adjoining surfaces, as shown in figure on left.

If there is only one line of rivets, this is termed single-lap riveting; if there are two lines, as in the diagram, it is known as double-lap riveting.

A *butt joint* is one in which the plate edges butt against one another, and are covered by a third plate overlapping the joint. This third or "cover" plate, sometimes termed *the butt strap*, is then riveted to the plates it is required to unite, thus—



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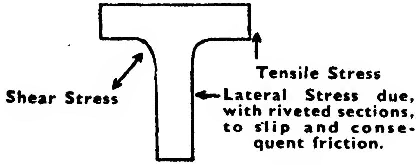
Butt riveting is known as "single" when there are two lines of rivets, as in the diagram, and "double" when there are four lines.

Some notes on rivet snaps will not be out of place here, though the information given can only summarize a subject on which much might be written. The first consideration is the steel for these tools. This should have a fine and dense structure, and should be durable, as well as adequately hard. On the other hand, it must not be brittle, and must resist loss of temper or hardness as a result of coming into contact with the hot rivets.

These requirements are best met by a special chromium vanadium steel (such as Edgar Allen & Co. Ltd.'s "Maxnap" steel). This steel is particularly suitable for pneumatically-hammered snaps. Rapid blows cause fatigue in steel, which



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results in eventual fracture and failure. The toughness of this steel resists fatigue, while its hardness maintains efficiency.

The snaps themselves must be smooth and well polished in the cup or concavity for forming the rivet heads.

On occasion, the rivet may not be adequately supported in the work, and as a result the snap may give way and form the head badly. To prevent this, a cruciform chisel punch is sometimes used. This is self-centring and stiffer than a flat chisel punch. It can also be used where both ends of the rivet are formed at one operation from a plain wire.

The following table, based on figures compiled by V. L. Miller, gives pressures for small steel rivets.

Rivet Dia. in.	Type of Rivet	Amount of Rivet to form Head, in.	Tons Pressure
$\frac{3}{32}$	Round-head	$\frac{3}{16}$	1·15
$\frac{1}{8}$	„ „	$\frac{7}{32}$	2·25
$\frac{5}{32}$	„ „	$\frac{1}{4}$	3·00
$\frac{3}{16}$	„ „	$\frac{9}{32}$	4·50
$\frac{3}{32}$	Countersunk	$\frac{7}{32}$	2·25
$\frac{1}{8}$	„ „	$\frac{3}{16}$	3·50

In dealing with stainless steel rivets, cone or "pan" heads are better for hot riveting, and button heads for cold riveting. The rivets are heated in an electric or muffle furnace whose temperature is controlled by a heat-measuring instrument termed a pyrometer. Pneumatic hand riveting machines are mostly used, and these demand higher air pressures than for mild steel rivets.

CHAPTER XVI

Planishing

THIS work would be incomplete without some reference, though necessarily brief, to the planishing, or flattening, of metal sheets. When a steel sheet or plate comes from the rolling mill, it is not, as may be imagined, a perfectly flat piece. There will be slight but perceptible and numerous "humps and hollows." In some instances these may not greatly matter and can be left in. If, however, the plate is needed to form some kind of instrument, e.g. a circular saw for cutting various materials at good speeds, or some integral part of a construction demanding a really flat surface or a disc suitable for cold pressing, these irregularities have to be removed.

Again, planishing may be a repairing job, to straighten out a buckled sheet, accidentally damaged.

In any event, this is work calling for a high degree of skill. In general, a buckled or irregular sheet is caused by the steel's shrinking at different rates in different places, as it cools after being heated, so that the grains are elongated here and compressed there. Obviously this is a strained condition of the metal, and the planisher eliminates the strains, with a consequent relief or increase of tension, by hammering every spot where the crystals or grains have contracted, i.e. where the steel has tightened. If the bulge is in the middle, the planisher will have to concentrate most of his blows on the circumferential zone of the plate, whereas the central portion will be untouched. On the other hand, if the edges have buckled, the centre will get the most hammering, and the blows will become fewer and fewer as the edges are approached. The force of the blows is gauged by the plate thickness, and the skill of the planisher lies in adjusting the blow so accurately to the plate as to preclude any need of further hammering to eliminate the effects of too severe a blow.

A flat plate or piece of metal is often interposed between hammer and work so as to prevent damage by hammer indentation. Planishing hammers are generally made with a slightly convex striking face so as not to cut or dent the steel.

Plates and sheets are often passed through idle rolls in order to flatten them in advance of planishing and so simplify the latter operation. With flattening proper we shall deal in the next chapter. Rolling in this way collects up a number of smaller bulges to form one larger one, on which the planisher can more easily work. Thin plates and black sheets can be and often are stretched in a hydraulically operated stretching machine in order to flatten them out. They are fed into the machine three or four together, their extremities being gripped in special knee grips. A load is then applied powerful enough to stretch the grains of the steel and eliminate the bulges.

CHAPTER XVII

Flattening

There would be no need to deal specially with the flattening of steel were it not that one type of flattening operation involving machinery has not hitherto been dealt with, and that for certain requirements steel sheets and strips are needed with so extreme a degree of flatness that special methods have to be used. Ordinary commercial flatness in a steel piece, plate, sheet, or strip can be produced by one or other of the processes already dealt with, e.g. hammer forging (or hammer flattening), rolling, or planishing.

In this chapter we shall deal briefly with those forms of flattening known as roller and stretcher levelling or flattening, designed to produce the one "commercial," the other stretcher level, flatness. Roller levelling is carried out in a roller flattening machine, which embodies two sets of several horizontal rolls of relatively small diameter. These are assembled in a frame. The upper and lower rows of rolls are arranged as in Fig. 85, i.e. offset or staggered, and by this means they mesh together. The result is that when a sheet to be flattened is passed between the two rows, it is curved or flexed alternately upwards and downwards, as in Fig. 85. The consequence is that the sheet surfaces receive a greater amount of cold work than the sheet's interior.

The rows of rolls can be moved in relation to each other, so that by screwing them down to a greater or less extent the pressure they exert upon the sheet can be regulated. Assuming that the rolls have been properly meshed, the sheet will emerge from the operation extremely flat, far flatter than could be achieved in any other way, but no greater in length.

At the feed or insertion end of the machine, the axes of the upper and lower rolls are nearer together than at the side of emergence. This means that when the sheet is first introduced it is more severely flexed than when it passes out, the last few rolls straightening it. Only one sheet at a time is usually fed in, but in some instances more than one may be introduced at once, according to the thickness.

Roller levelling or flattening is done both hot and cold. Hot levelling is usually employed for hot-rolled plates or sheets measuring more than 0·6 in. in thickness. Its object is to straighten out the kinks and bends or other forms of warping resulting from hot rolling or open annealing.

Thinner sheets, particularly those of steel containing alloying elements such as nickel, molybdenum, etc., cool so rapidly

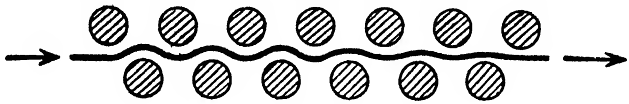

FIG. 85

during and after rolling that "hot" flattening is not feasible—the rolled sheets are too "springy" and, after passing through the machine, still retain their rolled ripple or undulating corrugated shapes, but if reheated (or tempered) they can usually be flattened quite satisfactorily.

In cold flattening, it is essential that the steel should have been given a fully-softening treatment, otherwise the original "kinks" will not be removed.

Modern roller levelling machines use much smaller rolls than formerly. This has been rendered necessary by the introduction of broader and thinner cold-rolled sheets. Roller levelling is also carried out on occasion as a means of preventing the phenomenon known as "stretcher strain" during drawing. (See page 86.)

The principal trouble likely to be encountered in roller levelling is a corrugated effect in the sheet caused either by incorrect adjustment of the rolls in relation to the thickness of the sheet, or to excessive warping of the sheet before it is fed into the machine. The process is not costly, and gives good commercial flatness.

Stretcher levelling is designed to produce sheets of extreme flatness, such as are employed for panelling where only a small amount of forming work is carried out on the sheets, which, when completed, have to be dead flat and undistorted.

The process is hydraulic, and comprises the seizing of each end of a sheet by jaws secured to pistons. These pistons are gradually withdrawn from each other by the hydraulic power, so that the sheets are slowly stretched. If the sheets are not too thick, it is possible to stretch more than one at once, but since the grip of the jaws upon two or more sheets can never be so strong or satisfactory as upon one, it is seldom that this practice is adopted. The process may be likened to seizing between thumb and finger of each hand a length of crinkled paper and slowly stretching it until all the crinkles have been taken up, and the paper lies dead flat. In stretcher levelling, the steel is pulled or stretched to a point slightly beyond the elastic limit (see *The Structure of Steel*). The effect of this is that when it is taken out of the machine it will not spring back into its former unevenness, but will spring back uniformly across its full width and stay flat.

The sheets to be flattened by this process have to be of great softness and ductility, while their elasticity must not be so great that the stretching power required to make them stay flat when stretched is beyond the capacity of the machine. It is customary to temper the sheets before they are stretcher levelled, as otherwise stretcher-strains may occur, or undesirable surface strain marks appear.

To ensure satisfactory levelling by this method, the sheet must be uniform in physical properties over its entire area, or variations in elastic contraction will occur and spoil the flatness of the sheet. The thickness must also be uniform, or there will be a danger of imperfect grip by the machine jaws, with a consequent slipping of the sheet. This will lead to uneven stressing of the metal, and a consequent variation from point to point in elastic contraction, again leading to impaired flatness. With higher physical properties in the sheet steel, the levelling operation grows harder, because not only does the metal possess a higher degree of elasticity, thus taxing to the utmost the machine's power capacity, but also it becomes less easy to obtain a satisfactory grip.

Light-gauge sheets (0·031 in. and below) are extremely difficult to flatten by this method because of the tendency for them to fracture across their width or to buckle in a direction parallel to their width.

CHAPTER XVIII

Radial Expansion

"RADIAL expansion," or, as it is more frequently called, "autofrettage," is a process whereby, in a thick-walled tube, increased resistance to distortion by internal pressure may be obtained by inducing in the tube stresses opposite in kind to those set up by the internal pressure. The word "autofrettage" really means "self-binding" or "self-hooping," and was originally applied to the process on account of the resemblance of the effects produced to those secured by shrinking on successive tubes one over the other, as commonly used in gun construction.

We shall first describe the radial expansion process itself, which is carried out by hydraulic pressure. Two methods are employed, one known as the *open method* and the other as the *container method*. In the *open method* no attempt is made to keep down the amount of expansion to a predetermined figure by some external means designed to prevent expansion beyond this point. In the *container method* the cylinder has a strong hollow tube with walls of good thickness placed over it, so that it cannot expand to a diameter greater than that of the internal diameter of this constricting tube.

In general the container method is the more advantageous, because if the cylinder should have different thicknesses of wall in different places, or is of tapering form, it can be treated at the one operation by the employment of a radial pressure great enough to expand the section having the thickest wall to the required extent. In the open method, on the other hand, each section has to be expanded separately, employing radial pressures in proportion to the wall thicknesses in each section. There is, however, one drawback to the container method, in that it conceals the presence of soft spots and irregularities in the structural state of the steel. These would be revealed by the open method.

To produce the radial pressure requires first a low-pressure water pump, which forces water into a hydraulic intensifier. The intensifier develops a high hydraulic pressure. In the cylinder is an arbor or spindle, held in position. High-pressure pipes and connections carry the water under high pressure from the intensifier to the cylinder *bore* or interior. To retain the high pressure within the cylinder, suitable packings have to be employed. The water pressure is carefully measured by pressure gauges, and other gauges are used to measure the internal diameter of the cylinder before and after application of the pressure. The external diameter of the cylinder is also carefully measured during the process of expansion.

The liquid of low compressibility (i.e. barely capable of compression) used to create the high pressure inside the cylinder is generally glycerine.

After the process is complete, the cylinder is given a low-temperature stabilizing heat-treatment, as explained, after which it is cleaned and allowed to cool in air. The next stage is a turning down and reboring of the cylinder to the finished dimensions, i.e. it will be machined both outside and inside, since there will inevitably be some slight size variation due to both the expansion and the heat-treatment. This machining work takes away a little of the *elastic strength* given by the radial expansion and the stabilizing treatment, but this reduction will not be of great importance.

In order to understand the process it will first be necessary to consider how the stress is distributed across the wall of a thick tube when internal pressure is applied. At each point there is a compressive stress in the direction of the radius, and a tensile stress in the direction of the circumference, both of which increase from the outside to the inside, and the circumferential stress is the greater of the two at all points. It will be sufficient for the present purpose if we confine our attention to this stress, which is distributed across the wall in the manner shown in Fig. 86. Taking as an example a tube with wall thickness equal to the bore diameter, the greatest stress, represented by AB, is $1\frac{1}{4}$ times the internal pressure. It is five times as great as the stress CD at the outer surface. The greatest pressure that may be applied may be taken to be determined by the greatest stress AB that may be carried by the material. If for the purpose of illustration we say this is 20 tons per sq. in., then the internal pressure that will produce it is 16 tons per sq. in. But Fig. 86 shows us how uneconomically the material of the tube is being used. No part, for example, outside the middle radius is carrying a stress greater than $6\frac{1}{2}$ tons per sq. in. Now it can easily be proved that the area of the figure *ABCD* will be equal to one-half the product of the internal pressure and the diameter of

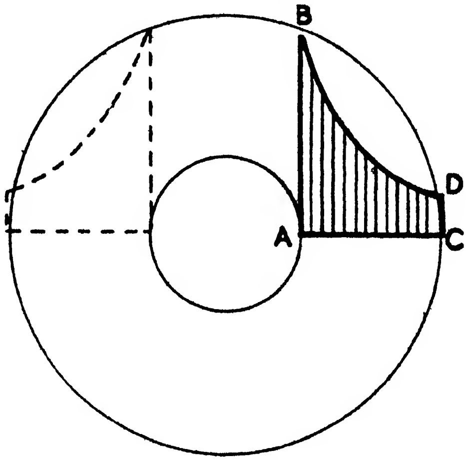

Fig. 86

the bore; so that if we can. by some means, increase the stress in the outer part and reduce it in the inner, we shall be able to allow the same internal pressure with a reduced value of the stress *AB*, or, what amounts to the same thing, the tube will be able to carry a greater internal pressure without either increasing its size or the greatest stress in the material. One way of doing this, much used in gun construction, is to divide the tube into two or more concentric parts, shown (for the case of two parts) by Fig. 87, boring the outer one to a slightly less diameter than the outer surface of the inner tube, and "shrinking" it on to the latter; that is, expanding it by heat so that it will slip over the inner tube, when on cooling and contracting it will grip it with a pressure depending on the shrinkage allowance. By this means a radial pressure is set up increase the stress *AB*, but will bring parts of the cylinder progressively remote from the bore to the yield point stress, the interior layers merely continuing to extend under the constant stress, so that the diagram of stress distribution has a flat top, as shown in Fig. 89. If we continue to raise the pressure, this flat top will finally reach the outside surface. If the stress *AB* as before is 20 tons per sq. in., the internal pressure corresponding to this condition for a tube whose wall

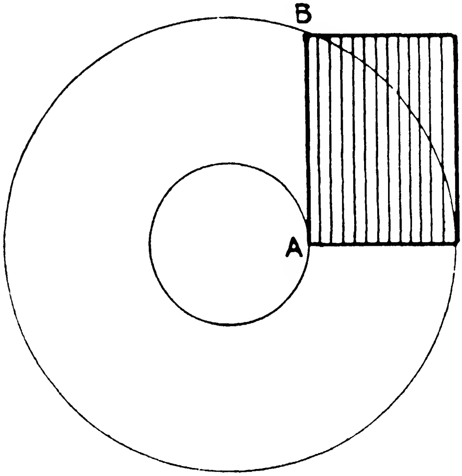

FIG. 89

thickness is equal to the bore diameter will be about 40 tons per sq. in., or more than double the pressure required to bring the internal surface to the stress of 20 tons per sq. in. while the whole cylinder was elastic. It might at first sight be thought that before the condition represented by Fig. 89 is reached, a very large amount of deformation will have taken place. This, however, will not be so. It is a characteristic of plastic deformation that the density of the material does not change appreciably, so that the area of cross-section of the tube wall also will not change appreciably if, as is usually found to be the case, there is little or no change in the length of the tube. When at the external surface the stress just reaches that corresponding to *Y* in Fig. 88, its diameter will have increased by about 0·15 per cent. The bore will therefore have increased in diameter by about 1·35 per cent. These are small quantities, but their occurrence has given the name "radial expansion" to the process.

Let us assume that a pressure just short of 40 tons per sq. in. has been applied to our ideal tube so that the external surface has been brought almost, but not quite, to the limit of stress Y. The condition is one of equilibrium, and so long as the pressure is not raised any further, no further deformation will take place. What will now happen when the pressure is lowered to zero? To answer this question we must go back again to the stress strain diagram in Fig. 88. It is typical of all materials that have been overstrained, that is, have been carried beyond the yield point Y, that when the stress is removed they behave approximately as elastic bodies. This means that the contraction that takes place from the final condition reached is roughly proportional to the amount by which the stress is diminished, and the ratio of these is roughly the same as that of extension to stress during loading. If, for example, in Fig. 88 the stress is relieved after the extension has reached a point C, the line CD represents the relation between stress and deformation during unloading. This line is roughly parallel to OY. We will assume that in the ideal material of our illustration the line is straight and continues to be so when the stress changes to compression—in other words, we assume perfect elasticity during unloading, and then during loading in compression. It will easily be seen that relieving the pressure in the tube is the same thing as applying negative internal pressure of the same amount as the existing positive pressure. If our ideal material remains elastic up to the same limit in compression as it did previously in tension, then we must deduct from the stress represented by the horizontal line in Fig. 89 elastic stresses corresponding to the negative pressure. The final result will be a stress distribution of the type shown in Fig. 90. The internal layers are in compression, and the external layers in tension; the same kind of effect, in fact, as was shown to result from shrinking one tube over another. If now we apply internal pressure, the internal surface will not reach a tensile stress of 20 tons per sq. in. until the internal pressure again approaches 40 tons per sq. in., and at that point the whole cylinder will be under a stress of 20 tons per sq. in., *without any other than elastic stresses occurring*; and, if the ideal properties assumed are retained, the same pressure may be applied repeatedly without any further permanent deformation.

This is what is meant by "autofrettage." We have taken, for the purpose of simplicity in illustration, an ideal material, and we must notice now what modifications must be made

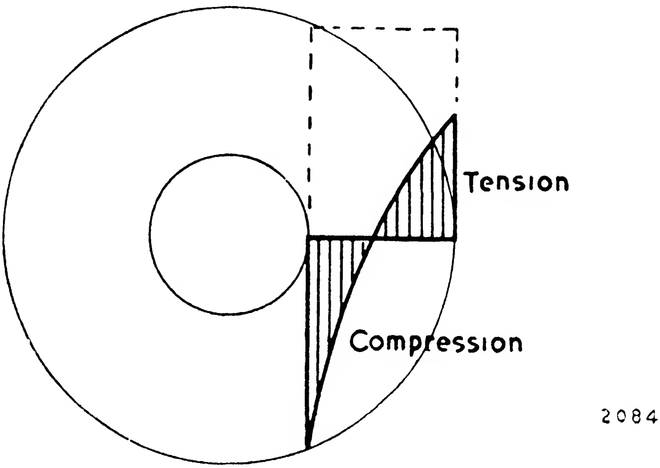

Fig. 90

to the kind of results mentioned owing to the departure of actual materials from the properties assumed. In the first place, no known metal will go on extending indefinitely at the same stress that causes plastic flow to begin. Mild steel, however, approximates to this condition over a considerable range. For instance, the yield point stress is not exceeded until the extension has reached about $1\frac{1}{2}$ to 2 per cent, which, it will be noticed, is greater than the extensions required in the above illustration. A mild steel tube of the proportions assumed may thus be put into a state of complete autofrettage without exceeding the yield point range of extension in any part. But there is one important respect in which the ideal conditions assumed are not found in actual materials. It was assumed in the ideal material that plastic flow occurred under constant tensile stress. In mild steel, at all events, it is not the tensile stress, but more probably the shear stress, that remains approximately constant, and although this makes no difference to the shape of the tensile test diagram, it does affect considerably the stress distribution over the tube wall, which is no longer of the simple type shown in Fig. 89. The consideration of the actual stress distribution is too complicated to deal with in this work; but it may be remarked that while the effects of compression and tension in the tube wall are produced in the manner described, the pressure it is possible to apply to the tube is substantially less than the figures given above. Further, the stress strain line during unloading in a tension test when the yield point has been passed is not straight, as has been assumed, and when compression begins the deviation from straightness is increased. These, and other less important factors, all modify the extent of the advantage that can be obtained by autofrettage.

A property, possessed by almost all ductile metals, that may be made use of in increasing the strength of a tube is that of strain-hardening. This effect is sometimes confused with that of autofretfage, but it should be clearly understood that the two are essentially distinct processes, and it is possible to obtain the benefits of autofrettage without appreciable strain-hardening. As, however, the effects of strain-hardening enhance those of autofrettage, advantage is generally taken of it where possible. In most of the higher carbon and alloy steels the yield point is not so clearly marked as in mild steel, and there is little if any range of plastic yielding over which the stress remains more or less constant. Strain-hardening increases rapidly as soon as the yield point is passed. Radial expansion of comparatively small amount applied to a tube of such materials will therefore induce considerable strain-hardening; and the increased resistance to distortion such tubes show is probably attributable as much to this property as to the effects of autofrettage.

STRAIN-HARDENING

In view of what has been stated above, some further explanation of what is meant by the term "strain-hardening" may not be out of place here. Unlike true "autofrettage," strain-hardening relates to the enhanced hardness and changes in the other physical properties of the steel when it is stressed beyond its yield point and is *permanently* deformed by the application of cold work, such as by cold rolling or cold drawing. The enhanced hardness caused by this cold working does not reach its maximum value immediately, but only after a certain period of time, if allowed to stand at ordinary atmospheric temperatures. For this reason, the term "strain-age-hardening" is more appropriate, since it at once indicates that the hardening is a function of the time that the steel is allowed to stand after it has been cold worked.

The maximum hardness, after cold working, can be accelerated by reheating the steel to a temperature not exceeding 250° C. It is worthy of note that in consequence of cold working, both the yield point and tensile strength (for an explanation of these terms see *The Structure of Steel*) are raised. The increase in the value for the yield point is, however, at a much greater rate than that of the tensile strength, so that when subjected to a considerable amount of cold work the two values may be almost identical.

We acknowledge the assistance we have received from Professor G. Cook in the preparation of this chapter, especially in the part dealing with the stress distribution.

INDEX