METALLURGICAL MATERIALS, ALLOYS AND MANUFACTURING PROCESSES

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ALLOYS AND MANUFACTURING PROCESSES

By

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With a Foreword by

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FOREWORD

ALL workers in industry, technicians and artisans alike, realise to-day the importance of knowing as much as possible about the materials with which they work. This knowledge is not only necessary to us in obtaining a proper understanding of our job, but it is essential if any real satisfaction is to be gained from doing it. For these reasons alone the publication of a book on metallurgical materials is welcome.

Although intended primarily for engineering and metallurgical students, this book is so comprehensive in scope that it should contain much of interest to workers in a larger field, particularly to those engaged in all branches of foundry work.

J. W. GARDOM.

8th April, 1946.

PREFACE

THE decision to write this book originated from the suggestions of a number of engineering students keenly interested in metallurgy, and who, in order to secure information on all the aspects relative to a metallurgical course dealing with engineering materials, found it necessary to consult a number of separate volumes. It is thought that similar difficulties may exist at other educational centres for certain metallurgical and engineering courses. Whilst in general lecturers are able to deliver the subject-matter verbally and comprehensively during series of class meetings, the author has usually found it desirable that the student should have readily available all the necessary data in condensed form for the purpose of reference and revision, otherwise resort is often made to the tedious practice of writing or copying of notes.

In this book an attempt has been made to present in a brief and simple manner the more important principles of the metallurgy of the common engineering materials, their properties, treatments and manufacture; refraining as far as possible from including too advanced metallurgical data and theories. In other words, the book is mainly compiled in the form of a handbook, with perhaps a little more elaboration than usually found in reference handbooks, and it is hoped that engineers, students and others connected with the metal industry will find something of interest in its pages.

Many of the practical methods of melting, production methods and equipment are illustrated pictorially, and in this connection the author wishes to tender his thanks to the many firms who have generously contributed drawings, blocks and photographs.

Grateful acknowledgment is also made to those who gave kind assistance with the revision of the proof chapters—Mr. L. H. Hounsfield, A.R.C.S., A.M.I.C.E., M.I.Mech.E., M.I.A.E., with Mechanical Testing; Messrs. Foster Instrument Co., Ltd., with Industrial Control and Measurement of Temperature; Messrs. Davy and United Engineering Co., Ltd., with Mechanical Working of Steel; Messrs. British Aluminium Co., Ltd., with the section dealing with aluminium and alloys in the Non-Ferrous Metals and Alloys chapter; the British Oxygen Co., Ltd., for information on the welding of steels; and Messrs. Morgan Crucible Co., Ltd., for information on crucible melting furnaces.

Thanks are also due to Messrs. Crane, Ltd., Ipswich, for facilities for the production of many of the photographs and photomicrographs; to the British Standards Institution for permission to include extracts of specifications; and to Mr. J. W. Gardom for his perusal of the proofs and for his introductory Foreword.

V. N. WOOD.

CONTENTS

LIST OF PLATES

This book contains 33 *plates as follows* :—

All other figures are in the text.

CHAPTER I

MANUFACTURE OF IRON AND STEEL

IRON is a white ductile metal and one of the chemical elements. It has a specific gravity of 7·8. Although in the crust of the earth to the extent of approximately 4·4 per cent, it is only present in the pure state in very small amounts and of meteoric origin.

The chief source of iron for manufacture into pig iron is from combinations with a large proportion of other elements, most of them non-metallic, and from these it must be separated by a reduction process known as smelting. These combinations of iron with other elements are known as iron ores.

Ores of iron. There are many kinds of iron ore, some too low in iron content, and others containing too high a proportion of certain elements, notably sulphur, to be of value commercially.

The most important are those known as magnetites, red hematites, brown hematites, and clay ironstones, all being always associated to some extent with earthy and other foreign matter known as " gangue."

The ores richest in iron content are the magnetites, largely mined in Sweden, and, as their name implies, they are magnetic, the iron being in combination with oxygen in the form of magnetic oxide of iron Fe_3O_4 containing the equivalent of 66 to 69 per cent of metallic iron. They are of exceptional purity, containing very little phosphorus and sulphur, a condition which leads to the production of the finest irons and steels.

The red hematites contain their iron in the form of ferric oxide Fe_2O_3, and are, like magnetite, usually low in phosphorus and sulphur. The available iron content of 50 to 60 per cent is rather lower, as the oxide of iron is associated with more other impurities, chiefly alumina and silica. Pig iron manufactured from ores low in sulphur and phosphorus is known as " hematite iron," which has various special uses, such as special foundry irons, malleable cast irons, and for the production of steel in the acid process. These ores are mined in Spain, and also in Cumberland in this country.

Brown hematites form the most abundant sources of ore for the production of pig iron, and occur in beds in Northamptonshire and Lincolnshire. They are to a large extent phosphoric, containing approximately 0·5 per cent phosphorus, and 40 per cent of iron in the form of hydrated oxides, that is to say, the oxide is in chemical combination with water $Fe_2O_3H_2O$. The irons produced from these ores are used as ordinary foundry irons and in the production of basic steel.

Clay ironstones consist of impure carbonates of iron $Fe\,CO_3$ and also contain various amounts of clayey substance. The iron content varies according to the amounts of impurities present, but is generally between 27 and 33 per cent. The chief impurities are silica, alumina, and carbonates of lime and magnesium. The best known deposit of this type of ore is the Cleveland Ironstone, often somewhat more phosphoric than other ores, and a content of phosphorus in excess of 1 per cent is common.

Before use in the blast furnace the ore is often subjected to a roasting or calcining treatment during which some of the sulphur is removed, and also carbon dioxide from any carbonates present. The ore for calcining may be segregated into large heaps along with layers of slack coal, and then fired. When the roasting is complete, the residue is left for a time to weather, whereby further sulphur may be washed out.

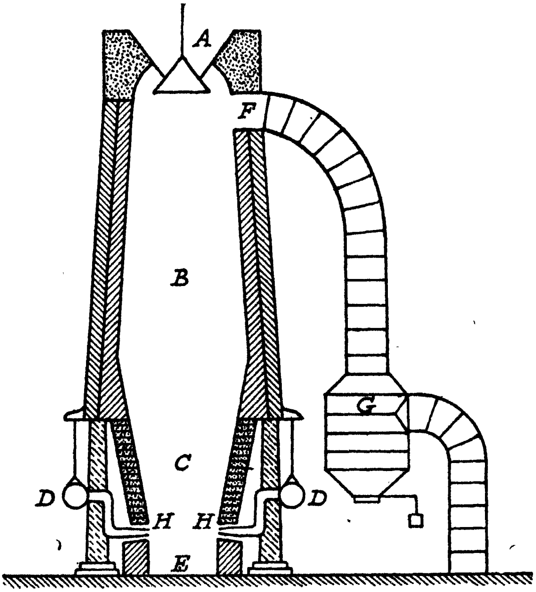
Calcining is also carried out in large kilns charged from wagons on rails running over the top, the ore afterwards being withdrawn from the bottom of the kiln.

THE BLAST FURNACE

Blast furnaces vary greatly in dimensions according to the output of iron required. They consist of a tall, cylindrical stack lined with silicious firebrick. Fig. 1 shows the general lines of a blast furnace. The hearth is the bottom and usually straight portion which occupies approximately the lower 8 ft., and is 10 to 18 ft. in diameter. Directly above, the furnace widens to its maximum diameter, this section being known as the bosh, 10 to 17 ft. in height and 17 to 23 ft. in diameter. The stack above this tapers very gradually to the top of the furnace body, giving a total height of between 70 and 100 ft.

The hearth is kept in a comparatively cool condition by a continuous flow of water round its circumference. The water-cooled tuyeres through which the blast enters the furnace are 8 to 16 in number, 4 to 7 in. in diameter, and are arranged round the top of the hearth. 30 to 40 in. below the tuyeres and rather to the side of the furnace is the hole for removal of slag. The tapping hole for the molten iron is situated at the front and at the bottom of the hearth.

The charges of iron ore, coke, etc., are, in modern practice, mechanically hauled up a steep incline in "skips" or rails, and tipped into the furnace by way of a revolving distributor, and are admitted evenly by lowering the cone operated by cylinders working on air pressure. The stack is kept full by charging alternate layers of fuel, flux such as limestone, and iron ore. The fuel is usually coke, which acts as a reducing agent by reducing the iron ore to metallic iron, and its combustion near the smelting zone provides sufficient heat to maintain the iron in a fluid condition.



A	Cup and cone.
B	Stack.
C	Bosh.
D	Blast main.
E	Hearth.
F	Gas main.
G	Dust catcher.
H	Tuyeres.

FIG. 1.—General lines of Blast Furnace with Downcomer.

The blast varies in pressure between 5 and 12 lb. per sq. in. with the size and shape of the furnace, and usually enters in a preheated condition, the preheating taking place in stoves by the combustion of waste gases from the furnace. The stove is cylindrical in shape with a round top, almost as high as the furnace itself, and is honeycombed with specially shaped firebrick. The principle of the hot blast stove is illustrated in Fig. 2. The waste furnace gas is burnt along with the air necessary for combustion, and heats up the brickwork of the stove. When the brickwork has attained a sufficiently high temperature, a system of valves enables the gas to be directed to another stove. Then the blast, which is passed through the heated stove in the other direction, takes up heat from the brickwork and enters the blast furnace at a temperature of 500 to 700°C. Stoves are used alternately —whilst one is being heated by the waste gas from the furnace, another is giving up its heat to the blast on its way to the furnace.

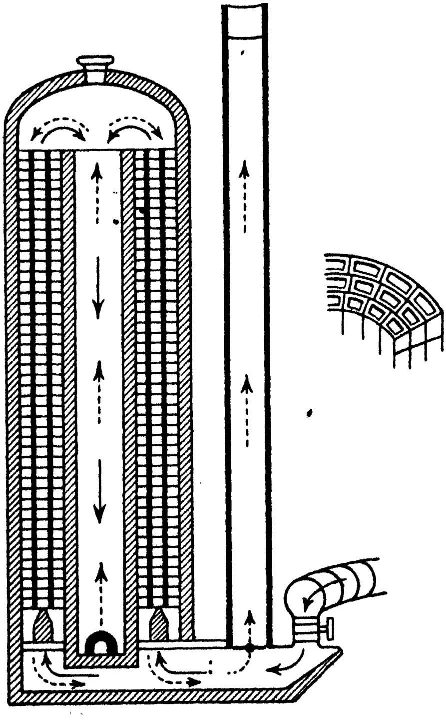


FIG. 2.—Sectional Diagram of Blast-Furnace Stove.

The chemical reactions which take place as the charges proceed down the stack are rather complicated and often reversible, but gradual reduction of the iron ore begins just below the top charges or stock line, at a temperature of about 300°C. Metallic iron is formed lower down the stack at about 700°C., where it is in a spongy condition. From this stage the iron begins to absorb carbon, and, when it reaches the smelting zone, it trickles over the coke, from which it completes its saturation with carbon.

The location of the smelting zone is dependent upon the volume and pressure of the blast, but generally ranges from the tuyere level to the top of the bosh. In the smelting zone, strong reducing conditions prevail, where the metal oxides, and also the iron sulphide in the ore, are reduced according to the following equations :—

$$(1)\quad \underset{\text{Silica}}{SiO_2} + \underset{\text{Coke}}{2C} = \underset{\text{Silicon}}{Si} + \underset{\text{Carbon Monoxide}}{CO}$$

$$(2)\quad \underset{\text{Manganese Oxide}}{MnO_2} + \underset{\text{Coke}}{2C} = \underset{\text{Manganese}}{Mn} + \underset{\text{Carbon Monoxide}}{2CO}$$

$$(3)\quad \underset{\text{Phosphoric Oxide}}{P_2O_5} + \underset{\text{Coke}}{5C} = \underset{\text{Phosphorus}}{2P} + \underset{\text{Carbon Monoxide}}{5CO}$$

$$(4)\quad \underset{\text{Iron Sulphide}}{FeS} + \underset{\text{Lime}}{CaO} + \underset{\text{Coke}}{C} = \underset{\substack{\text{Calcium}\\ \text{Sulphide}}}{CaS} + \underset{\text{Iron}}{Fe} + \underset{\text{Carbon Monoxide}}{CO}$$

The lime indicated in the last equation is provided by the limestone charge or the calcium carbonate present in the gangue of the iron ore. The limestone also combines and fuses with any residual silica not reduced by the coke, and helps to maintain a fluid slag. It will be seen therefore that when the carbonates of lime and magnesium are present in considerable amounts, the ore is, to a great extent, self-fluxing.

The carbon in the coke combines with the oxygen of the air blown in, to form carbon dioxide, but this gas yields carbon monoxide either by dissociation or by combining with more carbon

$$(5)\qquad CO_2+C=2CO$$

The carbon monoxide released, as indicated in the above equation, rises up the furnace chamber, and brings about the reduction of the iron oxide in the ore according to the reaction

$$(6)\qquad Fe_2O_3+3CO=2Fe+3CO_2$$

Other reversible reactions take place in the stack, resulting in the inclusion of combustible matter in the waste gas led away in downtakes from the top of the furnace, the gas being utilised for heating the stoves.

It will be seen from reactions 1 to 4 that the stronger the reducing action, the more sulphur from the iron sulphide enters the slag in the form of calcium sulphide, and therefore the sulphur content of the iron is comparatively low. Also with increasing reducing action, more silica is reduced to silicon which dissolves in the metal, and consequently high silicon iron is generally associated with low sulphur. The amount of reduction in the smelting zone is controlled by the process of altering the burden of the furnace, that is, the ratio of ore to fuel. The heavier the burden, the less reducing are the furnace conditions, and pig irons of lower silicon contents are produced.

The blast furnace produces between 150 and 400 tons of pig iron per day, and the iron is removed in the molten condition from the tapping hole at the bottom of the hearth at regular intervals of 6 or 8 hours. The slag being lighter, floats on top of the iron contained in the hearth, and is removed at more frequent intervals from the slag hole from which it runs into large bogies on rails. When cool, the slag is ground and used as cinder for road making.

FIG. 3.—A Modern Blast Furnace.
(Courtesy—Messrs. Ashmore Benson and Pease, Ltd.)

After tapping, the iron is led down a long, slightly inclined vee-shaped main runner moulded in sand, from which branch off at right angles a number of comb-shaped moulds also moulded in sand and known as pig beds. The bottom comb of pig moulds is filled first and a specially shaped cast-iron stop coated with dried loam is placed across the main runner just above the bottom comb, thereby diverting the iron into the second comb. This process is continued up the pig bed until the cast is complete. As the furnace hearth becomes empty, any slag floating on the iron tends to run down the main runner along with the iron, but, being lighter and fluid, it is easily skimmed off with an adjustable steel plate which is backed with a heap of sand. Towards the end of the cast this skimming plate is progressively hammered down as the level of the molten iron falls in the runner, so that

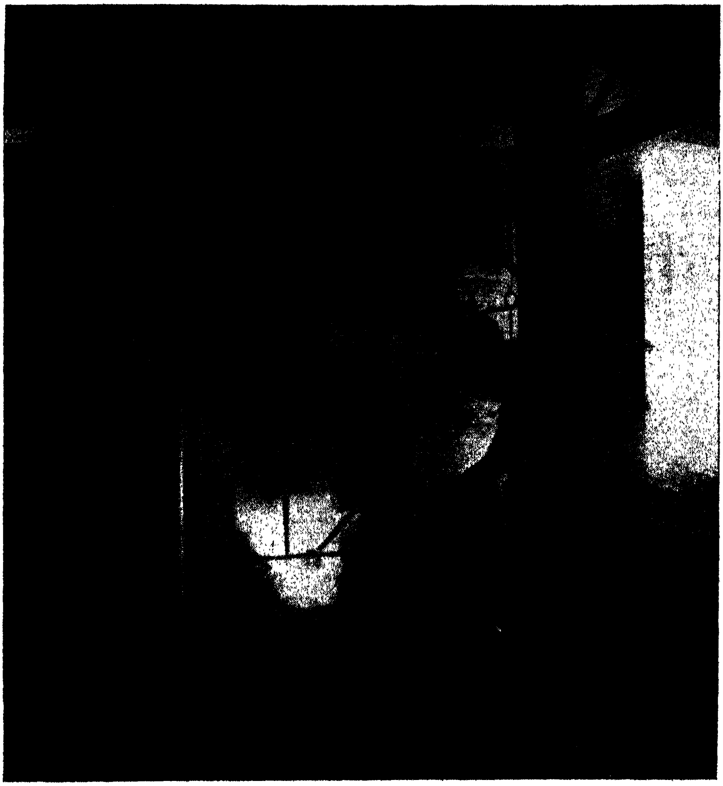


FIG. 4.—Tapping the Blast Furnace.
(Courtesy—The Stanton Ironworks Company, Ltd.)

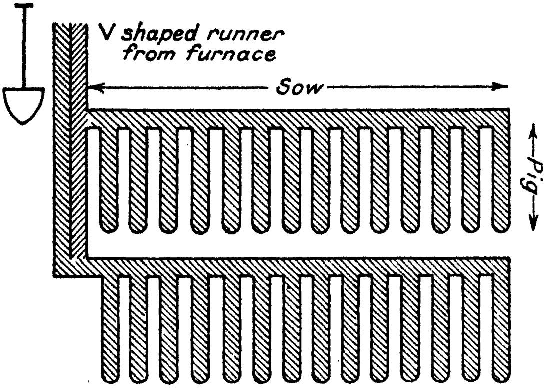


FIG. 5.—Diagram of Pig Beds.

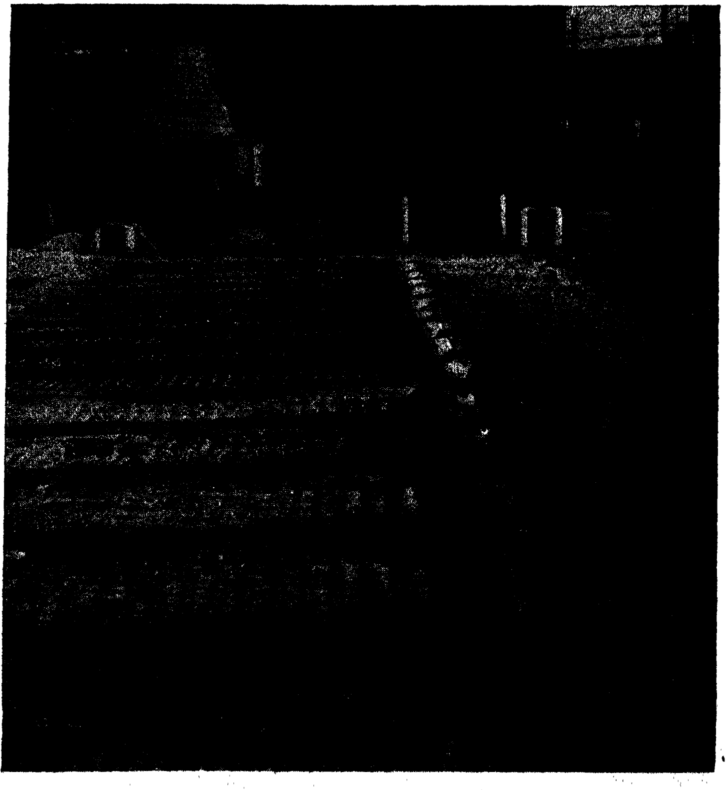


FIG. 6.—Leading the Molten Iron into Pig Beds.
(*Courtesy—The Stanton Ironworks Company, Ltd.*)

at no time does any quantity of slag find its way into the pig beds. The skimmed slag is led over into a further runner set at an angle to the iron runner and into a slag bogie.

Many blast furnace plants employ a casting machine for the production of pigs. The molten iron flows from a single or from double runners into a series of iron moulds closely connected together to form a continuously moving conveyor. As the moving moulds are filled with iron, they progress up an incline and by the time they reach the other end of the machine, the iron has solidified. When the moulds pass over the sheave at the extremity of the machine on their return journey, the pig iron falls into a truck underneath. The moulds are coated with lime wash to facilitate removal of the pig iron. Machine casting of pig iron has the advantage that no sand adheres to the pig, and is therefore cleaner than the sand-cast pig. It is also considered that the shape of the pigs, which are shorter in length and wider, renders them more suitable for handling and charging into other furnaces for re-melting. There is also a considerable saving in labour as compared with the sand-casting method.

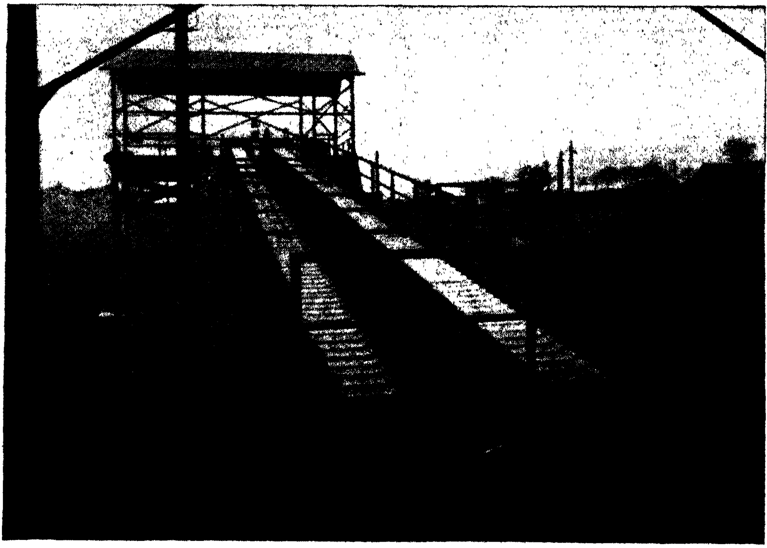


FIG. 7.—Machine Casting of Pig Iron.
(*Courtesy—The Stanton Ironworks Company, Ltd.*)

Grading of pig iron. The crystalline fracture of broken pig iron varies according to the chemical composition, and the fracture therefore gives some indication of the amount of silicon present, but the size of the pig and rate of cooling has also some influence on the appearance.

The sand-cast iron is usually graded by a series of numbers, often 1 to 5, preceded by glazed (silicious or silvery) and followed by mottled and white. The table on p. 220 gives the approximate composition of phosphoric pig iron graded by fracture.

WROUGHT IRON

Its manufacture. Wrought iron is manufactured in a reverberatory furnace constructed so that the fireplace is large compared with the working chamber, in order to obtain the high temperature necessary for the process. The sides and roof are lined with firebrick whilst the bottom is constructed with cast-iron plates covered over with a basin of fettling material consisting of hammer slag, iron oxide, and iron ore.

When the furnace is heated, this material frits together into a compact working bed which is finally smoothed down by working over it a ball of scrap iron when the furnace has attained welding heat.

About 4½ cwt. of close grey pig iron is charged into the furnace through the door at the side, along with a quantity of mill scale and iron ore. Melting of the pig iron is complete in about half an hour, during which period some silicon, manganese and phosphorus are removed by oxidation.

Then comes a period when the iron remains quietly molten, and at the same time the remainder of the silicon and manganese is removed, and also most of the phosphorus.

After the removal of these impurities comes the " boil," when the carbon combines with the oxygen of the scale and ore, and passes from the metal vigorously as bubbles of carbon monoxide, giving the bath the appearance of boiling. The remainder of the phosphorus is removed at this stage.

As the carbon is removed, the melting-point of the metal rises, and, because the temperature of the furnace is insufficient to maintain the bath in a molten condition, the metal becomes pasty. The temperature of the furnace is then raised to a welding heat, and the spongy iron is worked into conveniently sized balls up to 80 lb. in weight, which are removed through the working door and taken to presses or hammers, where most of the trapped slag is squeezed out.

When as much slag as possible has been removed, the iron is rolled into bars of suitable size. The analysis of the finished material is :—

Silicon	0·1 to 0·3	per cent
Manganese	Traces to 0·05	,,
Phosphorus	0·04 to 0·20	,,
Carbon	0·02 to 0·10	,,
Sulphur	Traces to 0·02	,,

Properties and uses. Wrought iron is easily welded and worked, withstanding repeated heatings and forging operations without deterioration. It is a soft material, has excellent ductility, and a bar can be bent double without fracture. It is characterised by fine included slag fibres, the presence of which distinguishes wrought iron from mild steel.

The use of wrought iron has, to a large extent, been replaced by mild steel, but, owing to its excellent forging and welding properties, it is still extensively used for general blacksmiths' work, chain links, couplings and ornamental work.

It has a tensile strength of 21 to 24 tons per sq. in. and 10 to 40 per cent elongation.

THE MANUFACTURE OF STEEL

Steel is not produced directly from iron ore but from iron taken from the blast furnace or cupola. By far the largest output of steel is manufactured by two processes known as the Bessemer and the Siemens-Martin open-hearth process. These may conveniently be sub-divided into acid and basic methods, being qualified by the type and composition of the metal charge to be dealt with. For the purpose of the two different treatments, the furnaces must be provided with a special acid or basic lining of refractory material, which serves a specific purpose during the process. By acid, we do not mean that the material is corrosive in the way in which we regard many well-known chemicals, but it does signify that the material will combine, as these linings do, with basic materials under the application of furnace heat. By refractory is meant " materials difficult to melt " and hence their application in the lining of furnaces. The more generally used refractories are those referred to below :—

Acid refractories

Fireclay. Contains varying proportions of aluminium silicate but is more or less rich in silica.

Ganister. A deposit of silica rock of mixed grading and containing 3 per cent of clay along with other small amounts of impurities. It is self-bonding and, after mixing with the correct amount of water, may be rammed into position to make up the lining of furnaces. On heating it sets into a very hard material.

Firebrick. Manufactured from selected clays.

Sand. Hard grains of silicious material, often containing small amounts of iron oxide which give sand its orange to red colour. Compositional range of sand is roughly 85 to 93 per cent silica, 4·5 to 7 per cent alumina, and 2 to 3·5 per cent iron oxide.

White or silica sand. Contains more than 97 per cent silica, and, as it is often too refractory to be used alone, it is sometimes mixed with a little of the red variety, the iron oxide helping to form fusible silicates under heat. The silicates so produced act as bonding agents.

Silica brick. Contains 95 per cent silica with a little iron oxide and alumina, and is manufactured to a great extent from ganister.

Basic refractories. This type of refractory should be practically free from silica and consists mainly of the following materials :—

Dolomite. Raw dolomite is essentially a mixture of the carbonates of calcium and magnesium ($CaCO_3$ and $MgCO_3$). Before use the material is burnt or calcined, that is to say, the carbon dioxide is driven off by heating to 900°C. or more for a sufficiently long period to convert it to the mixed oxides of calcium and magnesium.

Magnesite. Magnesium carbonate containing the equivalent of roughly 45 per cent MgO. When calcined it contains about 94 per cent MgO.

Limestone. Is calcium carbonate containing the equivalent of roughly 53 per cent CaO. When calcined it is converted into lime.

Neutral refractories. This class of refractory is chemically neutral in behaviour either because the substance itself is such, or because its acid and basic constituents are evenly balanced. Examples of such materials are :—

Carborundum. Containing 75 to 87 per cent silicon carbide.

Chromite. Made into chrome bricks, and contains 50 to 60 per cent chromium oxide.

Graphite. Chiefly carbon.

In lining a furnace for basic practice the lining may not be of basic material throughout, but a layer of neutral refractory such as chrome brick is often used to separate an outer lining of silica brick from an inner lining of basic material, thereby preventing chemical action between them at high temperatures.

THE BESSEMER PROCESS

This process consists essentially of the oxidation of impurities in molten iron by blowing air through it. The furnace used is known as a converter and consists of a mild steel shell, roughly pear shaped, and lined with refractory material either acid or basic in character, the choice depending upon the composition of the iron available. The air blast enters the converter through a wind box from which emerge a number of fireclay tuyeres. These may be situated in the bottom of the lining, but they may also enter at the side as in the Tropenas converter. The whole is supported and rotated on two trunnions, one being hollow in order to carry the blast to the wind box. The shape of the converter is such that, when lying on its side, the metal will not cover the tuyere holes, otherwise, when the blast is turned off, the metal would run down into the wind box (Fig. 8). The finished steel has a much higher temperature than the iron originally charged into the converter, the necessary heat being supplied by the chemical process of oxidation of the

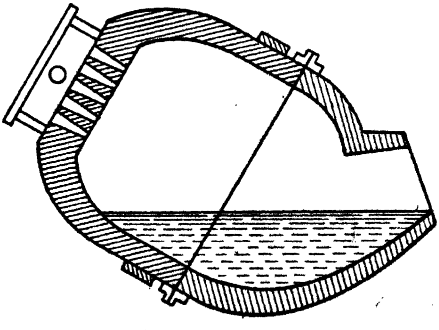


Fig. 8.—Sectional Diagram of the Bessemer Converter.

impurities in the charge. The elements carbon, silicon, manganese and phosphorus act as internal fuels.

In large Bessemer plants, molten iron from the blast furnace is transferred in ladles to a receptacle known as a metal mixer where the metal may be stored in large quantities. The molten metal is here thoroughly mixed and transformed into a condition of greater homogenity and at the same time kept hot whilst awaiting use at the converter. The mixer is usually fired by gas. There are two types, namely, active and inactive. In the active mixer the metal is pre-refined to some extent before use in secondary furnaces, since some oxidation of silicon and manganese occurs, and some reduction of sulphur takes place in basic-lined vessels. The mixer body is supported on rollers and is tipped either electrically or hydraulically. Capacities of mixers range from 250 to 1000 tons.

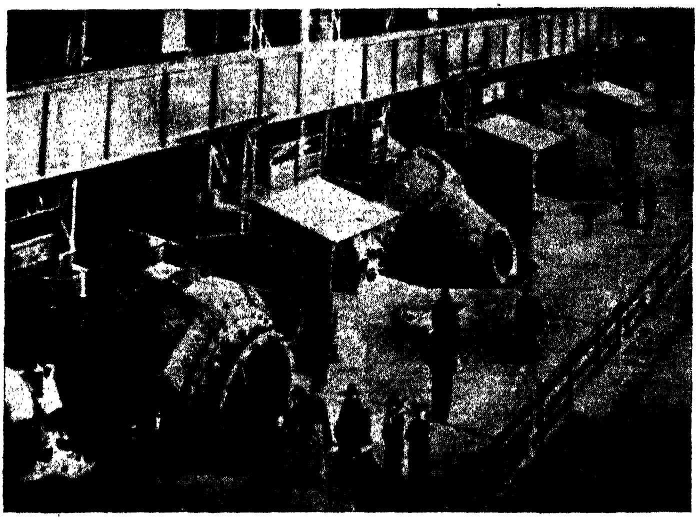


FIG. 9.—Bessemer Converters.

The Acid Bessemer process. The lining of the furnace is made up with ganister rammed into position. With a lining of this type no removal of sulphur and phosphorus occurs. The irons employed are always of the hematite variety containing about 2 per cent silicon, 0·5 to 1·0 per cent manganese and 3·5 per cent carbon.

When the blast is turned on and the converter tipped for blowing, the air bubbles vigorously through the metal. The process then consists of three distinct stages.

(1) When the silicon is oxidised to silica and the manganese is oxidised to oxide of manganese. The oxidation of silicon and manganese transfers heat to the metal, and the oxides of these elements rise to the surface. It is important that the initial temperature of the iron poured into the converter is not too hot, because, owing to the development of further heat during the oxidation of silicon and manganese, the second stage of the process may proceed before the first is completed, resulting in residual silicon in the finished steel.

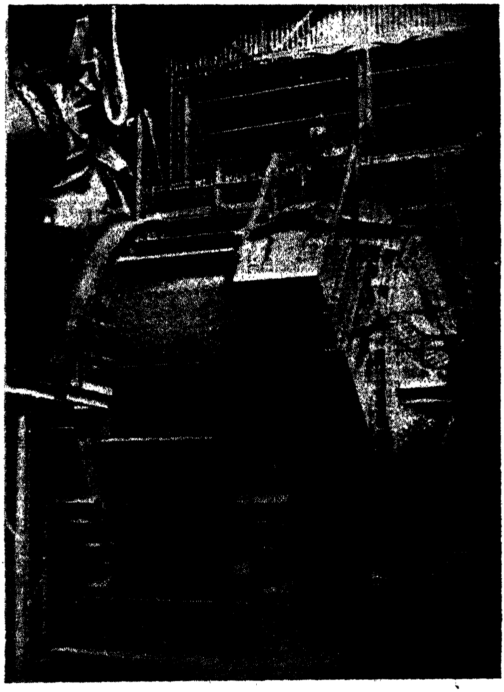


FIG. 10.—A 400-ton Metal Mixer. Inactive Type.
(*Courtesy—Wellman Smith Owen Engineering Corporation, Ltd.*)

(2) When the silicon content is sufficiently reduced, rapid elimination of carbon begins with the liberation of carbon monoxide, which bubbles vigorously through the slag and burns with a large flame at the mouth of the converter. This

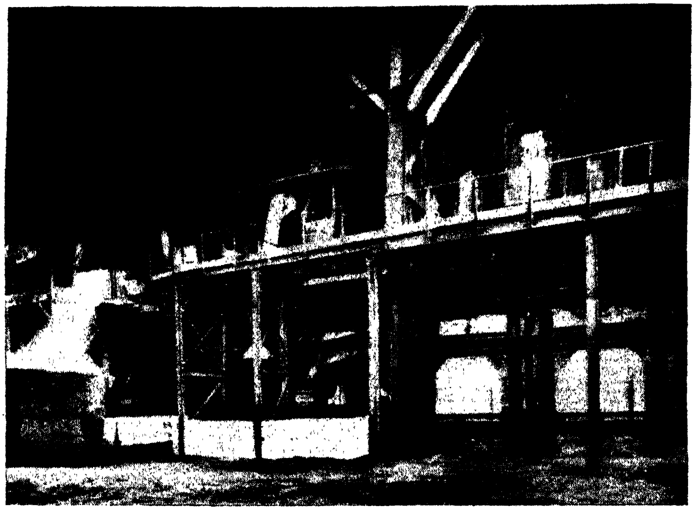


FIG. 11.—Tapping Side of a 400-ton Metal Mixer. Active Type. (*Courtesy—Messrs. Wellman Smith Owen Engineering Corporation, Ltd.*)

FIG. 12.—A Bessemer Converter during the " Boil " Period.

period is known as the "boil," and particles of white-hot slag and metal are showered into the air (Fig. 12).

(3) When all the carbon is oxidised, the flame suddenly drops and the blast is shut off. If the blowing is continued, if only for a short time, the steel may be overblown, due to oxidation of metallic iron, and steel containing a considerable amount of iron oxide is obtained. Under-blowing may result in a steel containing too much carbon.

The blown steel then has the following composition : 0·04 to 0·06 per cent carbon, 0·02 to 0·06 per cent silicon, traces of manganese, and the sulphur and phosphorus remaining low in practically the same proportion as in the original iron charged. The carbon and especially the manganese content are too low at this point, and the steel may contain some iron oxide. Deoxidation and recarburisation are then carried out by additions of iron-manganese-carbon alloys, either speigel (12 to 20 per cent manganese and 2 to 4 per cent carbon) or ferro-manganese (80 per cent manganese and 6 to 7 per cent carbon) until the correct composition is obtained. In addition to giving the required manganese content in the finished steel, the added alloys react with the iron oxide in the steel as follows :—

$$\mathrm{FeO}+\mathrm{Mn}=\mathrm{MnO}+\mathrm{Fe}$$

the manganese oxide rising to the surface of the metal. A little aluminium is also added to perfect the deoxidation.

Acid Bessemer steels are used for all types of castings, and the acid process is used in the production of manganese steel castings.

The Basic Bessemer process. The basic process is similar to the acid process, but the converter is lined with rammed dolomite, and high phosphorus metal can be completely dephosphorised. Pig iron low in silicon is charged, because excessive amounts of silica liberated during the process damage the basic lining of the furnace and retard the elimination of phosphorus and sulphur. The most suitable irons are those which contain considerable amounts of manganese, for oxidation to manganese oxide generates heat, and also because manganese oxide is basic in character it tends to counteract the acidity due to oxidised silicon. Another reason why higher manganese is desirable is because in this process the steel benefits by the retention of a little residual manganese in the blown steel, because over-oxidation of the steel itself is prevented. Manganese also tends to eliminate sulphur, but to a limited extent only. The approximate composition of the basic pig iron used is :—

Silicon	Less than 1 per cent
Phosphorus	Up to 2 per cent
Manganese	1 per cent or more

Again, active metal mixers may be used with much benefit, owing to the lowering of the sulphur and silicon contents.

The molten iron is poured into the converter and sufficient lime is added to maintain a basic slag. Silicon and most of the manganese are oxidised first, along with a little of the carbon. The remainder of the carbon is then eliminated and the flame drops. Only a small amount of the phosphorus is removed in the early stages, and the blowing is continued after the flame drops in order to further oxidise the phosphorus. The oxide of phosphorus is absorbed by the slag. This last stage of the basic process is known as the " after-blow." The oxidation of phosphorus is very exothermic and supplies heat during this period. A comparatively low temperature is desirable during the " after-blow" to avoid complete removal of manganese, thereby minimising the oxidation of the steel. The temperature at this stage can be controlled to a great extent by reserving a portion of the total lime charge until the carbon has been removed. The metal is cooled in this manner, just prior to the beginning of the " after-blow."

The blown steel has very low carbon and silicon contents, and the metal is finally adjusted to the required composition by the addition of iron-carbon-manganese alloys and ferro-silicon. Basic Bessemer steels are used to a large extent in the manufacture of all kinds of structural sections, boiler and ship plates, tubes, rails, axles, tyres and also for castings.

The slag, containing phosphates, is a valuable by-product, and is used as an agricultural fertiliser.

THE SIEMENS-MARTIN OPEN-HEARTH PROCESS

In this process pig iron and steel scrap are melted in comparatively shallow hearths by means of the combustion of gas generated in producers near to the furnace. With the furnace are connected two pairs of regenerative chambers containing firebricks arranged in chequer fashion, through which the gas, along with the air necessary for combustion, are passed independently of each other before entering the furnace chamber where combustion occurs. The regenerators are used in pairs, one pair being heated up by the hot waste products of combustion from the furnace, and, at the same time, through the other already heated pair is being passed the air and gas for combustion in the furnace chamber. By this system the in-going air and gas are preheated to a temperature of between 500 and 800°C., and this additional heat assists in providing the necessary temperature for melting the metal. Each pair of regenerators is used alternately, and, by means of a system of valves, the direction of the gas, air, and waste gases is reversed every 20 to 30 minutes. During the operation of the furnace, slag, dust and dirt tend to be carried over by the out-going gases, and to intercept this and minimise the choking up of the chequer brickwork, slag pockets are provided.

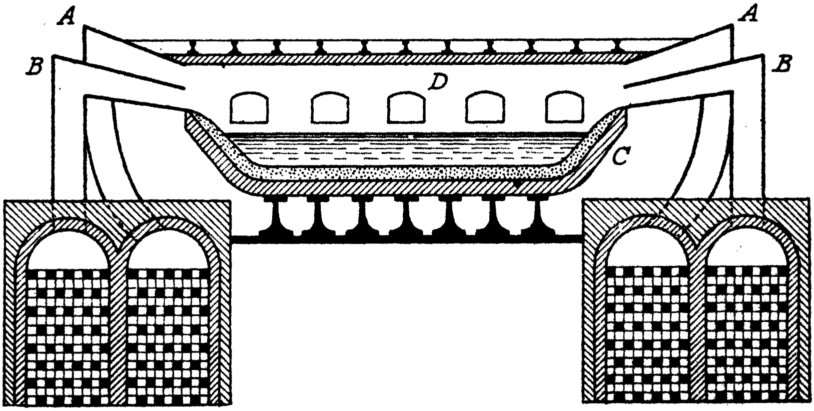


FIG. 13.—Sectional Diagram of Open-Hearth Furnace with Regenerators.
A and *B* Gas and air ports. *C* Hearth. *D* Charging doors.

Charging is carried out by the use of an overhead revolving charging machine or a ground type machine. The latter is used where it is desirable to have passing over, an overhead crane such as a ladle crane. The charge is placed in the furnace through a series of doors, often water-cooled, at the back of the furnace.

The furnace itself may be either of the tipping or fixed type, of capacities ranging from 10 to 300 tons and constructed of a very refractory material, usually silica brick.

The Acid Siemens process. The hearth, shaped like a shallow saucer, consists of silica sand built up layer by layer under heat.

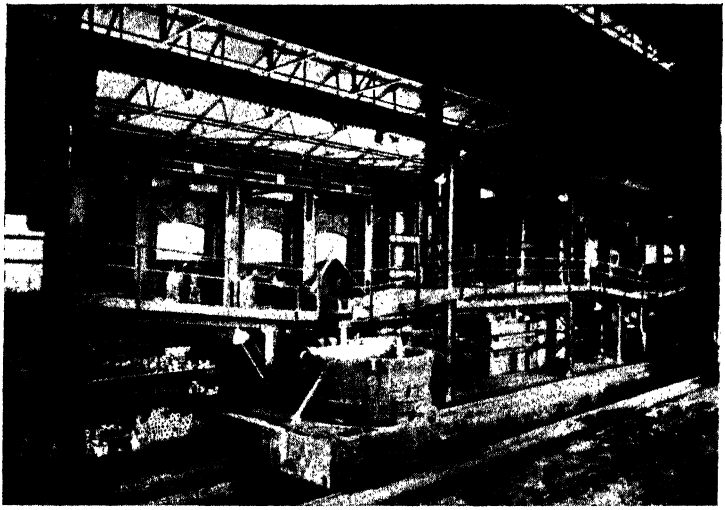


FIG. 14.—A 40-ton Open-Hearth Furnace. Fixed Type.
(*Courtesy—Messrs. Wellman Smith Owen Engineering Corporation, Ltd.*)

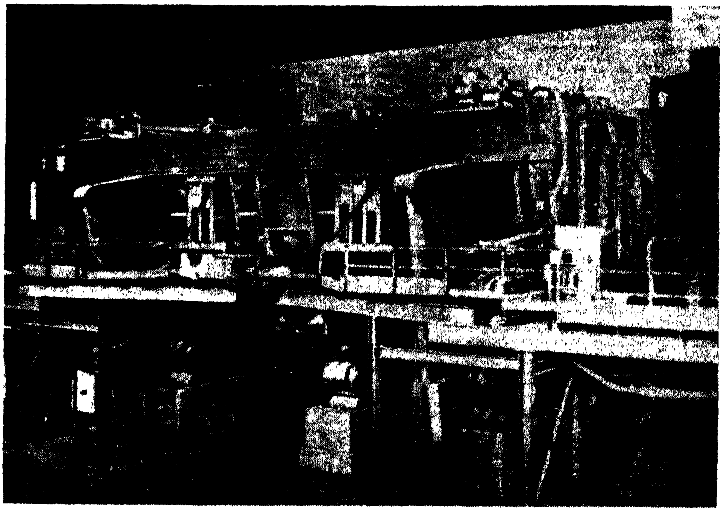


FIG. 15.—A 300-ton Tilting Open-Hearth Furnace.
(*Courtesy—Messrs. Wellman Smith Owen Engineering Corporation, Ltd.*)

Owing to the acid character of the lining, charges must be low in sulphur and phosphorus. The charge is made up with proportions of pig iron and good quality steel scrap, the ratio varying with the type of steel it is desired to produce. Higher proportions of the pig iron are used when a higher quantity of carbon is to be retained in the finished steel, and lower proportions when low carbon is required. Charges of all pig iron could be used but the oxidation period would be too prolonged.

A high average silicon content also prolongs the period between the melting down and commencement of the boil, but quantities of 1 per cent or so are necessary to react with any iron oxide which may be formed and helps to minimise excessive action on the lining of the furnace. Silicon, when oxidised, generates heat, which assists in the melting of the charge. The charge has an approximate manganese content of 0·5 per cent or slightly less.

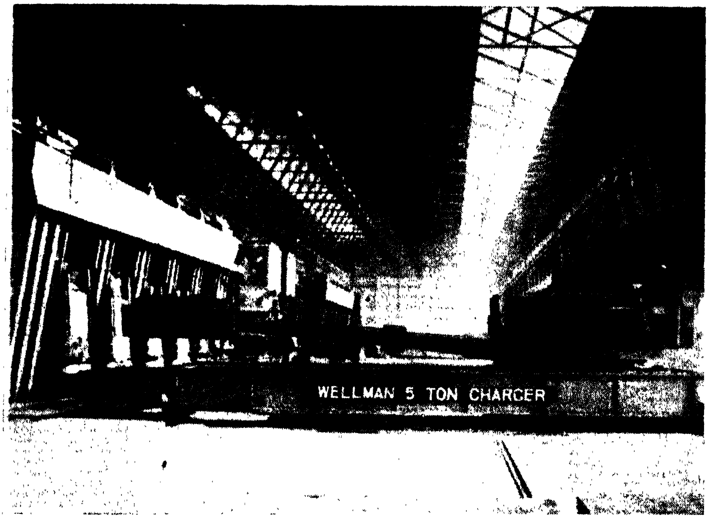


FIG 16.—A 5-ton Charging Machine. Revolving Ground Type. (*Courtesy—Messrs. Wellman Smith Owen Engineering Corporation, Ltd*).

The pig iron is charged first and the steel scrap on top of the pig.

During the process silicon and manganese are oxidised first, and then the carbon is brought down to the required value by additions of hematite iron ore, converting the carbon to carbon monoxide which bubbles through the bath and gives the metal the appearance of boiling.

A simple explanation of the reaction which takes place is that the iron ore Fe_2O_3 breaks up to a great extent at furnace temperature into magnetic iron oxide Fe_3O_4 and oxygen. The magnetic oxide reacts with the carbon in the metal.

$$Fe_3O_4 + C = 3FeO + CO$$

The carbon monoxide liberated dissolves in the metal and slag, and the boil commences when both are saturated with the gas. The oxidation of carbon during the boil is brought about by the reaction between the dissolved ferrous oxide FeO and the carbon in the metal.

FIG. 17.—A 4-ton Charging Machine. Revolving Overhead Type. (*Courtesy—Messrs. Wellman Smith Owen Engineering Corporation, Ltd.*)

$$FeO + C = Fe + CO$$

This reaction decreases the concentration of dissolved oxide in the metal, causing a migration of ferrous oxide from slag to metal, and this continues until a condition of equilibrium is reached, when no more oxidation of carbon occurs. Further additions of ore disturb the equilibrium and further oxidation is promoted. By the taking of spoon samples for rapid analysis,

FIG. 18.—A 300-ton Tilting Furnace. Charging side showing Water-Cooled Doors.

(*Courtesy—Messrs. Wellman Smith Owen Engineering Corporation, Ltd.*)

FIG. 19.—View of removable port end on a 50-ton Basic Open-Hearth Tilting Furnace.

(*Courtesy—Messrs. Wellman Smith Owen Engineering Corporation, Ltd.*)

the oxidation can be discontinued when the desired amount of carbon has been reached.

Deoxidation and adjustment of the manganese content is made with the usual manganese alloys as in the Bessemer process, either by addition to the bath, ladle, or both. To perfect the deoxidation, small quantities of the ferro-alloys of vanadium, titanium, or silicon may be added.

The Basic Siemens process. The hearth of the furnace is lined with burnt dolomite fritted in layer by layer under heat, and each layer having an application of basic slag. Basic pig iron and steel scrap make up the charge, and the proportions vary according to the composition of the pig iron, the required carbon content of the finished steel, etc. In this process, owing to the basic nature of the slag, phosphorus and sulphur are removed. The phosphorus content of the charge usually ranges from 0·25 to 0·50 per cent.

The amount of manganese in the charge is important for several reasons. It acts to some extent as a desulphurising agent, especially if high enough initially to promote the presence of some residual manganese in the steel when oxidation of the other impurities is complete. Also its oxide acts as a base to combine with any silica liberated from the silicon in the charge.

Along with pig iron and steel scrap is added a quantity of lime, the purpose of which is to maintain a strongly basic slag. When the charge is melted, a little fluorspar (calcium fluoride) is added to prevent the slag from becoming too viscous.

The silicon is reduced to a great extent during the melting-down period, along with the loss of some manganese. When the bath is molten, the oxidising medium in the form of iron ore is added from time to time, along with further additions of lime. When available, millscale is preferred to iron ore, since iron ore contains silica as an impurity, and the use of iron ore results in more lime being necessary to maintain a sufficiently basic slag, otherwise dephosphorisation is retarded. Carbon and phosphorus are oxidised together, the best conditions being obtained when the dephosphorisation is complete, when the carbon has been reduced to the desired amount. It is sometimes necessary, however, to continue with the oxidation after the required carbon value has been reached, in order to obtain a sufficiently low phosphorus content.

The steel is then deoxidised as in the previous processes, and the carbon increased to the desired amount by the addition of anthracite coal.

Acid and basic steels. Steels made by the acid process are considered as being rather superior in quality to basic steels on account of the process being more easy to control, there being generally less oxidation of the steel, and consequently less possibility of the presence of non-metallic inclusions. Acid steels are suitable for practically all purposes, particularly high-class castings. However, when the process is correctly controlled, that is, when the oxidation of impurities is complete when the carbon has been reduced to the desired value, and particularly when manganese is present throughout the heat, basic steels of very satisfactory quality are obtained, which renders them suitable for many purposes, including structural work, for tubes, and for the production of wire for ropes, etc.

Steel production in the electric furnace. Both acid and basic processes can be employed, and the lining of the furnace is accordingly made up with acid or basic materials. The acid process is used when good quality steel scrap is available.

However, as the price of electrical energy is comparatively high, the general aim is the production of high-quality steels from the cheaper type of scrap materials which may contain appreciable amounts of sulphur and phosphorus. In view of this, the furnaces, mostly of the arc type, operate with basic linings made up with domolite, magnesite, or mixtures of the two. Boiling anhydrous tar is used as a binding agent for the rammed lining. When the charge begins to melt, a quantity of the usual slag-making and oxidising materials—lime, iron ore and fluorspar—are added. Oxidation then proceeds along with the melting of the charge, and, when complete, the slag covering is removed. The slag removal is rather important owing to the subsequent processes of deoxidation and desulphurisation requiring reducing conditions, which, if the slag was still present, would cause the phosphate in the slag to be reduced and re-enter the metal.

The bath is recarburised by stirring in anthracite coal. The reducing conditions are promoted by additions of lime, fluorspar, crushed coal or coke and ferro-silicon. The lime and carbon are the chief desulphurising agents and act as follows :—

$$CaO + C + FeS = CaS + CO + Fe$$

and, as a result of this reaction, some of the carbon monoxide may dissolve in the bath. The dissolved gas is then removed by addition of the appropriate amount of ferro-silicon, the silicon acting in the following manner :—

$$2CO+Si=SiO_2+2C$$

which minimises the possibility of blowholes due to released carbon monoxide when the molten steel is poured, and solidifies.

TYPES OF MELTING FURNACE FOR IRON AND STEEL

The cupola. The cupola bears a similarity of construction to the blast furnace. It is, however, much smaller, and its other main distinction is that whilst the chief function of the coke in the blast furnace is to reduce the iron ore to iron, its purpose in the cupola is to melt pig iron, iron scrap and steel in the production of cast iron for use in foundries, or molten iron for small Bessemer plants, etc. The cupola is used in some instances as the primary melting unit in the duplex melting process, the refining and superheating of the molten iron being carried out in a secondary furnace of another type.

It consists of a cylindrical steel shell lined with firebricks and ganister. The shell stands on a brick foundation or on steel pillars, the latter type usually having hinged drop bottom doors. Ten feet or more from the bottom of the cupola is an opening for the introduction of the charges. The shell is usually continued for a distance of several feet to form a chimney. The wind belt is near the bottom of the stack from which emerge through the lining one or more rows of tuyeres. In the type known as the Balance Blast cupola, there is a row of main tuyeres near the bottom of the wind belt, and higher up in the same wind belt two or more rows of small auxiliary tuyeres. The bottom tuyeres are valved and their adjustment allows variation of the amount of air which passes through the upper and smaller tuyeres. It is claimed that this arrangement promotes preheating of the iron before reaching the actual melting zone, thereby effecting a saving in coke, and providing hotter and more fluid iron. The total tuyere area of cupolas in general, is about one-fifth to one-sixth of the cupola cross-sectional area.

The working bottom of sand is made up to slope slightly towards the tapping hole. The slag hole is situated midway between two tuyeres and 5 to 7 in. below the tuyere level.

A bed of coke reaching from the sand bottom to 18 in. to 3 ft. above the tuyeres is lit. On the bed is placed a charge of iron, and on top of this a charge of coke approximately one-tenth of the weight of the iron. Along with the coke is added a little limestone, about 50 lb. per ton of iron charged, and this combines with any sand adhering to the pig and scrap, and ash

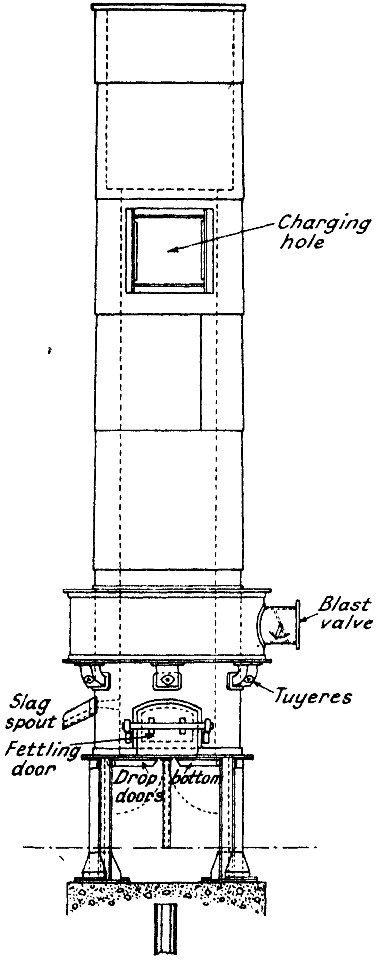


FIG. 20.—General Construction of the Cupola.

(*Courtesy—Messrs. Pneulec, Ltd.*)

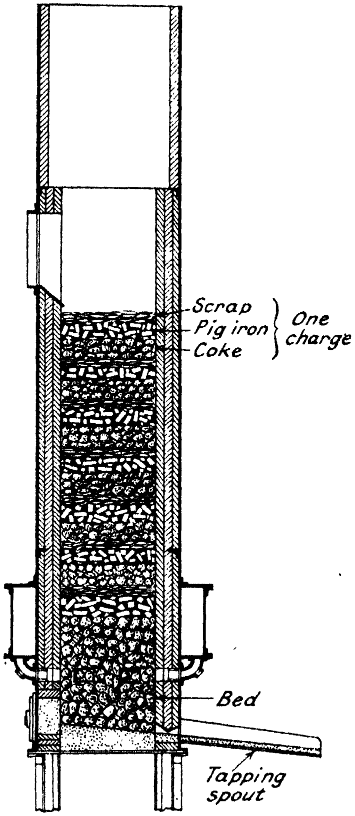


FIG. 21.—Cross-Section of Cupola showing Arrangement of Charges.

(*Courtesy—Messrs. Pneulec, Ltd.*)

from the coke, all of which when fused and molten form a fluid slag. The iron and coke are introduced in alternate layers until the charging door is reached. The weight of the charges depends upon the diameter of the cupola and is largely determined by practical experience. When the cupola contains the required number of charges, the tuyere covers are closed, the tap hole closed by plugging with damp clay, and the blast turned on. After a period of about ten minutes, drops of molten metal can be seen dropping by the tuyere sight holes. The iron collects in the bottom of the furnace, filling in the spaces between the coke lumps of the bed. When sufficient metal has collected in the well of the cupola, the clay plug at the tap hole is pierced with a pointed steel bar, and the molten iron is run down the spout into a ladle or other receptacle.

The melting zone is a short distance above tuyere level, and, as the top of the coke bed burns away whilst melting the first charge of iron, the first charge of coke above the first charge of iron takes its place. This sequence is repeated continuously with each following layer of iron and coke, and, with suitable practice, the bed is thereby maintained at a constant height. In cupola practice it is important that the bed should remain at the same height—a low bed leads to cold and sluggishly pouring iron, and a high bed gives high sulphur and carbon contents due to pick up from the excess coke. As the charges melt and the level of the material in the stack falls, other charges are introduced so that the stack remains full throughout the run, enabling them to be preheated before reaching the melting zone.

The blast pressure varies from about 7 oz. per sq. in. for small cupolas to 13 oz. per sq. in. for larger ones. 30,000 cu. ft. of air are required to melt one ton of iron. The melting rate of the cupola is roughly determined by its diameter, as 10 to 11 lb. of iron are melted per hour for every square inch of cross-sectional area at the melting zone.

If the operation of the cupola is consistent, and all metal, coke charges, etc., carefully weighed, a continuous supply of uniform metal can be obtained. The cupola may be operated on continuous tapping by allowing the tap hole to remain open, and the iron run into a large mixing ladle or receiver from which it is drawn as required. If a continuous supply of metal is not required, intermittent tapping is employed by closing the tap hole with a plug of clay, and re-opening when iron is required.

A disadvantage of the cupola is that there are oxidation losses which will fluctuate if the working conditions such as blast pressure and volume, height of coke bed, weight of charges, etc., are not consistent. Oxidation losses are usually allowed for when charges are calculated as indicated below :—

Silicon is decreased by oxidation from the theoretical amount charged by 0·25 to 0·40 per cent.

Manganese is decreased by oxidation from the theoretical amount charged by approximately 0·3 per cent.

In the case of the sulphur there is an increase of 0·015 to 0·030 per cent over the theoretical amount and which is absorbed from the coke.

The air or reverberatory furnace. The air furnace consists essentially of suitable firing equipment, a bed or hearth where melting takes place, and a chimney stack. Originally all air furnaces were hand-fired, burning lump coal in a firegrate at one end of the furnace, but, in general, pulverised fuel is now used, and in some cases oil firing has been adopted. The metal is melted by radiation from the flame and the shape of the roof is consequently important. The shape of the roof has undergone several changes in the course of time and different shapes are still used. In the early days of the air furnace, a roof with a double arch was employed in which the lowest point was near the middle of the hearth, the heat being mainly concentrated at that point. A more popular design now is a straight roof or one which slopes downwards to the chimney flue. The roof is sometimes made up in sections known as bungs, some being removable for charging purposes. The furnace is constructed of steel or cast-iron plates usually braced across with steel tie rods. The

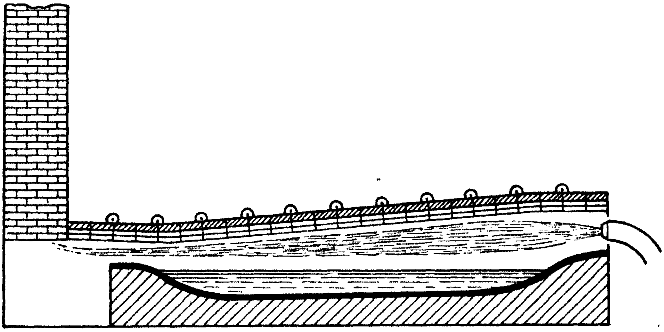


FIG. 22.—Sectional Diagram of Air Furnace.

lining consists of firebrick, and patching or repairing is carried out with ganister or fireclay. The well is made up with firebrick covered with a layer of fritted sand, the tap hole being situated at the lowest level of the well. In larger furnaces there may be more than one tap hole, the others being situated at various levels.

For furnaces fired with lump coal, adequate draught for combustion is provided by a good chimney, although forced draught is used in some instances.

Pulverised fuel, usually burnt with a combination of forced primary and secondary air, is considered to be cheaper and more convenient than lump coal firing. Also the times required for melting the charges are more consistent.

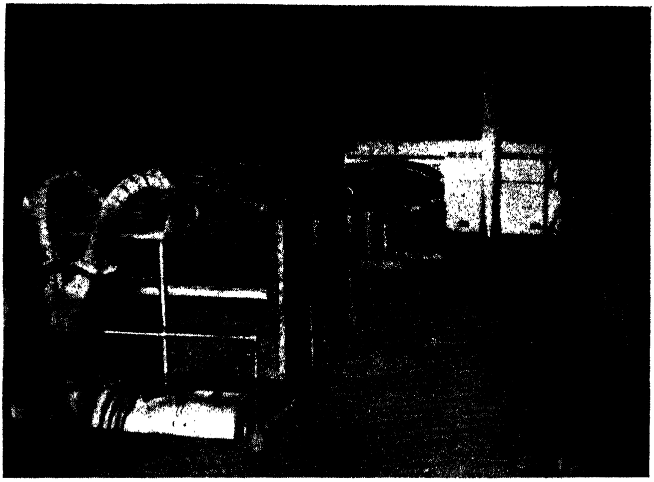


FIG. 23.—An Air Furnace (Whiting Corporation).
(*Courtesy—Whiting Corporation.*)

Air furnaces deal with charges of metal ranging from 5 to 30 tons, an average size being about 15 tons. There is a considerable loss of silicon, manganese and carbon due to oxidation, but an advantage of the air furnace is that when the charge is molten it may be held in the furnace while a sample is analysed, after which the composition of the bath can be adjusted by the necessary additions of pig iron or ferro-alloys. There is no appreciable pick-up of sulphur from the fuel.

A modification of the air furnace is what is known as the cradle furnace, which is actually a tilting air furnace mounted on rockers and wheels. For convenience in the delivery of metal, the cradle furnace employs lip pouring in a similar manner to a ladle, thus eliminating the use of a tap hole. This type of furnace lends itself very readily to the duplexing process for irons, particularly malleable cast iron; that is to say, it acts as a secondary furnace for superheating metal from other melting units such as the cupola.

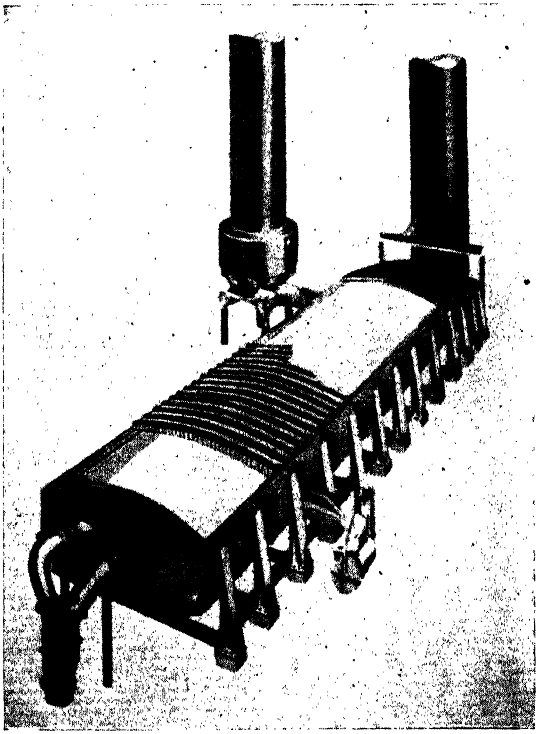


FIG. 24.—Cupola and Air Furnace for Duplexing (Whiting Corporation).

(Courtesy—Whiting Corporation.)

The rotary furnace. The rotary furnace is constructed in the form of a cylindrical mild steel shell with conical ends, and lined with a plastic refractory material. At one end is inserted the burner, and in the centre of the other an exhaust pipe for the removal of the products of combustion, coal ash, etc. The body of the furnace is mounted on four rollers which enable it to be rotated at a continuous low speed by contact with two race rings round the circumference. Each race ring rests on a pair of rollers. The side plates attached to the body are constructed as toothed segments, and the furnace may be tipped by a pinion shaft which engages the toothed periphery of the side plates. This tipping arrangement enables the furnace to be charged through the burner inlet by mechanical means from an overhead charging platform, and at the same time the slag runs out of the lower exhaust end.

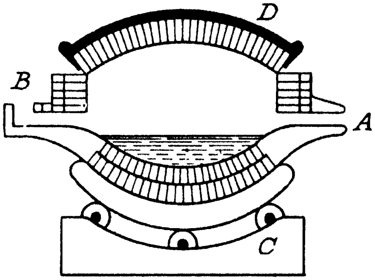


FIG. 25.—Sectional Diagram of the Cradle Furnace.

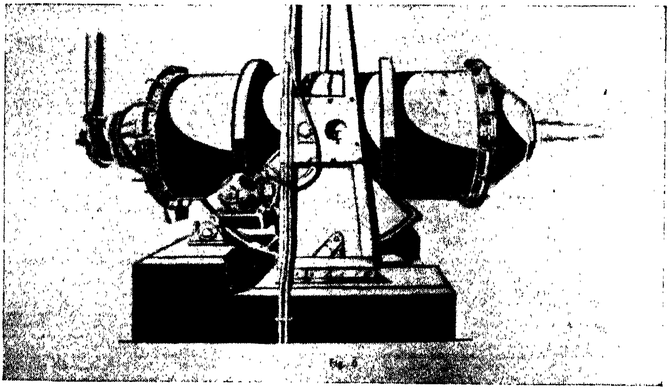


FIG. 26.—General Lines of Rotary Furnace.
(*Courtesy—Brackelsberg Melting Processes, Ltd.*)

Furnaces are made in a range of sizes from 1 to 50 tons capacity. Smaller types are often non-tilting and in these cases charging may be carried out by hand or some form of machine. The tap holes, usually two in number, may be used alternately, and are situated at the cone end near the burner, or on either side of the furnace body.

The hot gases and products of combustion are passed through a metal or brick regenerator situated in the chimney. The air necessary for the combustion of the fuel passes through the regenerator, and is thereby preheated resulting in a high flame temperature and quick melting. The flame passes over the charge. When the charge is liquid, the furnace is set in motion and rotated at the slow speed of about one revolution per minute. As the rotation proceeds, the lining gives up its heat to the charge.

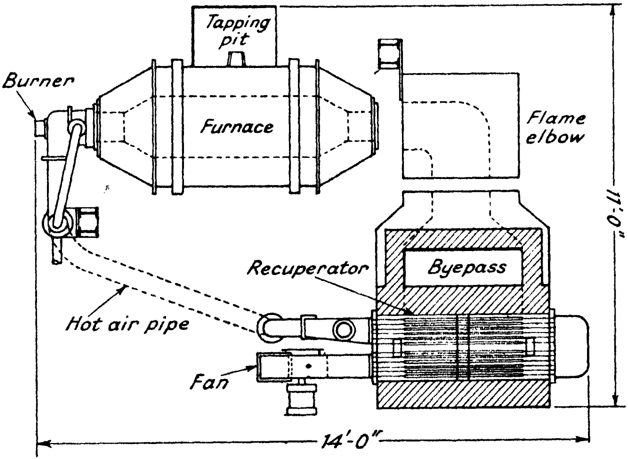


FIG. 27.—Diagram of Regenerator.
(*Courtesy—Brackelsberg Melting Processes, Ltd.*)

When the desired temperature has been reached, the rotation is stopped and the metal tapped.

Temperatures up to 1650°C. can be obtained with the rotary furnace, and it can be used for melting and superheating a variety of ferrous metals, from all steel charges to the cheaper types of cast iron by virtue of the fact that small scrap, borings and turnings can be incorporated in the charge.

The advantages of this furnace are that the slow rotation mixes the metal. There is no pick-up of sulphur as in the cupola, but there is a slight loss of carbon, manganese and silicon, but the composition can be largely corrected because the molten charge may be retained in the furnace until a spoon sample of metal is tested. The melting losses may also be allowed for when computing the charge, or regulated by adjustment to the fuel or air controls.

ELECTRIC FURNACES

Although the operation of the electric furnace is in general more expensive than the other types of melting furnace described, excepting perhaps when the running costs are somewhat offset by the use of cheap charges containing borings, clippings and so on, certain special advantages are gained by its employment.

It is an ideal unit for superheating both iron and steel, and very high metal temperatures can be obtained. It is easy to obtain a metal of predetermined composition without the danger of pick-up of injurious impurities from fuels. Melting is quick and the operation is clean. The three chief types of electric melting furnace for iron and steel are the direct arc, indirect arc, and the induction furnace.

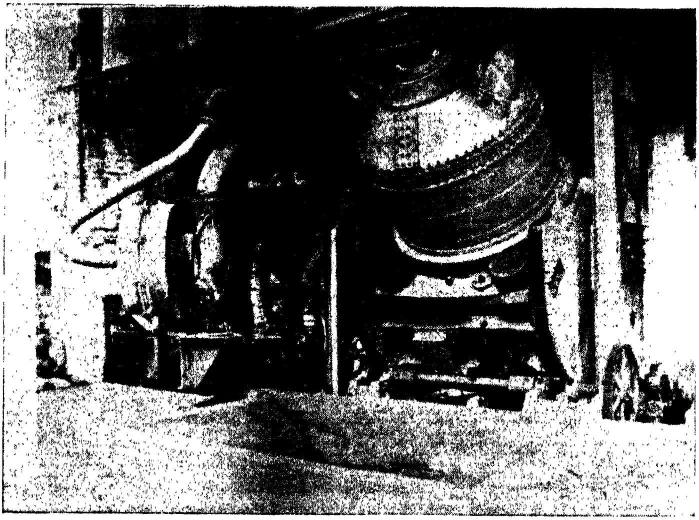


FIG. 28.—Rotary Furnace in charging position.
(*Courtesy—Brackelsberg Melting Processes, Ltd.*)

The direct arc furnace. This type of furnace employs a bowl-shaped hearth lined with acid or basic refractory material. The carbon electrodes are suspended vertically over the hearth and are securely gripped by clamps attached to a rigid electrode arm. There may be either two or three electrodes, but the three-phase type of furnace with three electrodes is the most generally used. The furnace is stationary whilst melting, but is constructed to tilt forward for pouring, and backwards for slagging or for fettling the hearth. The roof is domed and built in a separate mild steel ring often constructed in such a manner as to enable it to be detached for repairing. Furnaces with larger outputs use top charging, and in one method the roof and electrode superstructure is by hydraulic mechanism, smoothly and rapidly raised, swung to one side, and the furnace is then quickly charged by means of a drop-bottom bucket. Another charging system is to make use of a gantry to remove the roof and travels laterally. With small furnaces, charging is done through a door opposite the pouring spout.

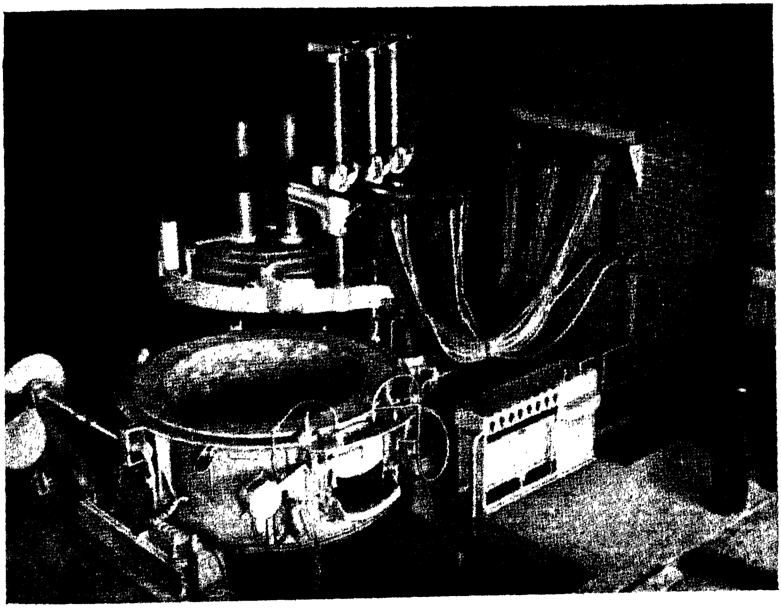


FIG. 29.—A 6–8-ton Electric Direct Arc Furnace. Top charging type, open for charging.

(*Courtesy—Birmingham Electric Furnaces, Ltd.*)

When the furnace is in operation, the arc strikes downwards on to the metal and the current actually passes through the charge or bath. Because the power input varies according to the length of arc, automatic electrode control is employed, which maintains the correct length of arc and consequently an almost constant power input.

Capacities of electric furnaces range from those of a laboratory type, melting approximately 20 lb. of metal, to those melting 30 tons, having power ratings of roughly 37 kVA to 10,000 kVA respectively.

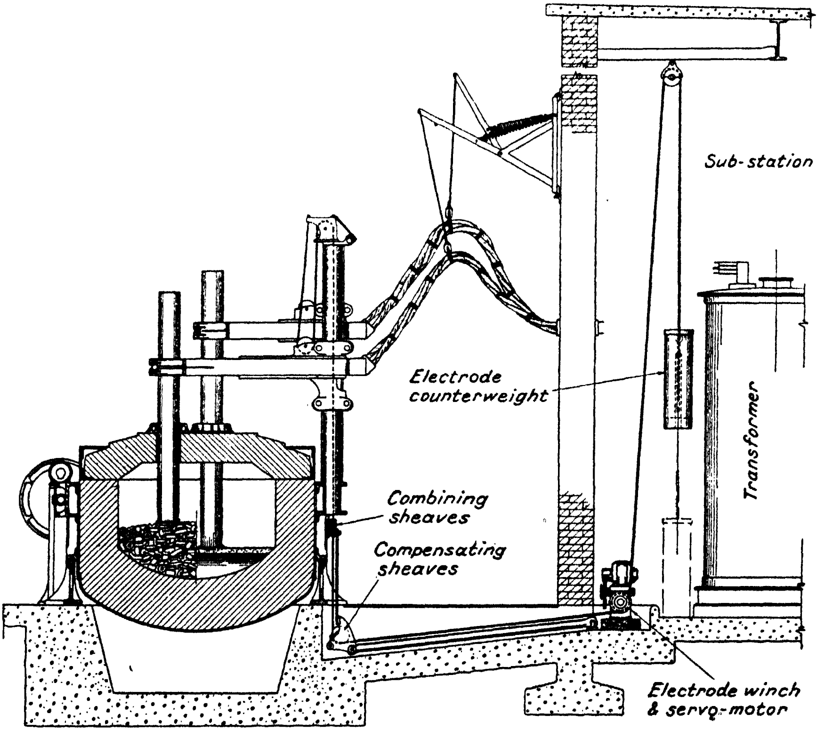


FIG. 30.—Schematic Diagram of Cross-Section of Furnace with Electrical and Mechanical Gear.

(*Courtesy—Birmingham Electric Furnaces, Ltd.*)

The electric furnace is used in the production of acid or basic steel, both for castings and ingots. Its application for cast iron is mainly for large-scale production in automobile and other foundries casting high-strength iron, also for duplexing or superheating molten iron taken from the cupola.

Rocking indirect arc furnace. This type of furnace consists essentially of a melting chamber which is cylindrical in form, lined with a refractory material of good quality backed by a layer of heat insulation which minimises heat losses, and the whole is encased in a robust steel shell. The pouring spout is formed in the charging opening, being situated on the mid-circumference. A graphite electrode enters the chamber on the axis at either end, the arc being formed between these two electrodes in the centre of the chamber. The arc is independent of the charge (indirect) and the control of its length is automatic.

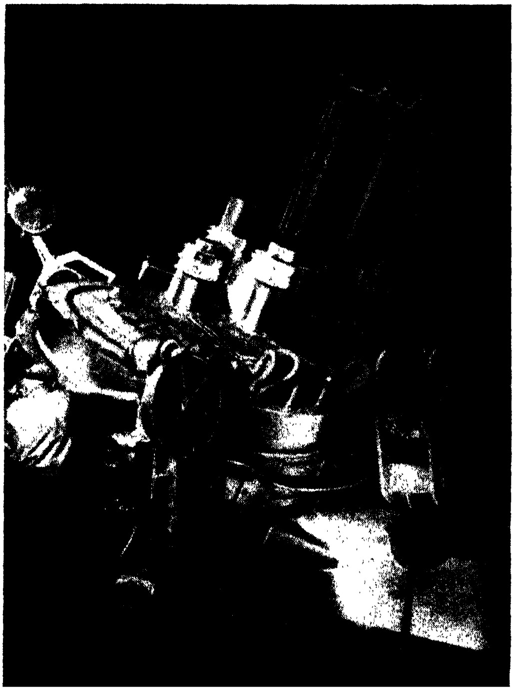


FIG. 31.—A Direct Arc Electric Furnace pouring.
(*Courtesy—Birmingham Electric Furnaces, Ltd.*)

The furnace casing is mounted on rollers on which the rocking takes place about its horizontal axis. The rollers are driven in alternate directions by an electric motor controlled by a reversing mechanism which oscillates the furnace through an angle adjustable up to nearly 180°. The rocking motion distributes the heat of the arc and the refractory lining gives up its heat directly to the metal. New portions of the lining surface are constantly coming under the influence of radiation from the arc by reason

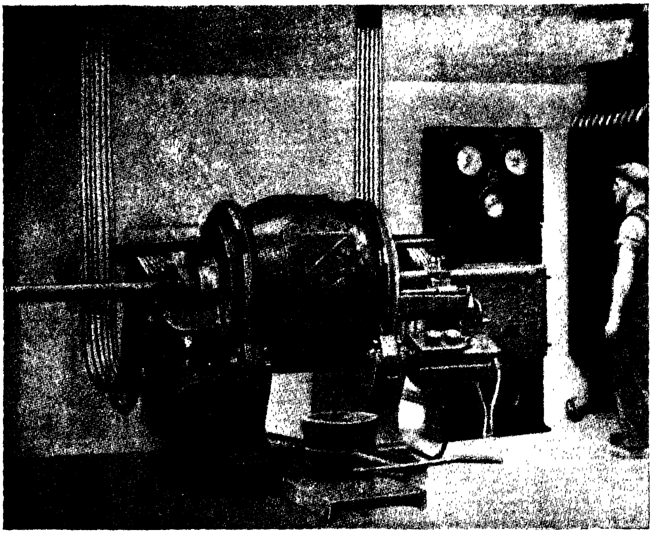


FIG. 32.—A Birlec-Detroit Indirect Arc Furnace. 350 lb. capacity.

(*Courtesy—Birmingham Electric Furnaces, Ltd.*)

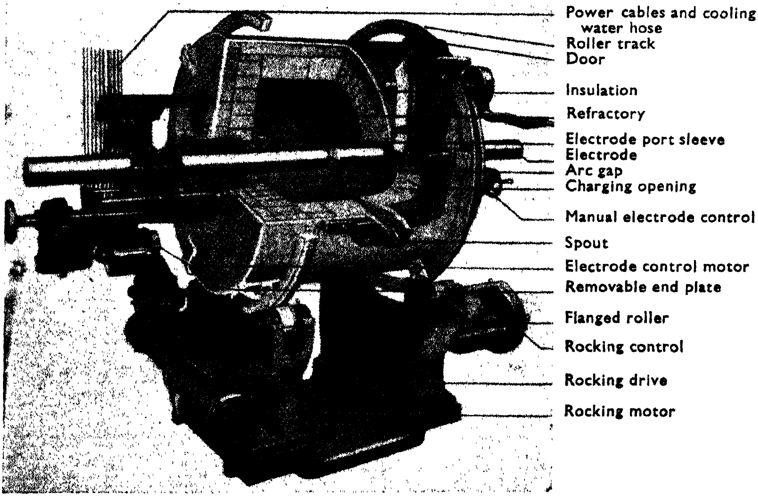


FIG. 33.—Cross-Section of Furnace.

(*Courtesy—Birmingham Electric Furnaces, Ltd.*)

of the rocking motion, and the lining is generally prevented from reaching excessively high temperatures, the result being a comparatively long life.

Rocking is commenced a few minutes after the furnace is switched on, a small rock being employed at first, and the angle of rock is gradually increased by an automatic device as melting progresses.

Owing to the close-fitting nature of the melting chamber of this type of furnace, a non-oxidising atmosphere can be maintained which results in negligible alloy and carbon losses from the metal. This makes possible the production of complex alloys which may be computed accurately from the ingredients of the charge.

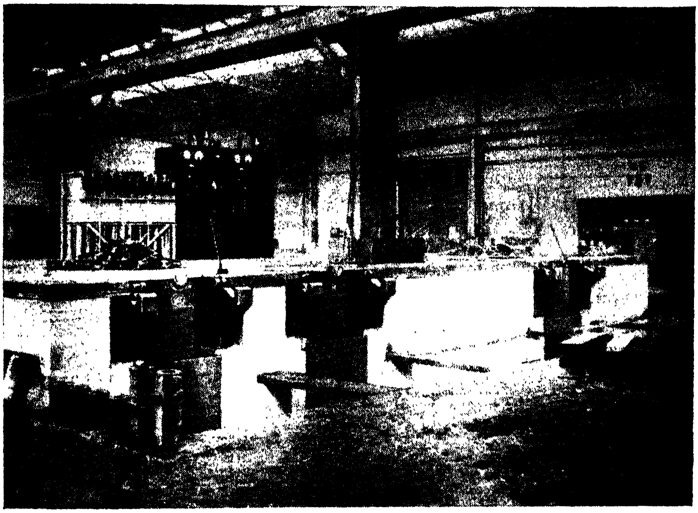


FIG. 34.—General view of a layout of three High-frequency Electric Melting Furnaces.

(*Courtesy—General Electric Company, Ltd.*)

The rocking arc furnace is used in the production of high strength and dense grey irons, alloy cast irons, malleable iron and alloy steels.

Furnaces are built in various sizes to hold charges ranging from 30 lb. to 3000 lb., and power ratings from 36 kVA to 875 kVA.

High-frequency induction furnaces (coreless type). The high-frequency induction furnace is crucible-shaped. The charge is melted by the heat produced in it by eddy currents developed by a high-frequency current carried by a water-cooled copper inductor coil surrounding the crucible. The current is supplied by a special motor generator set generating at the comparatively high frequency of about 500 to 2000 cycles.

The furnace is of simple construction (Fig. 35) and is usually arranged with the pouring spout on the axis of tilting so that the metal can conveniently be poured direct into the moulds.

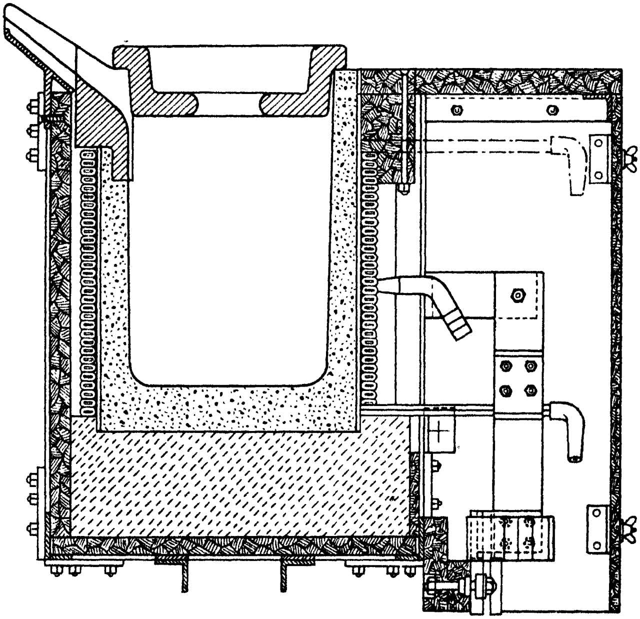


FIG. 35.—Sectional Diagram of High-frequency Coreless Induction Furnace.

(*Courtesy—Electric Furnace Company, Ltd.*)

The metal is contained in either a proper crucible, or a crucible built up in the furnace by a lining of suitable refractory material. Between the crucible and the coil there is a layer of heat-insulating material, and, although only 2 or 3 in. from the molten metal, the temperature of the coil never exceeds 90°C. Melting in the high-frequency induction furnace is rapid and clean in operation, and mixing of the ingredients of the charge is thorough owing to the stirring motion introduced by the eddy currents. Capacities range from approximately 5 cwt. to 8 tons.

A modification of the coreless type of furnace is that of the partially cored type (Fig. 36). A highly magnetic alloy steel container C, supports the inductor coil B and the crucible A, and is brought to the nucleus of a core D. It is claimed that economies are effected by the production of a strong and centrally situated magnetic field within the crucible containing the charge.

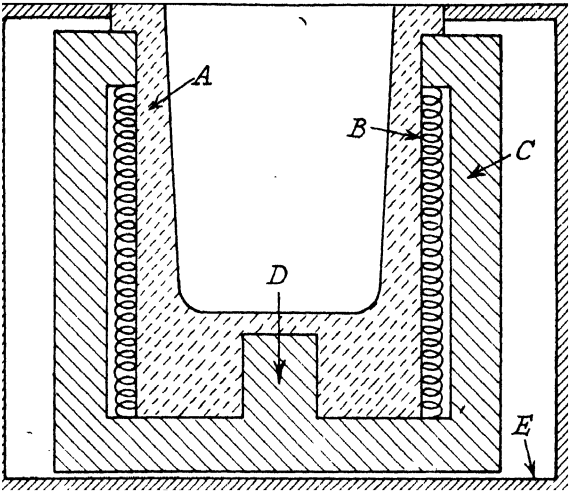


FIG. 36.—Cross-Sectional Diagram of Witton Furnace.
(Courtesy—General Electric Company, Ltd.)

High-frequency induction furnaces are used chiefly for the production of light steel castings, and also for melting special alloy steels, carbon tool steels and stainless irons.

CHAPTER 2

MECHANICAL TESTING

IN this age of speed and advancement in engineering practice there has developed in recent years a demand for materials which will respond to the higher duties required of them. As a result the metallurgist has introduced a large number of alloys to meet this demand, and we have seen the evolution of alloys of increased strength, ductility, and resistance to wear, heat, fatigue, shock and corrosion.

The severe conditions to which many engineering materials are subjected in service has led to more stringent specifications, new types of testing equipment, and a generally wider application of mechanical testing. As a result, acceptance tests are now demanded and employed for materials required for a wide variety of engineering purposes. The various forms of test specimen and minimum test values allowed are now largely standardised and defined by the British Standards Institute, American Society for Testing Materials, and other bodies.

THE TENSION TEST

Undoubtedly, the oldest and still most popular test is the test in tension, in fact, it is more widely employed than any other single test, and consists of applying a direct pull along the axis of a bar producing elongation and ultimate fracture. From the tension test, values for ultimate tensile stress, proportionality limit, yield point, modulous of elasticity, elongation and reduction of area may be obtained. When a steadily increasing load is applied to a metal tensile test specimen, up to a point it will extend proportionately to the load. The rate and the amount of extension varies with the type of material under test.

Let us first of all consider the behaviour of a test piece of mild steel and which is represented as a stress-strain diagram in Fig. 38. As the load is applied the extension of the specimen will be found to be proportional to the load, but eventually with increasing loads a point is reached where the stress and strain cease to be proportional, this being known as the *limit of proportionality.*

Up to this point, that is, between A and B, the extension is elastic, and if the load were to be released, the test piece would return to its original length. A further slight increase of stress after the limit of proportionality has been reached produces a permanent set in the metal, this value of stress being known as the ***elastic limit B***, but, generally speaking, the terms elastic limit and limit of proportionality are regarded as being synonymous.

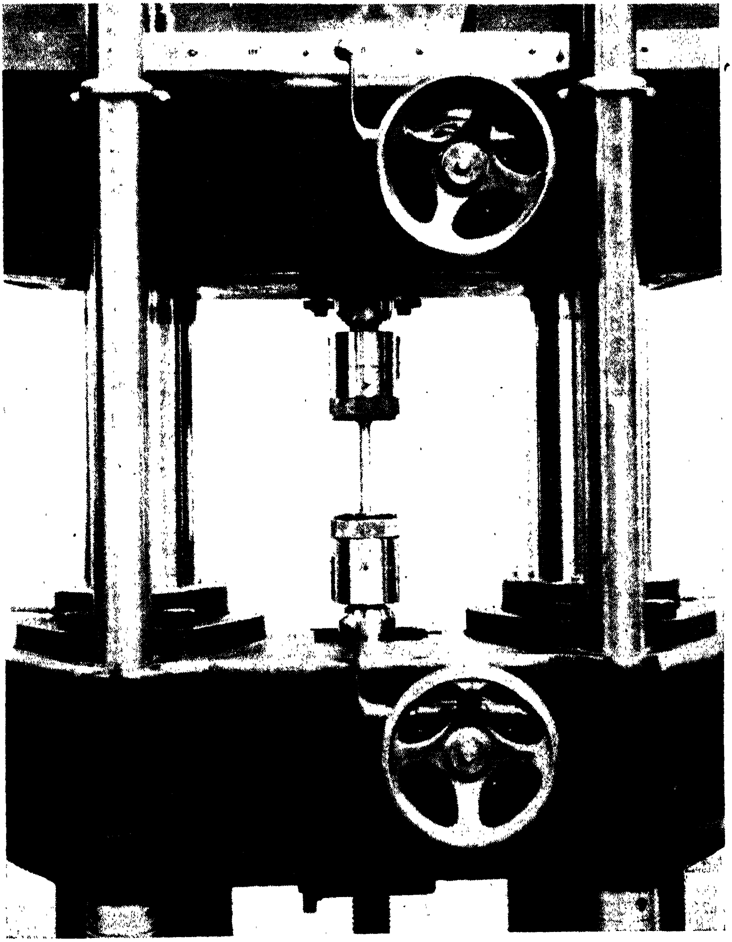


FIG. 37.—Illustrating Test Bar in Tension.
(Courtesy—Messrs. W. and T. Avery, Ltd.)

As the stress is further increased a point closely follows the elastic limit where a marked increase in strain occurs without an increase in stress. Normally, when testing soft mild steels there is actually a sudden drop in the amount of stress due to the sudden elongation of the specimen. This point is known as the *yield point*, and in a normal tensile test is shown by a sudden and momentary drop in the load at C.

It is then found that the stress and strain from D onwards can be simultaneously increased but they are no longer proportional. The material passes through a plastic stage where the cross-sectional area diminishes in approximately the same proportion as the increase in length. The greatly reduced area of the specimen is insufficient to sustain the load and ultimately a maximum is reached at E where the strain is in excess of the rate of loading, and the necking of the specimen is so rapid that the load decreases until rupture occurs at F. The point E indicates the *ultimate tensile stress* of the material, calculated on the original area.

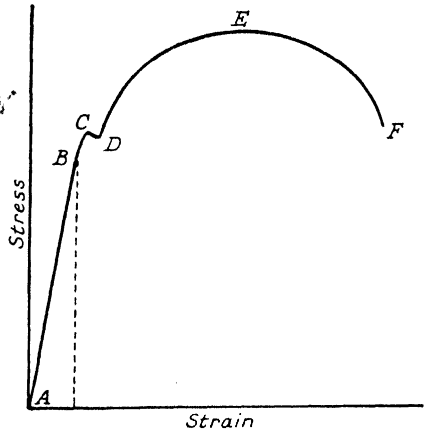


FIG. 38.—Stress Strain Diagram.

Metals of different composition behave rather differently when tested in tension, the following being a general classification :—

Certain non-ferrous metals, hardened, high tensile or cold-worked mild steels give a straight line from A to B, the stress being proportional to the strain, without a well-defined yield point and the specimen breaks at or near the maximum stress E. Other non-ferrous metals and cast iron give a curved line from the commencement of application of stress and have no range where the stress is proportional to the strain. Again there is no defined yield point and the specimen breaks at the point of maximum stress.

Alloy steels give a straight line from A to B where the stress is proportional to strain. There is no defined yield point, and stress and strain increase from D to E. Generally the plastic range, particularly in steels of the lower alloy contents, causes the specimen to break after the maximum stress has been passed, but this also depends upon the heat treatment.

When the material shows no well-defined yield point as in the cases cited above, it has become the practice to define the point at which a predetermined amount of permanent set occurs, and for this purpose the term *proof stress* is frequently employed in specifications.

The resistance to stretch within the elastic limit of a material is termed the *modulus of elasticity* and is the ratio between stress and strain. It is often referred to as *Young's Modulus* and is given by the relation

$$\text{E (Modulus)} = \frac{\text{Stress (lbs. per sq. in.)}}{\text{Strain (per in. of length)}}$$

Methods of testing in tension. Tensile tests are carried out in tensile testing machines which vary considerably in design, but all embody the combination of three general principles.

(1) *Grips for the specimen*

Either

(*a*) Split tapered jaws with serrated surfaces which automatically increase the grip on the specimen as the load is applied. The jaws are removable, interchangeable and supplied in sizes to grip bars of different diameters. This type of jaw is not suitable for very hard specimens.

(*b*) Threaded shackles for use with specimens having screwed ends. Or

(*c*) Split chuck with " keep " ring or wedge-shaped jaws for use with headed or dumb-bell type specimens. These are suitable for harder metals.

(2) *Straining mechanism*

Either

(*a*) Load applied by screw mechanism, motor-driven through reducing gears (Fig. 66). Or

(*b*) Hydraulic ram on which oil pressure is exerted by means of an accumulator or pump (Fig. 39).

(3) *Load-measuring attachment*

Either

(*a*) By the steelyard method employing single or multilever arrangement, with a movable counterpoise to maintain balance of the lever (Fig. 40).

(*b*) The use of a weighted pendulum, the deflection of which varies with the load applied.

(*c*) Measurement of the pressure of the fluid in the straining cylinder. Or

(*d*) Measurement of the deflection of a calibrated spring used on several makes of small machines.

Many modern testing machines have incorporated autographic recorders from which are obtained stress-strain records of the test.

An observation of the behaviour of the machine during the test will often indicate the yield point of the material although accurate measurements are determined by means of an extensometer or an autographic recorder. When the lever type of machine is used, the counterpoise is run out comparatively quickly in the early stages of the test, but as yielding sets in there is a sudden difference in the rate of movement of the counterpoise required to maintain balance, that is, the rate is much slower. The load applied when this change is noted is taken as the yield point. In the case of hydraulic self-indicating machines, the yield point is sometimes easily noted by the hesitation or slowing up of the movement of the load indicating finger as it passes round the dial. In testing mild steels, there is often a definite momentary falling back of the indicating finger when the yield point is reached.

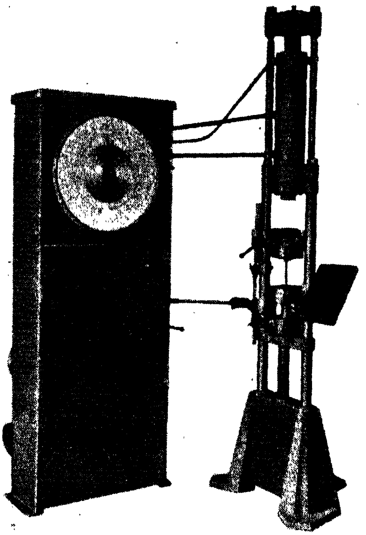


FIG. 39.—Hydraulic Self-Indicating Universal Testing Machine.
(*Courtesy—Messrs. W. and T. Avery, Ltd.*)

Another simple method for determining the yield point is to mark off the gauge length with a centre punch, and adjust the points of a pair of dividers to coincide with the gauge length on the test bar. One point of the dividers is firmly inserted in the lower punch mark, whilst the other point is held only in loose contact with the upper punch mark. When, during the application of the load, the bar elongates and the upper punch mark begins to separate from the loose point of the dividers, the load applied at that moment is taken for calculating the yield point.

The *Extensometer* is a small instrument which is attached to the bar during test. Since a test piece having a gauge length of 2 in. is only extended by 0·002 in. or less when the elastic limit is reached, the instrument is of necessity sensitive to very small strains and capable of measuring accurately to 0·0001 in. per in. of specimen. Extensometers vary as regards principle of operation, but are based on either, or a combination of the following :—

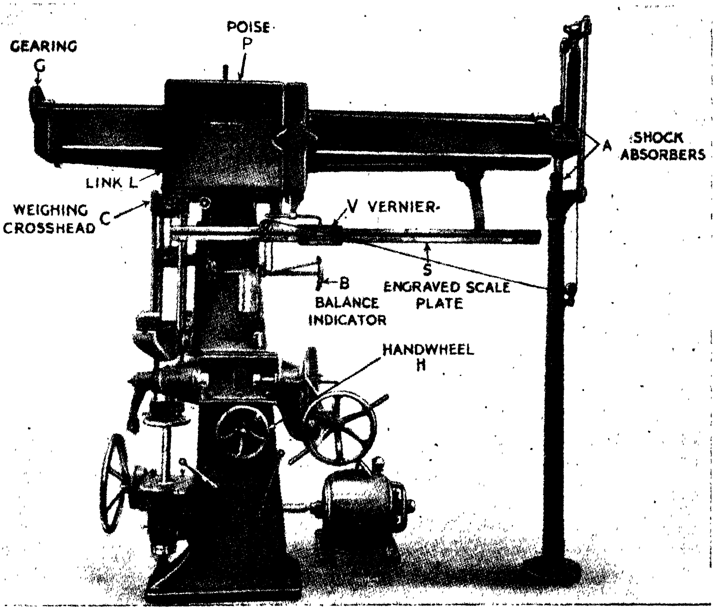


FIG. 40.—A Single Lever Testing Machine.
(*Courtesy—Messrs. W. and T. Avery, Ltd.*)

(*a*) The use of a micrometer or vernier.
(*b*) Measurement by dial gauge.
(*c*) Reading extension by means of a microscope.
(*d*) Mechanical methods of magnification.
(*e*) Optical methods of magnification.

Fig. 42 illustrates an extensometer which employs mechanical magnification along with a micrometer. Its principle of operation is evident from the diagrammatical illustration. B = vibrating reed or tongue having a downward movement five times the extension of the test piece.

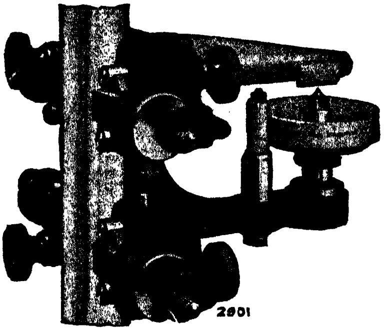


FIG. 41.—The Cambridge Extensometer.

(*Courtesy—The Cambridge Instrument Company, Ltd.*)

C = graduated micrometer head which is turned until just touching the tongue as it vibrates and from which the extension is read.

Elongation and reduction of area. These values give a measure of the ductility of the material, and are simply obtained from the two fractured halves of the test bar. The portions are clamped together and the extension over the original gauge length measured by means of a finely graduated rule in $\frac{1}{100}$ths of an inch, and the elongation calculated as a percentage of the original length.

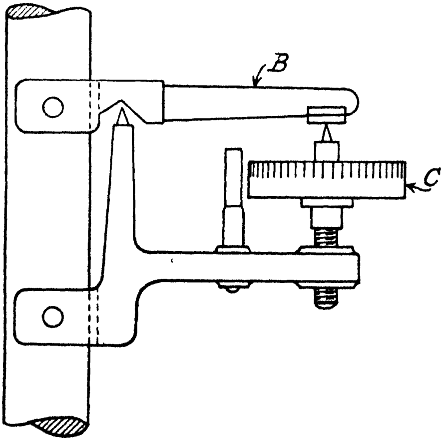


FIG. 42.—Cambridge Extensometer.

The reduction of area at the point of fracture is determined by measuring the new diameter, using a micrometer (pointed), and then calculating the reduction in area as a percentage of the original area.

Specially calibrated rules are obtainable for a standard test bar, so that calculations are dispensed with and the value for elongation can be measured directly from the dividers, and the reduction of area from the fractured end of the test bar.

Test pieces for tensile test. Test bars may be cast roughly to shape in sand moulds along with the castings which they represent, and, whilst the results obtained in testing are not strictly accurate due to the effects of the " skin " on the test piece, they often suffice for routine and comparative purposes in works laboratories where considerable quantities of test pieces are dealt with.

The more usual practice, however, is to machine down plain bars into tensile pieces, the dimensions varying to some extent with different types of material, particularly the forms of the ends of the specimen and the radius joining the parallel length with the ends. The latter requirements depend largely upon the ductility of the metal. With ductile materials it is satisfactory to make the radius from the parallel portion to the shoulder of the grip equal to the diameter of the parallel length. In the case of cast iron and other materials of low ductility, it is necessary to increase this radius considerably to several times this value owing to the tendency to fracture because of stress concentration at the transition point.

The grip ends of ductile materials are conveniently left plain for use with serrated grips or screwed with suitable threads for adaption to screwed shackles. Hardened or other materials of low ductility, such as cast iron, should have grip ends headed for testing in self-aligning shackles.

Specifications for tensile bars for various materials are covered by B.S.I. specifications, but in general conform roughly to the following table [1] :—

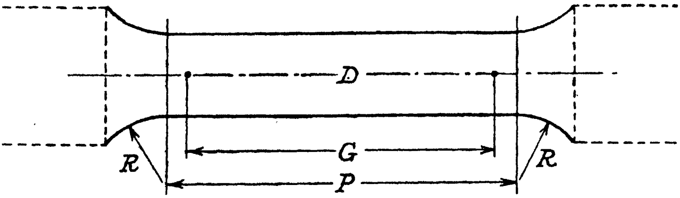


FIG. 43.—Diagram of Test Bar for Tension Test.

Cross-sectional area $A = \frac{D^2\pi}{4}$

Gauge length $G = 4\sqrt{A} = 3{\cdot}54D$.

Parallel length $P = \frac{9}{8}G$ minimum $= 3{\cdot}98D$ minimum.

Radius R at shoulder for wrought metals $=$.

$\frac{G}{4}$ minimum ($0{\cdot}88D$ minimum).

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[1] B.S. 18 Tensile Testing of Metals.

Diameter *D*	*Cross-sectional area* *A*	*Gauge length* *G*	*Parallel length* *P* (*minimum*)	*Radius at shoulder* *R* (*minimum*) *wrought metal*
in.	*sq. in.*	*in.*	*in.*	*in.*
0·798	0·5000	3·00	3·37	0·75
0·564	0·2500	2·00	2·25	0·50
0·424	0·1412	1·50	1·69	0·37
0·399	0·1250	1·41	1·58	0·35
0·357	0·1000	1·26	1·42	0·31
0·282	0·0625	1·00	1·12	0·25
0·226	0·0400	0·80	0·90	0·20
0·159	0·0200	0·56	0·63	0·14
0·125	0·0122	0·44	0·50	0·11

The above dimensions cover most ferrous and non-ferrous metals. Cast-iron tests bars are slightly different in dimensions, especially in the radius. Test bars are cast in the form of plain round bars which may be first used for making the transverse test, and the tensile test piece then turned from one of the broken halves.

The test bars are cast to such a size as to represent the main cross-sectional thickness of the castings as shown in the following table (abstracted from B.S.S. No. 786, 1938):—

Diameter as cast	*Gauge diameter tensile test*	*Area*	*Minimum parallel length*	*Minimum radius for shoulder*	*Main cross-sectional thickness of casting represented*
in.	*in.*	*sq. in.*	*in.*	*in.*	
0·6	0·399	0·125	1	1¼	Not exceeding ⅜ in.
0·875	0·564	0·25	2	3½	Over ⅜ in. and not exceeding ¾ in.
1·2	0·798	0·50	2	3½	Over ¾ in. and not exceeding 1⅛ in.
1·6	1·128	1·00	2	3½	Over 1⅛ in. and not exceeding 1⅝ in.
2·1	1·596	2·00	2	3½	Over 1⅝ in.

HARDNESS TESTS

Hardness is a very important property of materials, and testing for hardness finds a great application in ascertaining the suitability of the material for use in machinery, particularly in parts where friction and varying loads are likely to be experienced. The usual interpretation of the term hardness is its resistance to penetration or abrasion, but whilst hard materials resist penetration there are exceptions where a material may resist abrasion to some extent yet be softer than other materials which do not.

One great advantage of hardness testing is the ease and speed with which the tests may be carried out, and when making tests on steels and certain other materials, the determination of hardness makes possible an estimate of the approximate tensile strength. Moreover, certain treatments of parts during manufacture, such as mechanical working and heat treatment, influence the hardness of materials, and therefore a hardness test will often throw light on the nature of the treatment which the material has received during manufacture.

A wide range of machines are used in testing for hardness, varying both in principle and design. The whole range of hardnesses likely to be met with is, however, adequately covered by three types, namely :—

(1) Ball indentation machines.
(2) Diamond indentation machines.
(3) Rebound machines.

The ball indentation hardness method. In this, known as the Brinell method, a hardened steel ball is forced into the flat surface of the specimen by means of the application of a predetermined load. An indentation is produced on the surface of the metal, of which the depth and the diameter bear a relation to the hardness of the material. The type of impression, by reason of its outline, permits the measurement of the diameter by the use of a suitable microscope provided with a graduated eyepiece.

The hardness of the material is simply determined by the ratio :—

$$\frac{\text{Pressure in kg.}}{\text{Spherical area of the impression in sq. mm.}}$$

The type of impression produced will range between the types illustrated in Fig. 44, A being typical of softer and wrought metals, and B being typical of harder and cast metals. The contact surface is sharply defined and the dimension *d* can be readily measured by means of a suitable microscope. The Brinell figure can be calculated from the following :—

$$H=\frac{P}{\frac{\pi D}{2}(D-\sqrt{D^2-d^2})}$$

For normal testing a ball of 10 mm. diameter is employed along with a load of 3000 kg., but the use of this combination is limited to some extent by the sectional thickness and the size of the material under test, and also by the hardness of the material itself.

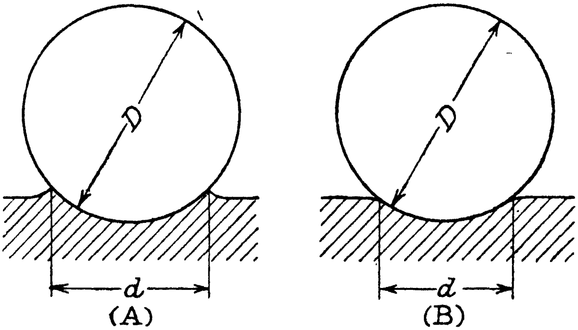


FIG. 44.—Types of Brinell Impression.

Experiments by Meyer showed that $\frac{P}{D^2}$ is constant for indentations of similar shape on the same material, and this relationship allows comparative tests to be made when the 10-mm. ball and 3000-kg. load are not applicable. $\frac{P}{D^2}=30$, so that :—

For a 5-mm. diameter ball a load of 30×5^2 is used $=750$ kg.
,, 2 ,, ,, ,, 30×2^2 ,, $=120$,,
,, 1 ,, ,, ,, 30×1^2 ,, $=30$,,

Owing to the ridge effect on the indentation (Fig. 44) when softer materials are tested, different values of $\frac{P}{D^2}$ are used, and it is found advisable to limit the ratio of the diameter of the impression to the diameter of the ball to between 0·25 and 0·50.

The approximate values of $\frac{P}{D^2}$ for the various classes of materials are :—

Steel and cast iron, 30.
Copper alloys, aluminium alloys, 10.
Copper and aluminium, 5.
Lead, tin and their alloys, 1.

Other factors which control the choice of load and diameter of ball are :—

(1) The width of the specimen shall not be less than 5 times the diameter of the impression.

(2) The thickness of the test specimen should be at least 10 times the depth of the impression given by the formula :—

$$\text{Depth of impression in mm.} = \frac{P}{\pi DH}$$

The effect of time on the size of the impression varies to some extent and the specified time of application of the load when $\frac{P}{D^2}=30$ is 15 seconds, and when $\frac{P}{D^2}=10$, 5 or 1 it is 30 seconds.

A typical Brinell machine is illustrated in Fig. 45. Its construction bears a similarity to a platform weighing machine. The weighing mechanism consists of a system of steel levers fitted with knife edges and bearings. Proportional weights to make up the desired load are suspended from the steelyards. A screw connected to the small handwheel is fixed in position by a catch. The specimen to be tested is placed on the platform and, by releasing the catch, the ball is brought down by turning the same handwheel until it almost contacts the surface of the specimen. The catch is replaced in position and the large handwheel is rotated which slowly applies the load through a worm drive. Application of the load is stopped when the steelyards rise to a horizontal position. When the load has been maintained for the prescribed time, the pressure is released by turning the large handwheel in the opposite direction, when the steelyards fall back to their original position. The diameter of the impression is found by the use of a special microscope, readings being taken to an

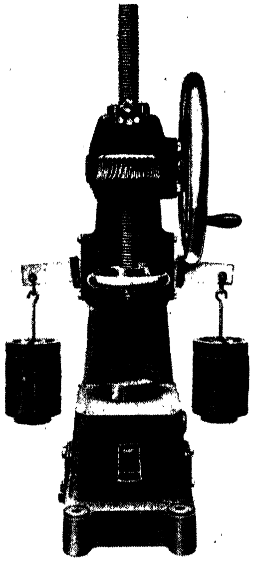


FIG. 45.—Brinell Hardness Testing Machine.
(*Courtesy—Messrs. W. and T. Avery, Ltd.*)

accuracy of 0·05 mm., still higher-powered microscopes being provided for use with the smaller diameter balls. The diameter is converted to Brinell number from a conversion chart. A precaution to be taken when using Brinell machines is that, when testing material with a hardness exceeding 500, a ball considerably harder than the test piece must be used, otherwise distortion of the ball occurs and low hardness figures result. Although ball hardness machines are quick and simple in operation, the upper limit to which they can be safely employed using a steel ball is 550 on the Brinell scale.

The diamond hardness method. Again, there are various types of machine utilising different methods of applying the load to the specimen. The diamond indentor may be pyramid-shaped, as in the Vickers machine, or in the form of a cone with a rounded point, as in the Monotron or Rockwell machines.

The diamond indentation machines have been designed to overcome some of the disadvantages associated with the ball machines. They allow the testing of a greater range of hardness values and, owing to the extreme hardness of the diamond indentor, they are applicable to the testing of super-hard tool steels. The small size of the diamond carries a further advantage that, in conjunction with the lighter loads employed, the impression made on the surface of the object is very small, and permits the testing of finished parts which would be damaged and often rendered unusable by the use of the ordinary Brinell test with its much larger impression. Also satisfactory tests can be made on thin sheet material.

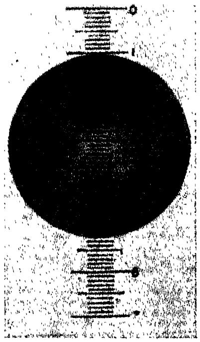


FIG. 46.—Measurement of Impression.

Well-known machines of this type are the Vickers Pyramid hardness testing machines and the Rockwell machine. The Vickers machine is illustrated in Fig. 47.

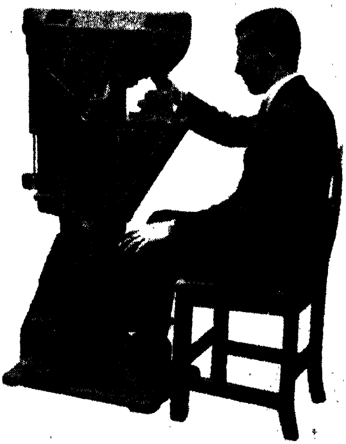


FIG. 47.—The Vickers Pyramid Hardness Testing Machine.
(Courtesy—Messrs. Vickers-Armstrongs, Ltd.)

The load is applied to the indentor by means of a dead weight operating through a 20 to 1 leverage system to a thrust rod acting on a tube which is free to move vertically. The indentor is situated on the lower end of the tube. The timing and rate of loading is controlled by a cam and dash pot mechanism which has the advantage that it is independent of the operator. Resetting of the loading mechanism for a subsequent test is readily carried out by depressing a foot pedal. Measurement of the impression is made across a diagonal of the pyramid impression by means of a special microscope attached to the machine. Incorporated near the top of the microscope tube is a specially designed micrometer ocular. The impression is measured by an adjustment of knife edges. The image of the impression is first focused sharply in the microscope by adjusting an elevating table holding the specimen, and finally by a fine adjustment screw on the side of the microscope. The left-hand knife edge is brought into operation by turning a knurled thumb screw until the knife edge just corresponds with the left-hand corner of the pyramid, and the actual measurement is

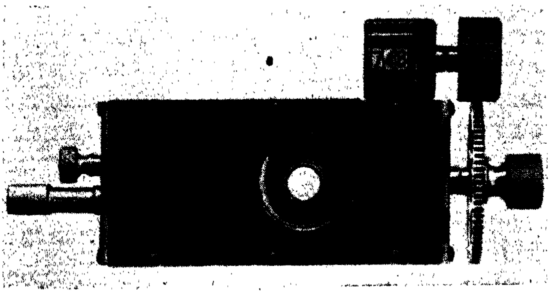


FIG. 48.—The Micrometer Ocular.
(Courtesy—Messrs. Vickers-Armstrongs, Ltd.)

then now completed by turning the knurled and geared micrometer screw connected to a counting mechanism and which also controls the second knife edge. The screw is turned until this right-hand knife edge corresponds with the right-hand corner of the pyramid impression. When both knife edges are correctly set according to the diagonal of the impression, the reading is taken from the counter at the side of the eyepiece of the microscope, and converted by means of tables to Vickers pyramid numbers. Any combination of weights can be used to make up the required load, and the microscope is provided with both a high- and a low-powered objective. Holders housing a 2-mm. or 1-mm. ball are interchangeable with the diamond indentor, enabling the machine to be used for carrying out the Brinell type of hardness test.

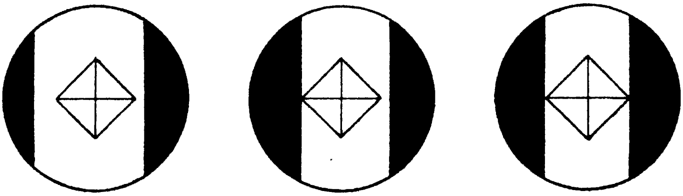


FIG. 49.—Measuring Diamond Impression.

Hardness tests on a wide variety of materials are possible on the instrument. A useful feature is that a sliding table may be fitted on which the specimen rests, and, after the impression has been made, a movement of a handle to the right to its fullest extent brings the impression directly under the microscope objective. Accessories are also provided such as extended diamond indentors with long shanks, extended microscope tubes, gear-testing equipment and vee blocks, permitting the testing of parts of intricate and varying shapes.

The indentation made by the Rockwell machine is not measured in the usual manner by means of a microscope but with a sensitive dial type gauge which records automatically the depth of the indentation. A steel ball may also be used with the instrument and two scales are employed—the " C " scale when using the conical diamond and the " B " scale when using the steel ball.

The Shore Monotron hardness tester embodies a slightly different principle. The diamond impressor is made to penetrate a definite predetermined standard depth into the specimen by means of a hand-operated handle, the depth being indicated by a dial. A further dial calibrated in units of hardness records the pressure required to make the diamond penetrate to the standard depth.

Rebound hardness testing. As distinct from the other two forms of hardness testing previously described, this is a dynamic test. The only instrument of this type in extensive use is that known as the Shore Scleroscope (Fig. 50). A small diamond - tipped tup, weighing about $\frac{1}{12}$ oz. and contained in a glass tube, is allowed to fall freely from a height of 10 in. on to the test piece. The tube contains a vertical scale reading from 0 at the bottom to 140 at the top. Suction provided by the manipulation of a rubber ball raises the tup to the top of the glass tube, where it is held in a small clip. The tup is released to fall on the test specimen by squeezing the same rubber ball. By rapid and careful observation the height of the rebound is noted against the scale, which gives a direct reading in Shore units. The harder the material, the higher the rebound and, of course, the higher the reading.

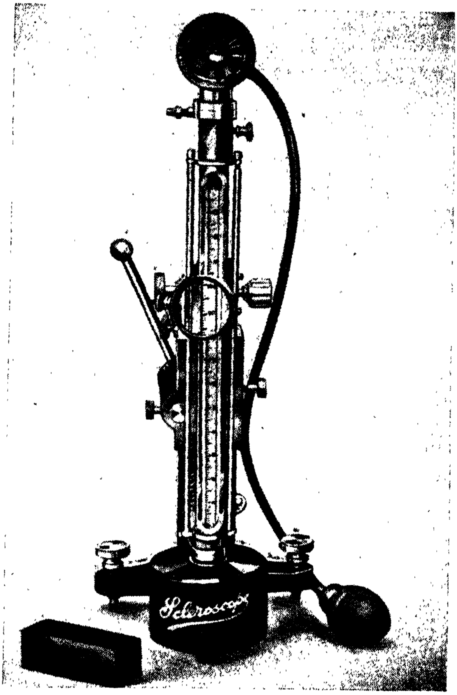


FIG. 50.—The Scleroscope.
(*Courtesy—Coats Machine Tool Company, Ltd.*)

The instrument may be used for testing any class of steel and non-ferrous metal, but the test piece must be firmly supported and a smooth surface used for the test. For the testing of small hardened steel parts it is particularly suitable, and rapid in use.

IMPACT TEST

The impact test supplies information regarding the capability of a material to withstand shock, and stress concentration. The characteristic of impact resistance indicates differences in condition which are not revealed by any other test and provides a valuable check on heat-treatment. For instance, different heat treatments on a material may produce the same characteristics such as the values obtained by testing in tension and for hardness, but impact resistance may vary widely.

There are several forms of impact test, but that which is probably the most generally used is the Izod test. The testing machine is illustrated in Fig. 51. A prepared standard specimen, either square or round, is clamped securely and vertically in an anvil fixed to the base of the machine and with the notch at its front face. The pendulum is held in its raised position by means of a spring-loaded trigger. On release, the pendulum, having a potential energy of 120 ft. lb., falls and strikes the specimen with the striking knife edge at a position 22 mm. above the notch. The energy absorbed by the specimen during fracture is a measure of the resistance of the material to shock or stress concentration. The residual energy in the pendulum causes it to continue its swing, and in doing so, carries forward a pointer

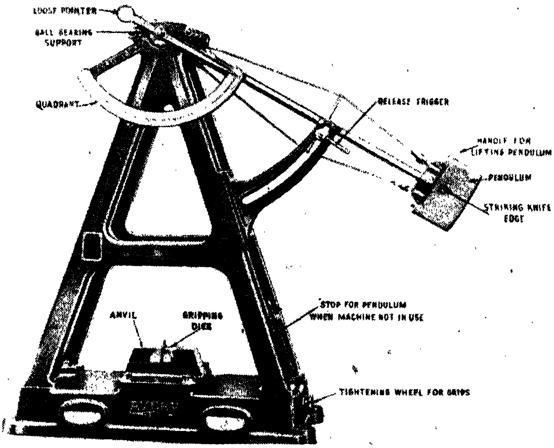


FIG. 51.—Izod Impact Testing Machine.
(*Courtesy—Messrs. W. and T. Avery, Ltd.*)

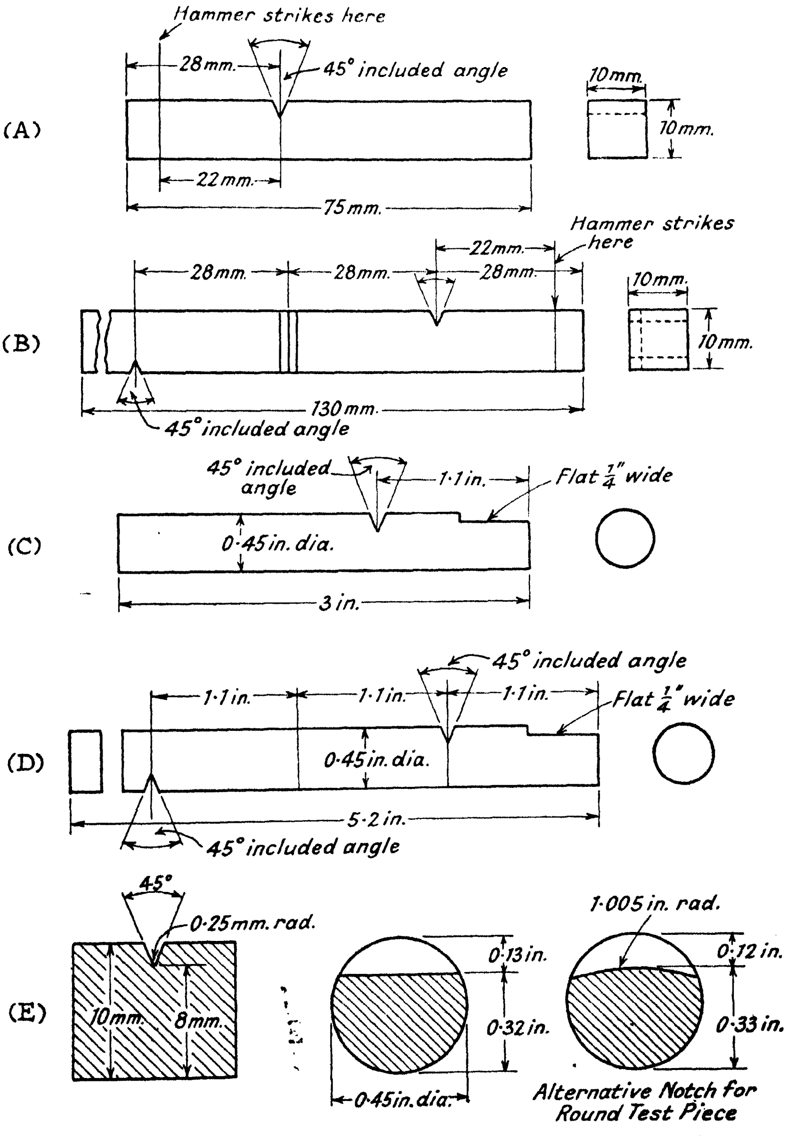


FIG. 52.—B.S.I. Standard Test Pieces for Notched Bar Impact Tests.

(A) Square test piece with single notch.
(B) Alternative test piece providing for three notches.
(C) Round test piece with single notch.
(D) Alternative round test piece providing for three notches.
(E) Notches for test pieces.

which indicates on a graduated chart the amount of energy absorbed by the specimen.

Bending, shear and compression tests. Whilst these are not carried out with the same frequency as the more common tests previously described, they do provide additional information relative to articles to be used for specific purposes.

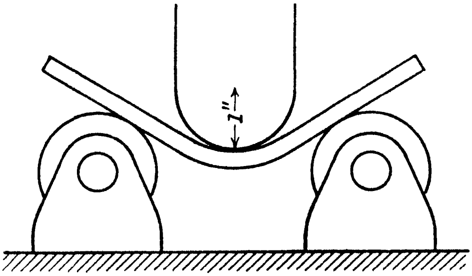


FIG. 53.—Bend Test.

The Bend test consists of bending a specimen of specified dimensions round a prescribed radius generally by the use of a former located at the centre of the span. The bending is continued whilst it shows no sign of fracture or cracking until the test piece assumes an angle of 180 deg. or any other predetermined angle.

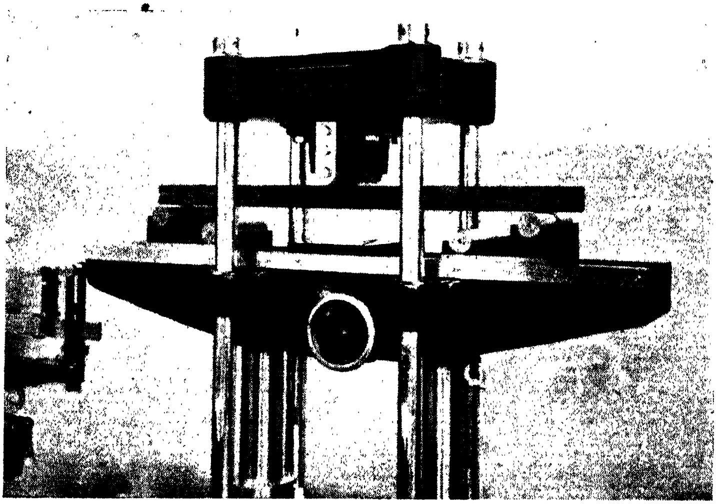


FIG. 54.—Transverse Test in Operation.
(Courtesy—Messrs. W. and T. Avery, Ltd.)

Owing to the rather brittle nature of cast iron the tension test is often supplemented by the *Transverse Test* in order to assess its resistance to fracture under bending loads. The standard tests employ round cast bars of various dimensions, the choice depending on the average thickness of the castings which they represent. For making the test the bar rests on two rounded supports spaced at a standard distance apart, loading being applied at the centre of the span through the medium of a radiused tool. The deflection of the bar just prior to fracture is measured by a dial indicator fixed in the frame of the testing machine.

The following table sets out dimensions of test bars and other testing requirements :—

Test bar	*Diameter*	*Overall length*	*Distance between supports*	*Main cross-sectional thickness of castings represented*
	in.	*in.*	*in.*	
S	0·875	15	12	Not exceeding ¾ in.
M	1·2	21	18	Over ¾ in. thick and not exceeding 2 in.
L	2·2	21	18	Over 2 in.

As the test bars are usually tested in the " as cast " condition, they may deviate slightly from the standard diameter due to moulding or pouring conditions, etc. The following formula for corrections may then be applied to obtain results in terms of the standard :—

$$\text{Breaking Load (Standard)} = \text{Actual breaking load} \left(\frac{\text{Standard diam.}}{\text{Actual diam.}}\right)^3$$

$$\text{Equiv. defn. on Standard} = \frac{\text{Actual diam.}}{\text{Standard diam.}} \times \text{Actual defn.}$$

The Modulus of Rupture is obtained by multiplying the breaking load by factor K, which is—

0·0204 for bar S[1]
0·0118 for bar M
0·0019 for bar L

$\text{K} \times \text{W (Breaking load)} = \text{Modulus of Rupture in tons per sq. in.}$

[1] Abstracted from B.S.S. 321, 1937.

The Shear Test measures the force which, when applied at right angles to the axis of a bar, results in the adjacent sections of the material sliding across each other. In making shearing tests a specimen, usually round, is passed through units containing hardened steel bushes. The units employed generally consist of one centrally situated and working between the two sides of a forked member. The test piece should closely fit the bore of the bushes in order to minimise bending action. Materials used in the production of gudgeon pins, bolts and rivets are tested for shear strength.

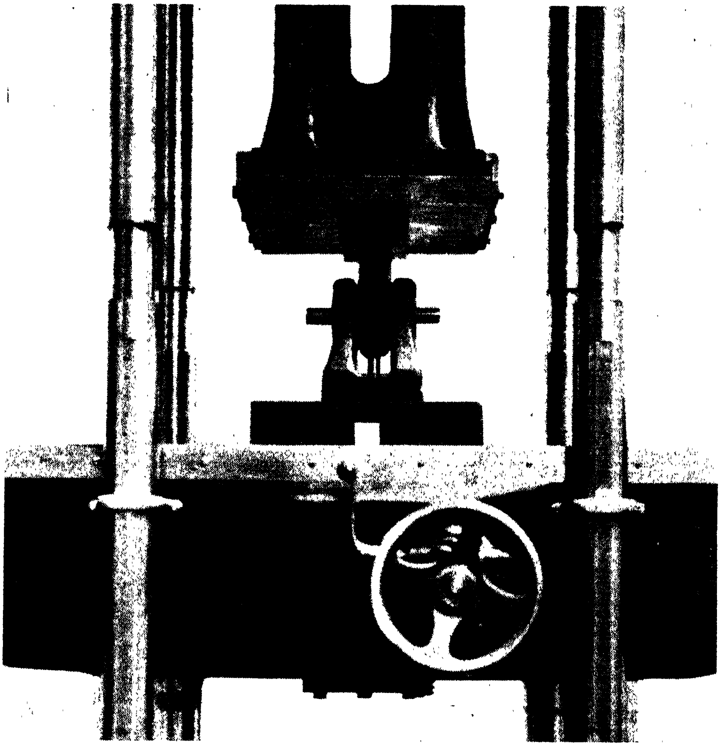


FIG. 55.—Shear Test.
(*Courtesy—Messrs. W. and T. Avery, Ltd.*)

The *Compression Test*, as the term implies, consists of compressing or crushing a specimen by subjecting it to an external load which tends to reduce it in length. To ensure accuracy the load should be applied parallel to the axis of the specimen, and to obtain this condition the specimen is mounted on compression seats having a spherical back. Tests in compression may be applied to ascertain the load required to cause failure of comparatively long columns, for example, the testing of pit props, and struts for aircraft construction, and the testing of concrete.

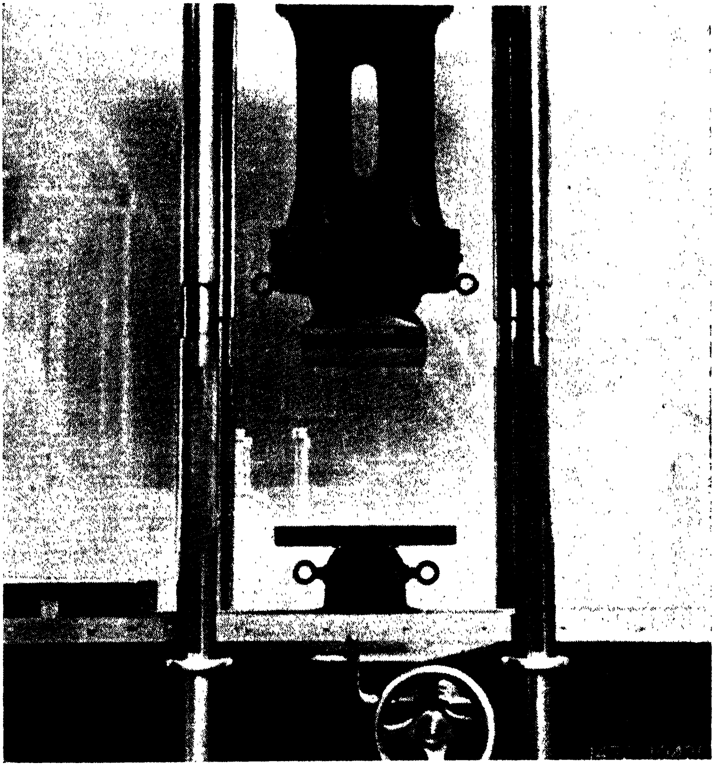


FIG. 56.—Tools for Compression Test.
(*Courtesy—Messrs. W. and T. Avery, Ltd.*)

TORSION TESTS

Torsion is the form of sheer stress which is set up in a bar when two equal torques tend to rotate its ends in opposite directions round its axis, each transverse layer of the bar tending to slide on the next. The stress at any point in a section is proportional to the distance of the point from the axis, being zero at the centre of a shaft and greatest at the surface.

Tests are generally made on specimens of round section, having enlarged ends and provided with keys to resist rotation. One end of the specimen is secured in a holder controlled by gearing through which the twisting moment is applied, whilst the other end fits into a holder connected to the load-indicating mechanism.

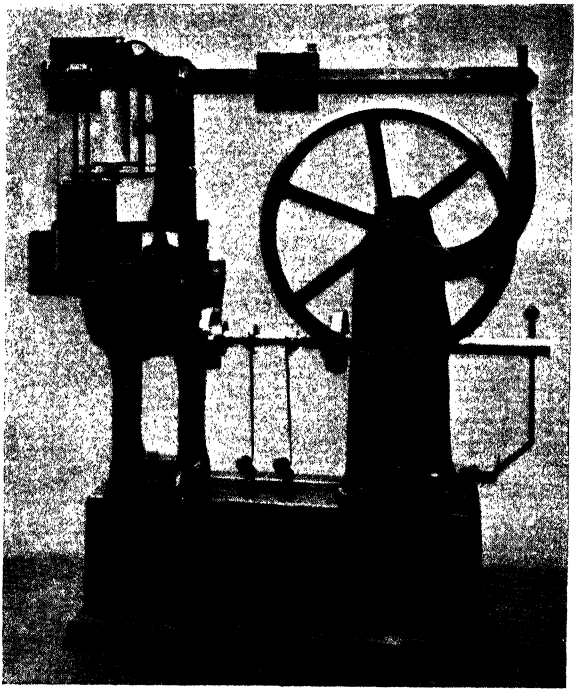


FIG. 57.—A Torsional Fatigue Machine.
(*Courtesy—Messrs. W. and T. Avery, Ltd.*)

The torsional stress on the specimen is communicated to the steelyard by a lever system and is there balanced off by the use of a movable poise operated by a small handwheel. A protractor is provided which measured the angle of twist. Machines may be equipped with autographic recorders.

When a solid bar of mild steel is tested in torsion the yield point is usually less marked than in the tension test owing to the material not at once being stressed to the same degree. The stress is greatest in the outside layers, but becomes more evenly distributed over the section as the plastic stage is traversed. Owing to more uniform stress distribution in comparatively thin walls, the yield stress can be obtained more accurately if the test piece is made in the form of a tube.

There is no appreciable reduction in the cross-section of the test piece and the stress-strain curve does not show the droop at the end of the test as in the tension test, but runs for a period almost parallel to the strain axis.

Torsion tests supply to the engineer valuable information regarding the torsional rigidity of material to be used in the production of transmission gear, crankshafts of engines, units of tubular construction, helical springs and any other product subject to torsional stress.

FATIGUE TEST

The fatigue value of a material is that stress or range of stress which must not be exceeded when subjected to repeated or alternating loading conditions if failure is to be avoided, and is always lower than the yield stress value of the material.

When stress variation occurs in cycles the repeated variation is known as a *stress cycle.* The algebraic difference between the maximum and minimum values of the stress applied is termed the *range of stress.* The *fatigue range* is the range of stress within which an indefinite large number of repetitions of stress will not cause failure. The greatest stress that can be applied in a given stress cycle without eventually causing failure is known as the *fatigue limit* or sometimes referred to as the *endurance limit.* When the range of stress is maintained invariably throughout the test, the number of cycles required to cause failure is known as *endurance.*

The type of stressing producing fatigue fractures may be in tension and compression, bending, shear, torsion or a combination of these. Machines are produced for adaptability in making use of each or a combination of these various forms of stress, and all find application in testing.

As the greatest number of fatigue failures appear to be due to reversed bending stresses, testing machines of this type are by far the most popular, and the equipment is comparatively simple. A test piece of standard dimensions in the form of a round bar is rapidly rotated and has a load applied which stresses the bar in bending, the outer fibres of the material suffering alternate tension and compression as the bar rotates. The specimen takes the form of a cantilever with the load applied at the free end through the medium of a ball race. This type of test was first introduced by Wöhler and is known as the Wöhler test.

Often a four-point loading system is employed in which the Sondriker test piece is used. The specimen is supported horizontally in bearings at both ends and loaded at two equidistant points in its span, a method which gives a constant bending movement over the gauge length.

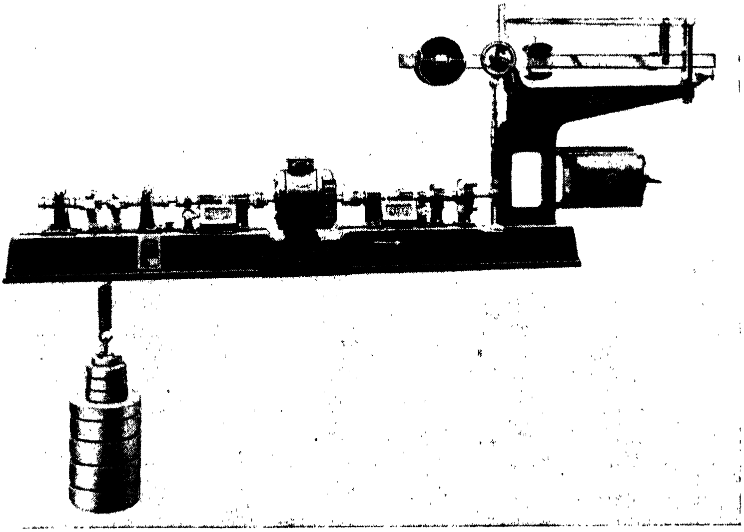


FIG. 58.—Fatigue Testing Machine for Rotating Specimens.
(*Courtesy—Messrs. W. and T. Avery, Ltd.*)

The tests mentioned above are chiefly applicable to specimens turned to a standard shape and the tests are practically limited to the testing of materials. As it is often desirable to test finished machine parts, methods of testing these parts for fatigue resistance have been devised.

Small machine parts of many kinds are tested by vibration in a machine which applies controlled magnetic impulses to the test specimen which is mounted in a manner closely resembling service conditions (Metro-Vickers machine).

Another machine, illustrated in Fig. 60, is used for testing full-sized machine members under service conditions, including temperature and corrosive influences, and permits testing under loads of 6 and 20 tons. The "Pulsator" machine produces axial push-pull stresses with or without initial static load. By means of the use of special tools, alternating bend stresses can be produced, also provision is made for the testing of flat or round specimens of material. The Pulsator is a dual mass resonance machine, one mass being formed by its oscillations system and the other by the machine base. The cross spring beam is in direct contact with the gripped specimen, and is oscillated by an exciter consisting of a flexible shaft operating an out-of-balance rotor at one free end of the beam. Its other free end is compensated by a counter weight in such a way that the

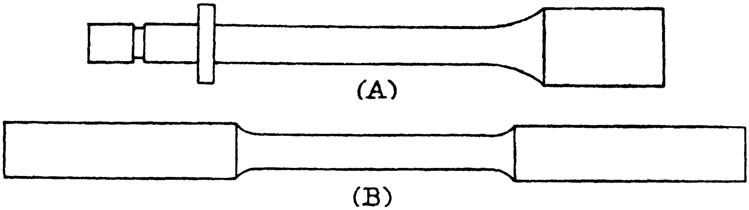


FIG. 59.—Fatigue Test Specimens.

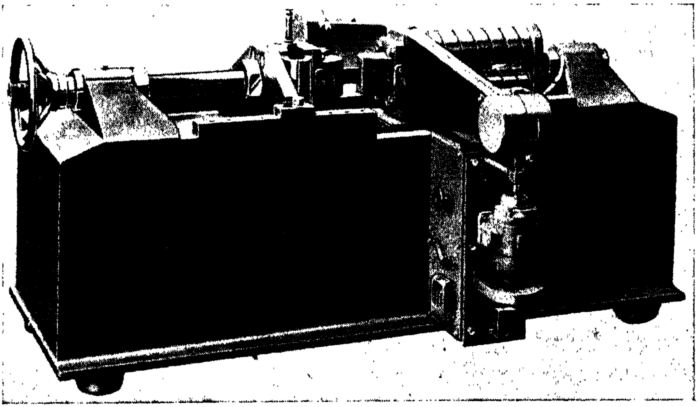


FIG. 60.—Fatigue Testing Machine which can be used for full-sized machine members.

(*Courtesy—Messrs. W. and T. Avery, Ltd.*)

two halves of the springbeam have exactly the same natural frequency. By this means the test piece is subjected to axial push-pull stresses and the oscillations are transmitted to the loop dynamometer through the test piece. The number of stress cycles varies between 2600 and 2900 per minute. Tests may be carried out with (*a*) No initial static load, and the maximum pulsating load can be applied. (*b*) Equal amounts of static and pulsating load between zero and maximum. (*c*) Unequal amounts of static and dynamic stresses between zero and maximum.

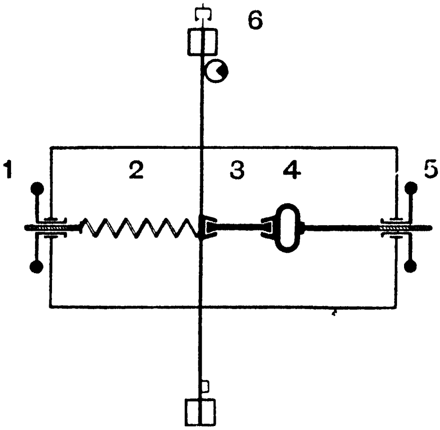


FIG. 61.—Diagram showing working principle of " Pulsator " Machine.

1. Adjustment of initial static load.
2. Springs for applying static stresses.
3. Specimen. 4. Loop dynamometer.
5. Adjustment to length of specimen.
6. Regulation of amplitude.

(*Courtesy—Messrs. W. and T. Avery, Ltd.*)

In fatigue testing and in service, the design of the machine component affects its fatigue value and is greatly influenced by geometric form, dimensions, location of shoulders, threads, notches, grooves, keyways, sharp-edged oil holes, surface finish and very often external influences such as extremes of temperature, corrosive agencies, etc. As an example, threads of a vee type with a sharp root may cause failure due to stress concentration set up at the root of the thread. Rounding off the tool which cuts the vee at the root of the thread increases the endurance limit by a considerable amount.

Failures due to fatigue occur first in the form of a fine hair crack which spreads gradually throughout the cross-section without any premonitory symptoms, causing the effective section to become so reduced that it suddenly fails under the load imposed. After fracture, fatigue failures show two distinct zones, one exhibiting a rather brittle appearance and the other a more ductile fracture. In more brittle materials, however, the difference between the two zones is not so apparent. The shape of the zones depends largely upon the type of material and mode of stressing.

CREEP TESTING

When stressed at high temperatures, metals have a tendency to undergo continuous deformation, and from this phenomenon, known as "creep," a method of testing has been developed involving the minute but continuous deformation which occurs under a predetermined load. The amount of deformation depends on the temperature and the load applied. The test is carried out under conditions whereby a constant predetermined

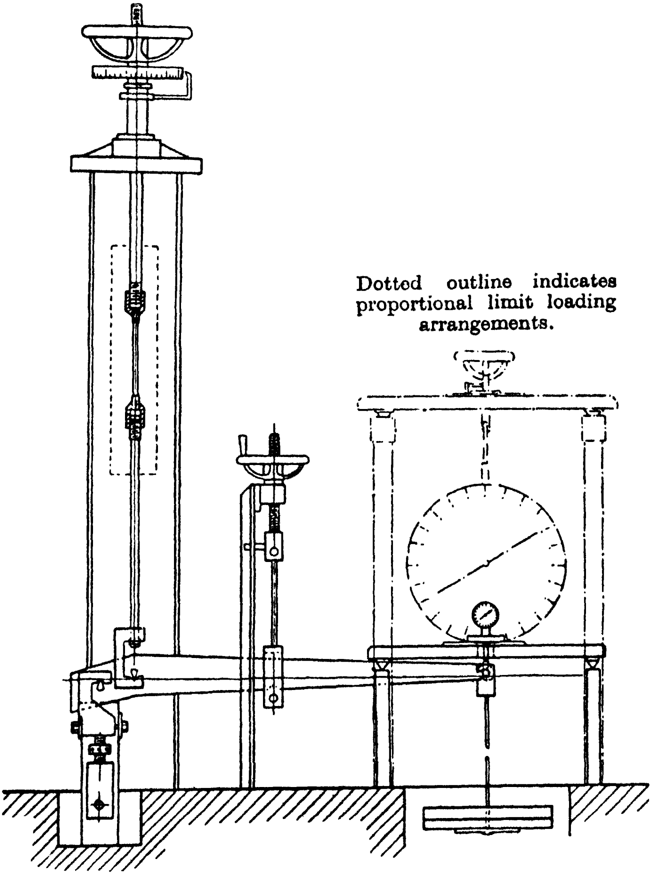
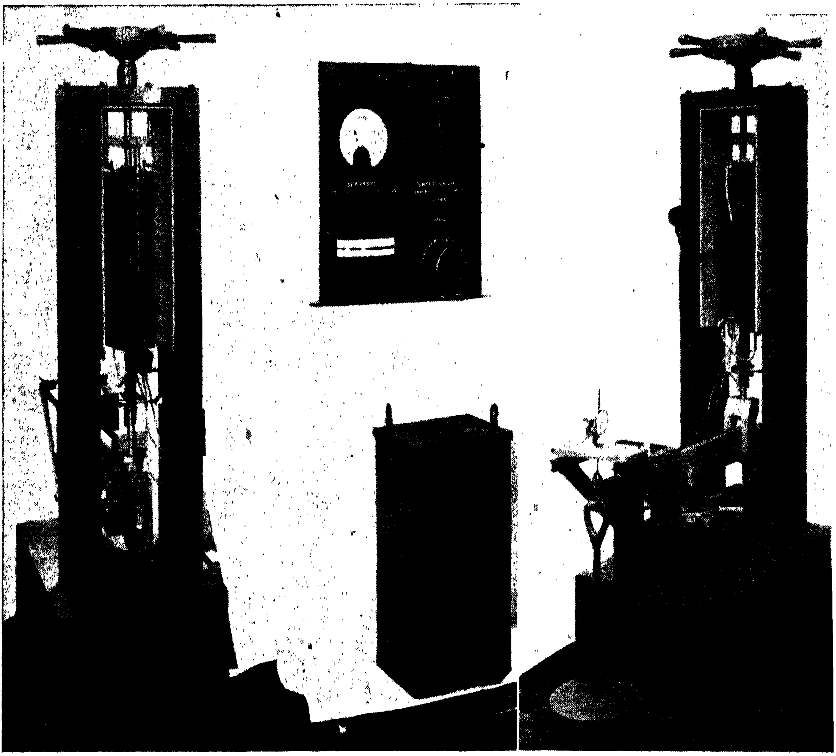


FIG. 62.—Showing loading arrangements of Creep-Testing Equipment.

(*Courtesy—Messrs. Metro-Vickers Elect. Company, Ltd.*)

load is applied at a predetermined constant temperature over a considerable period of time.

In creep testing the specimen, in the form of a tensile test piece, is heated in an enclosed wire-wound and electrically-heated tube furnace, thermostatically controlled and suitable for prolonged operation up to 900°C. For loading the specimen, a single 10 to 1 lever is employed supporting calibrated weights at its free end. Two methods for measuring the creep are employed. For comparatively coarse measurements a dial indicator is supported over the end of the lever, but as errors are likely to be introduced by distortion of the frame due to changes of temperature, the use of a special type of extensometer is favoured.



Front view. Rear view.

FIGS. 63 and 64.—Complete Single-Unit Creep-Testing Equipment.
(*Courtesy—Messrs. Metro-Vickers Elect. Company, Ltd.*)

An extensometer employing two mirrors, also telescopes and scales, is clamped over specially enlarged portions at either end of the 8-in. gauge length of the specimen by means of split clamps.

The ordinary method of creep testing involves rather long periods of time, sometimes extending into months. To overcome this disadvantage a high-temperature slow tensile method of testing has been devised, and, whilst it is recognised that it does not determine quantitatively the true creep resistance of a metal, it does serve a very useful function in indicating the relative creep resistance. The test is of relatively short duration. A machine for making the slow tensile test at elevated temperature is illustrated in Fig. 66. The load is applied by means of a constant speed motor through a train of gearing providing rates of strain of from 0·001 to 0·25 in. per minute as desired. The latter rate corresponds approximately with commercial rates of testing in tension, and enables the machine to be used for ordinary testing at normal temperatures. The motor-driven

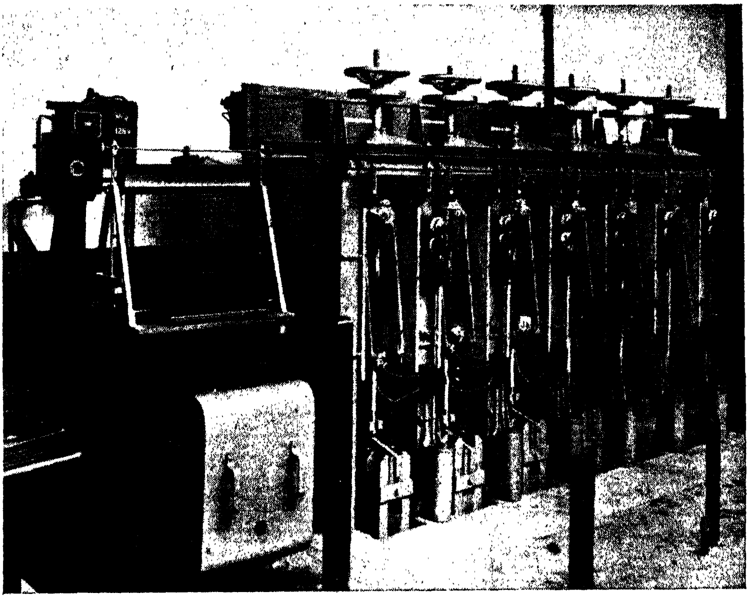


FIG. 65.—A Six-Unit Creep-Testing Equipment.
(Courtesy—Messrs. Metro-Vickers Elect. Company, Ltd.)

loading mechanism may also be disconnected and a lever fitted for ordinary creep testing. The method of heating the specimen and the automatic temperature control is similar to that used in ordinary creep testing. An autographic recording mechanism is fitted for slow tensile tests, in which the load and the extension are recorded automatically by a photographic method, and this recording device may also be used for direct visual measurement. The standard size of specimen for tensile testing is 2 in. gauge length and 0·357 in. diameter (i.e. 0·1 sq. in.). The apparatus is designed to exert a maximum stress of 45 tons per sq. in. on the test piece.

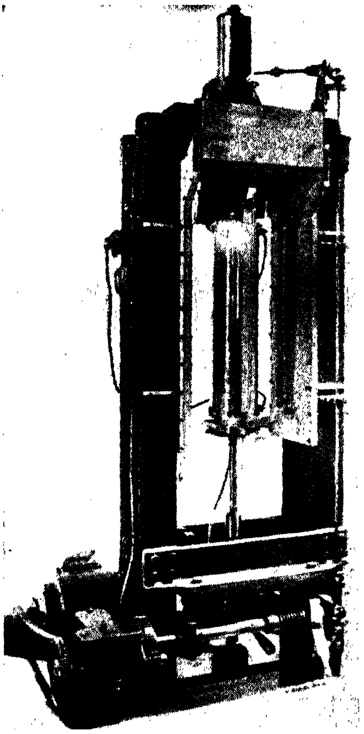


FIG. 66.—High-Temperature Slow Tensile-Testing Equipment.

(*Courtesy—Messrs. Metro-Vickers Elect. Company, Ltd.*)

The *limiting creep stress* is the stress at any temperature, which, if exceeded, will cause continuous creep and eventually failure of the stressed part. The limiting creep stress is reduced with increase of temperature, and this value must be considered in connection with metals working under stress at high temperatures such as are employed in high-pressure steam plant, boiler parts, superheaters, valves and parts of internal combustion engines.

MECHANICAL TESTING OF SMALL TEST PIECES AND MATERIALS FROM SMALL PARTS

It is often desirable to test specimens taken from actual products such as castings and forgings, and frequently the size and shape of the article does not permit the cutting of a convenient section for turning into a test piece for testing in the larger type of testing machine. A small part will sometimes fail prematurely in service and valuable information may be gained if a test piece can be taken from it for test in tension, hardness, etc.

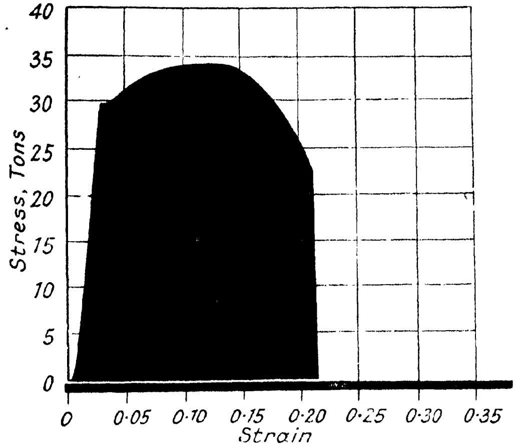


FIG. 67.—Photographic Stress-Strain Record.
(*Courtesy—Messrs. Metro-Vickers Elect. Company, Ltd.*)

Checks on the quality of the material in components before and after long service are also useful sources of information. A universal and portable testing machine which supplies the information regarding the quality of such material is the Hounsfield Tensometer.

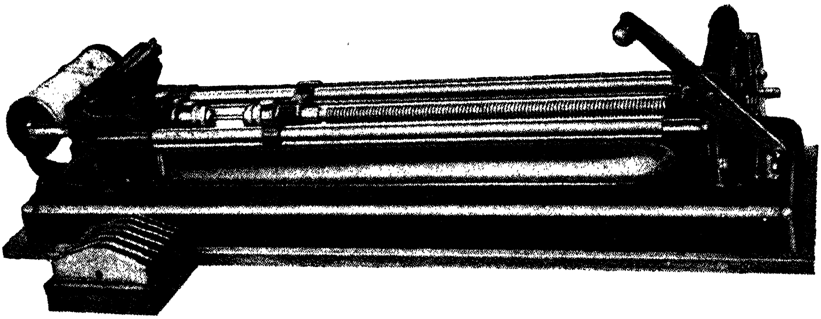


FIG. 68.—The Hounsfield Tensometer.
(*Courtesy—Tensometer, Ltd.*)

The general construction of the instrument is illustrated in Fig. 68. A tensile test piece is held in a pair of split chucks pinned to spherically mounted attachments. The load, ranging up to 2 tons, is applied through a hand-operated handle and geared mechanism. This force acts through the test piece and is measured by the deflection of a calibrated spring beam, which, in deflecting, acts on a piston in a mercury cylinder whereby mercury is displaced into a small-bore glass tube adjacent to a graduated scale. Attached to the instrument is a recorder drum, slowly rotated by means of gearing from the movement of the operating handle. The pointer of a cursor is made to follow the head of the mercury column in the tube and a pricker is regularly operated to produce a series of punctures on a sheet of graph paper attached to the recorder drum. The load is recorded as ordinates and the straining of the test piece is recorded at abscissae

FIG. 69.—Some applications of the Tensometer.
(*Courtesy—Tensometer, Ltd.*)

giving a stress-strain diagram on the chart. Accessories either incorporated in, or supplied with, the machine enable, in addition to tensile tests, a wide variety of other tests to be made, including notched bar, cast-iron bend, uniform bending movement, Brinell hardness, compression, punch-shear and cupping. The machine is also applicable to the testing of strip, plate and wire, plastics and textiles. The measure of the ductility of the material can be rapidly and simply determined from the fractured test piece by the use of gauges for elongation and reduction of area. Although the machine deals mainly with miniature test pieces ranging in diameter from 0·126 to 0·506 in. and in overall length from approximately 1 in. to 2½ in., the results obtained from the tests are remarkably accurate and, indeed, the machine can be used with confidence even when sufficient material is available for conducting tests using the larger and standard test bars in other testing machines.

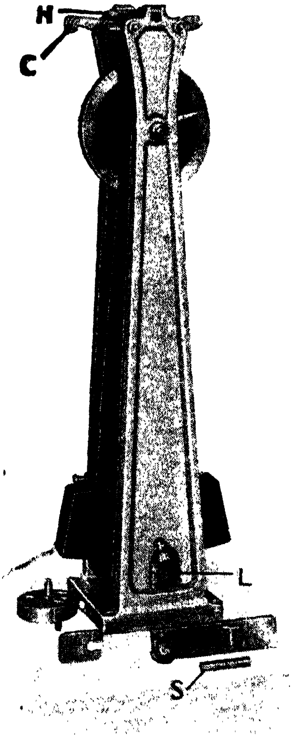


FIG. 70.—The Hounsfield Balanced Impact Machine. (*Courtesy—Tensometer, Ltd.*)

For the purpose of testing small specimens for impact value, small impact machines have been devised. A useful machine for conducting this type of test is the Hounsfield Impact Machine. Briefly, it consists of two swinging tups mounted on ball bearings and housed in an upright frame. The tups are designed and arranged so that they move one inside the other, the outer one being of double construction and in which the anvils are carried. Both tups are initially held in the elevated position by catches and, when released by manipulation of the hammer H, swing in opposite directions from the same height, so that the moving weight is divided equally between them. The test piece S, having a standard V notch which is engaged by the notch register, is fixed in the inner tup and located at the centre of percussion of the moving tups. When the tups pass one another after breaking the test piece, a non-return pawl mechanism prevents them from swinging backwards. The indicating pointer P records the difference in movements between the tups and is read from the scale K. The machine gives comparative results with materials, and good Izod equivalents are obtained on ferrous metals if the result is multiplied by 2·5.

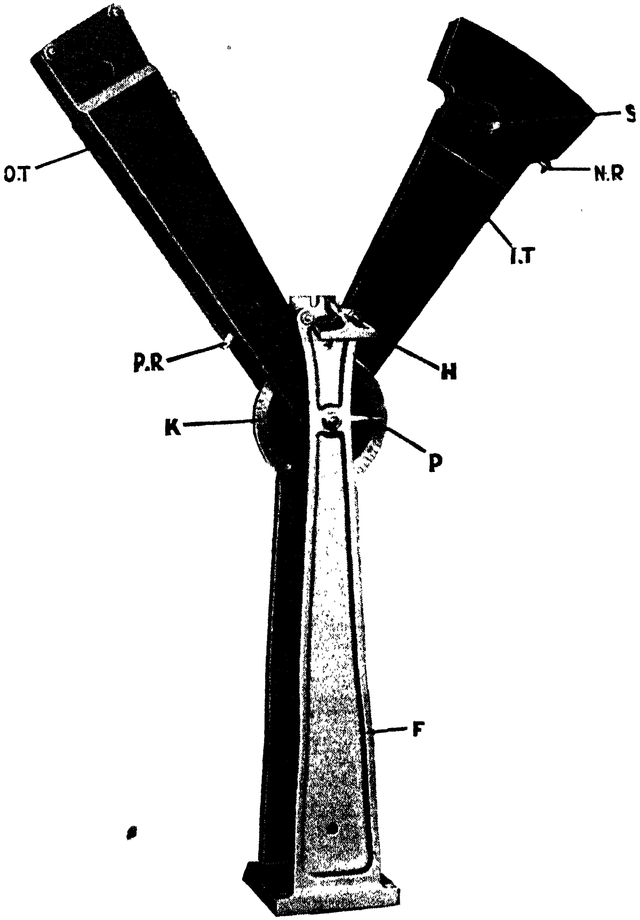


FIG. 71.—The Hounsfield Balanced Impact Machine with tups in elevated position ready for test.
(*Courtesy—Tensometer, Ltd.*)

CHAPTER 3

PHYSICAL EXAMINATION OF METALS

METALLOGRAPHY

METALLOGRAPHY is the term applied to the optical examination of the internal structure of metals by visual means using a metallurgical microscope. It is often found that, although two samples of metal are identical as regards chemical analysis, they differ very widely in other properties, and the microscope provides a means of determining the physical condition of the metals. In many instances positive information is obtained regarding the mechanical and heat treatments which a sample of metal or a finished part has received during its manufacture.

The preparation of specimens. The specimen to be examined is cut to a convenient size. Holding and manipulation of the specimen is simplified if it is not tall in relation to the section of the face to be polished. Taking the simple example of a cylindrical specimen, its height should be less than the diameter. For thin specimens, such as sheet and wire, special methods of mounting are employed.

Where possible, the specimen should be lightly cut to a convenient size with a sharp hacksaw. Excessively hard materials may require cutting with an abrasive wheel, during which precautions must be taken to keep the specimen in a comparatively cool condition. This precaution must also be taken when preliminary grinding the surface to be examined, by using a flow of water as a coolant, or by frequent dipping in water because, with some metals, particularly hardened steels, a slight increase in temperature, even though it may be only local, will give an alteration in structure.

The scratch marks made by the wheel are then erased by means of a fairly fine file. As it requires considerable experience to maintain a flat surface by applying the file to the specimen, it is better to hold the file in a vice or lay it flat on a bench, and firmly but not too heavily rub the specimen on the file at an angle of 90° to the scratch marks made by the wheel. The pressure should be just sufficient to feel that the file is actually cutting. This step, of course, is not possible with very hard materials and filing is omitted.

The remainder of the operations may be carried out by hand or on a motor-driven horizontal polishing disc. In the former method, strips of various fineness grades of coarse emery, and also what is generally known as French emery paper about 3 in. wide, are firmly fastened with drawing-pins to flat boards of hard wood of suitable size. Alternatively, the whole required series of papers may be pinned on to a long board which has, running down its entire length and most of its width, a long piece of inlaid glass, allowing a wooden border on both sides for pinning on the papers. With this latter arrangement, provided that the specimen is manipulated in the correct manner, a perfectly flat surface is obtained. The specimen is held face downwards on the first grade of emery paper and, by resting the elbow on the bench and using it as a pivot, the specimen is passed backwards and forwards with firm but not heavy pressure at an angle of 90° to the scratches previously made on the file or cutting wheel. The operation is continued until these scratches are removed. The process is repeated on the other progressively finer grades of papers, each successive transfer being accompanied by the rotation of the specimen through a right angle. The French emery papers are brown in colour, and number 1, 1M, 1F, 0, 00, 000 and 0000 in progressively finer grades. It is essential that transfer from one paper to the next should not be made until all scratches are in the same direction. After leaving the 000 or 0000 paper, the specimen has a smooth bright finish except for a series of very fine scratches running in one direction. The specimen is then ready for finishing.

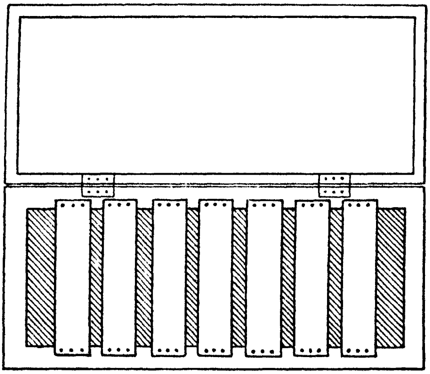


FIG. 72.—Plan of Polishing Board.

Finishing is carried out on a strip of selvyt cloth, chamois leather or any other non-gritty soft cloth without excessive pile. A substantial application of polishing powder, with a supply of water to form a paste, is made to the cloth. Several polishing powders are available, namely, chromic oxide, rouge, zinc oxide, manganese dioxide, tin oxide, magnesium oxide and diamantine, the last named being a specially prepared form of aluminium oxide. Choice of polishing powder depends upon the type of material being polished. For quick rough work and for very hard specimens chromic oxide is very satisfactory, but this has the disadvantage that soft constituents, such as graphite in cast irons, tend to become damaged, and for this type of constituent magnesium oxide or diamantine is preferred, but the process is much slower. A favourite powder for average speeds on ferrous work is rouge, but this often has the property of clinging to the surface of certain specimens, and the surplus is not easily removed. The specimen is considered as being completely polished when, by wiping on a clean soft cloth, the removal of the surplus abrasive paste leaves a mirror-like surface free from scratches.

When a polishing wheel or disc is used, a groove round the disc and a spring enables the papers to be changed as desired. For final polishing, the cloth may be fixed to the disc, and clamped over this is a bottle with a fairly fine jet, from which water is allowed to drop at a slow and constant speed to keep the paste fairly fluid. The speed of the wheel should be 400 to 600 revolutions per minute and the specimen should be moved to and fro across the wheel during the operation.

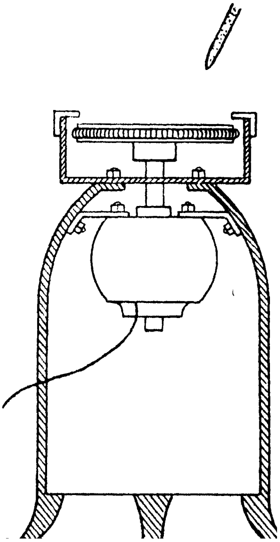


FIG. 73.—Polishing Wheel.

During preparation, specimens of the softer metals, particularly non-ferrous metals, are easily and deeply scratched, and a layer of amorphous metal tends to flow over the surface of the polished face in a similar manner to a very viscous liquid. This condition is aggravated by excessive pressure. Consequently much greater care is necessary in the polishing of the soft metals, lighter pressure being required and the polishing papers may, with advantage, be soaked in paraffin before use. The final polishing of non-ferrous alloys is often carried out by means of a good quality liquid metal polish on selvyt cloth or chamois leather but, prior to etching, any grease should be washed off with a solvent. Magnesium and aluminium alloys may be finished with magnesia or alumina.

Methods of mounting specimens for polishing. Some specimens, for various reasons, require special means of mounting. For the examination of surface hardening, case hardening, decarburisation and plating, it is often desired to examine the structure up to the edge of the specimen. Even the most carefully polished unmounted specimen will show some degree of curvature at the edge, rendering an examination of a flat field very difficult. For examination of edges several methods of mounting may be employed.

In the first method the specimen is mounted in a metal of low melting-point. For this purpose a copper, brass, or steel ring is placed on a smooth steel plate, which has been slightly warmed. The specimen, having its surface for examination ground or filed flat, is placed face downwards on the steel plate and in the centre of the ring. The ring is then filled by pouring in the molten metal which, in solidification, firmly mounts the metallographic specimen. Polishing can now be continued in the usual manner. Tin can be used as the mounting medium when nitric acid is the etching reagent, and lead where the material is etched with a reagent with hydrochloric acid as a constituent. The low melting-point fusible alloys such as Wood's metal mentioned in chapter 10 are also often useful for mounting specimens for polishing. The choice of mounting metal is important, for if both mounting metal and specimen are attacked by the same reagent preferential attack may result, and the purpose of the mounting would be defeated.

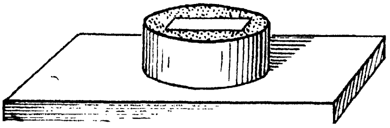


FIG. 74.—Setting of Specimen in Fusible Metal.

A more satisfactory method of mounting is by the employment of an hydraulic mounting press using bakelite or a transparent plastic as the mounting medium. The specimen is mounted by using specially designed mould outfits, electric mould heaters, and coolers. Slight heat along with pressure is applied and the mounting material perfectly surrounds the metallographic specimen, and the close adherence of the plastic which, on cooling, becomes a hard solid, makes possible the examination of the extreme edges. The mounting medium does not tend to smear

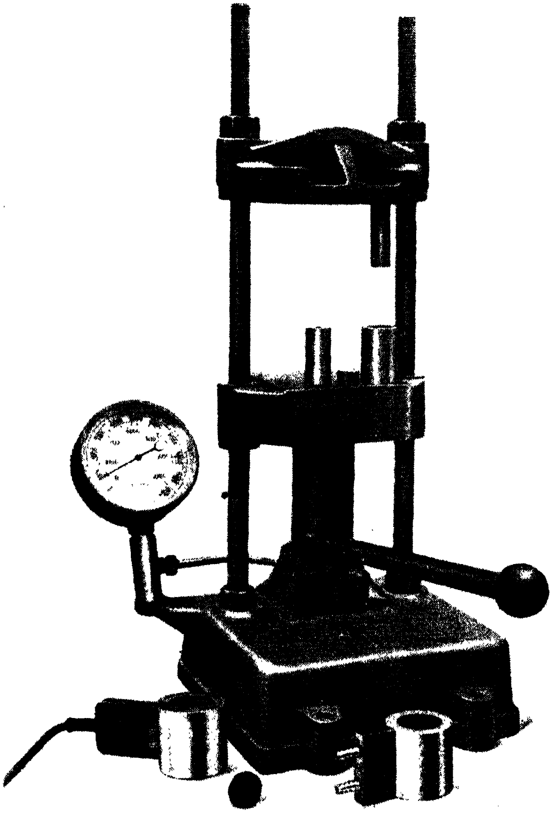


FIG. 75.—The " Millen " Hydraulic Mounting Press for Metallographic Specimens.

(*Courtesy—Messrs. Griffin and Tatlock, Ltd.*)

across the metal face when polishing, as is liable to happen when fusible alloys and metals are used as mounts. The differential etching action encountered with fusible metal mountings is avoided as bakelite is impervious to the normal etching agents. All kinds of specimens of inconvenient shapes, such as wire, sheet, etc., can be polished and examined in bakelite mountings.

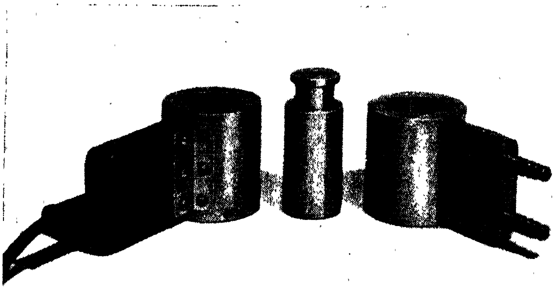


FIG. 75*a*. Mould Outfits for Millen Press.

Etching the specimen. Non-metallic inclusions, like graphite in cast iron, slag in steel, and other metals not soluble in the matrix of a metal or alloy (e.g. lead in brass), stand out clearly under the microscope after the polishing operations, and often require no further treatment. It is usually necessary, however, to use a chemical or combination of chemicals, known as etching reagents, to reveal the detailed structure of the metal. During polishing a thin film of amorphous metal flows across the face of the specimen in varying degrees depending upon the composition of the specimen, the weight applied during polishing, etc., and this condition is particularly prevalent with the softer metals. The etching reagent removes this amorphous layer and attacks the constituents of the metal underneath, revealing the true structure. Etching reagents react by the gradual solution of the metal from the surface downwards, the rate of solution being dependent upon the degree to which the constituents are impervious or acted upon. The time of etching is governed by

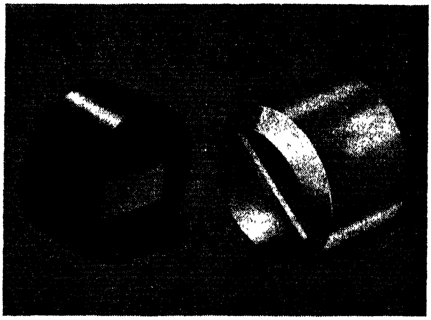


FIG. 75*b*.—Mounted Specimens.

the reagent used, its strength, and the type of material under examination, but the most convenient and satisfactory period is one that gives the desired result in not less than 10 seconds nor more than about 2 minutes. Very often more than one etching operation is necessary to remove the amorphous film, and develop the true structure. In this case the practice is to give the specimen several repeated polishings on the wet abrasive cloth, and etching operations alternately until the desired condition is obtained.

The uniformity of etching obtained with alcoholic solutions is usually greater than that with aqueous solutions, and staining of the surface is less common.

The chief and more frequently used etching reagents are listed below :—

Iron and steel

(1) 2 to 5 per cent solution of nitric acid in absolute alcohol for general structure, and particularly ferrite grain boundaries.

(2) Saturated solution of picric acid in alcohol for general structure, but gives better definition of pearlite than nitric acid in alcohol.

(3) Alkaline sodium picrate. 2 gm. of picric acid dissolved in a solution of 25 gm. of caustic soda in 75 c.c. of water. The specimen is immersed in the boiling reagent for 5 to 10 minutes. On withdrawing, the specimen is quickly washed in water. Used for revealing cementite and which appears blackened by etching (Kourbatoff's Reagent).

(4) 10 gm. potassium ferricyanide, 10 gm. potassium hydroxide in 100 c.c. water (Murakami's Reagent). For distinguishing carbides in chromium and tungsten steels. Cementite requires a longer immersion to colour than alloy carbides.

(5) 10 per cent hydrochloric acid with 10 per cent by weight of ammonium persulphate for stainless steel.

(6) 20 c.c. hydrochloric acid, 40 c.c. nitric acid, and 40 c.c. glycerine for high-speed steels.

Copper and copper alloys

(1) 10 per cent solution of ammonium persulphate in water. If etching is too slow for any alloy, the addition of 25 per cent of strong ammonia will decrease the etching time, often with beneficial results. Used with alloys of copper and zinc.

(2) 10 c.c. ferric chloride, 30 c.c. hydrochloric acid, 100 to 120 c.c. water. Used for phosphor bronze and high-strength brasses.

The above two reagents will satisfactorily etch practically all the copper-rich alloys.

Nickel and nickel alloys

(1) Ferric chloride solution as above.

(2) 50 per cent nitric acid, 25 per cent glacial acetic acid, and 25 per cent water by volume.

Bearing alloys

(1) 5 to 20 per cent hydrochloric acid for alloys rich in tin.

(2) 1 to 5 per cent nitric acid for alloys rich in lead.

Aluminium alloys

(1) 1 to 10 per cent hydrofluoric acid in water.

(2) 5 to 20 per cent sodium hydroxide or potassium hydroxide in water.

(3) 20 c.c. nitric acid, 20 c.c. hydrofluoric acid, and 60 c.c. glycerine.

Magnesium alloys

(1) 2 per cent nitric acid in alcohol.

(2) 2 per cent oxalic acid in water (useful for grain boundary etching).

Tin alloys

(1) 5 per cent hydrochloric acid in alcohol.

Zinc and zinc alloys

(1) 1 to 4 per cent nitric acid in alcohol.

(2) A few drops of a solution of 94 c.c. nitric acid and 6 gm. chromic acid, added to 50 c.c. water.

Lead and lead alloys

(1) 5 per cent nitric acid in alcohol.

(2) Acetic acid and up to 3 per cent addition of hydrogen peroxide.

After etching, the specimen is washed thoroughly in running water, then in absolute alcohol or acetone to remove the water. The alcohol or acetone quickly evaporates in the air, but the evaporation is often accelerated by a warm steam of air from a hair dryer.

The microscope. Examination of the structure of metallographic specimens is carried out with a microscope employing reflected light. A microscope consists essentially of :—

(1) A stage for holding the specimen and which may be racked up and down to accommodate various heights of specimen. By racking up the stage the image of the structure of the metal is brought into rough focus at a set distance from the objective, this distance depending upon the magnifying power of the objective, being shorter with higher magnifications. The objectives used for high-power examination have the shorter working distance between the surface of the specimen and the bottom lens of the objective. Care is therefore necessary when racking up the stage that the specimen does not come into contact with the lens of the objective, which may become damaged as a result.

With magnifications of about 800 and over, the working distance is increased by smearing the face of the specimen and the lower lens of the objective with cedar-wood oil, and racking up the stage until the two films of oil meet. After use, the oil is easily removed by wiping with xlene on a soft clean cloth.

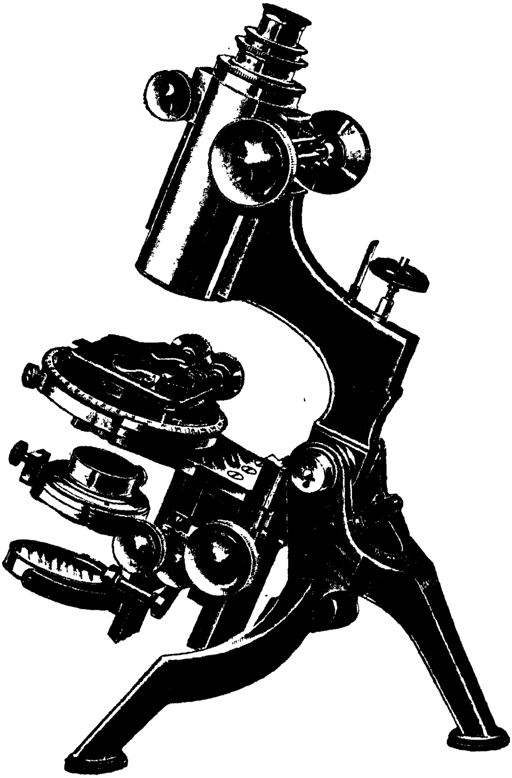


FIG. 76.—Typical Metallurgical Microscope. Bench Type.
(*Courtesy—W. Watson and Sons, Ltd.*)

(2) The microscope body tube, to which is clipped or screwed the objective at the lower end, and an eyepiece, sometimes termed ocular, is inserted at the top of the tube. An eyepiece is a combination of two lenses set in a short cylindrical

tube and may be interchanged according to the magnification required. The initial magnification at the objective is increased by the magnifying power of the eyepiece. Data regarding the optical equipment are usually marked on the accessories, or given in the microscope makers' specification,

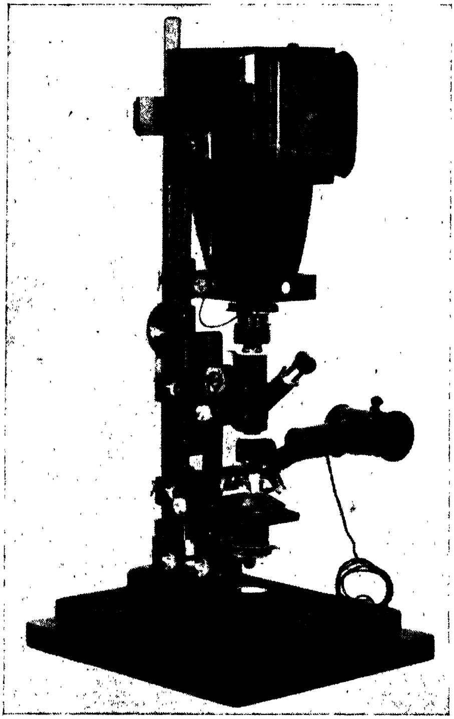


FIG. 77.—Photomicrographic Apparatus.
Vertical Type.
(*Courtesy—W. Watson and Sons, Ltd.*)

from which the magnification can be calculated approximately from the formula :—

$$M = \frac{T}{f} n$$

where T = the tube length from the front of the ocular to the tip of the objective and including the vertical illuminator.

f = the focal length of the objective.

n = the magnifying power of the eyepiece.

Incorporated in the body tube is a micrometer screw for fine adjustment of the focus.

(3) A vertical illuminator for directing the illuminating rays of light on to the specimen. Two forms are in general use: a glass prism and a thin glass plate type, and housed in an attachment between the lower end of the body tube and the objective. For convenience in some microscopes, both the glass plate and the prism are mounted in the illuminator on a device which permits immediate changing from one to the other. The light enters at the side of the vertical illuminator and at right angles to the body tube. The source of light may be daylight, an electric filament bulb, or an arc lamp.

The glass prism is mostly used in examination at the lower powers of magnification, the principle being illustrated in Fig. 79. The rays of light enter from the side and strike the face of the prism, from which they are deflected downwards on to the surface of the specimen. The specimen reflects the rays back again up the body tube, past the prism to enter the eyepiece of the microscope.

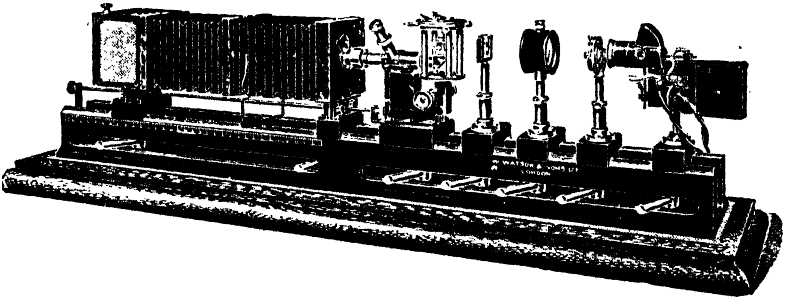


FIG. 78.—Photomicrographic Apparatus. Horizontal Type. Watson's Metallograph.
(*Courtesy—Messrs. W. Watson and Sons, Ltd.*)

The glass plate is placed at an angle of 45° to the optical axis. With this type of illuminator all the rays of light are not reflected downwards, but some pass through the glass plate, as indicated by the dotted lines in Fig. 80, and are lost in the microscope body tube. As a result, with the same source of light for both types of vertical illumination, the density of the light rays reaching the eyepiece are less with the use of the glass slip than with the prism. A much better and more detailed image is obtained by the use of the glass slip illuminator.

(4) For the taking of photographs a reflex camera attachment is employed. A ground-glass screen is provided which slides into place at the end of the bellows, and on to this the image is thrown prior to final focusing. To carry out the final focusing, the ground-glass screen is removed and a plain glass plate is inserted in its place, and the micrometer screw in the body tube of the microscope is slowly turned until, by viewing through a focusing magnifier resting on the glass plate, the image appears sharpest in outline. At the other end of the bellows is a sliding light-screened collar surrounding the eyepiece. The camera is also provided with a time shutter for controlling the lengths of exposure given to the photographic plate. The latter is contained in a light-proof holder and fits into an arrangement at the end of the camera. When ready to make the exposure, the slide of the holder is withdrawn, and the plate is then exposed to the rays of light. When taking photographs, filters of green, yellow, or other colour are used to eliminate rays of undesirable light, thereby reducing glare and giving a sharper image. The colour of the filter used depends to some extent upon the source of illumination, the magnification, type of photographic plate, and the colour tone of the metallographic specimen.

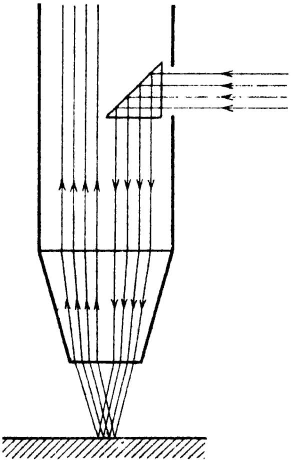


FIG. 79.—Vertical Illuminator with Prism.

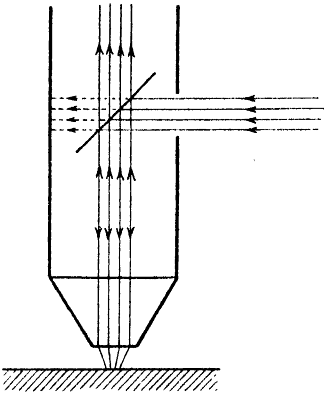


FIG. 80.—Glass Slip Type of Illuminator.

All are familiar with the appearance of the usual bench type of microscope. A camera attachment may be used in conjunction with this for taking photographs of metallographic specimens. During recent years special types of photomicrographic apparatus have been developed, both of horizontal and vertical designs, in which the introduction of various devices enables the same instrument to serve with little alteration, as a routine microscope for visual examination or as a photomicrographic apparatus. Sometimes, in addition, certain makes of instrument may be employed as a micro-drawing apparatus and for projection of the image on to a white screen for demonstration purposes. Illustrations of typical modern instruments are Figs. 77, 78 and 81.

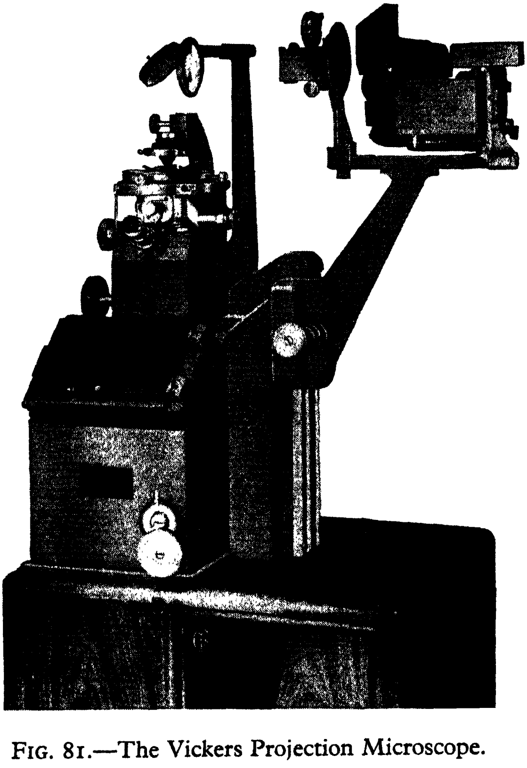


FIG. 81.—The Vickers Projection Microscope.
(Courtesy—Messrs. Cooke, Troughton and Simms, Ltd.)

The magnification of the image on the photograph is predetermined by the use of what is known as an objective micrometer, consisting of a polished piece of metal of suitable size. In the centre of the micrometer are very fine graduations in the form of a metric rule 1 mm. in length, and divided into 100 equal divisions. The graduations are placed under the objective of the microscope, and focused on to the ground-glass screen fitted in the end of the camera, where they are clearly seen. A convenient number of the divisions are then measured with an ordinary type of rule graduated in centimetres and millimetres. For example, if 50 graduations of the micrometer give an image measuring 8·5 cm. on the ground-glass screen, the magnification of the image on the photograph would be 8500÷50=170 diameters.

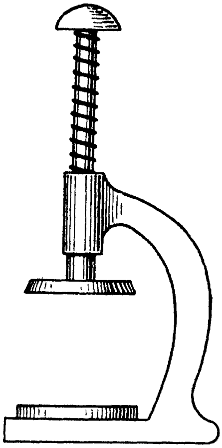


FIG. 82.—Plasticine Levelling Press.

Various outfits require different methods of levelling or setting the specimen. The surface of the specimen to be examined must be set at right angles to the axis of the objective. The use of the bench type of microscope and the vertical types of photo-micrographic outfits necessitate the levelling of the specimen on plasticine held on a small glass slide. This may be carried out by two methods. The first employs a hand-mounting press, as shown in Fig. 82. The specimen is placed face upwards on the plasticine, and levelled by depressing the plunger, so that the disc which is exactly parallel to the base of the press firmly presses the specimen into the plasticine. On withdrawal of the hand from the knob, the spring brings the plunger and disc back to its normal position.

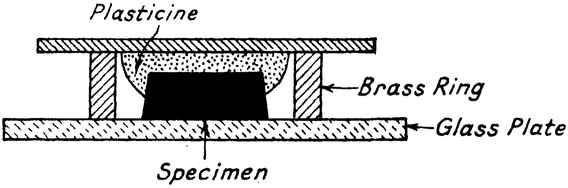


FIG. 83.—Levelling with Glass Plate Plasticine and Ring.

In a satisfactory alternative method of mounting, the specimen is placed face downwards on a glass plate and surrounded by an accurately parallel ring. A piece of plasticine, attached to a strip, is pressed on to the specimen until the strip contacts both sides of the ring. On lifting the strip, the specimen adheres to the plasticine, and examination under the microscope can be proceeded with without further levelling.

With most types of horizontal microscopes, mounting is not necessary, as the specimen is placed face downwards on the stage. The stage is constructed to house a disc with a hole in the centre and, as a choice of discs is usually provided, the operator chooses one which has a hole slightly smaller than the dimensions of the specimen. The light enters through a horizontal collimating tube, and is reflected upwards into the objective and then on to the face of the specimen.

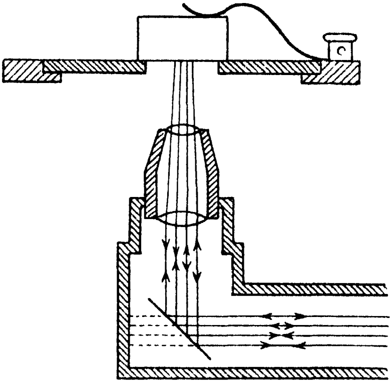


FIG. 84.—Specimen Inverted in Stage

SPECIAL METHODS OF REVEALING THE STRUCTURE

(1) **Electrolytic polishing.** An interesting method of final polishing when the specimen leaves the 000 emery paper is by electrolytic means, and is finding increased favour as a quick

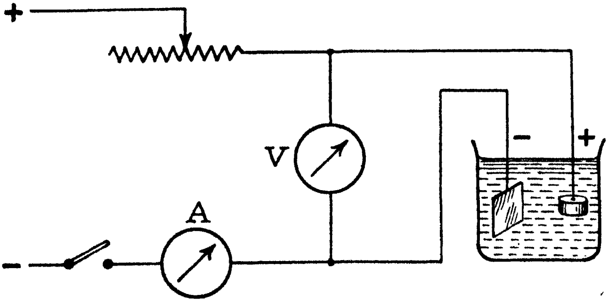


FIG. 85.—Circuit for Electrolytic Polishing.

nethod instead of the often laborious process of using the wet brasives. It is applicable to all metals, but is especially con-enient for the final polishing of the softer non-ferrous metals, vith which difficulty is often experienced in the final removal of cratches.

The specimen forms the anode of the circuit and the cathode nay be a plate of iron or aluminium of a considerably larger urface area than the specimen. The current density, voltage nd composition of the electrolyte is varied with the type of metal nder examination. Voltages in the order of 1 to 100 are used vith current densities of 0·07 to 0·16 amps. The time required or the operation also depends upon the type of material and is etween 4 and 10 minutes.

Etching after polishing can then be carried out with the usual tching reagents, or etched electrolytically.

(2) **Electrolytic etching.** The specimen is made the anode y being supported in an electrolyte by a length of platinum vire. The cathode consists of a piece of platinum foil. The lectrolyte solutions used are ammonium nitrate and other eutral salts. Weak ammonia may be used for etching copper nd brass, sodium thiosulphate for bronzes, and dilute sulphuric cid along with a small quantity of hydrogen peroxide for copper-ickel alloys. Small currents of 0·01 amp. per sq. cm. of etching rea is usually sufficient.

(3) **Polish attack.** Final polishing is carried out by lightly ubbing on a soft pad moistened with a suitable etching reagent—mmonium nitrate for steels and dilute ammonia for copper and ts alloys. The method has only a limited application owing to he amount of care necessary to produce good results, and avoid-ng over-emphasis of the grain boundaries.

(4) **Polishing in relief.** This is a method which has only a ery limited application now, but was used more frequently in he early days of metallography when the choice of suitable tching reagents was not so wide. Hard constituents are thrown nto relief by polishing the specimen on a soft cloth impregnated vith rouge after it leaves the emery papers. It can, however, ive some indication of the distribution of the hard-wearing con-tituents such as phosphorus in cast irons, carbides in iron and teel, and hard particles in bearing alloys.

(5) **Heat tinting.** This is a method of examination which lepends upon the preferential oxidation of the constituents of

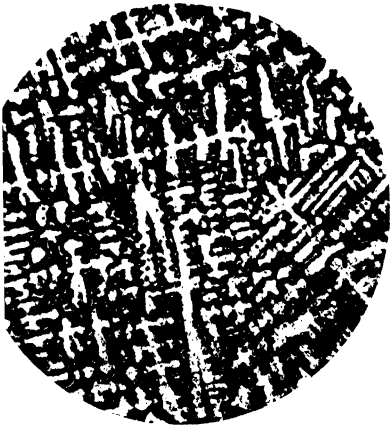


FIG. 86.—Heat-tinted Nickel Bronze. × 50 Dias.
52 Ni, 33 Cu, 12 Sn.

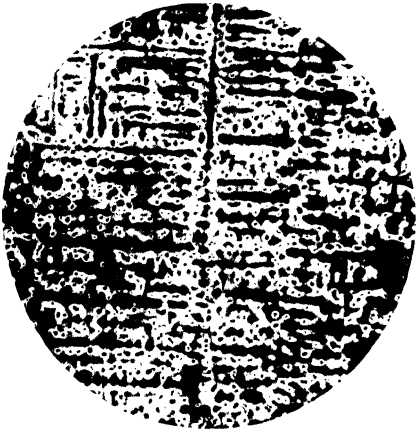


FIG. 87.—Heat-tinted 85/5/5/5 Gunmetal. × 50 Dias.

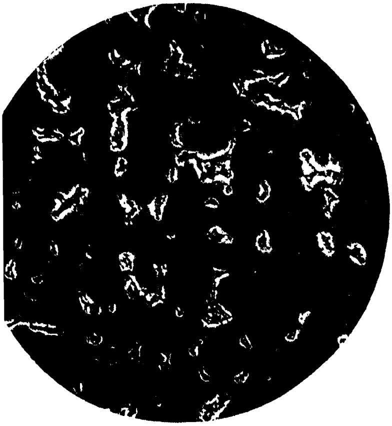


FIG. 88.—Heat-tinted Phosphor Bronze. × 100 Dias.
88·5 Cu, 11·0 Sn, 0·5 P.

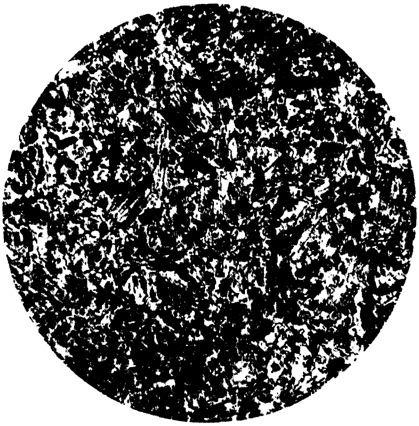


FIG. 89.—Heat-tinted Manganese Bronze. × 50 Dias.

an alloy when heated in air. The method takes rather more time than the dip-etch procedure with the normal etching reagents, but it is a valuable means of revealing phosphides and dendritic structures, particularly in non-ferrous metals. It has the advantage that the structure in areas of unsoundness due to blow holes or other types of porosity can be examined more satisfactorily. This is because of the tendency of any etching solution trapped in the cavities when the dip method is used to creep back over the surface of the specimen after drying and standing some length of time. The surface of the specimen then becomes stained.

After complete polishing, de-greasing, and warming to remove moisture, the specimen is floated, polished side uppermost, in a shallow trough of tin which rests on a small hot plate. The tin is thereby heated uniformly, and is maintained by suitable control at a temperature of approximately 280°C. With the copper-nickel alloys containing substantial percentages of nickel, a temperature of about 360° is often required to give suitable tinting conditions.

When a purple tint is observed over the surface of the specimen, it is withdrawn from the tin and quickly cooled by floating in another shallow trough or dish containing mercury, carefully avoiding contact of the face of the specimen with the mercury. If the desired depth of tint or contrast is not obtained, the operations may be repeated. The time required is 3 to 6 minutes for gunmetals, brasses and phosphor bronze, 10 to 15 minutes for cast iron, and a considerably longer period for manganese bronze and the copper-nickel alloys containing high proportions of nickel.

(6) **Sulphur printing**. The specimen is ground flat, and need not be perfectly polished as for micro-examination. It should be free from grease. A sheet of gaslight or bromide photographic printing paper is soaked in 5 per cent sulphuric acid, and the surplus acid removed with blotting paper. The face of the specimen is then carefully and lightly pressed on to the prepared paper so that complete contact of the surface is made with the paper. After about 2 minutes the paper is peeled off the specimen. The acid on the paper reacts with the manganese sulphide and iron sulphide in the metal, liberating hydrogen sulphide which combines with the silver salt in the paper to give a dark brown stain of silver sulphide. An indication of the distribution of sulphur is indicated on the print (Fig. 227). For a permanent

record, the print may be given a quick rinse in water, and fixed in hypo solution in the same manner as an ordinary photographic print.

(7) **Macrostructures.** The macro method of etching and examination consists of roughly polishing a large specimen or section of a complete casting, forging or ingot, and etching with a reagent which acts quickly on the metal giving a short period of contact. The sample is usually too large to be examined by the ordinary metallurgical microscope, and the quick deep etch gives a visual indication of the distribution of impurities, general structure, porosity, large dendritic structures, and the method is particularly valuable for showing the flow lines in forged or rolled articles.

Macro-etching can be accomplished by a large number of reagents and the choice depends upon the features desired to be revealed in the metal. Some of the common reagents are :—

Iron and Steel

(1) An 8 per cent aqueous solution of copper ammonium chloride is poured over the surface of the specimen to produce a coarse loosely adherent deposit of copper. The metal is then treated with a solution containing 120 gm. copper ammonium chloride, 50 c.c. hydrochloric acid, and 1000 c.c. water. When etching is complete, the copper deposit is wiped away. The effect obtained can often be improved by lightly rubbing the surface on fine emery paper, when the structure standing in relief appears in contrast.

(2) Stead's Reagent. 10 gm. cupric chloride, 40 gm. magnesium chloride and 20 c.c. hydrochloric acid. The salts are dissolved in the acid with a minimum amount of hot water. 1000 c.c. of alcohol completes the reagent.

During use, copper is deposited on the areas low in phosphorus. The reagent will also reveal primary dendritic structures in cast steel.

Copper and copper alloys

(1) 25 gm. ferric chloride, 25 c.c. hydrochloric acid, and 100 c.c. water.

(2) 50 c.c. ammonia, 2·5 gm. ammonium persulphate, and 150 c.c. water. The solution is especially useful for brasses containing the beta phase.

Aluminium and aluminium alloys

(1) 20 per cent aqueous solution of hydrofluoric acid.

(2) Reagents of increased activity can be produced by mixing with dilute hydrofluoric acid, suitable proportions of hydrochloric and nitric acids.

Interpretation of structures. The various pure metals crystallise in various polygonal forms, some cubic, some hexagonal and some tetragonal. If the crystals of a solidifying molten metal were able to form and grow freely, crystals of perfect geometric shapes would be obtained, as is the case when certain saturated solutions of chemicals are allowed to crystallise. Crystals of definite geometric shape are known as idiomorphic crystals.

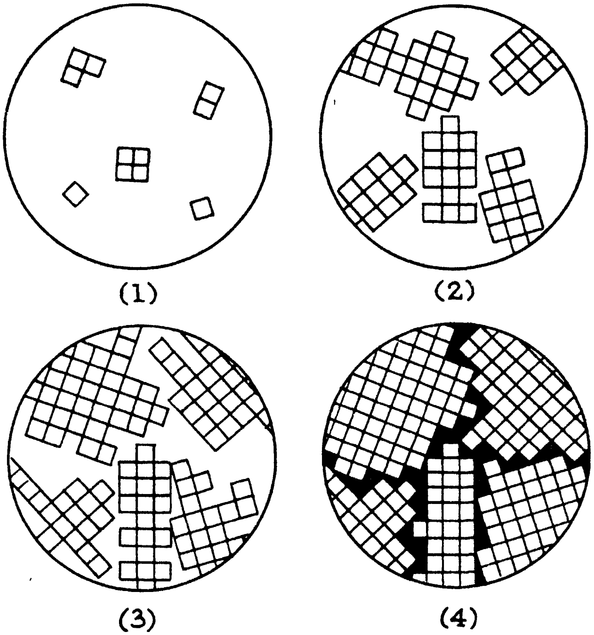


FIG. 90.—Diagram showing Crystal Formation in Pure Metals.

Crystallisation commences from a series of nuclei or centres in the cooling liquid or molten metal, and in the early stages of their growth they have idiomorphic shapes, but as they grow they impinge and mutually limit further growth. Each grain or crystal consists of a large number of unit cells of the same geometric design as the complete crystal. When pure metals have completely solidified, their grains have no apparent geometrical form (allotriomorphic crystals), but their internal molecular pattern is just as perfect as that of the idiomorphic crystals.

Where the growing crystals impinge, the remaining thin layer of liquid metal between them solidifies in the form of amorphous metal and makes up the grain boundaries. The grain boundary is regarded as an undercooled liquid, highly viscous and analogous to pitch, sealing-wax, etc. At elevated temperatures the grain boundary is the weakest part of the metal owing to its decreased viscosity when heated, and therefore stressed metals fail at their grain boundaries, particularly easily at temperatures approaching the melting-point of the metal.

When examined under the microscope in the etched condition, the shape and size of the grains, and the grain boundaries can be clearly observed. The etching reagent, having removed the amorphous layer covering the surface of the specimen, exposes the true crystal surfaces to the illuminating rays of light from the microscope. The crystals appear in tones of black, white and half-tone according to the orientation or angle at which the cells of each crystal bear in relation to the rays of light. Those faces at right angles to the rays of light from the objective, reflect back the light directly into the objective and appear bright in colour. Those crystals having their faces set in such a manner as to reflect the light at various angles from the vertical, appear half-tone or dark. The grain boundary of amorphous metal

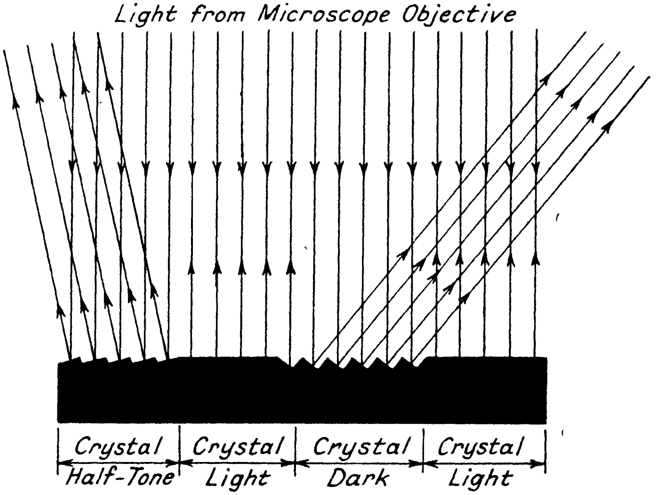


FIG. 91.—Effects of Orientation of Crystal Grains on the Rays of Light from the Microscope.

has been attacked to form a minute channel and, because it does not reflect much light directly back into the objective, appears as a dark network.

When slowly cooled to allow complete diffusion and homogenity, some metals which are soluble in each other in the solid state to give one constituent only, exhibit crystalline structures similar to those of the pure metals. However, when an alloy which gives a complete solid solution is cooled more quickly, a dendritic or cored structure is formed. Solidification takes place through a range of temperature increasing from a small range, when one of the metals greatly predominates, to a larger range when the metals are present in approaching equal proportions (see Fig. 133). As the temperature of solidification is reached, the solid nuclei which form in the molten mass have not the same composition as the remaining molten alloy, but are slightly richer in the metal of the higher melting-point. These solid nuclei attract others and form long crystallites which shoot out in all directions into the liquid. As solidification proceeds, other crystallites are thrown out at right angles to the primary crystallites, until impingement takes place between arms of other forming crystals. Other arms are eventually thrown out like twigs from the branches until no further growth can take place. The metal which finally solidifies at a lower temperature between the crystallites of this tree-like structure, is deficient in the metal of the higher melting-point. Each crystal grain, then, is not homogeneous, and a slight difference in composition exists between different parts of the same crystal. The etching reagent attacks the crystal in varying degrees depending upon the difference in composition in the same crystal, enabling the structure to be clearly seen under the microscope. This dendritic structure is often seen in small castings. A typical appearance of a cored structure is Fig. 92. On annealing, diffusion takes place inside the crystals, the dendritic structure disappears, and crystals of homogeneous composition are obtained (Fig. 240).

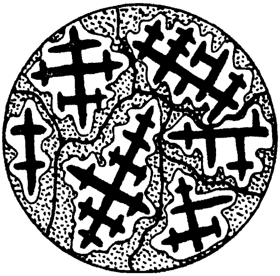


FIG. 92.—Illustrating formation of a Dendritic Structure.

Another effect which is found in castings and ingots cooling quickly from the outside, is the formation of fringe crystals.

Owing to differential rates of cooling throughout the sections, the crystals near the inside have more or less equal axes, but on the outside where cooling or solidification is most rapid, are seen crystals elongated in a direction at right angles to the surface, and are known as fringe crystals. Fig. 93 illustrates the crystals obtained in square and rounded ingots and also in a round cast test bar. Where the fringe crystals meet at right angles, lines of weakness are formed, and the obvious conclusion is that to avoid planes of weakness and to some extent liquid shrinkage defects, sharp corners in castings should be, as far as possible, avoided.

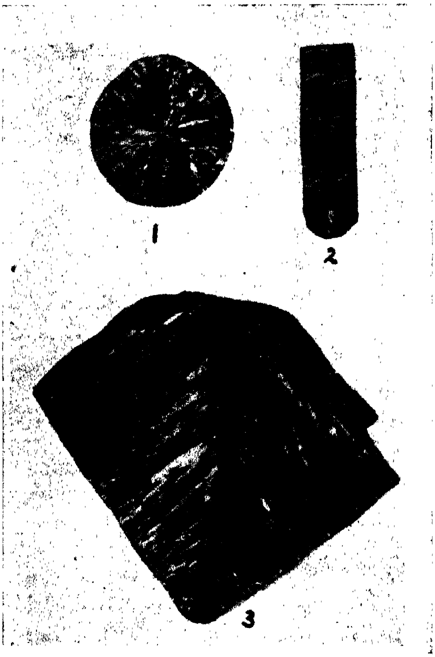


FIG. 93.—Fringe Crystals in
(1) Round Bar
(2) Ingot with Rounded End
(3) Sharp-cornered ingot.

When a metal is strained, gliding or slipping takes place in layers inside the crystals. Every crystal possesses weaknesses along which the crystals will deform when severely strained, and are known as cleavage or gliding planes, the number of planes depending upon the geometric class to which the crystal belongs. When parts of the crystal slip along the cleavage planes, inequalities of level are produced on the surface in the form of steps and are known as slip bands. Crystals possess several systems of cleavage planes, and slip bands may be developed in several directions. At first the slip bands are developed in one direction only, but when the metal is more severely stressed other systems of slip bands appear.

Slip bands cannot be seen on the surface of a specimen which is polished after being cold worked, but instead, on etching, an intersecting system of fine lines known as strain lines which usually change direction at each crystal boundary are observed (Figs. 237 and 193). The appearance of strain lines in a metallographic specimen indicates therefore that the metal has been strained by cold working.

Annealing of the metal after cold working results in recrystallisation developing along the cleavage planes of the original crystals, often growing and forming new crystals at the expense of others. The structure under the microscope then appears with the crystals exhibiting parallel bands, sometimes of different orientation. This structure is known as the " twinned crystal " structure and is evidence that the material under examination has been cold worked and subsequently annealed (Fig. 238).

When more than one constituent or solid solution is present in a metal, each constituent is attacked in varying degrees, enabling the structure and approximate composition of the alloy to be interpreted.

Some metals and alloys have certain characteristic structures indicating special physical conditions promoted by special treatments, and these will be dealt with in the following chapters where their other properties are considered.

X-ray examination of metals. Radiography is a non-destructive method of testing which is applied to reveal the location of faults in castings and other articles. The X-ray apparatus consists essentially of an X-ray tube, rectifying tubes and step-up transformers. The X-ray tube is constructed of glass and operates as a vacuum. The cathode contains a tungsten spiral heated to red heat by a low-voltage alternating current. The anode containing a tungsten plate known as the target is maintained at a very high voltage. Electro-magnetic radiations or X-rays are produced by electrons leaving the cathode and striking the target at a great speed. The latter is so arranged that the rays are deflected through the side of the tube and in the direction of the material under examination. Because the radiations are injurious to operators, parts of the apparatus are lead-lined. Apparatus capable of higher penetration is required for the more dense ferrous and non-ferrous alloys than for the light alloys, and the voltage of industrial equipment may be as high as 1000 kV according to the size and type of material to be examined.

For dense metals of thick section, gamma rays are used. The difference between X-rays and gama rays is one of wave-length or frequency of electro-magnetic radiations. The wave-length of ordinary light is about 5000 Au whilst X-rays may vary between 500 and 1 Au. The large difference between the wave-lengths enables the X-rays to penetrate materials which are opaque to ordinary light. The gamma rays are of extreme high frequency and of shorter wave-length. Consequently, they have greater penetrating power.

When it is necessary to radiograph a casting or other article of excessive thickness and density, a small quantity of radium or thorium salts, or a small capsule of radon gas can be employed. The gamma rays emanating from these radio-active materials have been used successfully for the radiography of steel having a thickness of 10 in. or more.

The rays may be viewed on a screen or recorded on a photographic film. A radiograph is obtained by the ability of a proportion of the rays to pass through objects opaque to light, and then to react upon the emulsion of a photographic film. The quantity of radiation reaching the film is governed by the density and thickness of the object under examination. For example, 1 in. thickness of aluminium will not absorb and reduce the intensity of the rays to the same degree as 1 in. of steel, whilst 1 in. of steel will not reduce their intensity to the same degree as 2 in. of steel. The variations in intensity of the rays reaching the film give a photographic contrast on the film. When uniform beams of rays without any object in their path are directed on to the film, no contrast will be observed on developing the film, that is to say, it will be of uniform density throughout. If a solid piece of metal is exposed to the rays, two distinct shades will be found on the developed film, a light area conforming to the shape of the object and surrounded by a dark background. If the piece of metal contains a hole, or a porous cavity, there will then be three distinct shades in the radiograph, the hole or cavity exhibiting an intermediate shade.

X-ray diffraction and crystal structure. There is no doubt that the modern metallurgical microscope is an extremely valuable piece of equipment for determining the type and general crystal structure of a metal or alloy, and the treatments which it has undergone during manufacture. It gives a useful indication of the cause of defects, and the general mechanical properties of the material. The mechanical properties of metals vary, of course, with different compositions but much is dependent upon physical structure and, in this respect, X-ray methods provide information which is unobtainable by the optical microscope. Crystals are made up of atoms, and the manner and order in which they are arranged greatly affects the properties of the metal.

Pure metals are relatively weak because the atoms making up the crystals are arranged in regular simple patterns, which allows the various planes or faces to glide over each other more easily. Alloying elements introduce a new arrangement of atoms into the pattern, which disturbs the regularity and increases the strength. Heat treatment and mechanical working will also disturb the atomic arrangement.

The X-ray diffraction method of examination is increasingly becoming recognised as a valuable means of determining the physical condition of metals. It will reveal changes in chemical and physical conditions from point to point in a substance, it will show the presence of strains in metals, the progress of heat-treatment, and the formation of new compounds during treatment.

Briefly, the method is that a beam of X-rays falling upon the crystals is scattered or diffracted according to the atomic arrangement in the material under examination. From the distribution and strength of the diffracted beams, the required information regarding the nature of the material is deduced. The specimen is usually in the form of a powder placed in a very small, thin-walled glass tube of about $\frac{1}{32}$ in. in diameter, but as the preparation of the powder from a solid piece of metal may destroy some characteristic which it is desired to observe, the method of allowing the X-rays to fall on a surface of a small solid specimen can sometimes be employed. In certain cases thin strips of foil may be used. A slit system allows a beam of rays from an X-ray tube to fall upon the powder mounted in the centre of a cylindrical chamber, which serves as a camera having a photographic film placed round the rim for recording the diffracted beams.

Electron microscope. A recent development in the examination of metallographic specimens is the employment of the Electron Microscope, which enables the resolution of much finer detail and permits examination at diameters up to a hundred times greater than obtained with the ordinary light microscope. Electrons leave a high-voltage hot tungsten filament and by means of a magnetic condenser are concentrated on the specimen. Very thin specimens are used to avoid scattering of the electrons. The microscope column operates as a vacuum. The specimen housed in a cartridge is placed in an object chamber provided with an airlock arrangement whereby the specimen is introduced without breaking the vacuum. The electrons, having left the specimen, then pass through the objective lens. Then follows a projector lens which allows the image to be observed on a fluorescent screen. A permanent photographic record can also be taken. The lenses of the system, the condenser lens, the objective and the projector lens are magnetic and formed by suitably designed pole pieces excited by iron-cased coils.

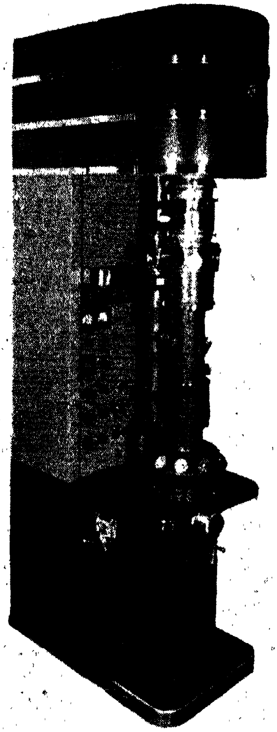


FIG. 94.—The Electron Microscope. Type " B."
(*Courtesy—Radio Corporation of America.*)

When specimens are too thick to be penetrated by the electrons, removable films or replicas can be prepared with suitable materials on the surface of the specimen, and which are easily removed and examined directly, which obviates the destruction of the original.

Also by the use of special accessories, the electron microscope can be used as a diffraction camera indicating the relative depths of the irregularities of the minute structure and which leads to its interpretation, since the diffraction of electrons from surfaces gives a similar type of information about the structure of that surface as the diffraction of X-rays does about the solid structure.

CHAPTER 4

INDUSTRIAL MEASUREMENT AND CONTROL OF TEMPERATURE

THERE are many methods of measuring temperature, the choice depending entirely upon the accuracy, magnitude and range of temperature it is desired to measure. Of course by far the oldest method is that of observing with the human eye the colour of the heated body, by which a rough indication of temperature is obtained; but with sufficient experience fairly accurate assessments can be made and, by comparing the relative colour of objects side by side, differences of temperature are readily and definitely detected. The scale of colour temperature is approximately as follows :—

Colour	*Temperature °C.*
Dull red	700
Cherry red	900
Orange	1100
Yellowish white	1300
Dazzling white	1500

The use of materials or mixtures of materials having known fusion points provides a more positive but still rather empirical method of temperature measurement. Such substances as kaolin, quartz, feldspar, magnesia, iron oxide, lime, and boric acid are mixed in definite proportions so as to flux at a predetermined temperature. The material is moulded into certain shapes, perhaps the best known being the slender trihedral pyramid known as the " Seger " cone. The cones of various known melting-points are stood on a refractory slab in the furnace and usually in such a position that their behaviour can be observed, and the end point is considered to be reached when, on heating the furnace, the cones become so plastic that the tip bends over and touches the refractory slab on a level with the base of the cone. Because the presence of flame around the cone can give false indications of temperature, the cone, if possible, should be mounted in a recess so that the heating influence is radiation, and not direct heating from flame.

Another shape employed is a rectangular bar of material, several of which are placed in step formation on a refractory stand, supported at the ends leaving a standard length in the middle left unsupported. By using a series of bars of known fusion points, progressively higher furnace temperatures will cause the bars to sag or bend in turn. By the fusion method temperatures of 600° to 2000°C. are usefully indicated and, whilst they have useful metallurgical application, they are extensively used in the manufacture of bricks and ceramic materials. The accuracy, however, depends to some extent on the rate of heating and the furnace atmosphere.

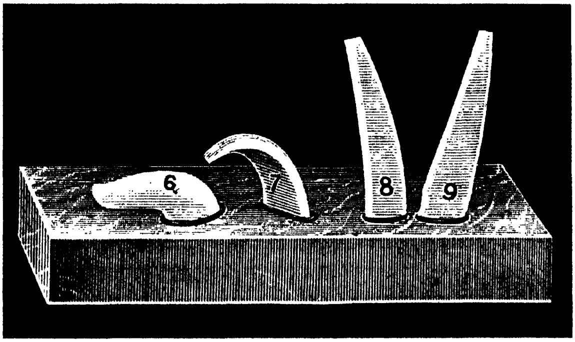
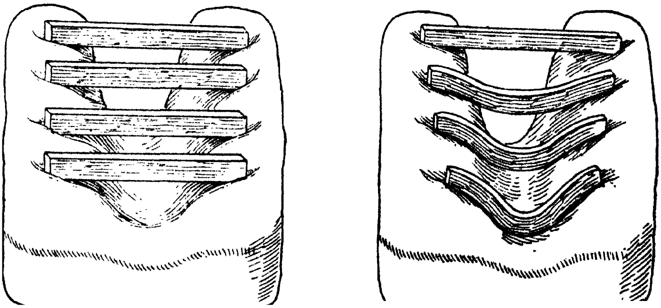


FIG. 95.—Seger Cones.
(*Courtesy—Messrs. Brady and Martin Ltd.*)



Before Using *After Using*

FIG. 96.—Holdcroft's Thermoscope Bars.

A recent development whereby the actual temperature of parts undergoing heat treatment may be determined, is the em-

FIG. 97.—Indicating Paint. When 235°C. is reached the original white colour of Thermindex Colour E.104 changes to dark grey.

(*Courtesy—Messrs. J. M. Steel and Co., Ltd.*)

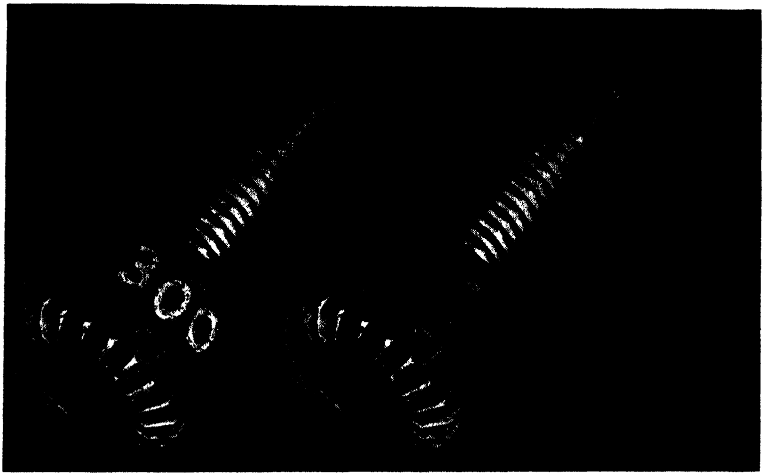


FIG. 98.—Indicating Crayons. The clear light-coloured mark drawn with Tempilstik 300°F., melts and practically disappears when 300°F. is attained.

(*Courtesy—Messrs. J. M. Steel and Co., Ltd.*)

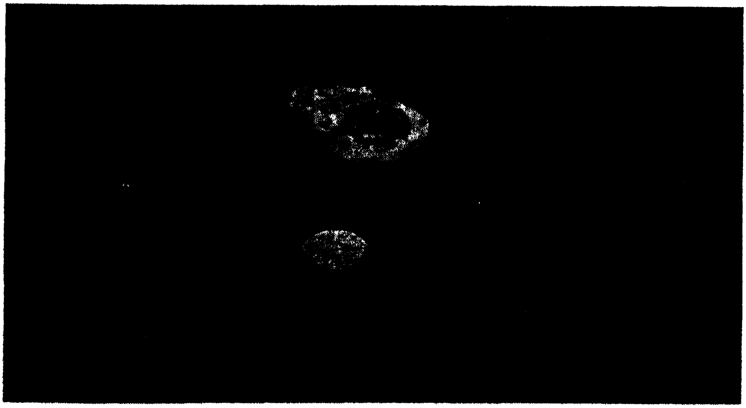


FIG. 99.—Indicating Pellets. Melt sharply at a specified temperature.

(*Courtesy—Messrs. J. M. Steel and Co., Ltd.*)

ployment of chemical indicators supplied in the form of paints, crayons or pellets. The characteristics of these materials are given below.

Type	*Method of indication at specified temperatures*	*Temperature range*	*Stated accuracy*
Paint .	1. Sharp change of colour	80–800°C.	±5°C.
" .	2. Liquifies, darkens and remains glossy.	80–870°C.	±1%
Crayons	Make a mark similar to ordinary chalk, which melts at the stated melting-point, and practically disappears.	80–370°C.	±1%
Pellets .	Melt sharply upon or near a heated surface.	80–870°C.	±1%

A few of the specific operations in which these indicators can be especially convenient and economical are preheating for welding, hard facing, torch or flame cutting, local stress relieving, pipe bending, brazing and soldering, hot working of the light alloys and locating hot spots in heat-treatment furnaces. They are useful in heat treatment to indicate uniformity of treatment and as a visible and permanent check that items have attained the desired treatment temperature.

The increasing accuracy of temperature control demanded in the many industrial processes of heat treatment makes it necessary to employ apparatus and instruments of a more scientific, accurate and delicate nature. Whilst the ordinary liquid expansion thermometers give accuracy, their use is limited to the lower range of temperature, and instruments embodying other principles of temperature measurement are employed, and the choice depends upon local conditions such as the physical properties of the substance whose temperature is to be measured and the desired temperature range. It is now necessary to classify the chief methods and types of instrument, together with the ranges of temperature and conditions for which they are suitable.

Liquid expansion thermometers. These include the familiar thermometer consisting of a glass stem of small bore and thick walls, sealed at the end and having attached to it at its lower end, a bulb which serves as a reservoir for the liquid. The bulb is usually completely filled with the thermometric liquid which extends also part way up the lower portion of the bore in the stem, whilst the remaining space in the stem is either vacuous, or contains, in many modern mercury thermometers, an inert gas such as nitrogen under pressure. The stem is graduated with a suitable temperature scale.

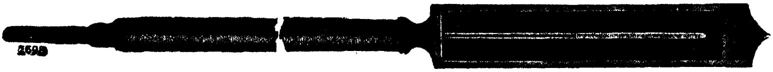


FIG. 100.—Molten Metal Thermometer.
(*Courtesy—Cambridge Instrument Co., Ltd.*)

Special glasses are used in the construction of thermometers and for the higher temperature readings, boro-silicate along with nitrogen filling is used. By the use of various thermometric liquids such as mercury, alcohol, toluene and pentane, a considerable range of temperature is covered, from —200°C. with pentane and to +500°C. with mercury.

For industrial use lens-fronted tubes and scales in large figures (Fig. 100) facilitate reading, and in many instances the bulb and the lower portion of the tube is armoured by fitting with a steel case for protection against breakage. Certain thermometers for fixing to walls of ovens are of an angle pattern and fitted with an adjustable stop flange.

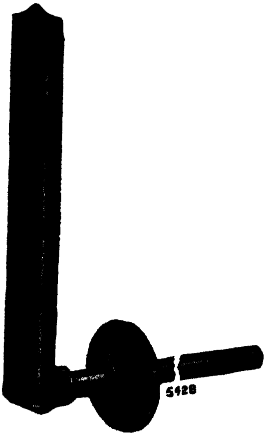


FIG. 101.—Bake Oven Thermometer.
(*Courtesy—Cambridge Instrument Co., Ltd.*)

Glass thermometers suffer from the disadvantages that their use is limited on account of their fragility, short length when a reading well inside a heated chamber is required, and difficulty in reading in dark and inconvenient positions. These disadvantages are overcome by the mercury-in-steel thermometer, in which the mercury is contained in a steel bulb connected by a fine flexible steel capillary tube to a Bourdon pressure gauge. As the temperature of the bulb is increased, the expansion of the mercury raises the pressure in the system thereby actuating the pressure gauge. Since the capillary is fine and contains a very small volume of mercury compared with that in the bulb, changes of temperature in the capillary have little effect on the accuracy of the readings. The length of capillary can be such that temperature readings can be taken up to approximately 100 ft. away from the bulb. The instruments may be either indicating, recording, or both.

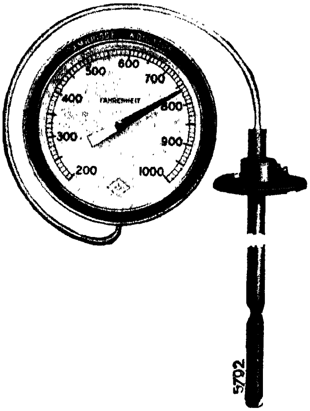


FIG. 102.—Dial Index Thermometer. Mercury-in-Steel Type.

(*Courtesy—Cambridge Instrument Co., Ltd.*)

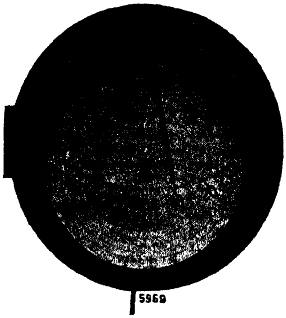


FIG. 103.—Combined Indicating and Recording Thermometer. Mercury-in-Steel Type.

(*Courtesy—Cambridge Instrument Co., Ltd.*)

Vapour-pressure thermometers. These share to some extent the advantages of the mercury-in-steel thermometers in that long lengths of capillary can be used, and in the order of up to 200 ft. They are also simple in design and used either as indicating or recording instruments. A quantity of volatile liquid such as di-ethyl ether or one of a number of other organic liquids partly fills a metal bulb which is connected to a suitable calibrated pressure gauge of the Bourdon type. Variations in the temperature of the bulb cause corresponding variations in the pressure of the saturated vapour above the surface of the liquid in the bulb, actuating the pressure gauge to give a measure of the temperature of the bulb.

A disadvantage of this method of temperature measurement is that each liquid only permits of a small and limited range of temperature, but the general range by using different liquids is about —50° to 400°C., although recent developments in the manufacture of the mercury in steel thermometers are making possible the use of mercury vapour instead of liquid mercury, enabling temperatures in the range of 350° to 800°C. to be measured.

Electrical resistance pyrometer. The basic principle is the variation of electrical resistance in pure metal wires with changes of temperature. The wire is wound in the form of a coil on a mica frame and is termed the thermometer coil or bulb. Platinum is the metal most commonly used, although nickel is sometimes used for temperatures lower than 500°C. The variation in resistance with temperature is measured by an arrangement known as the Wheatstone bridge, consisting of a series of resistances, a galvanometer and a standard cell.

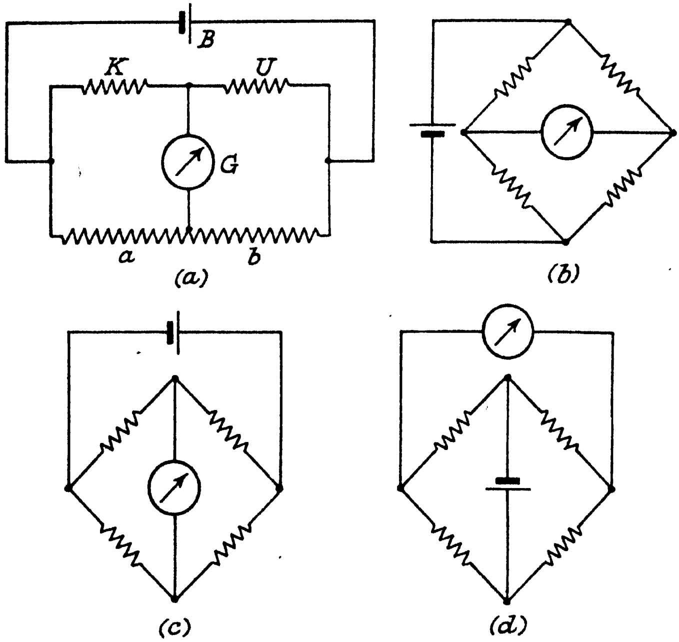
The principle of the Wheatstone bridge is illustrated in Fig. 104 (a). B is a dry cell (battery), K is a known resistance and U is an unknown resistance. $a\ b$ is a variable resistance where adjustments are made to obtain equal pressures or balanced resistance at each side of the galvanometer so that it registers zero.

Then
$$U=\frac{K\times b}{a}$$

Figs. 104 (b), (c) and (d) give other representations of the Wheatstone bridge. If the resistances on either side of the galvanometer are not equal, then a deflection is obtained.

The usual connections for resistance pyrometer equipment are illustrated in Fig. 105 (a). The bridge resistances r^1, r^2 and r^3 have fixed values. The fourth bridge resistance B is the bulb connected by twin cable to the bridge. When the bridge is balanced the galvanometer will read zero, but variation of bulb resistance with temperature will cause a deflection to one side or the other depending upon whether there is a rise or fall in temperature. The deflection for increments of temperature is calibrated on a scale to give a direct reading of temperature. These conditions only apply when there is a fixed value of current from the cell, so that with instruments having a galvanometer with the normal suspension or phosphor bronze spring control the current is always adjusted to a predetermined figure by the introduction and use of an adjustable resistance in the circuit (Fig. 105 (b)). When, as in some instruments, the controlling or restoring torque is obtained by electromagnetic reaction and the exciting current is drawn from the same battery as that which feeds the bridged circuit as a whole, then there is no need to standardise the current in the bridge, since deflecting torque and restoring torque will remain proportional irrespective of battery voltage within wide limits.

The method described above is known as the deflection method, and it will be clear that it is necessary for a periodic adjustment of the current, a procedure which can be avoided by the use of the " balanced bridge " or " null " method whereby the bridge is balanced and the indicator brought to zero by a variable resistance on the same side of the bridge as the bulb. The resistance is measured and the temperature calculated from the measurement, or it may be indicated directly on a calibrated scale as balance is achieved. The Whipple indicator employs the latter principle. A recording instrument may also be used where a mechanism performs the balancing operation automatically and the direct temperature is continuously recorded by a pen on a moving chart. (Callender Recorder.)



(a) (b)

(c) (d)

FIG. 104.—Diagrams of Wheatstone Bridge.

For industrial applications the bulb or resistance element is connected by a pair of leads to the bridge unit, where such leads are not exposed to large variations of temperature. This two-lead method of wiring, owing to simplicity, easily lends itself to multiple thermometer work, a number of different resistance thermometer bulbs being connected as required and in turn to the measuring bridge by means of a selector switch. However, changes of temperature in the leads affects their resistance and, as they form part of the thermometer circuit, any change of temperature in them has a similar but slighter effect, to alteration of temperature in the bulb itself. For greater accuracies this effect is avoided by the use of a triple cable, as in Fig. 105 (d), which provides an equal amount of leads resistance on each side of the bridge.

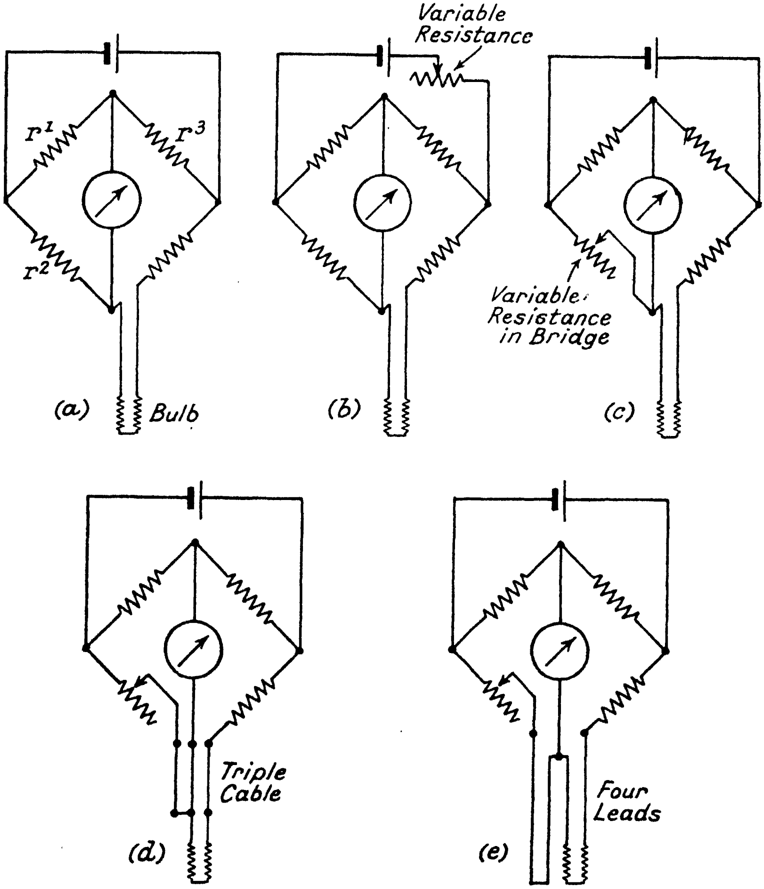


FIG. 105.—Resistance Pyrometer Circuits.

The four-lead method is also frequently used where accurate compensation is obtained by introducing to both sides of the bridge circuit two wires of similar length and resistance (Fig. 105 (e)).

The resistance coil is housed in and protected by a fireclay inner sheath surrounded by an outer sheath, fixed with a suitable head for connection of the leads.

The use of the electric resistance pyrometer has several disadvantages, and care of equipment is necessary to maintain accurate readings. The resistance coil is delicate and requires careful handling, care is necessary in supporting it, and attack by exposure to corrosive gases must be avoided. Distortion straining and corrosion are likely to cause changes in its resistance. These factors somewhat tend to limit its use in favour of the thermo-electric pyrometer.

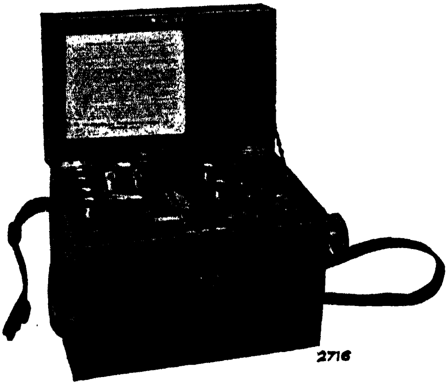


Fig. 106.—Whipple Indicator. A portable self-contained Wheatstone Bridge.

(*Courtesy—Cambridge Instrument Co., Ltd.*)

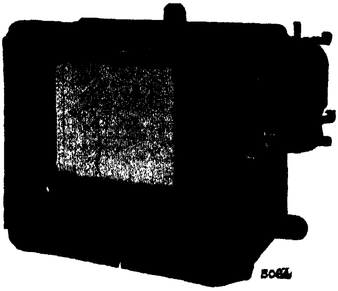


Fig. 107.—Recording Wheatstone Bridge. A modern form of the Callender Recorder.

(*Courtesy—Cambridge Instrument Co., Ltd.*)

Thermo-electric pyrometers. The thermo-electric pyrometer is now the most extensively used instrument for industrial measurement of temperature. It operates on the principle that when two metal wires of dissimilar composition are joined at their ends to form a complete electric circuit and one of the junctions heated, an electric current flows through the wires. The heated connection is known as the hot junction whilst the other connection is known as the cold junction. Now if the cold ends of the wires are separated and connected to a millivoltmeter, a deflection of the pointer is obtained. The extent of the deflection is controlled by the difference in temperature between the hot and the cold junction, that is to say, if the hot junction remains constant, a greater amount of current flows as the cold-junction temperature decreases.

Suppose, for instance, we are reading a hot-junction temperature of, say, 600°C., and the measuring instrument has been calibrated for a cold-junction reading of 20°C., and by reason of local conditions the cold-junction temperature changes to 35°C. If, under these conditions, the hot junction remains steady, less current will then flow through the circuit because the temperature difference is less, giving an error on the indicator. Then, by disconnecting the thermocouple wires at the instrument and re-setting the " zero " by means of the adjustment lever or screw to the new cold-junction temperature, afterwards re-connecting the cold ends of the wires to the indicator, then the hot-junction reading will be more or less corrected. The most accurate method is to add the E.M.F. corresponding to the variation in cold-junction temperature to the observed E.M.F., since the great majority of thermocouples yield an E.M.F. which is not strictly proportional to temperature. It will be seen, therefore, that for consistently accurate readings it is necessary to control the temperature of the cold junction. This is carried out in one of several ways.

Because normally the cold junction is at the head of the thermocouple it is often subject to fluctuating temperatures owing to being near to the furnace (Fig. 108 (a)). A more stable cold junction is found in the measuring instrument itself, and, if care is taken in choosing its location, in most industrial pyrometric installations the cold junction is transferred by a twin cable, known as compensating lead, from the head of the couple to terminals in the instrument (Fig. 108 (b)). The two wires in the leads are, in the case of base metal thermocouples, made from the same material as the couples but often in stranded form for flexibility, and combined to form one cable. The compensating leads for platinum-rhodium couples are made from wires of copper, and an alloy of copper and nickel, and which give the same E.M.F. as the couple itself. (The types of thermocouple will be discussed in more detail later.)

When the distance to the indicator is considerable, as is often the case when a row of furnaces have their thermocouples connected to indicators or recorders housed together in a common position, a comparatively short length of compensating lead can

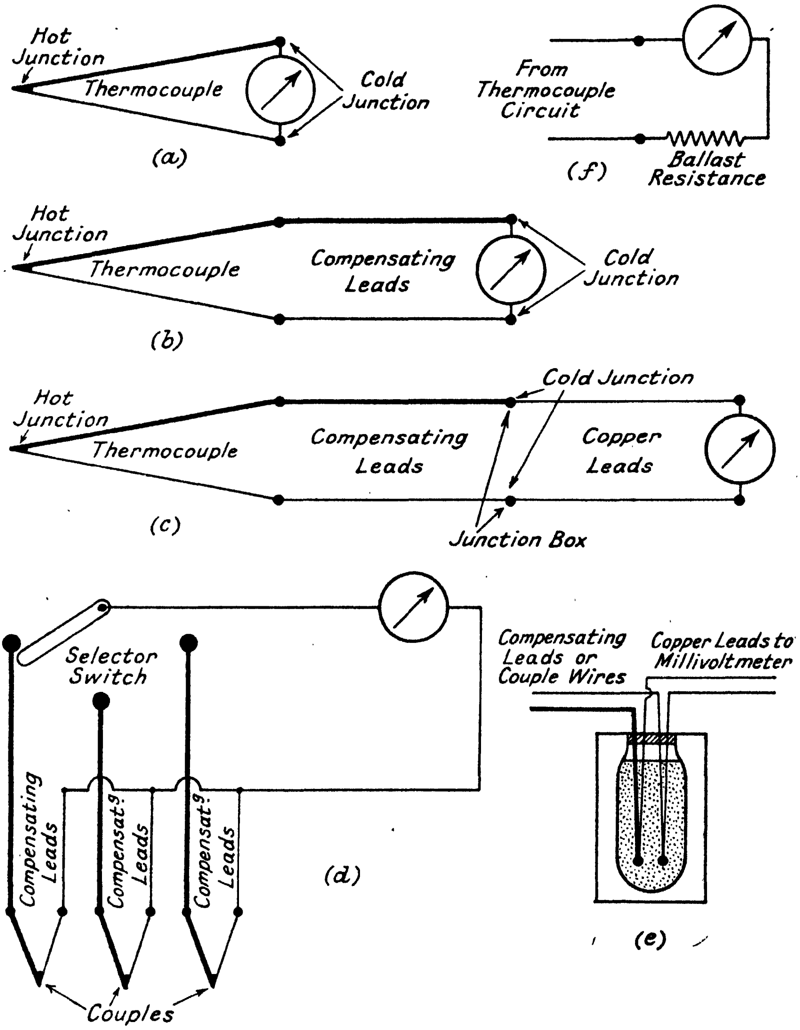


FIG. 108.—Thermo-Electric Circuits.

be run to a junction box containing terminals, this being placed where the temperature is low and constant, and from which copper leads run to the indicator (Fig. 108 (c)). This method of wiring is frequently adopted when a number of thermocouples are to be selectively connected as required, and in turn through a switchboard to a single measuring instrument remote from the general locality of the thermocouples (Fig. 108 (d)).

In many instruments with compensating lead connections, automatic compensation of cold-junction temperature is provided for by a controlling spring device in the galvanometer movement.

The temperature of the cold junction can be kept reasonably constant by burying several feet in the ground.

For more accurate cold-junction control, a vacuum flask filled with oil and surrounded by a heat-insulating material, is sometimes used (Fig. 108 (e)), or alternatively, an electric thermostat. Copper leads complete the circuit between the cold junction and the indicator.

In order that the measuring instrument shall have a high electrical resistance relative to the external circuit, a ballast resistance of low temperature coefficient is often included in the wiring of the instrument. Then slight increases of resistance in the leads or thermocouple wires above the hot junction due to temperature changes, are very small in relation to the resistance of the remainder of the circuit, and they then have little effect on the accuracy of the instrument (Fig. 108 (f)).

Compensating leads. The metal wires are selected according to the types of metal of which the thermocouples are composed. The rubber insulated wires are braided with cotton or asbestos to form one single lead. When the leads are subjected to high temperatures, asbestos covering is most satisfactory, and it is usually advisable to protect them in steel conduit tubing. In damp situations lead covering is often employed over the insulation.

Thermocouples. The choice of thermocouple is governed by several factors, principally the cost, and the maximum temperature which the couple is likely to receive in service. The E.M.F. and stability under various operating conditions are also important. The materials mostly used for thermocouples are divided into two groups :—

(1) Base metal. These are the cheaper variety, very extensively used, and cover temperatures up to 1100°C. Owing to their relatively low cost, thick wires can be used, resulting in lower resistance of the external circuit and, unless used frequently at temperatures approaching the maximum for

which they are intended, they give long life. They develop an E.M.F. several times greater than those in the other group, and consequently a more simple and robust millivoltmeter can be used.

(2) Rare metal. These couples cover the higher range of temperature up to 1,500°C. The metals employed are platinum, rhodium and iridium. Combinations of platinum and rhodium are the most frequently used. Couples containing iridium, although higher temperatures can be read with them, are used only in special instances, chiefly on account of the volatilisation of iridium in use. For industrial work, when readings are required above the range of the platinum-platinum rhodium couples, the use of an optical pyrometer is recommended.

The choice of thermocouple is usually made from the following :—

	Suitable continuous reading	*Upper limit of temperature*	*Millivolts*	
			At 100°*C.*	*At upper limit*
1. Copper and Constantan (Cu 60% Ni 40%)	400°C.	500°C.	4·3	27·4
2. Iron and Constantan	700°C.	800°C.	5·6	47·3
3. Chromel (Ni 90% Cr 10%) and Alumel (Ni 98% Al 2%)	950°C.	1100°C.	4·1	52·4
4. Platinum and platinum rhodium (10–13% Rh)	1300°C.	1500°C.	0·6	17·4

A couple consisting of tungsten and molybdenum wires allows of high temperature readings in the order of 2000°C., but because it has certain irregularities in its E.M.F. below 1250°C. and should always be enveloped in an atmosphere of pure hydrogen, it is only used in special circumstances.

Non-metallic substances such as carbon and silicon carbide are possible couples for high-temperature work, but only to a very limited extent as their use is still undergoing development. The carbon-silicon carbide and similar thermocouple combinations present two difficulties in use; the first is the instability of the temperature-E.M.F. characteristic of the couple, this being such that it is necessary to calibrate the thermocouple every day in order to ascertain its precise E.M.F. for any given temperature on that day. The cause of this instability is difficult to determine, but that it does exist is beyond question. The second difficulty is due to the high E.M.F. developed by this form of couple at any given temperature as compared with the E.M.F. at the same temperatures developed by normal base metal thermocouples. It has been impossible to find so far a combination of ductile base metals for use as compensating leads which will give the same order of E.M.F. as that developed by the carbon-silicon carbide couple, hence the only satisfactory way of using the couple is to connect it by copper leads direct from its head, and, where necessary, water cool the head.

Insulation and protection of thermocouples. Electrical insulation between the two wires is essential—by impregnated asbestos for the lower temperatures, and for higher temperatures the wires are threaded through silica or fireclay capillary tubing. Each couple is insulated from earth by a porcelain or ebonite head having terminals for connection of the leads. The insulated wires are inserted in a tubular sheath with closed ends for protection against rapid oxidation or other deterioration due to the action of gases or liquids into which the couple is immersed. The sheath, of course, should have low permeability to gases and ability to withstand shock, particularly thermal shock due to rapid changes of temperature. The sheath is chosen having regard to service temperatures, commonly fused silica (up to 1250°C.), porcelain (1400°C.), alundum or Pythagorus (1700°C.), or silicon carbide (2000°C.).

For industrial pyrometers an outer sheath is desirable to totally surround the inner sheath, for the purpose of blanketing the inner sheath from thermal shock, helping to minimise mechanical breakage and render the couple more impervious to gases. These outer sheaths may consist of mild steel (up to 800°C.), mild steel with special surface treatment such as calorising (900°C.), nickel-chromium (1100°C.), and refractory sheaths for higher temperatures. The refractory sheaths are extensively used for the lower range also, but they are brittle and easily broken, and for this reason the metallic sheaths are often preferred. The metallic sheaths, however, give a slight lag in temperature reading.

Fireclay sheaths are cemented into suitable metal sockets in the couple connecting head. Metal sheaths are often screwed into a socket or clamped with a nut and bolt through a collar arrangement on the head.

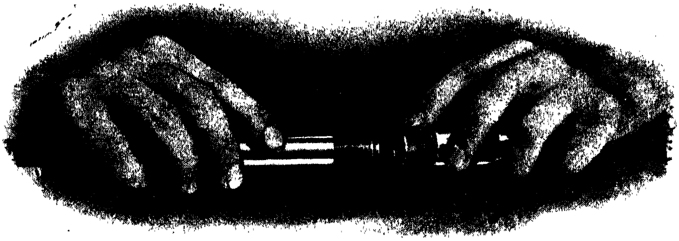


FIG. 109.—Method of Attaching Concentric Connector to Tube Type Stem.
(*Courtesy—Foster Instrument Co., Ltd.*)

Base metal thermocouples are available in the form of a rod $\frac{5}{8}$ in. in diameter. The couple elements take the form of an outer tube as one element with the other insulated and running up the centre (Foster). These couples are robust, easily connected by a "screw-on" concentric connector, and in many cases can be used without a protecting sheath.

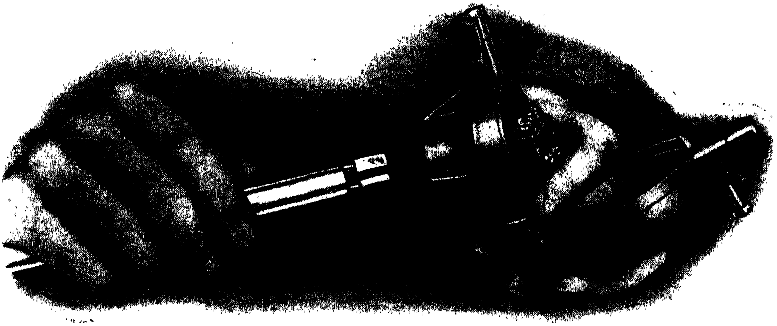


FIG. 110.—Method of Attaching Wire Type Thermocouple to Connecting Head.
(*Courtesy—Foster Instrument Co., Ltd.*)

Indicators and recorders. Indicators are instruments mostly of simple design which are cheaper than recorders, and usually fixed close to the furnace equipment where the furnace operator can conveniently observe the changes in temperature. They may be obtained in various types. The moving system can be either pivoted or suspended, and consists essentially of a moving coil mounted between the poles of a permanent magnet, the extent of the coil movement varying with the temperature and the current produced in the system. The movement of the coil controls a pointer along a curved scale calibrated in degrees of temperature.

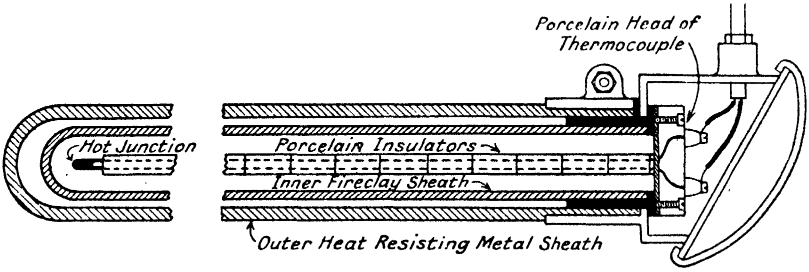


FIG. 111.—Section of Thermocouple.

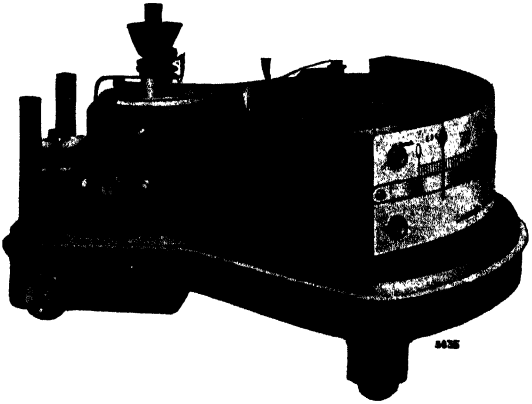


FIG. 112.—Pivoted Coil Indicator, with casing removed.
(*Courtesy—Cambridge Instrument Co., Ltd.*)

Indicators with suspended coils are more sensitive than the pivoted type and are particularly employed when the E.M.F. for full scale deflection is low. The coil is suspended freely by a fine metal thread, but a simple lever device enables the coil to be clamped when the indicator is moved from place to place. It is necessary that this type of instrument should be maintained strictly level when indicating temperature. It is very satisfactory for laboratory use on account of its sensitivity.

Indicators with pivoted coils are used to a much greater extent for industrial purposes than the other type. The coil is mounted on an axis on which it swings supported by two jewelled pivots, and the torque taken by fine springs. They are very suitable for workshop use as they have the advantage that accurate levelling is not necessary and the pointer quickly comes to rest without oscillation.

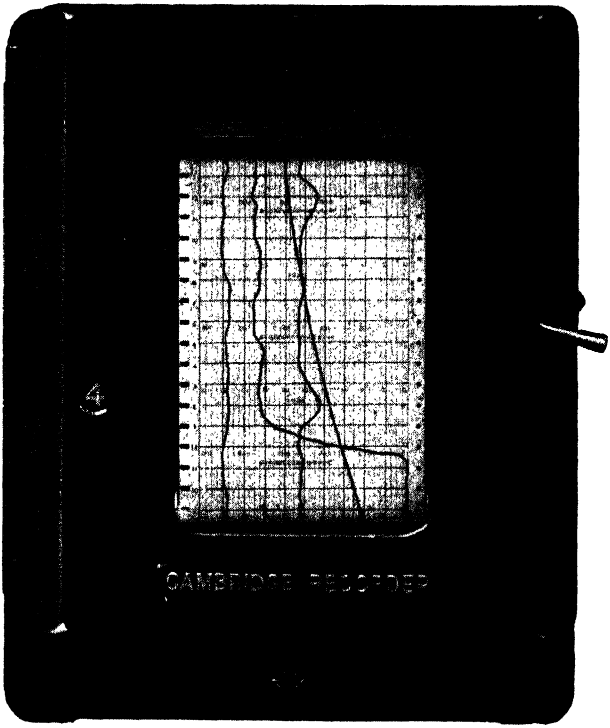


FIG. 113.—Four-point, four-colour Temperature Recorder, electrically driven from mains supply. Continuous chart.

(*Courtesy—Cambridge Instrument Co., Ltd.*)

Recorders are instruments for giving permanent records of temperature over considerable periods of time. The recorder consists of a moving coil galvanometer along with a revolving drum into which is connected a chart. A continuous chart is often wound from a spool and rewound on to a mechanically driven empty spool passing on its way over a metal drum situated just beneath the galvanometer pointer. On the charts the temperature record is automatically marked.

The recorder is usually of the type which has a calibrated scale above the pointer and operates both as an indicator and a recorder. Because of the use of an ink-impregnated thread for producing the record mark, most recorders are termed "thread recorders." The mechanism is clock-driven, either hand-wound, electrical and automatically wound at definite intervals, or driven completely by a small electric motor. The pointer of the galvanometer swings over the upper surface of the drum carrying the chart. A thread impregnated with a slow-drying ink passes between the pointer and the chart. The thread of either a fixed length tied at the ends passes continuously round small pulleys

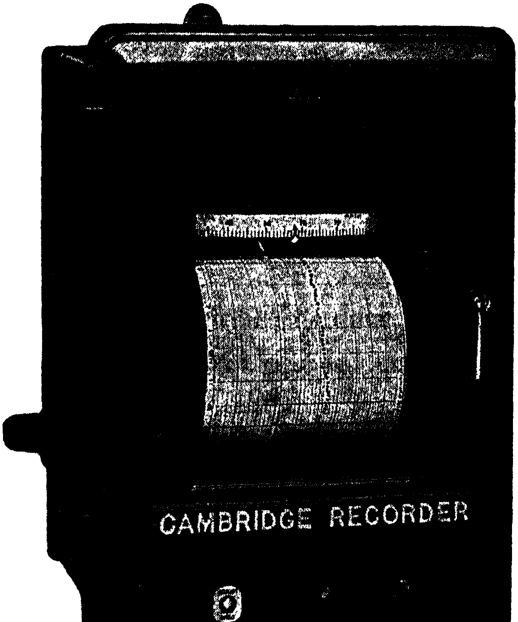
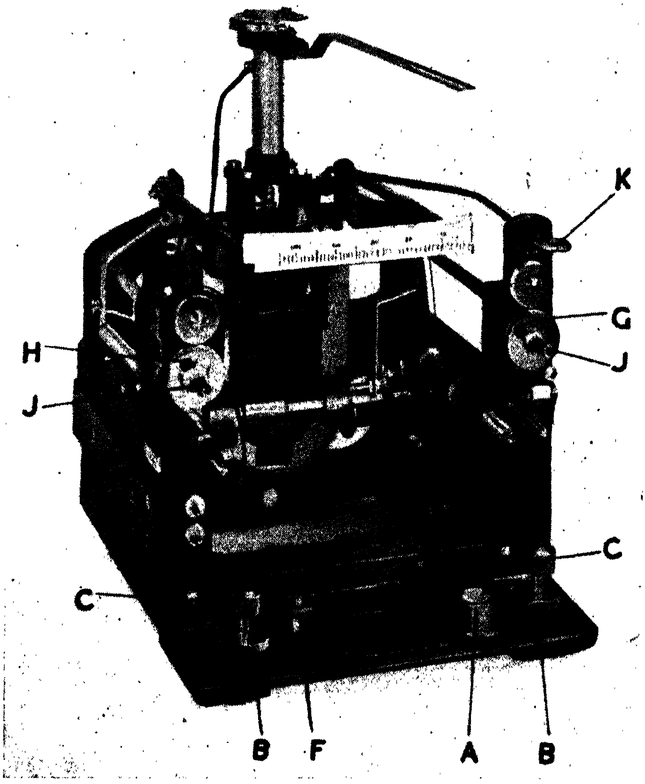


FIG. 114.—Two-Point Recorder with 25-hour chart on a revolving drum.
(*Courtesy—Cambridge Instrument Co., Ltd.*)

on the corners of a frame. Alternatively it is sometimes wound on a narrow bobbin, again from which it is passed across the top of the chart over small pulleys, and by a ratchet mechanism, is re-wound on to a similar bobbin on the other side of the instrument. Once every minute or half-minute the pointer is automatically depressed by a strip of metal known as a chopper bar operated by a driven cam, so that the impregnated thread is forced down on to the chart, and almost immediately the bar rises again. A dot of ink is formed on the calibrated chart, giving a record of the position of the pointer at the moment when it was



A Spirit level.
B Levelling screws.
C Locking heads for B.
F Terminal for breaking circuit.
G Inked thread unwinding bobbin.
H Inked thread winding bobbin.
J Knurled heads.
K Galvanometer clamping arm.

FIG. 115.—Showing internal construction of a recorder similar to the above, but with drum removed.

(*Courtesy—Cambridge Instrument Co., Ltd.*)

depressed. As the chart or drum is very slowly rotating this action is repeated at frequent and regular intervals and a series of dots is formed sufficiently closely spaced to appear almost a continuous line. The pointer swings freely between the chopping intervals, and absence of frictional errors allows it to settle quickly to its true position ready for the next dot.

To obviate the need for the use of a number of separate recorders when more than one temperature record is required, temperature recorders may be constructed so that a number of records from different thermocouples are obtained on one chart and at the same time. The leads from the thermocouples are connected to the recorder and by means of a change-over switch in the recorder operated mechanically through the depression of the chopper bar, the different circuits are connected to the galvanometer in turn. The records are distinguished by the character of the dots which may be of a common colour and differently spaced, or each record may be of a different colour. Bobbins, each containing an impregnated thread of a different colour, are mounted on a tilting frame, and the recorder mechanism so operates the frame that each thread comes in turn under the chopper bar. On some recorders a number in a circular disc with a background of similar colour to that of the thread at that moment under the chopper bar, appears near the top or side of the recorder with each dotting interval, indicating at a glance which thermocouple is in circuit at any moment. Any number of records from one to six can be obtained on one recorder, and the instrument is then known as a single-point, two-point, three-point recorder, and so on.

Potentiometric method of E.M.F. measurement. This method of measuring the E.M.F. of a thermocouple is more accurate than that of direct deflection, and eliminates any errors due to changes in the resistance of the leads and couple. Potentiometers may be indicating or recording.

The portable indicating instrument is used for accurately standardising other thermo-electric indicators and recorders, or for laboratory use when fine measurements are required.

The principle of the potentiometric arrangement is that the current from a small voltage accumulator is balanced by a rheostat against the current from a standard cell, and a galvanometer pointer indicates when balance is acquired. When the thermocouple is connected, any " out of balance " is corrected and measured by the use of a selector switch and/or a sliding contact which introduces into the circuit an E.M.F. equal and opposite to that developed by the thermocouple, thus restoring the galvanometer to its zero position. The balancing resistance is in the form of a series of resistance coils, whilst a slide wire connected in series with them provides the fine adjustment. The galvanometer pointer indicates when the balance point has been reached. This arrangement is known as the "null" method and is that usually employed (although the "out of balance" can be measured by the direct deflection of the galvanometer). The E.M.F. of the couple is proportional to the resistance reading, and the scale is often calibrated from the resistance

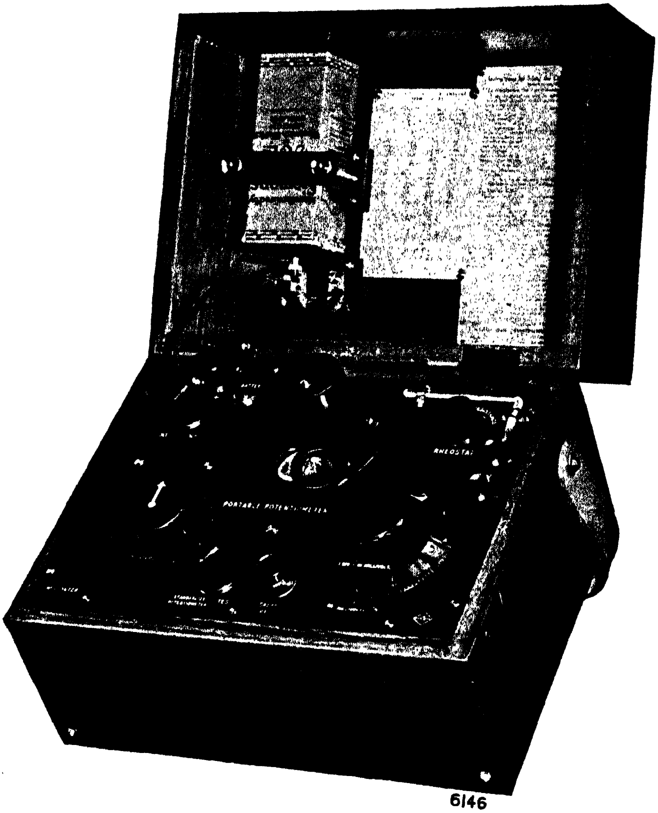


FIG. 116.—Portable Workshop Potentiometer.
(*Courtesy—Cambridge Instrument Co., Ltd.*)

to read in millivolts. Also by calculation from the known constants of the type of thermocouple used, from reference tables, or from prepared graphs, the reading in millivolts can be calculated to degrees of temperature. Provision for direct temperature readings is made on the dials of some instruments in addition to millivolt readings. The potentiometer is capable of accuracy in the order of 0·001 millivolts.

A correction for cold junction temperature is necessary and is made by placing a thermometer near the terminals on the instrument where connection of the leads from the thermocouple is made. The corresponding E.M.F. of the thermocouple at this temperature is added to the main E.M.F. reading. Depending upon the type or make of potentiometer the correction is made by mathematical calculation or from adjustable scales on the panel.

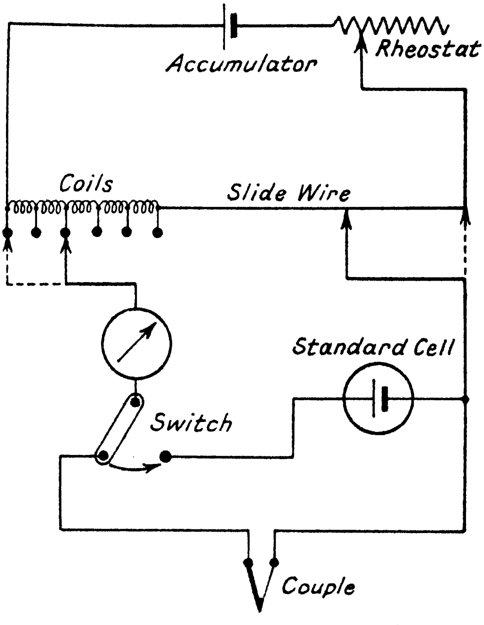


FIG. 117.—Simple Potentiometer Circuit.

The potentiometer arrangement may be used in recording instruments where mechanisms set into motion a restoring device which varies the resistance of the circuit to maintain the galvanometer pointer at zero. The balancing operation is automatic and almost continuous, and at the same time a pen is moved across a revolving chart giving a permanent record of the adjustments made. The instrument is so calibrated that the record is in degrees of temperature. An advantage of these potentiometric recording instruments is that, when desired, an open scale can be employed having a relatively narrow temperature range, thereby facilitating accurate readings.

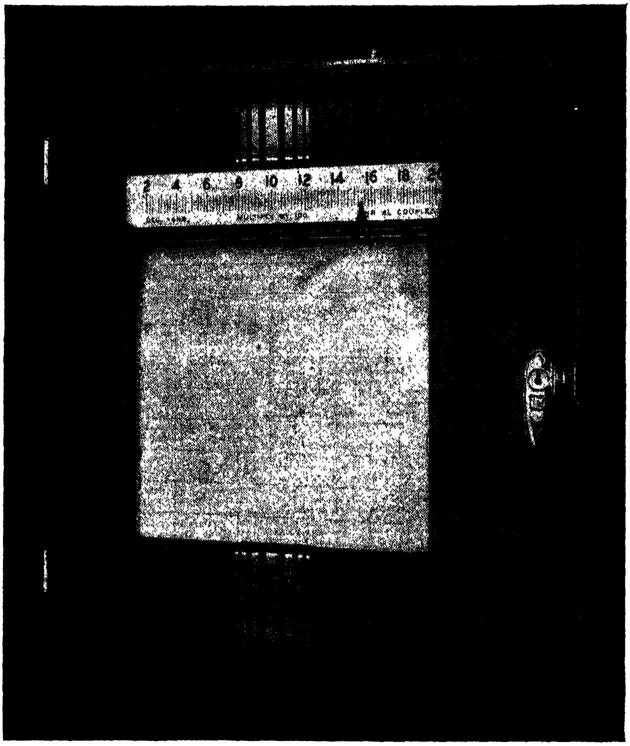


FIG. 118.—Indicating and Recording (Potentiometric) Controller.
(*Courtesy—The Integra Co., Ltd.*)

Automatic temperature controllers. Many modern metallurgical processes demand very rigid temperature control over extended periods and by the introduction of mechanical devices into indicating or recording instruments uncertainties of the human element are eliminated, and almost invariably there is a saving in time, labour and fuel.

These controllers are commonly used in conjunction with thermocouples, but may be used also with resistance thermometers and Féry telescopes. They can be indicating, recording, or both. The system of automatic control is chiefly applied to firing by gas, oil or electricity. Instruments are available employing direct deflection or " null " methods.

The indicating controller has two pointers on the scale, one being set to the required point of control, and can be adjusted as

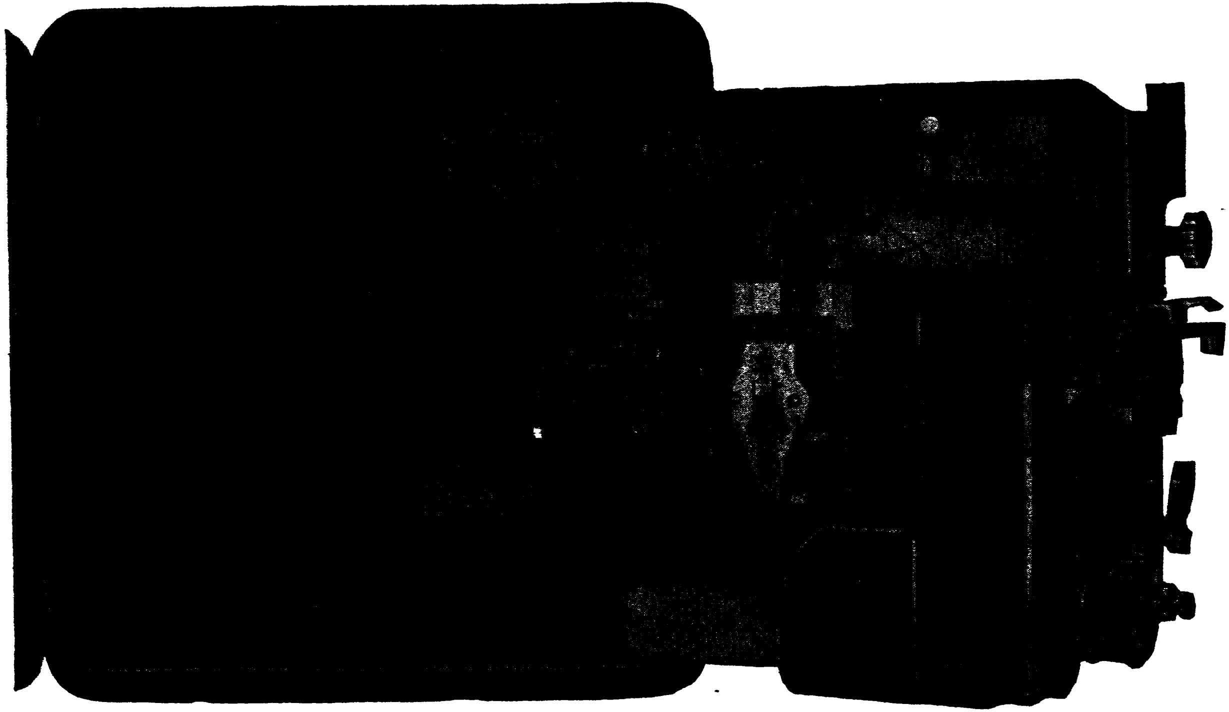


FIG. 119.—The instrument illustrated in Fig. 118 with the mechanism opened. The galvanometer, standardiser, and balancing mechanism swing out together. The terminal board, dry cell and motor fuse are on the back wall.

(*Courtesy—The Integra Co., Ltd.*)

required by means of a key. The other pointer from the galvanometer indicates the actual temperature. Any deviation of the galvanometer pointer from the set point of control, sets in motion mechanical devices for the operation of valves, motors or switches. Fig. 121 shows a mechanical method of control which is more or less self-explanatory. One or other of the contacts, having their positions set by the adjustable control pointer on the scale, is depressed with each fall of the mechanically operated presser bar. A tilting mercury switch operates as the presser bar causes the pointer to depress one of the contacts. The mercury switch then makes or breaks the electrical circuit for energising valve motors or furnace-heating elements.

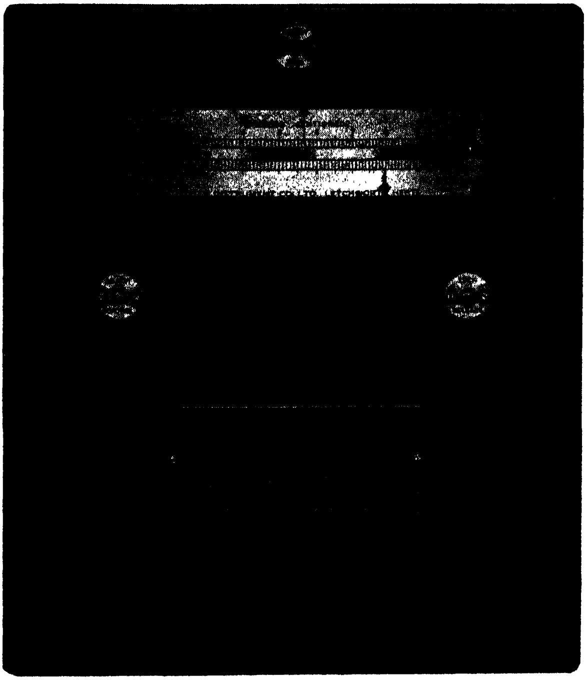


FIG. 120.—Potentiometric Indicating Automatic Temperature Controller.
(*Courtesy—Foster Instrument Co., Ltd.*)

The controllers employing the " null " method are balanced by the potentiometric method except in the case of resistance thermometers, when the Wheatstone bridge is used. The balanced position of the pointer is adjusted by a rheostat with a calibrated scale, to correspond with the temperature at which control is required. Any increase or decrease of temperature causes a right or left deflection of the pointer and operates contacts controlling the heating system.

When absolute automatic control is not necessary an alternative is the signalling system, in the form of the automatic operation of such devices as coloured lights, bells or horns at given temperatures. This immediately informs the furnace attendant, having additional duties other than temperature regulation, when attention is required. Automatic controllers and alarms are also made to operate in conjunction with mercury-in-steel thermometers, the warning or control being operated by electrical contacts in the dial.

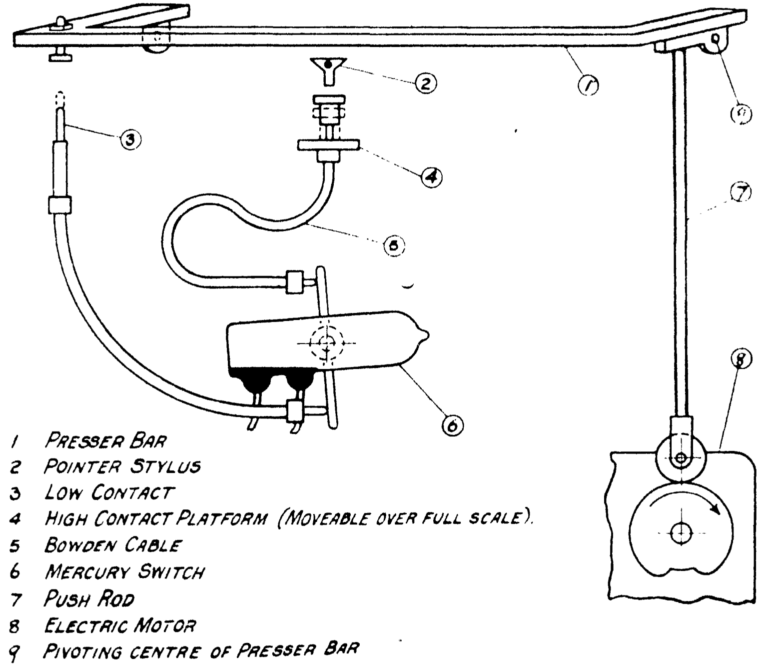


FIG. 121.—Diagram of Automatic Controller.
(*Courtesy—Foster Instrument Co., Ltd.*)

Special thermocouples. Molten metal. For the rapid reading of molten metal temperatures the usual types of protecting

FIG. 122.—The Foundry Pyrometer for Molten Metals.

(*Courtesy—Foster Instrument Co., Ltd.*)

sheaths are dispensed with. Up to temperatures of 1200°C. base metal couples are used in the form of thick wires lightly protected by woven asbestos or other suitable coating material, and often the tip is left exposed to facilitate rapid reading. The molten metal forms the hot junction for the couples, which are connected by leads to a portable indicator.

It is possible by using a rare metal couple lightly sheathed in silica, and by quick immersion technique, to read molten steel temperatures, although the optical pyrometer is usually preferred for ferrous metals, nickel alloys, etc.

Another type of couple employs long wires in a terminal block with clamping screws so that, should the end of the wires become shorter by alloying with or burning away by the molten metal, they can be fed through as required, thus maintaining the same length.

For surface temperatures. The thermocouple consists of the couple materials welded and rolled out into a thin flexible strip with the junction in the centre, and actually connected to the indicator in such a manner that the equipment is in one piece and completely portable.

Special types of surface thermocouples can be clamped to the hot body and connection

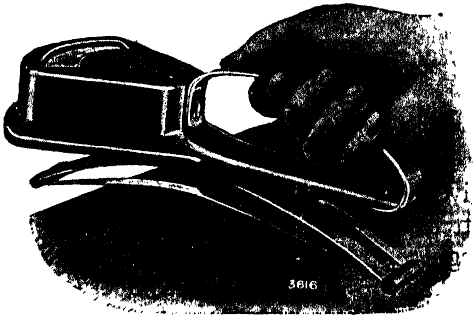


FIG. 123.—A Surface Temperature Pyrometer.

(*Courtesy—Cambridge Instrument Co., Ltd.*)

made by compensating leads to distant indicators or recorders.

Radiation pyrometers. These instruments measure the radiant energy emitted from a hot body. As they usually operate at a distance from the source of heat, no part actually comes into contact with the hot body. The radiation pyrometer is usually employed for temperatures higher than those read with thermo-electric couples. The heat radiation from the hot body is focused by means of a concave mirror on to a small and sensitive thermocouple mounted at the point of focus. In some instruments a convex lens is used, following the principle of the familiar " burning glass " when used to focus the rays from the sun. The E.M.F. generated by the thermocouple is indicated on a millivoltmeter calibrated to read in degrees of temperature.

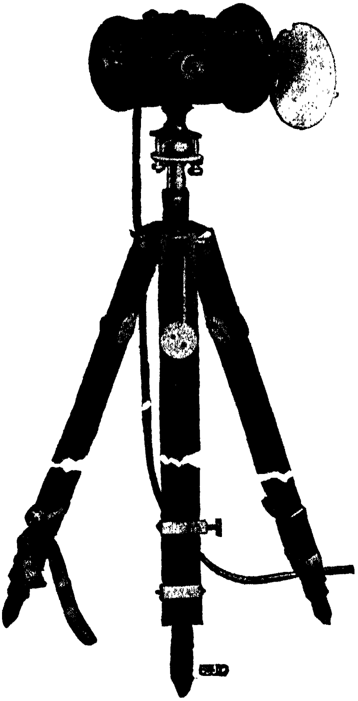


FIG. 124.—Féry Radiation Pyrometer Telescope. (*Courtesy—Cambridge Instrument Co., Ltd.*)

A well-known instrument of this type is the Féry radiation pyrometer which is constructed in the form of a telescope containing an adjustable concave mirror C for focusing the rays on to the thermocouple. Mounted just in front of the thermocouple and facing the concave mirror are two small flat semi-circular mirrors M fixed to form a complete circle, but the two halves are set at a slight angle to each other. There is a hole in the centre N to allow the focused radiant heat to reach the couple. In focusing, the operator looks through an eyepiece E and sees an image of the hot body in the semi-circular mirrors. If the focusing is incorrect the

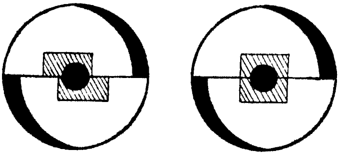


FIG. 125.—Method of focusing the image in the Féry Telescope. (*Courtesy—Cambridge Instrument Co., Ltd.*)

image appears divided into two unaligned parts. The true focus is obtained by turning the knurled head F on the side of the telescope body which adjusts the position of the concave mirror until the two halves of the image are seen to coincide. The Féry radiation pyrometer is, to a large extent, independent of the distance of the instrument from the hot body, provided that the image covers the thermocouple, but the body sighted upon should be at least 1 in. in diameter for every 2 ft. of distance between the object and the telescope.

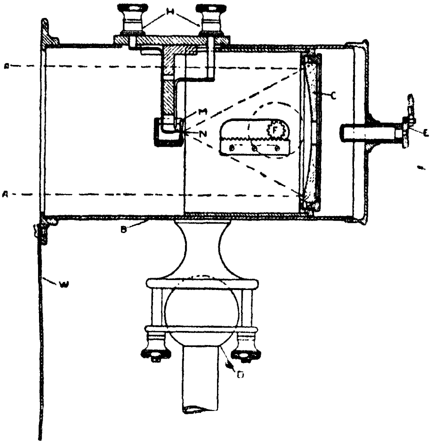


Fig. 126.—Diagram of Féry Radiation Pyrometer.
(*Courtesy—Cambridge Instrument Co., Ltd.*)

There are also radiation pyrometers of the fixed-focus type (Foster) in which the telescope takes the form of a long tube with an aperture at the end directed towards the hot body and a concave mirror at the other. When the aperture is filled, or more than filled, by radiation from the source of heat, the concave mirror always focuses on a fixed point. At this point the thermocouple is mounted. The controlling factor is of course the cone EFG and the size of the hot body so that the distance of the telescope from the hot body should be such that there is always coincidence or overlapping of any section of this cone.

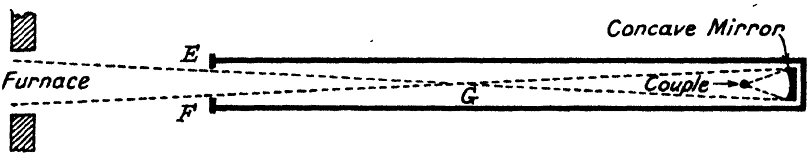


Fig. 127.—Fixed-focus mirror-type receiving tube.

Radiation telescopes can be used in conjunction with indicators, recording, combined indicating and recording and also automatic regulating instruments.

There are, however, certain corrections to be made when radiation pyrometers are used under certain conditions. Some materials emit more radiant energy than others at given temperatures when in the open. The extent of the error depends upon the reflecting power or emissivity of the substance. Carbon, having no reflecting power, is known as a "black body," and gives a true reading, whilst in the case of other materials and molten metals the readings will be lower than true temperatures, since most outfits are calibrated under "black body" conditions.

Any material in a furnace uniformly heated, and observed through a comparatively small opening in the furnace chamber, conforms very closely to "black body" conditions. Thus if a piece of bright copper and a piece of clay are placed inside the same furnace they will emit the same radiation and give similar readings on the radiation pyrometer, although they give totally different readings at the same temperature in the open.

When temperature readings of materials are taken in the open, they are, of course, comparative and bear a definite relation to true temperature when surface and other conditions are constant. Often when the emissivity characteristics of the material are known, fairly accurate corrections can be made by adding the error to the observed reading.

The optical pyrometer. There are several types of optical pyrometer, the one most popular and extensively used to-day being the Disappearing Filament Pyrometer, where the intensity of the colour of the hot body is compared against the adjustable intensity of the filament of an electric lamp. The instrument consists of a telescope arrangement inside which is a filament lamp, and carrying also an eyepiece and an objective. The telescope is focused until an image of the hot body is in the plane of the filament, and by the adjustment of a rheostat one way or the other, the tip of the filament will merge into the background of light from the hot body. The rheostat controls the current through the lamp and the amount of adjustment is indicated on an ammeter with a scale calibrated in degrees of temperature. Fitted in the eyepiece is a filter of monochromatic red glass to cut out glare when reading high temperatures, but for lower temperatures of approximately 700° to 850°C. the filter should not be included in the optical system, otherwise the intensity of light is so low as to make detection of difference in brightness between the object and filament very difficult. Instruments in which the colour filter can be turned in or out the fields of vision have a double temperature scale. Fig. 130 illustrates a simple circuit for an optical pyrometer using an ammeter, but it has the disadvantage that the lower portion of the temperature indicator scale is blank and useless, and merely represents the amount of current used in heating the lamp filament to 700°C. The full range of the scale can be used if the zero is mechanically set back so that the lower end of the scale commences at 700°C.

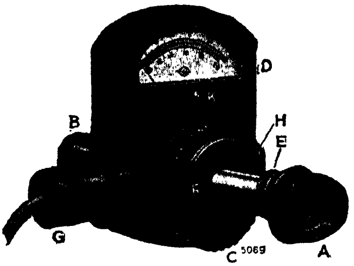


FIG. 128.—The Disappearing Filament Pyrometer.
(*Courtesy—Cambridge Instrument Co., Ltd.*)

The greater part of the scale is rendered serviceable by measuring the voltage drop across the lamp. The scale then becomes more extended at higher temperatures, and the useless portion below visible temperature is relatively smaller.

The Wheatstone bridge can be used as a means of using the whole of the indicator scale without setting back the zero. The lamp filament is made the resistance of one of the arms of the bridge and the galvanometer is calibrated in degrees with the zero corresponding to 700°C. or any other suitable temperature. The bridge is balanced when the filament reaches the predetermined zero temperature, and as the filament becomes hotter its increase in resistance throws the bridge out of balance and the pointer moves up the scale.

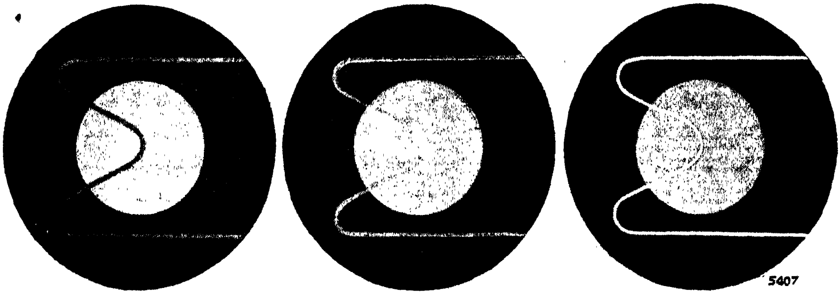


FIG. 129.—Illustrating the method of filament adjustment.
(*Courtesy—Cambridge Instrument Co., Ltd.*)

Because different materials have different reflecting powers, errors are introduced when temperature readings are taken in the open, and, since instruments are usually calibrated under " black body " conditions, the necessary corrections have to be added.

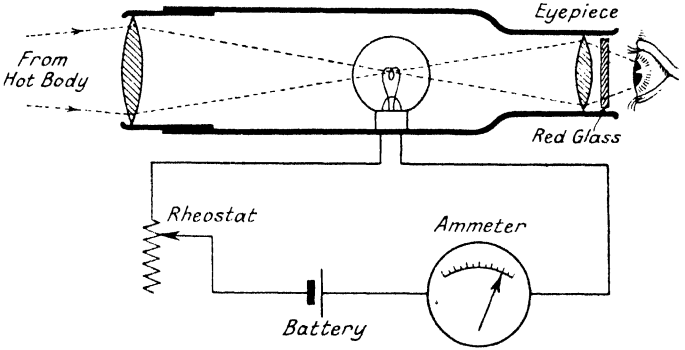


FIG. 130.—Simple Circuit for Optical Pyrometer.

The Wanner type of optical pyrometer has a circular field seen by the observer. This circle of light is divided into two halves, one illuminated by rays from the hot body and the other by the standard lamp in the instrument. Both lots of rays are passed through a monochromatic red screen. The light from the two sources are polarised in planes at right angles to each other. The analyser, a nicol prism carried in the eyepiece, is adjusted until an exact balance of brightness exists in the two semi-circles. The reading is made on a scale round the circumference of a large circular plate in terms of position of the analyser calibrated to degrees of temperature.

FIG. 131.—Wanner Type Optical Pyrometer.

(Courtesy—Cambridge Instrument Co., Ltd.)

Photoelectric pyrometers. These pyrometers are of recent development. The radiations from the hot body enter a receiving instrument where is housed a cell containing a substance sensitive to light. The cell is activated by the radiations from the object, and the small current produced is amplified in a separate unit away from the receiver. The amplified current can be used to operate temperature-indicating or recording instruments.

The response of the photocell to the radiations is almost instantaneous, which renders the instruments adaptable for reading temperatures of moving articles when visibly hot, such as the stock on rolling mills. The receiver is effectively used for taking readings at a distance from the object.

As with optical and radiation pyrometers true temperature readings are only obtained under " black body " conditions.

Checking the accuracy of pyrometric equipment. The accuracy of pyrometric equipment is easily and conveniently checked by several methods, the choice depending upon the type of instrument, thermocouple, etc.

For checking thermo-electric couples, recorders and indicators, the portable potentiometer is very useful. The reading obtained is compared with that on the apparatus under check.

Alternatively the couple can be immersed in a crucible containing a molten pure metal which is allowed to cool. When the freezing point of the metal is reached the temperature will remain constant for a time. Knowing the freezing point of the metal the pyrometer may then be calibrated. This method is particularly useful for calibrating equipment used for molten metal temperatures in non-ferrous work. The freezing-point method can be used also for checking optical and radiation pyrometers, when the instruments are focused on the bottom of a re-entrant tube partly immersed in the metal.

Optical and radiation pyrometers can also be calibrated by sighting into a furnace and comparing with a standard thermocouple or potentiometer.

CHAPTER 5

HEAT TREATMENT OF STEEL

THE heat treatment of steel consists of various operations by which such properties as hardness, tensile strength, ductility, toughness, grain size, effects of mechanical treatment, and so on; can be adjusted to the desired condition in order to render the material most suitable for the purpose intended. This modification is brought about by heating the steel, whether carbon or alloy steel, to certain definite temperatures and cooling at critical speeds.

Certain changes take place in the steel during heating and cooling, and in order that the types of changes and the temperatures at which they take place are known and clearly understood, it is necessary for us to study step by step the principles involved.

THE IRON CARBON EQUILIBRIUM DIAGRAM

Cast iron or steel containing carbon can be said to be an alloy of the two elements, iron and carbon.

An alloy is a solution, when the constituents are in the liquid state, and a solid solution when the constituents are solid or frozen.

A solution can be said to be an intimate mixture of two substances, that is, closer than that of a mechanical mixture (e.g. soot and sand), but looser than that of a chemical combination. Furthermore, when two substances make a solution they retain their individual characteristics, for example, salt dissolves in water, and, although the salt cannot be seen by even a powerful microscope, it is still present as salt and the water as water, no chemical action having taken place to alter their characteristics. If we freeze our salt-and-water solution, we obtain a solid solution of salt and water. Metals will also mix with and dissolve in each other to a more or less degree.

Let us first consider the case in which two metals are totally insoluble in each other, both in the liquid and the solid state. Lead and aluminium are two such metals. Above 659°C. both are liquid, but on reaching 659°C. the aluminium solidifies so that the *mixture* consists of solid aluminium and liquid lead. On cooling further to a temperature of 327°C., which is the freezing point of lead, the lead solidifies and we have then a mixture of solid aluminium and solid lead. (Of course, unless the liquid mixture is well agitated during cooling, the aluminium, being lighter, will float on top of the lead.)

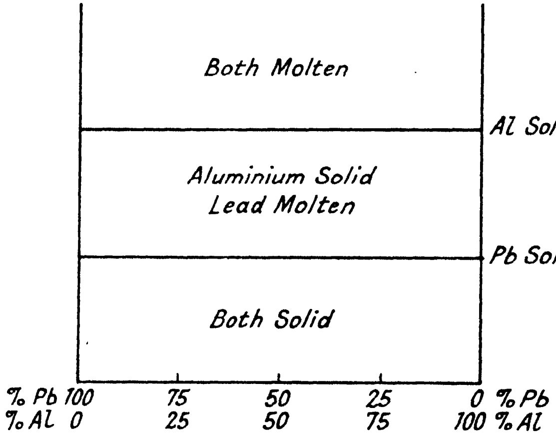


Fig. 132.—Aluminium-Lead Diagram.

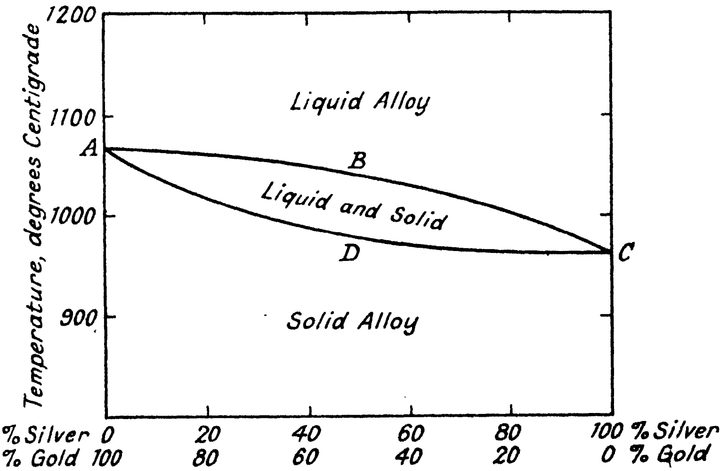


Fig. 133.—Gold-Silver Diagram.

Now let us consider the case where two metals are totally soluble, for example, silver and gold. These will dissolve in each other when molten and also when solid in any proportion. In the diagram, ABC. is known as the *liquidus* and ADC. is known as the *solidus*. Above the line ABC. we have a *liquid solution* of silver and gold. Now take a point above the curve ABC. representing a composition of 80 per cent gold and 20 per cent silver. On cooling and reaching a point on ABC. corresponding with that composition, *solid solution* crystals begin to separate from the molten alloy, each crystal containing gold and silver in the same proportion (80 per cent gold and 20 per cent silver) until the solidus line ADC. is reached. At this point, where the whole mass is solid, we have a solid solution of 80 per cent gold and 20 per cent silver. No matter what other proportions of gold and silver are taken, the alloy finishes on complete solidification with one homogeneous solid solution made up of the original proportions.

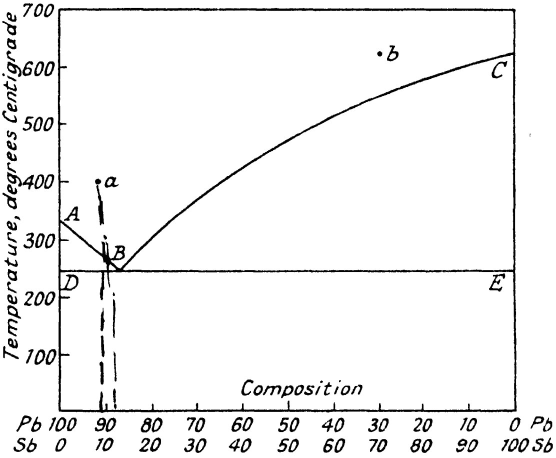


FIG. 134.—Lead-Antimony Diagram.

The above is a simple set of conditions, and we now turn to observe what happens when two metals are cooled which are soluble in each other when melted, but not completely soluble when solid. The alloys of lead and antimony are typical. First of all take a point (a) where the liquid solution contains 8 per cent antimony and 92 per cent lead at 400°C. Both remain in liquid solution until a temperature is reached on line AB at 280°C. where lead begins to precipitate, and, since it is well below its freezing point, solidifies. The remaining liquid solution becomes richer in antimony as a result, and progressively so with further precipitation of lead as further cooling takes place. This is represented by line AB. A temperature is finally reached where the alloy becomes totally solid. This temperature is 248°C., and in the diagram corresponds with a composition of 12·5 per cent antimony and 87·5 per cent lead. The solid alloy consists then of two constituents : free lead precipitated at temperatures above 248°C. and a solid solution containing 12·5 per cent antimony and 87·5 per cent lead. Similarly free lead is precipitated on cooling with all alloys containing up to 12·5 per cent antimony but in varying proportions depending upon the original antimony content, and in all cases the alloy on final solidification consists of what is known as eutectic alloy having a composition represented by point B, and free lead.

Now let us consider a composition of 70 per cent antimony and 30 per cent lead in the molten state at (b). On cooling and reaching a temperature on line BC, antimony separates from the liquid solution, and progressively on continued cooling, and therefore the remaining liquid becomes richer in lead. When a temperature of 248°C. is reached the alloy becomes solid, and consists of eutectic of the same composition as before, along with free antimony. Similarly, free antimony separates on cooling with all alloys containing more than 12·5 per cent, and on final solidification consists of eutectic and free antimony.

On cooling a liquid alloy of eutectic composition, that is, with a content of 12·5 per cent antimony and 87·5 per cent lead, neither free lead nor antimony separates, and the solid metal then consists of eutectic only, no solidification or freezing taking place until a temperature of 248°C. is reached.

The point B is known as the *eutectic point*, and occurs at the lowest temperature at which any alloy of the series will melt, this temperature being known as the *eutectic temperature*. Immediately on solidification, eutectics separate into very fine constituents which may consist of pure metals, solid solutions or intermetallic compounds ; and in structure may be globular, lamellar, angular or crystalline.

We are now in a position to study the iron-carbon equilibrium diagram. Dealing with the upper portion first, it will be seen on examination that we have a eutectic point at B corresponding to 4·3 per cent carbon, and if the line ED were continued straight across without upward movement to A, this part of the diagram would be very simple and we should merely have the case of the lead-antimony alloys over again. However, with the iron-carbon alloys there is a difference in two respects. Firstly, in alloys containing more than 1·7 per cent carbon, instead of pure iron separating from the molten alloy on cooling, we have a solid solution containing 1·7 per cent carbon and known as austenite, this separation being represented by FB. Secondly, owing to the different behaviour on cooling of alloys containing above and below a carbon content of 1·7 per cent, a line XY can be drawn vertically in the iron-carbon equilibrium diagram corresponding to this carbon value, and splitting the diagram into two portions, the left-hand side being similar to the gold-silver alloys and the right-hand side being similar to the lead-antimony alloys. Everything to the left of XY is defined as steel, and everything to the right of XY is defined as cast iron. Consider a point at 1 per cent carbon cooling from 1550°C. On reaching a temperature of approximately 1440°C. the liquid solution begins to freeze. On solidification at about 1300°C. the alloy consists of a solid solution of 1 per cent carbon in iron, also in the form of austenite, the carbon content of which is 1 per cent. Now consider an iron-carbon alloy containing 3 per cent carbon at 1400°C. The liquid

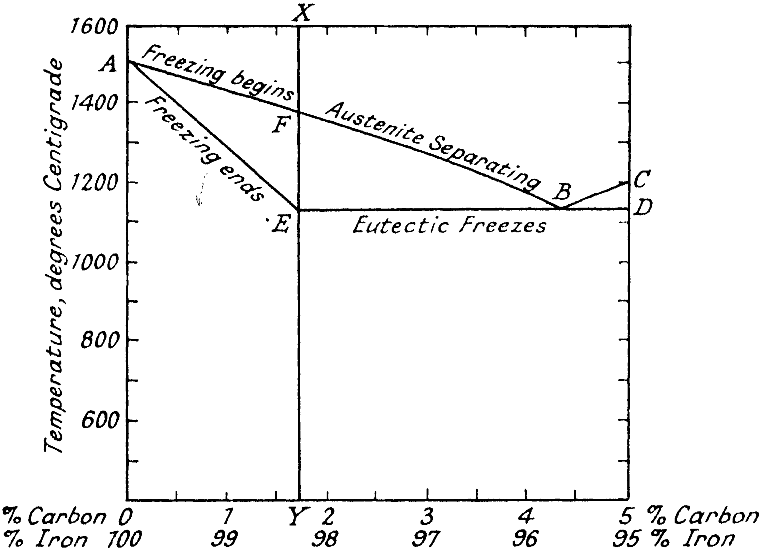


FIG. 135.—Upper Portion of the Iron-Carbon Equilibrium Diagram.

alloy cools without any change until a temperature of about 1270°C. is reached—here austenite, as a solid solution of 1·7 per cent carbon in iron, which is the maximum concentration of carbon in austenite, begins to separate out and continues to do so on cooling until a temperature of 1130°C. is reached. As a solid solution of iron containing 1·7 per cent carbon separates from a liquid alloy originally containing 3·0 per cent, the remaining liquid of course must progressively become richer in carbon, this effect on cooling being represented by the downward movement to the right—line FB. Final solidification is at point B where the alloy consists of a solid solution of 1·7 per cent carbon in iron, and a eutectic of 4·3 per cent carbon in iron.

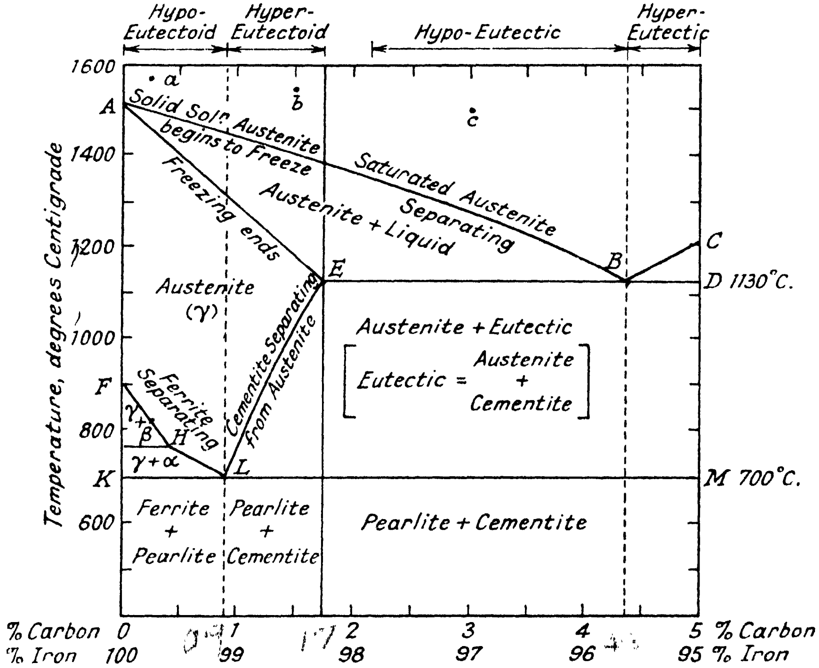


FIG. 136.—The Complete Iron-Carbon Equilibrium Diagram.

The effects of cooling a liquid alloy containing more than 4·3 per cent carbon need not be considered, as such commercial alloys are rarely met with, carbon dissolving in iron with difficulty when exceeding that amount.

On cooling further, however, the solid solutions are unstable, and by a study of the complete iron-carbon diagram we shall be able to discover exactly what occurs. Examining the left-hand portion relating to steels we consider a steel containing 0·25 per cent carbon at point (a). It freezes on cooling through AB and AE and becomes a solid solution of austenite. On continued cooling and reaching a temperature of about 810°C. on line FHL, pure iron begins to separate from the solid solution of austenite, enriching the remaining austenite in carbon. The pure iron which continues to separate progressively as cooling continues is known as *ferrite.* When a temperature of 700°C. is reached, the remaining austenite is transformed into a constituent known as *pearlite* which contains 0·89 per cent of carbon. All alloys of iron and carbon containing less than 0·89 per cent carbon, consist on cooling completely, of *ferrite* and *pearlite*—the higher the carbon content the less the amount of ferrite.

Now considering a steel containing 1·5 per cent of carbon cooling from point (b), we find that, as in the previous case, it freezes on cooling through AB and AE and becomes a solid solution of austenite. On further cooling in the solid state, it reaches a temperature on EL where a solid solution known as *cementite* (Fe_3C and containing 6·67 per cent carbon) begins to separate as indicated by EL, and impoverishing the austenite in carbon content until again at 700°C. the remaining austenite is transformed to pearlite at point L. All steels containing more than 0·89 per cent carbon consist, on cooling completely, of cementite and pearlite—the higher the carbon content the larger the proportion of cementite.

The point L at 700°C., after which the steel does not change any further on cooling, is known as the *eutectoid point.* A steel containing 0·89 per cent carbon consists on complete cooling of all pearlite, there being no separation of either ferrite or cementite, and is known as *eutectoid steel.* When steels contain less carbon than eutectoid composition they are termed *hypo-eutectoid,* and those which contain more carbon than eutectoid composition are termed *hyper-eutectoid.*

Pearlite consists of a fine structure of two constituents arranged in laminated form, that is, alternate microscopic plates of ferrite and cementite. As the carbon content of the eutectoid is 0·89 per cent it is obvious that it is normally composed of constant proportions of cementite (6·67 per cent carbon) and ferrite (carbonless iron). Fig. 142 shows the laminated form of pearlite. At high magnifications the cementite appears under the microscope in the form of laths showing an outline, and in a ferrite matrix. Pearlite derives its name on account of the iridescent colours resembling mother of pearl when viewed by oblique illumination. At lower magnifications, pearlite in the etched state is dark in appearance. Free ferrite is light in colour and, when present in sufficient amounts, clearly exhibits boundaries separating each grain. Cementite being the least attacked by the etching acid appears very bright and does not exhibit the distinct network of grain boundaries.

Cooling curves. A change from liquid to solid or vice versa is always accompanied by a gain or loss of heat. This is also the case when materials change from one allotropic form to another, such as the changes which take place in the solid state in the iron-carbon diagram.

Take the cooling curve of water for instance. When cooled in an atmosphere with a temperature below its freezing point, there is a steady decrease in temperature until 0°C. is reached, where there is a sudden check in the cooling curve, and the temperature of the freezing water actually remains constant for a period. When freezing has ended, the temperature of the ice again begins to fall steadily. The check in cooling rate is due to the latent heat being evolved during freezing or solidification. A similar principle applies to the solidification of metals.

In the iron-carbon diagram the changes from F to K are known as allotropic changes, that is, atomic changes within the crystals. Suppose we cool pure iron from above 900°C. At this temperature it is in the austenitic or gamma form and is non-magnetic. As no carbon is present it does not follow the rule of lines FHL and the eutectoid point does not apply, but on reaching 900°C. there are atomic changes within the crystals and the iron is converted to beta iron which is also non-magnetic. On cooling to 768°C. a further atomic change takes place, and alpha iron is formed which is strongly ferro-magnetic. When these changes take place there are two arrests in the cooling curve. No further change takes place on continued cooling. Pure iron, then, at normal temperatures, consists of all ferrite or alpha iron and is strongly ferro-magnetic. The two changes outlined above occur in the reverse order on heating from normal temperatures.

When the steel contains up to 0·35 per cent carbon there are three change points, one on FH where ferrite begins to separate,

PLATE II.

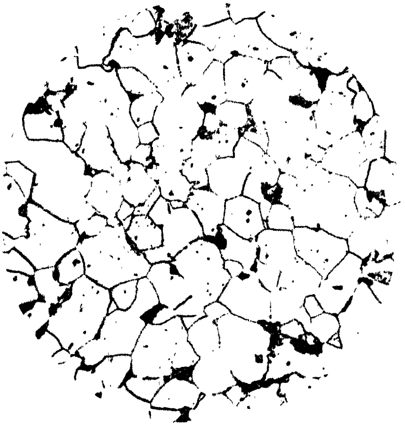


FIG. 137.—Steel containing approx. 0·08 per cent carbon. Mostly ferrite grains with small areas of pearlite. × 100 Dias.

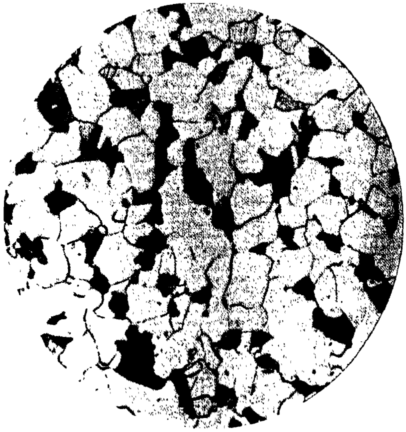


FIG. 138.—Steel containing 0·20 per cent carbon. More pearlite areas. × 100 Dias.

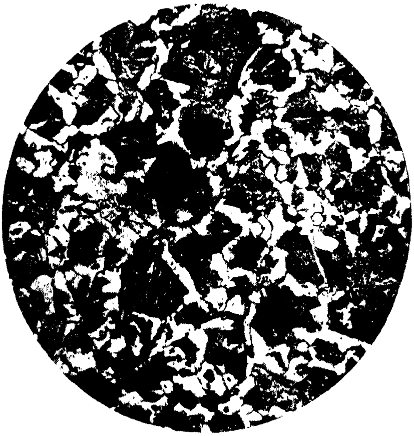


FIG. 139.—Steel containing 0·45 per cent carbon. × 100 Dias.

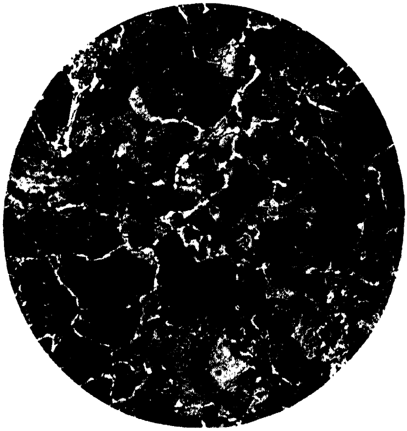


FIG. 140.—Steel containing 0·75 per cent carbon. Mostly pearlite with ferrite network. × 100 Dias.

FIG. 141.—Steel containing 0·85 per cent carbon. Pearlitic. × 100 Dias.

FIG. 142.—Steel containing 0·85 per cent carbon at higher magnification showing laminated structure of pearlite. × 500 Dias.

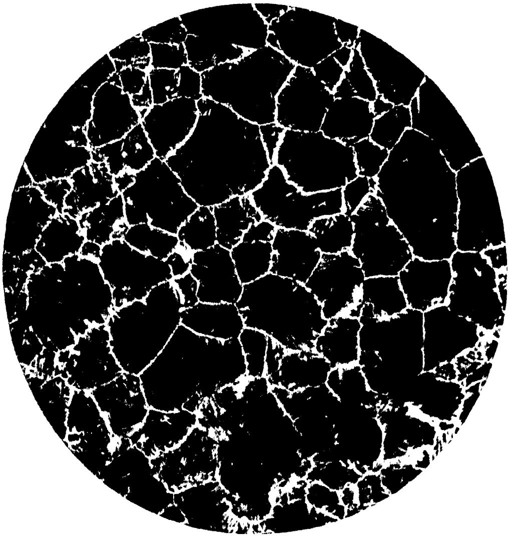


FIG. 143.—Steel containing 1·1 per cent carbon. Mostly pearlite with network of cementite. ×50 Dias.

PLATE IV.

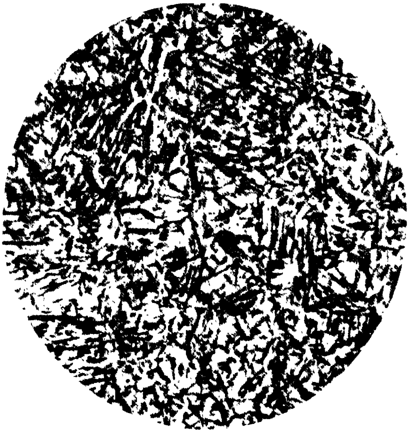


FIG. 147.—Martensite in hardened 0·38 per cent C steel. ×250 Dias. Water quenched from 860° C.

FIG. 148.—Martensite and Troostite in same steel as above, but oil-quenched from 860° C. ×250 Dias.

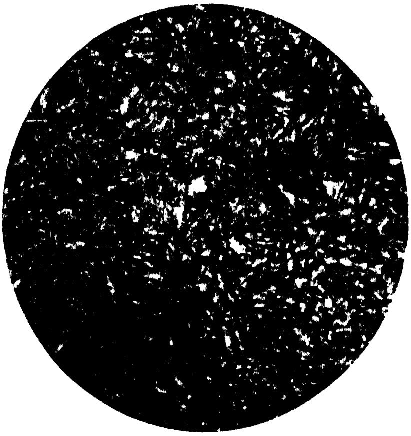
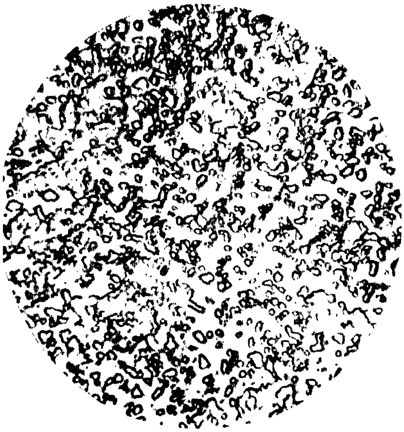


FIG. 149.—Sorbite in 0·90 per cent C steel, hardened and tempered. ×500 Dias.

(*Kindly supplied by Messrs. Edgar Allen and Co., Ltd.*)

PLATE V.



IG. 150.—1·2 per cent C steel in Spheroidised condition. 600 Dias.

Kindly supplied by Messrs. Edgar Allen and Co., Ltd.)

FIG. 151.—Case Structure in Case-hardened automobile gear wheel. 200 Dias.

FIG. 152.—Core Structure in Case-hardened automobile gear wheel ×200 Dias.

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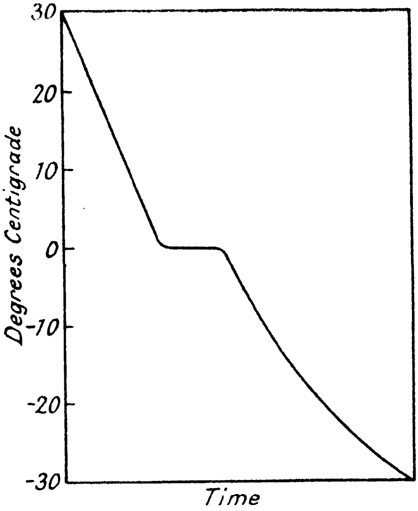


FIG. 144.—Cooling Curve of Water.

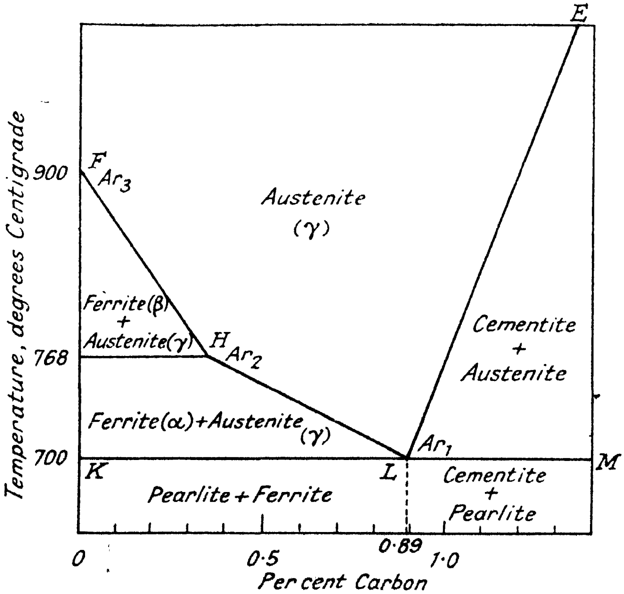


FIG. 145.—The Steel Diagram.

one at H the magnetic change point, and one at the eutectoid point L. On heating, the changes take place at slightly higher temperatures than on cooling, due to what might be termed molecular inertia or thermal lag. A change point is denoted by the letter A, and to distinguish between the points whether on heating or cooling, the A is followed by *c* or *r*, *c* being the point on heating (initial letter of the French word " chauffage "=heating) and *r* being the point on cooling (initial letter of the French word " refroidisement "=cooling). In addition, these letters are followed by a number to indicate the particular change, the upper change point on FH being 3, the magnetic change point, and on HL is 2, and the eutectoid change point is ·1. Thus the points on FH are Ac_3 and Ar_3, at H and along HL they are Ac_2 and Ar_2, and at L they are Ac_1 and Ar_1. The temperature arrests on cooling which take place at L increase in magnitude with increasing amounts of carbon in the steel. With steels of higher carbon content there is actually an increase in temperature, and often steel with carbon contents approaching eutectoid composition are seen to glow perceptibly during the austenite–pearlite change, and for this reason the change is often referred to as the Recalescence Point.

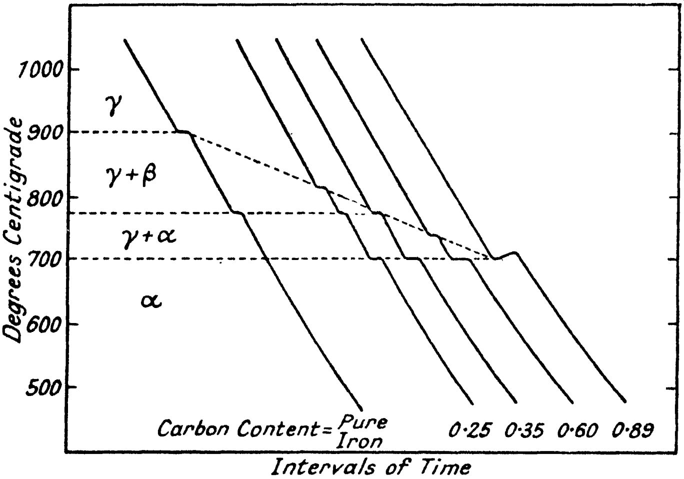


FIG. 146.—Cooling Curves of various Steels.

Steels containing between 0·35 per cent and 0·89 per cent carbon have two arrest points, one on HL which is Ar_{3-2} or Ac_{2-3}, and one at L which is again Ar_1 or Ac_1.

Steel of eutectoid composition has one change point only at L, Ar_{3-2-1}, or Ac_{1-2-3}.

A knowledge and understanding of the critical change points forms the foundation of the successful heat treatment of steel.

Hardening of steel. When steel is heated to bright red heat and rapidly cooled, for example, plunging into water, it becomes harder, stronger and more brittle. To produce hardness it is necessary to cool from a temperature above the upper Ac point of the steel, that is, with hypo-eutectoid steels containing up to 0·89 per cent carbon, to a little above the temperature where the iron is in the gamma or austenitic form. At these temperatures, 30° or so above line FHL, the carbon is dissolved in the austenite. Because the grain size increases with temperatures in excess of the Ac_3 point, the steel is damaged by overheating, resulting in excessive brittleness.

Although to harden hyper-eutectoid steels it is not always necessary to take into solution all the cementite before quenching, Ac_{1-2-3} must always be exceeded and a temperature near line LE may be reached.

The hardness of quenched steel increases with increases of carbon content. Iron free from carbon is only hardened very slightly when rapidly cooled from above the Ac_3 point, with 0·25 per cent carbon the increase in hardness is perceptible, but it is only when the carbon content approaches 0·4 per cent that ordinary steel acquires sufficient hardness for commercial hardening purposes when it is used in the production of propeller shafts, axles and crankshafts. Springs and saws contain about 0·7 per cent carbon. Metal-cutting tools are usually made from steels containing 1 per cent or so of carbon, while very hard implements, such as files and razors, will contain 1·4 to 1·5 per cent.

The quicker the rate of cooling from above the critical temperature the harder will be the steel, and the different quenching speeds are obtained by the use of different quenching mediums. Progressively higher quenching speeds are obtained by quenching in air blast, oils of different conductivities, water, ice water, ice brine, mercury, etc.

Theory of hardening. As previously explained, to obtain hardness the steel must be heated above the Ac_3 temperature where it is in the austenitic condition. Rapid cooling does not allow the normal changes characteristic of slow cooling to take place and, as a result, quenching tends to retain the iron in the gamma and beta forms. Austenite itself is not easily retained in quenched carbon steels except in the case of very thin sections extremely rapidly cooled, or in alloy steels. Instead, although the gamma to alpha iron change is completed, other constituents are produced which bear some relation to, and are in fact harder than, austenite.

Constituents of hardened steel. *Martensite* is the hardest constituent of hardened steel, having a Brinell of 675 to 725, and appears in the microstructure as a needle-like pattern. It is produced by rapid quenching.

Troostite is next in hardness to martensite and appears in the microstructure as a black-etching almost structureless constituent and is obtained by :—

(1) Cooling the steel at a rate less rapid than that required to produce martensite, but more rapid than that which produces sorbite, the next transitional product.

(2) By quenching in oil or water when the Ar_1 point is just reached.

(3) By tempering the hardened steel.

Troostite has a Brinell of about 450.

Sorbite is similar to pearlite but harder, and with a less perfectly developed structure consisting of very fine particles of cementite in ferrite, and in granular form rather than laminated. It is less hard than both martensite and troostite, but it is much more tough, having a Brinell approaching 300. It is a desirable constituent in heat-treated parts for " all-round " properties of strength, hardness, and shock resistance. It is produced by cooling at a rate rather faster than that which normally produces pearlite, or by full tempering.

The transformation of austenite into pearlite may therefore be arrested by different cooling rates giving varying degrees of hardness, and are represented in the following order of hardness :—

Martensite, Troosite, Sorbite, Pearlite.

Tempering. Hardened steel is generally too brittle to be used without some degree of tempering except for certain projectiles with properties of penetration or fragmentation.

Theoretically with normal rates of cooling, the molecular structure of steel should be such that the steel is soft, but, after quenching, the hard condition is not in equilibrium at the lower temperatures. Steel in the fully hardened condition is, therefore, highly stressed and rigid with a result that it is very brittle, has little ductility, and is liable to cracking. If we increase the temperature by reheating we relieve the stresses, and progressively higher temperatures alter the structure with a decrease in brittleness and an increase in ductility.

This procedure of reheating to remove some or all of the hardness is known as tempering, and is carried out by treating at temperatures ranging from 100°C. to just below the lower Ac point.

Tempering breaks up martensite into troosite or sorbite. Tempering at temperatures approaching 400°C. breaks up martensite with formation of troosite, whilst at 500° to 600°C. sorbite is formed. Intermediate tempering temperatures produce mixtures of these constituents.

Different tempering temperatures can be obtained by the use of boiling water, hot oils, molten lead, molten salt baths, and furnaces with or without controlled atmospheres.

Low-temperature tempering by an experienced operator is sometimes carried out by the observation of colour changes due to oxide formation on the polished surface of steel, the colours produced on heating ranging from pale straw at 210°C. to blue at 300°C.

The effect of increased tempering temperatures on the mechanical properties of steel is indicated by the following figures obtained by quenching a 0·564 in diam., 0·4 per cent carbon steel bar in water from 825°C., and tempering at increments of 100°C.

Condition	*Yield point tons per sq. in.*	*Max. stress tons per sq. in.*	*Elongation per cent on 2 in.*	*Reduction of area per cent*	*Brinell*
Untempered . .	—	70	2	5	350
Tempered at 200°C.	—	68	4	9	330
„ 300°C.	50	62	8	17	280
„ 400°C.	48	58	14	28	265
„ 500°C.	40	50	18	38	220
„ 600°C.	31	44	24	47	200
„ 700°C.	30	40	30	55	190

Annealing. Steel is annealed in order to remove the effects of cold work, internal stresses resulting from work of any kind, undesirable structures in castings, and to remove the effects of rapid or irregular cooling. It also promotes the formation of a finer grain size in coarse-grained material.

Annealing is a heat treatment in which the steel is heated in a furnace to a temperature just above the upper Ac_3 point, held at this temperature for a specified time and then slowly cooled in the furnace. This treatment is *full annealing*, giving maximum softness, ductility and recrystallisation of the metal. With steels containing more than 0·89 per cent carbon, the heating is to just above the pearlite to austenite change.

When it is desired to produce maximum softness without complete recrystallisation of the metal, a temperature of 670–720°C. is employed, the maximum temperature being below the critical range.

To minimise oxidation and give protection to surfaces of articles they are often annealed packed in sealed metal boxes. This procedure is termed "*pack or box annealing.*"

Bright annealing is annealing in a controlled or artificial atmosphere whereby oxidation is completely obviated.

Normalising. Normalising consists of heating the steel to above its critical temperature as in annealing, but cooling is carried out in air. The yield point, tensile strength, toughness and hardness is greater than obtained in annealed steels owing to the formation of sorbite instead of pearlite, whilst the ductility is not materially affected.

If steel has large grain size caused by overheating during mechanical treatment or over-annealing, or has coarse brittle structure in the cast state, normalising will restore the small grain size and promote more uniform properties throughout.

Spheroidising. This is a heat treatment in which the cementite plates in pearlite, under suitable conditions of temperature and time, gradually change shape until they take the form of very fine spherical areas evenly distributed through the soft ferrite.

The operation is carried out by heating the steel to slightly above the Ac_1 point and subsequently holding for a number of hours just below this point, the usual spheroidising temperatures being 680 to 720°C.

Steel in the spheroidised condition has maximum softness and ductility, and is in the best condition for good machineability.

Spheroidising finds the greatest application in the harder steels containing higher carbon contents as in tool steels, for, in addition to giving better machining properties, the cementite particles will dissolve rapidly when heated to the hardening temperature (Fig. 150), and in general aids materially in obtaining a product of uniform quality.

Austempering. Austempering is a heat-treatment process consisting of heating the steel into the austenitic range and quenching in a bath of molten lead or salt, and holding in the bath at a constant selected temperature for various periods depending upon the composition of the steel treated. The molten bath is maintained at a temperature above that at which martensite is formed on quenching, and at the same time affecting the cooling rate through the critical range so that it is fast enough to prevent formation of lamellar pearlite. The resulting structure shows a very fine " emulsion-like " distribution of the carbide. The holding time in the molten bath must be sufficiently long to enable the austenite to completely transform so that none will remain to change to martensite on further cooling. The process is most effective in high carbon steels.

Considerable hardening takes place and, since the volume changes in the metal when martensite is formed are avoided, tendency to cracking is minimised. Compared with the quench-temper method of hardening, greater toughness for a given hardness is produced, and is clearly revealed when tests are made for impact, elongation, and bend.

✓ CASE HARDENING

The requirements of certain types of machine parts are a hard-wearing surface with a tough core capable of withstanding sudden stresses, as, for instance, occur in gears and gudgeon pins. Carbon steels heat treated in the normal manner to produce hardness have not the necessary shock resistance. By the special treatment of case hardening, the required properties can be introduced into ordinary mild carbon steel.

Case-hardened parts are produced from steels ranging from 0·08 to 0·35 per cent in carbon content, and which may be divided roughly into three grades :—

(1) Carbon 0·08 to 0·12 per cent for the toughest core and for articles of thin section.

(2) Carbon 0·12 to 0·20 per cent for general purposes.

(3) Carbon 0·20 to 0·35 per cent for parts where the case needs supporting by a stronger and harder core, as in ball and roller bearings.

Preparation of the steel. The articles are machined, leaving a minimum of surplus material for final grinding to size. They are then packed by completely surrounding with a carburising material contained in a steel box, the top of which is sealed with fireclay to prevent entry of air. As the case is martensitic and difficult to machine after treatment, any areas of parts which must be afterwards machined or drilled are protected from the influence of the carburising medium by an application of fireclay or copper plating.

The carburising medium may consist of wood charcoal, charred leather, or a mixture of wood charcoal and an energiser such as barium carbonate or sodium carbonate. A popular mixture is wood charcoal with 35 to 40 per cent of barium carbonate.

Carburising. The box and parts are placed in a furnace and heated to a temperature in the region of 900°C. for a period depending upon the required case depth. Various depths of case are used for different applications and range from roughly $\frac{1}{64}$th to $\frac{1}{16}$th of an in., involving carburising periods of about 2 to 11 hours respectively, average periods for average case depths being 4 to 5 hours. The furnace and box are then allowed to cool, after which the box is removed.

Contact with the carburising medium at the soaking temperature causes austenite near the outside edges to absorb carbon, and diffusion of carbon takes place inwards. On cooling, the steel consists of an outside layer or case of steel containing about 0·9 per cent carbon merging into a core which has retained its original composition.

Heat treatment. After carburising, the articles must be further heat treated, as it is necessary to refine the grain which will have grown considerably during the prolonged heating at temperatures above the Ac_3 point. To obtain the most satisfactory results the steel is given two heat treatments :—

(1) Reheating to 870 to 920°C. and air cooling to refine and toughen the core. After this treatment the case is too coarse in grain and brittle, as the temperature employed is much higher than the critical temperature of a 0·9 per cent carbon steel.

(2) Further reheating to about 760°C. and quenching. The structure of the case is now refined and is finely martensitic. The grain size of the core is unaffected by this second treatment as it is well below its critical temperature. Actually, the toughness of the core is increased, the final structure consisting chiefly of ferrite and sorbite. There is an intermediate layer of troosite at the carbon content gradient area between the core and case.

The case-hardened part is then with advantage given a slight further re-heating to about 150°C. to relieve hardening strains in the case.

As an alternative treatment to save time and treatment costs, one quenching only after carburising is sometimes employed, from a temperature of 800 to 830°C. The case is refined to some extent and is certainly hard, but the core after this treatment is not as tough as desirable for many applications, and thin sections are easily fractured.

Occasionally free cementite may be found in the case, indicating that the carbon content of the case is in excess of eutectoid composition. This may be found when carburisation is faster than the inward diffusion of carbon, and is usually caused by carburising for too long a period or at too high a temperature, thus producing too deep a case with a tendency for flaking or peeling. The cementite may be removed by annealing or by very slow cooling from the carburising temperature.

Care is necessary in the final grinding in order to avoid local overheating with development of fine surface cracks and soft spots in the case.

Cyanide case hardening. This method involves the use of a bath of molten sodium cyanide maintained at a temperature of about 900°C., into which the parts are immersed for periods ranging from 15 minutes to 2 hours, giving case depths of 0·01 in. to 0·025 in. respectively. The quenching is usually carried out directly from carburising temperature, but further heat treatment may be applied if desired. The case is very hard due to the formation of some nitride of iron in addition to absorption of carbon.

Sometimes the articles are coated with a paste containing some cyanogen compound, heated to about 900°C., and quenched. The case-hardening effect is rather superficial and the method is only used when cases of considerable depth are not necessary.

Flame hardening. (Shorter process.) By the use of the Shorter process much of the distortion attendant with the usual case-hardening practices is greatly eliminated, and is especially adaptable to symmetrical objects such as gears, worms, piston pins, cams and crankshafts, and many other machine parts too numerous to list. The operation consists of locally heating and quenching the surface of the object by means of a machine-controlled oxy-fuel gas burner-quench unit. There are four distinct variations of operating the Shorter process.

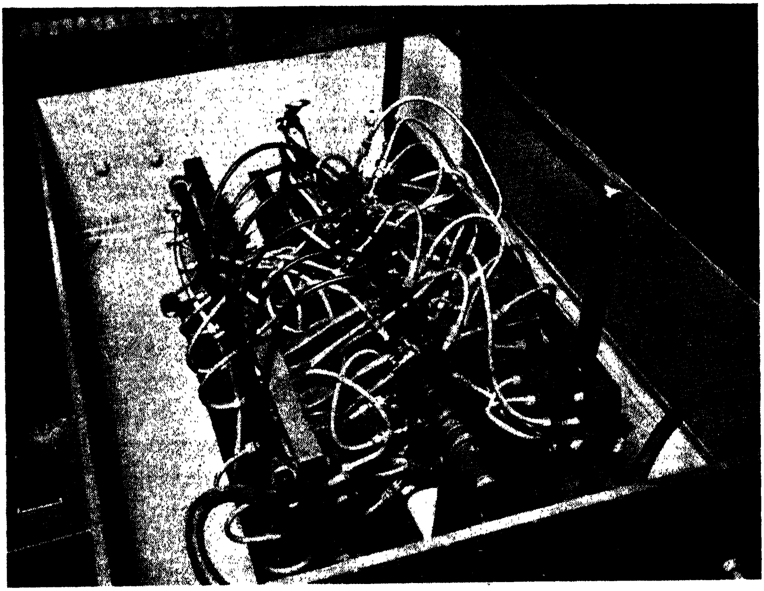


FIG. 153.—Shorter Type W.1. Automatic Hardening Machine, showing view of a camshaft mounted on the centres with the heating and quenching set up ready for automatic operation. 30/50 shafts per hour.

(*Courtesy—Shorter Process Co., Ltd.*)

(1) In which the flame progresses over the surface and the heated area is immediately quenched out by a water jet attached to the burner so as to follow immediately behind it.

(2) In which the part is rotated past a stationary burner quench.

(3) In which the part is rotated and the burner quench traverses the peripheral surface.

(4) In which the part is spun and the heating-quenching operations are in sequence.

The time of heating and the exact timing of the sequence of heating and quenching must be exactly dermined and maintained, and for this purpose mechanical devices for specific applications have been developed.

Obviously low carbon steels with their low hardenability are unsuitable for the purpose of Shorter hardening unless first carburised; the most suitable range to which the method can be applied is that of between 0·4 to 1·00 per cent carbon. With certain alloy steels the carbon content may be as low as 0·25 per cent. The surface hardness and depth of hardening produced compare with those found in ordinary case-hardening practice.

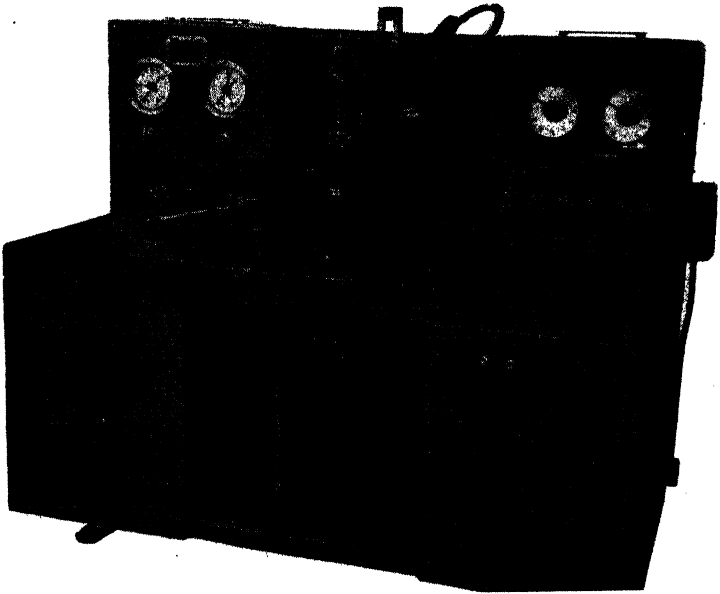


FIG. 154.—Shorter Type N.3. Automatic Hardening Machine, showing timing clocks and pressure clocks.

(*Courtesy—Shorter Process Co., Ltd.*)

Another development in surface hardening employs electric induction heating, and is termed the " Tocco " process. A high-frequency current is passed through copper sleeves surrounding the part, producing eddy currents which heat the surface to be hardened. Water jets passed through holes in the inductors completely envelop and quench the whole part.

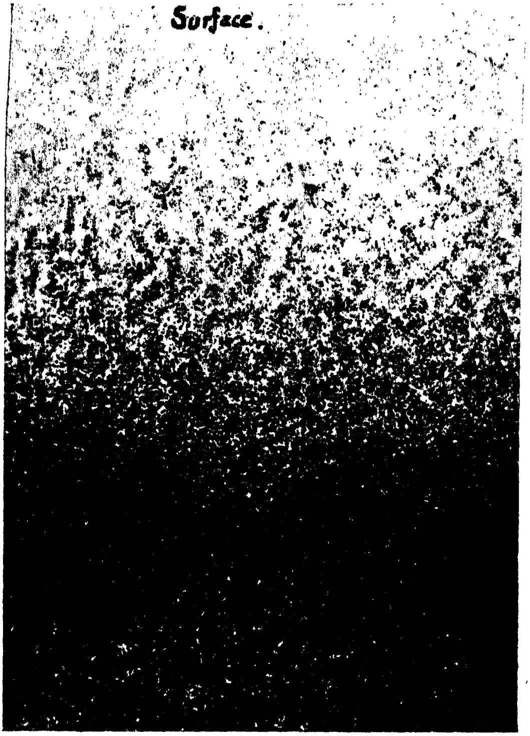


FIG. 155.—Shorter Process Case, showing transition structure from case to core.

(*Courtesy—Shorter Process Co., Ltd.*)

Gas carburising. Carburising is sometimes carried out by heating the articles in a furnace filled with hydrocarbons formed by decomposition at carburising temperatures of organic substances such as pine tar, turpentine, benzol, mineral oil, and various gases. Gas carburising is a speedy method used chiefly for producing the shallower type of case.

METHODS OF HEATING STEEL FOR HEAT TREATMENT

Early types of heat-treatment furnace employ the burning of solid fuel on a grate, and the temperature control is largely affected by the use of dampers. Most modern furnaces employ other fuels which give greater flexibility of application and control. The chief sources of heat are from the use of fuel oil, producer gas, towns gas, pulverised coal, and electrical energy. Producer gas burnt along with preheated air is a favourite fuel for use in steelworks for dealing with large stock such as ingots, billets and large castings. For smaller work, where non-scaling is desirable, muffle type furnaces are used, either oil fired, gas fired, or electrically heated, and in which the atmosphere in the chamber may be controlled by the introduction of suitable gases.

Another method of heating whereby the work is isolated from direct contact with the flame or products of combustion, is that employing radiant tubes which act in a similar manner to electric resistors. Gas is burnt in heat-resistant alloy steel tubes arranged in the walls, roof and floor of the furnace, and the products of combustion are exhausted from the tubes by means of induced draught.

Immersion in molten lead or molten salt baths is often employed for heating steel, and has the advantage that the work is protected from the influence of air and furnace atmospheres. Heating is quicker and more uniform than heating by radiation in a muffle furnace. Molten lead is applicable for temperatures ranging from 340 to about 900°C. When salt baths are used, molten mixtures of potassium nitrate and sodium nitrate sometimes along with sodium nitrite provide temperatures at the lower end of the range for tempering, whilst medium temperatures for hardening and tempering are obtained by the use of combinations of sodium chloride, sodium carbonate, calcium chloride, and barium chloride. For the higher scale of temperatures and for the hardening of high-speed steels, salt baths, which are predominantly barium chloride, are suitable.

CHAPTER 6

MECHANICAL WORKING OF STEEL

STEEL may be shaped either by pouring the molten metal into a mould or by the application of mechanical pressure. The choice of method depends largely upon the shape of the article and the cost of production. Many shapes are far too complicated to produce by mechanical means, in which case they are cast in the steel foundry, employing moulds and cores. However, the more simple shapes and sections can be more quickly and economically produced by various methods of mechanical working, both in the hot and the cold state.

HOT WORKING

Preparation of the steel. The steel is taken from the furnace in a casting ladle, and transported over the casting pit where cast-iron ingot moulds stand in rows. By means of a hand-operated lever, the molten steel is allowed to run from the ladle and fill the mould. Casting the ingots can be carried out by travelling the ladle from mould to mould, or by placing the moulds on cars and running trains of cars underneath the ladle. The moulds are open at the bottom and stand on an iron plate, and are somewhat narrower at the top than the bottom so that subsequent stripping of the mould from the ingot is facilitated by reason of the taper. Stripping is accomplished with a stripping machine built into a crane, and with this device the moulds are gripped at the sides, whilst a ram incorporated in the machine presses at the same time on the ingot from above. The mould is thereby lifted from the ingot which remains standing.

When stripped, the ingots are not a uniform heat throughout and not in a suitable condition for hot working. Indeed, in the case of large ingots, the interior may still be molten whilst the outside is solid. Before working it is necessary that the ingots shall be at uniform temperature, so they are placed in closed bricked-in pits which allow the heat to equalise. It is often unnecessary for the pits to be heated for the equalising process, but should heating be required, arrangements are provided for this purpose and employing either producer, coke oven, or blast-furnace gas. Alternatively, before working, the ingot may be allowed to cool and reheated to the required working temperature.

The steel heated to 1000°C. or more, is removed from the reheating furnace or soaking pits, and by means of a crane is placed on the revolving rollers of a roller track on which it is led to the rolling mills.

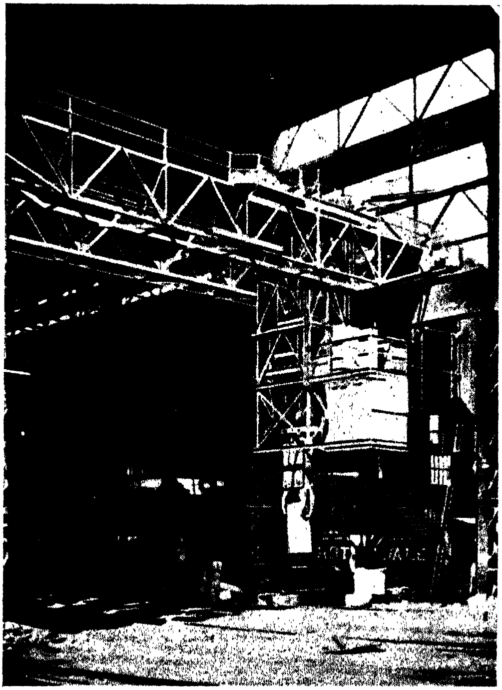


FIG. 156.—A 5-ton Ingot Stripping and Charging Machine.

(*Courtesy—Messrs. Wellman Smith Owen Engineering Corpn., Ltd.*)

Rolling. The rotating rolls of the rolling mill grip the ingot as it comes along and draw it through. Each passage of the steel between the rolls is called a " pass." In passing through, the thickness of the ingot, which may be 20 in. or more at the beginning, is reduced considerably and the length of the ingot is proportionately increased. The first reducing mill is often called the "cogging mill" because of the presence of grooves or shallow depressions which are often formed across the rolls, and which serve the purpose of allowing a better grip on the ingot. After the first pass, the gap between the rolls is decreased as the top roll is lowered by means of housing screws hydraulically operated in old-type mills, or by electric-motor. The rolls are then reversed, and a mechanical device tilts the ingot and an electrically driven roller table passes it back into the rolls, effecting a further reduction in section and increase in length. In the cogging mill the ingot is reduced to blooms (rectangular sections of cross-sectional area greater than about 36 sq. in.), billets (rather longer than blooms and smaller in cross-section), and slabs

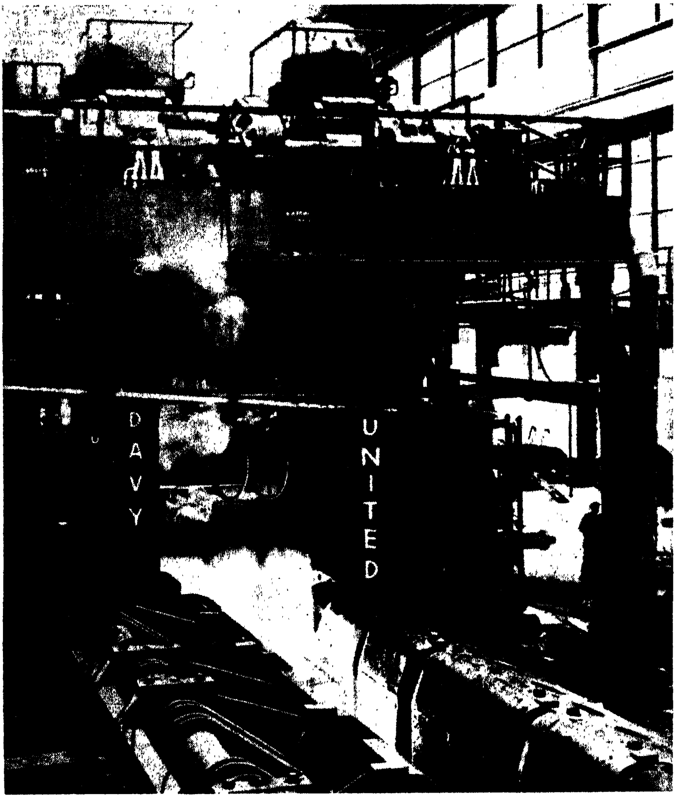


FIG. 157.—A 45 × 80-in. Reversing Blooming and Slabbing Mill. (*Courtesy—Messrs. Davy and United Engineering Co., Ltd.*)

(sections with a width at least double the thickness and having a similar cross-sectional area to blooms).

The amount of reduction in cross-section at one pass is known as " draught," and is controlled by the temperature of the steel, its cross-sectional shape and its composition. Carbon steels permit greater reduction per pass than alloy steels. Another controlling factor is the angle of contact between the work and the rolls which must be less than 30°, since a greater angle does not allow the rolls to grip and pull the steel through.

The sections from the cogging mill are cut to the desired length by means of shears, and either taken away to the store yard for use as required, or conveyed to smaller rolling mills for further working. The subsequent rolling is carried out on smaller mills often arranged in the form of a train, each separate set of rolls being known as a stand, and the steel is progressively reduced in cross-section as it passes from one to the other.

Some continuous mills are called tandem mills, where the stands are placed tandem fashion one in front of the other. Because of the reduction in cross-section, the length of the steel leaving the rolls is greater than that entering them, so that the speed of the rolls in each following stand is increased according to the amount of reduction in the preceding stand. The long length of steel as it leaves the last stand, travelling at a rate of up to 8 ft. per second, is automatically cut into suitable lengths by flying shears or rotary shears. The speed of rolling is such that the steel retains its heat to a large extent, because the normal loss of heat through radiation is replaced by that generated as it undergoes squeezing or working.

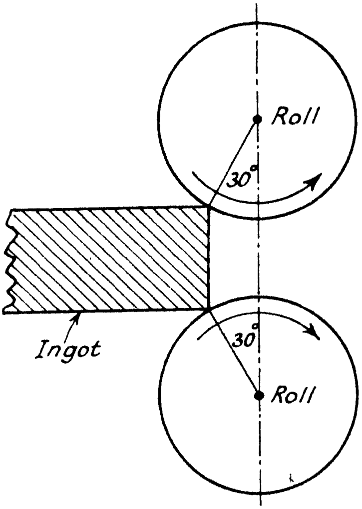


FIG. 158.—Maximum Angle of Grip in Rolling.

The diameter of the rolls varies from 45 in. or more for large cogging rolls, to 10 to 12 in., or even smaller for rod or strip mills.

A single stand rolling mill may be reversing or non-reversing. In the latter, which is the oldest and simplest type, the steel is drawn through the rolls and then passed back over the top so that it receives work in one direction only, and this procedure of course involves a loss of heat, time and effort. The development of the reversible mill enables the product to be rolled backwards and forwards.

FIG. 159.—A 21-in. and 46 × 66-in. Four-High, Five-Stand Continuous Hot Strip Mill.

(*Courtesy—Davy and United Engineering Co., Ltd.*)

A rolling mill may be "two-high" or "three-high." Two high mills have two rolls mounted one above the other. Three high mills employ three rolls lying one above the other and which always rotate in the same direction. The steel passes through between the bottom and the middle roll, and then passes back between the middle and the top roll. The raising and lowering of the material between passes is effected by tilting table which are actually the ends of the roller racks at both sides of the mill, and can be elevated to a distance corresponding to the diameter of the middle roll.

Rolls for the production of sections have grooves or " passes " in which the steel is completely enclosed and shaped when rolled. When a considerable number of passes are required to reduce the stock to the required section, two sets of rolls may be used, namely, roughing rolls and finishing rolls. Roughing rolls produce a section roughly to the required shape, whilst the finishing rolls complete the finished section, the passes often diminishing in size from one end of the rolls to the finishing pass on the other. A wide range of sections are produced, including rails, joists, channels, tees, angles, hexagons, rounds, ovals, etc.

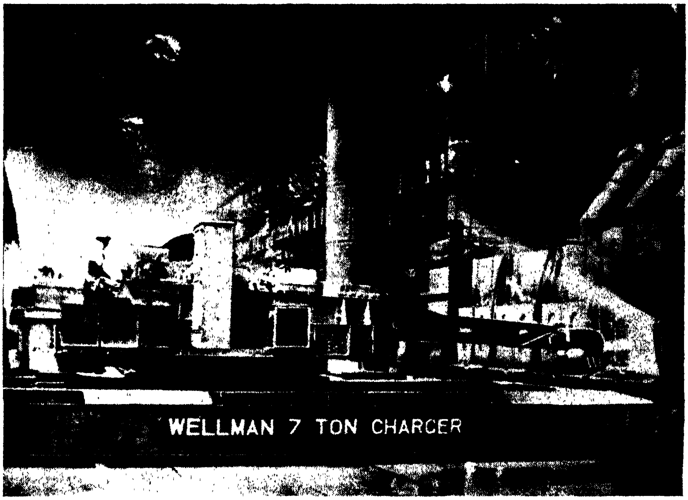


FIG. 160.—Charging a slab into a reheating furnace.
(*Courtesy—Messrs. Wellman Smith Owen Engineering Corpn., Ltd.*)

Plates and sheets are rolled from slabs. The slabs are brought to rolling heat in a reheating furnace and rolled out to plate or sheet between plain rollers in a three-high, tow-high reversing or four-high tandem mill. During the rolling a little salt or heather is often thrown on to the surface of the plate causing a series of minor explosions which break away the scale from the steel. A pointer on the screw-down gear indicates the thickness of the plate, which is then allowed to cool and trimmed with

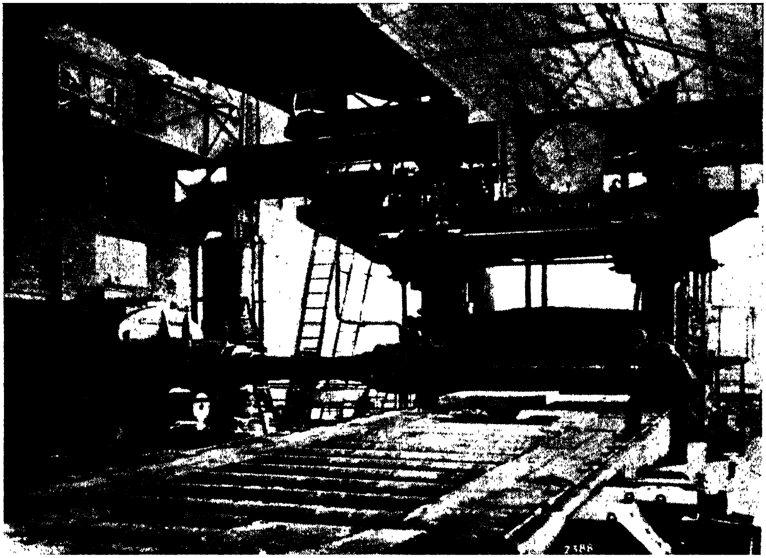


FIG. 161.—A 36-in. × 9 ft. 0 in. Three-High Plate Mill. (*Courtesy—Messrs. Davy and United Engineering Co., Ltd.*)

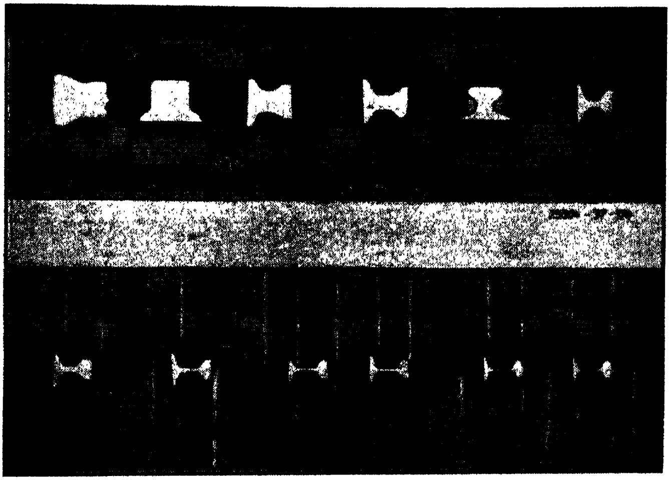


FIG. 162.—Grooves or passes in the roughing and finishing rolls for rolling rails.

mechanical shears. Long sheet strips are rolled on universal mills, normally built for strip widths from 4 to 55 in., and which have in addition to the horizontal rolls, vertical rolls. The vertical rolls work the material from the side and obviate the shearing of the edges. Modern practice is to hot roll steel strip in coil form from slabs in widths up to, say, 72 in. wide in four-high continuous mills (Fig. 159).

Forging. Owing to their size, shape, and so on, many articles cannot be conveniently rolled, in which case they are worked by forging, using presses or hammers. Forging by hammer consists of reducing the hot metal by blows from a mechanical hammer driven by steam or compressed air. It may be double acting or single acting. When lifted by power, but its fall is due to gravity alone, it is called single acting; but when the steam or air pressure is employed to add to the power of the downward blow, the hammer is double acting. Forging by hammers is applied to work of simple shape such as axles, bars, bolts, levers, etc.; also as a preliminary operation to drop forging. The method is also used for the cogging or reducing of smaller types of ingots, notably of such materal as high carbon, stainless, high speed, and other classes of high quality steel.

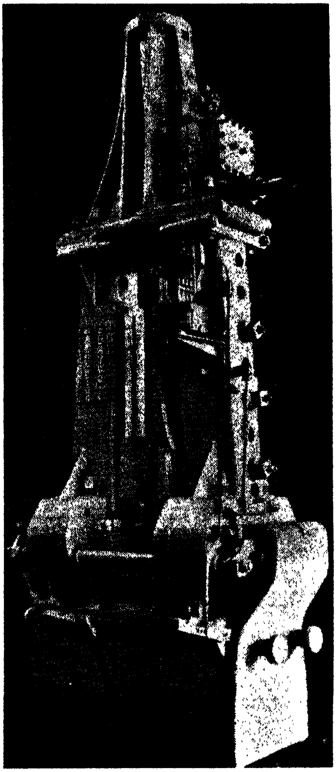


FIG. 163.—A small high-speed die forging hammer.

(*Courtesy—Messrs. Eumuco (England), Ltd.*)

Forging improves the quality of the steel, as mechanical pressure breaks up the grain to give a steel of finer texture, strength and toughness. Forgings in the ideal condition are those in which the effects of the work penetrate to the interior of the steel, but since, owing to the immense vibration from the terrific blows, there is a limitation to the size of hammer which can satisfactorily be used (about 30 tons), and therefore to the size of section to which hammering is applied, so that forging by hammering is employed with better effect to thinner sections. Also because the pressure is felt only momentarily by the work with each blow, the effects of hammering are only superficial on thick sections.

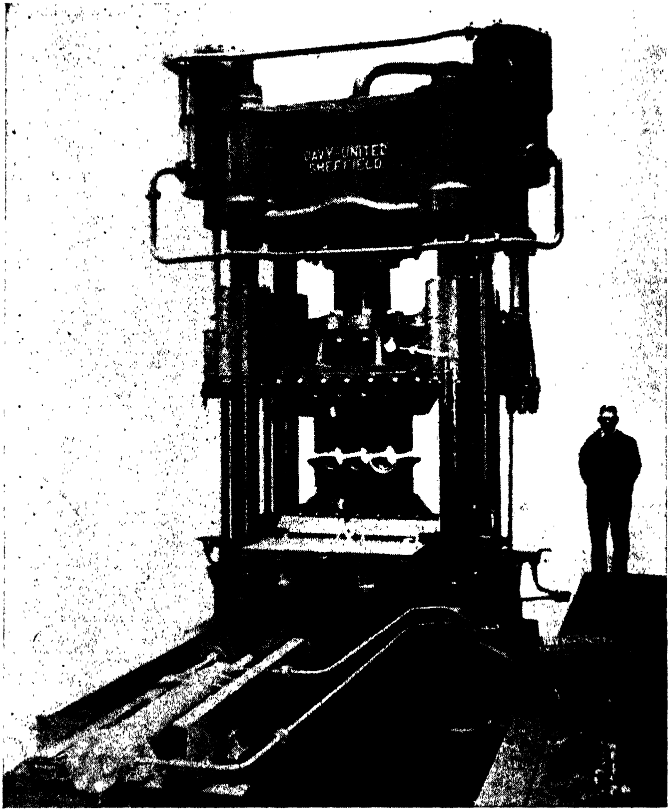


FIG. 164.—A 1000-ton axle forging press with three-grooved tools. (*Courtesy—Messrs. Davy and United Engineering Co., Ltd.*)

When articles are required which are not so simple in shape and considerable numbers of identical parts are required, such as spanners, hammer heads, crankshafts, and other machinery parts, the method of drop forging lends itself to rapid production. In this operation a piece of heated steel of correct size is forged by repeated blows between a lower die fixed to the anvil block and an upper die attached to the head of the hammer. The size of the metal is such that it completely fills and takes up the contours of the die, leaving only a small easily removable fin of excess metal squeezed out between the two halves of the die.

FIG. 165.—Pressing an Automobile Wheel hub.
(*Courtesy—Messrs. Eumuco (England), Ltd.*)

The general aim in drop forging is to mechanically shape the steel as nearly as possible to the required dimensions, so as to leave the minimum of metal to be removed in the finishing operations of machining or grinding to produce the completed part.

The normal structure of cast steel does not show any tendency of the crystals to line up in any definite direction, but when pressure is applied by mechanical working the crystals are deformed by elongation in the direction in which the mechanically produced stresses are applied, and they tend to flow in the form of lines. A structure of this type is termed *fibre,* and steel is more resistant to impact failure or failure due to alternating stresses when the stresses are applied at right angles to the direction of the fibres. If the flow of the fibre is cut by tools during finishing operations, or cut or torn during actual forging operations, the strength is affected at these localities, since severed fibres obviously have not the strengthening effect as whole ones.

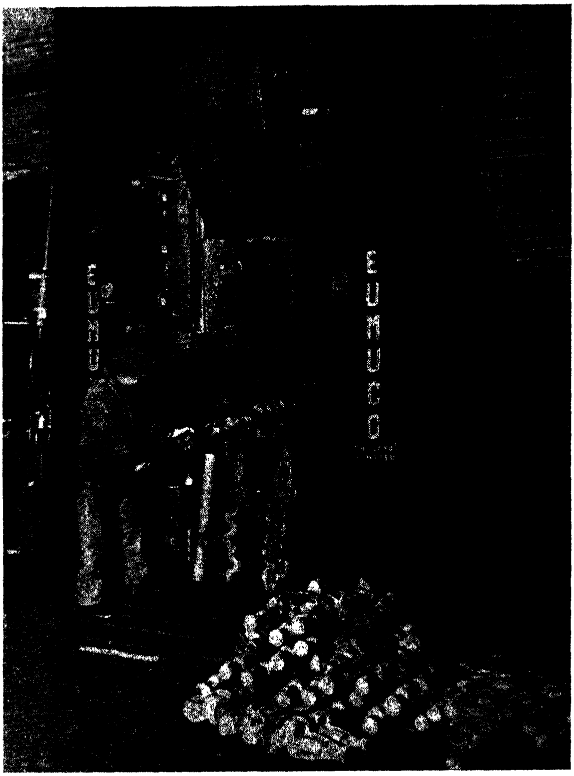


FIG. 166.—Forging Crankshafts.
(*Courtesy—Messrs. Eumuco* (*England*), *Ltd.*)

If the cutting of fibres cannot be altogether avoided they are at least kept away from the point in the part where the greatest stress is to be applied in service, and where the maximum strength is required. It is therefore desirable in the production of machinery parts by drop forging, that the design of the part and the forging dies are skilfully controlled to give a smooth and continuous flow of fibre.

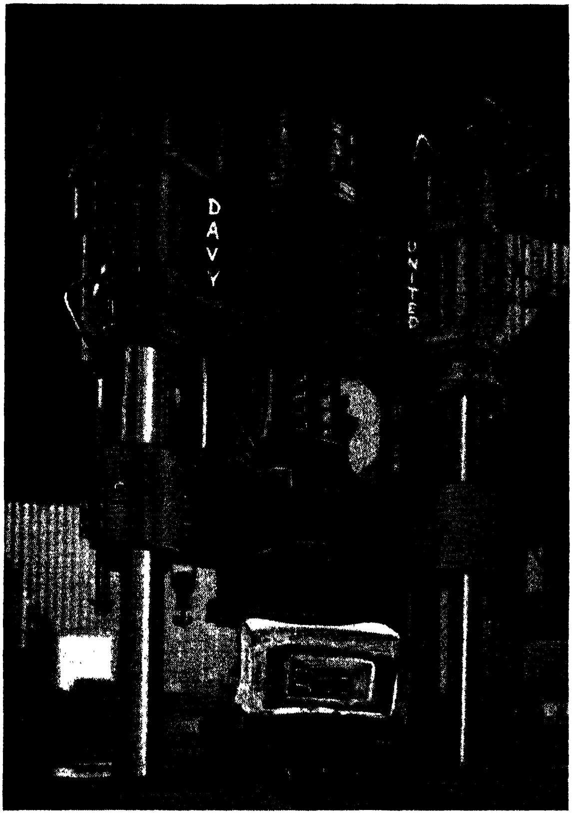


FIG. 167.—6000-ton Steam-Hydraulic Forging Press.
(*Courtesy—Davy and United Engineering Co., Ltd.*)

In order to induce the correct fibre direction in certain articles, for example, gears in which the stresses are always applied across the teeth, the operation of up-setting or up-ending is employed where the piece of steel is forged so that the main pressure is along its major axis. To do this a piece of stock bar, sufficient to make one article, is turned on end for forging so that the length is decreased and the diameter increased. The fibre will then flow radially from near the centre so that when the teeth of the gear are made, it will run from the root to the tip of every tooth, giving a gear of uniform strength. If a gear is cut from a flat bar the fibre direction will vary in each tooth, the great majority running diagonally at various angles whilst others run horizontally or longitudinally.

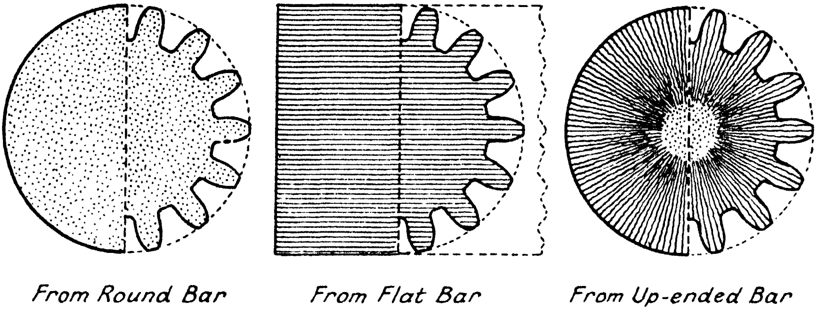


FIG. 168.—Showing fibre direction in gear blanks.

The method of up-setting is applied in forging machines where large numbers of small simple-headed articles such as bolts are produced. The stock is gripped between dies and the portion to be headed protrudes into the shaped recess of a cylindrical-shaped die. The heading tool slides forward with a powerful thrust and works the metal to the desired shape. The length of unsupported metal for heading in the die is limited in relation to the diameter of the stock if buckling is to be avoided.

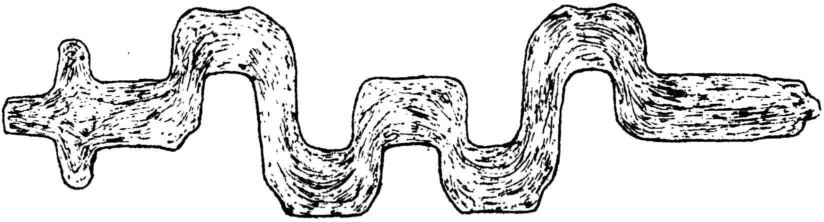
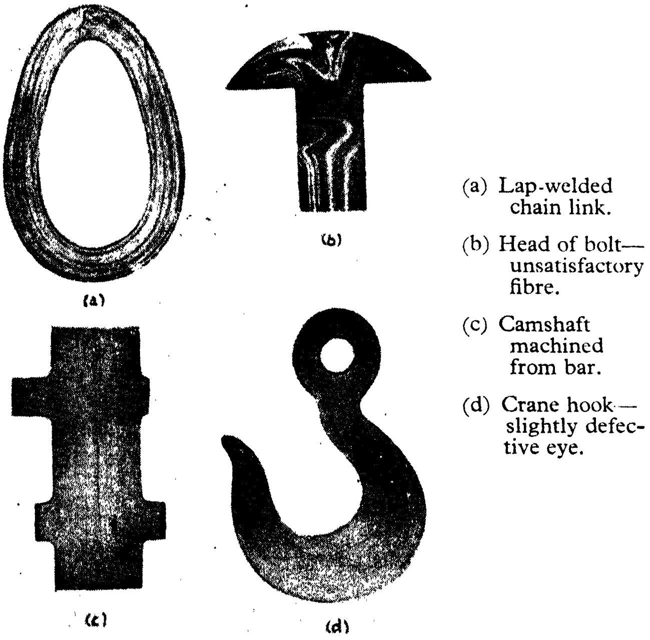


FIG. 169.—Desirable fibre direction in a drop-forged crankshaft.

Pressing. Hydraulic presses are used for the reduction of very large ingots, and for shaping marine shafts, gun barrels, hollow high-pressure boiler drums, thick armour plate, etc., by means of heavy and steady pressure. For this purpose massive presses are employed, some developing pressures up to 20,000 tons.

Before being worked the ingot is heated to the forging temperature, and then conveyed to the press. During forging the ingot is turned on chain slings driven by electric power so that the pressure is evenly applied all round.



(a) Lap-welded chain link.

(b) Head of bolt—unsatisfactory fibre.

(c) Camshaft machined from bar.

(d) Crane hook—slightly defective eye.

FIG. 170.—Fibre direction in Common Engineering Articles a, b, c, d.

For the forging of a hollow body the reheated ingot is held in a vertical position, and a hole bored in the centre by driving in and withdrawing a piercing mandrel. The ingot is then pushed over another mandrel on which it is forged out to the required sectional thickness. For the production of a large hollow body the ingot is trepanned (drilled) cold before reheating.

To increase the diameter of a hollow body, it is forged over a large mandrel placed on strong supporting trestles. During the forging, the mandrel is turned gradually so that the diameter of the work is increased and the sectional thickness decreased a little at a time.

Making steel tubes. Tubes may be produced from strips of sheet to form seam-welded tubes, or from solid stock for the production of seamless tubes.

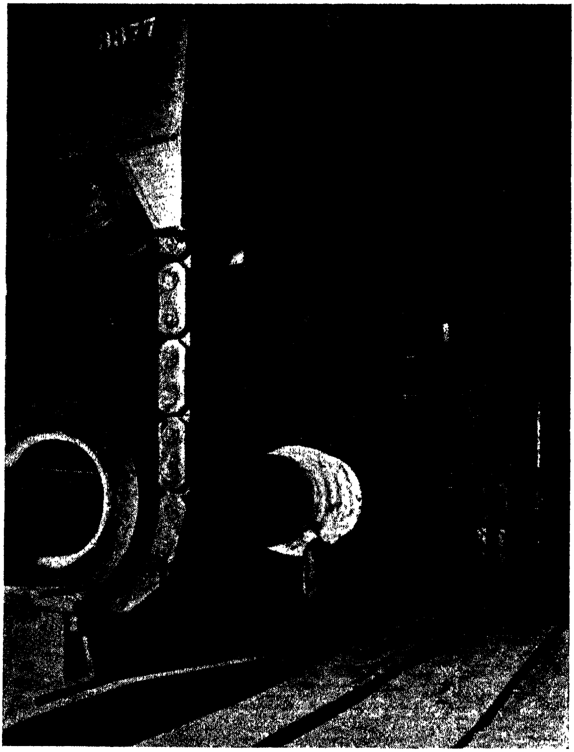


FIG. 171.—7000-ton Electro-Hydraulic Forging Press —Forging a pressure vessel for chemical plant.
(*Courtesy—English Steel Corporation, Ltd.*)

Lap-welded tubing is made from wrought iron or low carbon steel. For the production of large tubes, a long sheet of steel with a width slightly larger than the circumference of the intended tube is bent by rolls roughly to the shape of the tube with its edges overlapping. For making tubes of smaller diameter the material is brought to shape by passing through a die. The roughly shaped tube is passed at welding heat through a pair of rolls with the seam to be formed facing upwards. The shaped rolls employed join the lapped ends by pressure over a mandrel situated between the rolls and attached to a long rod. The tube is then rolled to the correct size, straightened and tested. Large tubes which would collapse of their own weight if raised as a whole to a welding heat are bent from plate in bending rolls to give a truly circular cylinder with slightly overlapping edges which are heated in short successive lengths to a welding heat and welded together by rollers applied by hydraulic pressure.

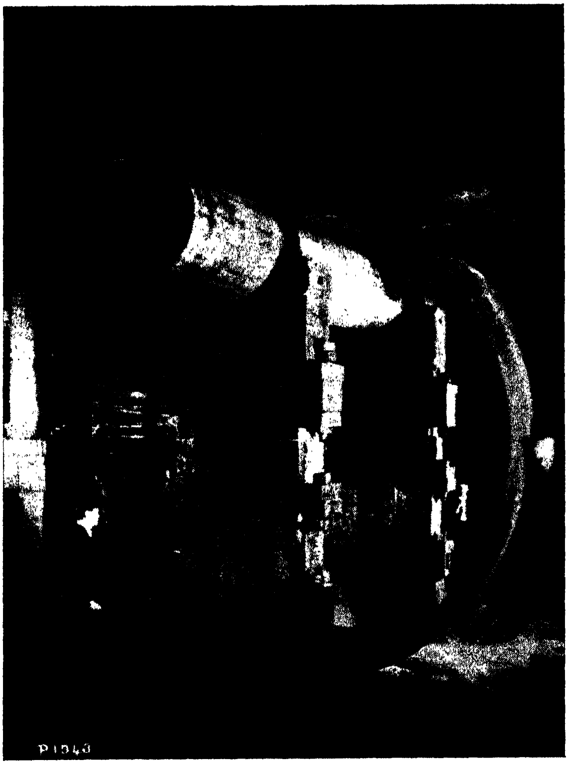


FIG. 172.—Forging a gear wheel rim from a trepanned ingot under a 7000-ton press—finished forging for pair of Gear Wheel Rims 14 ft. 3 in. diameter.

(*Courtesy—English Steel Corporation, Ltd.*)

Butt-welded tubes are inferior to lap-welded tubes and are generally made in small sizes. The steel strip of correct width is drawn at welding heat through a bell-shaped die which curls it to shape and welds the edges together by pressure without lapping. Large tubes are often bent from plate in bending rolls to give a truly circular cylinder with well-aligned edges which are then welded together by continuous seam-welding machines.

Drawn seamless tubes are produced by the push bench process which is simple in operation and high in output. A billet is punched in a hydraulic press to assume a body in the shape of a thimble or cylindrical bottle. The body is then formed into a tube by pushing it on a mandrel through a series of 7 to 11 drawing rings, rollers, or dies of gradually decreasing size. The tube is passed into a reeling and polishing mill with inclined rolls, where the applied circumferential rolling loosens the tube on the mandrel, and gives a smooth finish to both the internal

FIGS. 173–175.—Production of a Roll Lap-welded Tube.

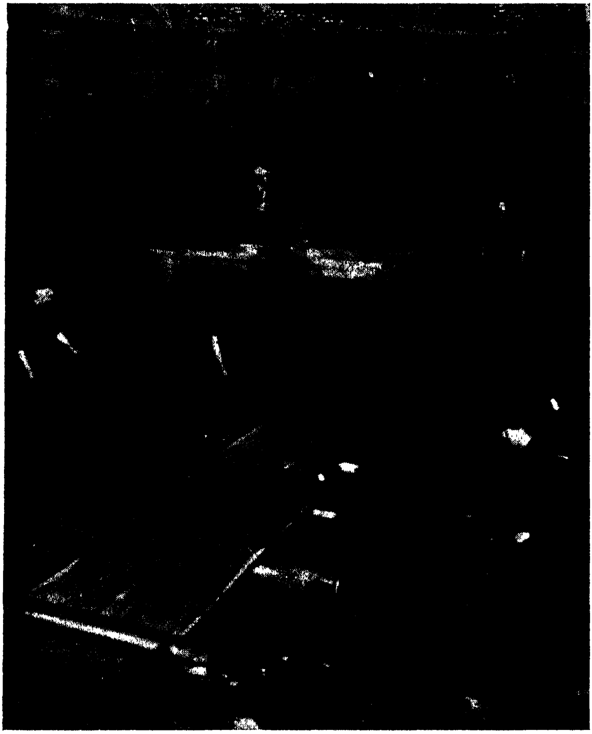


FIG. 173.—The blank sheet of steel (skelp) being turned up.

FIG. 174.—The shaped and reheated steel passing through the rolls.

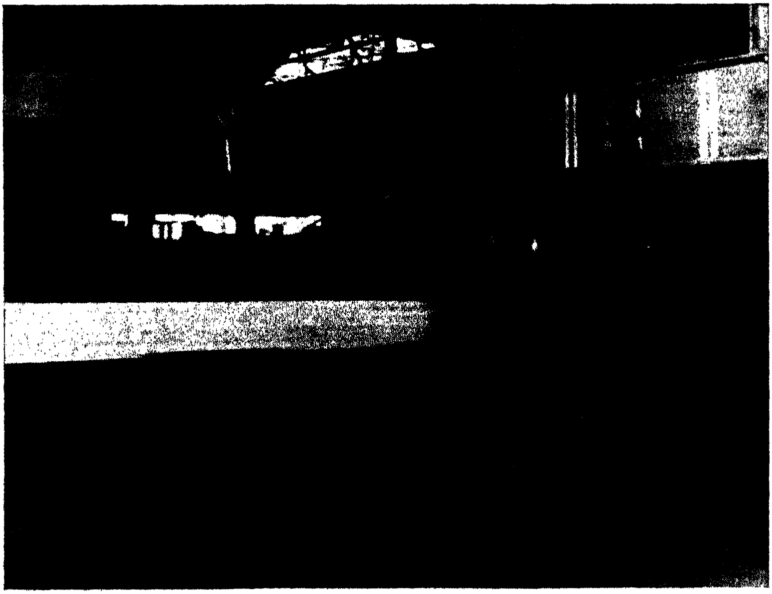


FIG. 175.—The lap-welded tube leaving the rolls.

and external surfaces. The mandrel is withdrawn, the tube is sized in a further mill, and finally both ends are trimmed.

Another method of making seamless tubes is that in which they are rolled out on the Pilger mill. The preliminary process entails the piercing of a round ingot between a pair of inclined rolls, or rolls shaped with a taper from the middle towards the edges. Correspondingly shaped guide rolls or two fixed guides hold the ingot in position, while the inclined working rolls so stretch the outside of the ingot as to produce a cavity on its axis, and this is immediately engaged by the piercing head which controls the development of the cavity so that the final hollow

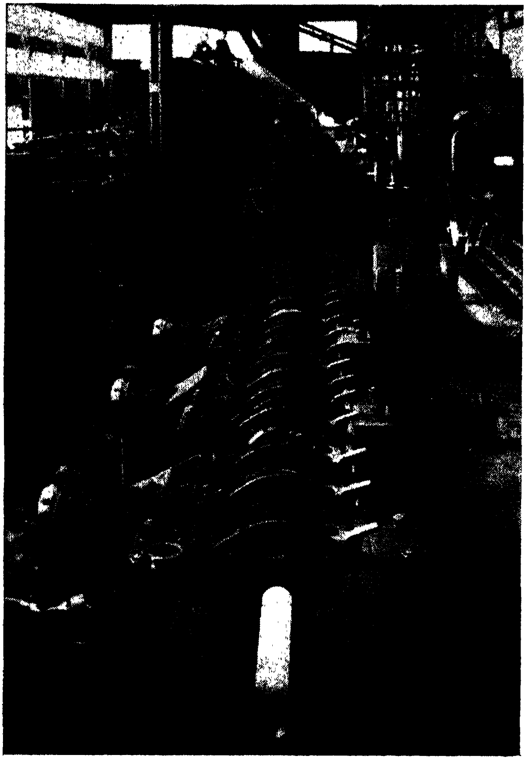


FIG. 176.—Push Bench for Seamless Tubes. The view shows the tube emerging from the series of reducing dies.

(*Courtesy—Messrs. Wellman Smith Owen Engineering Corpn., Ltd.*)

bloom has a bore approximately equal to the diameter of the head. The hollow bloom rolled out in this manner has an inside diameter of approximately the thickness of the mandrel. The thick-walled bloom is taken to the Pilger mill, threaded over and rolled on a mandrel rod between rollers with grooves of a special eccentric circumferential shape, permitting the tube to be rolled by a number of cycles which are repeated until the tube has been elongated and at the same time the wall thickness brought to the required dimensions. The tubes are finished by reheating and passing through a sizing mill where they are given the exact specified diameter, and finally through a straightening machine.

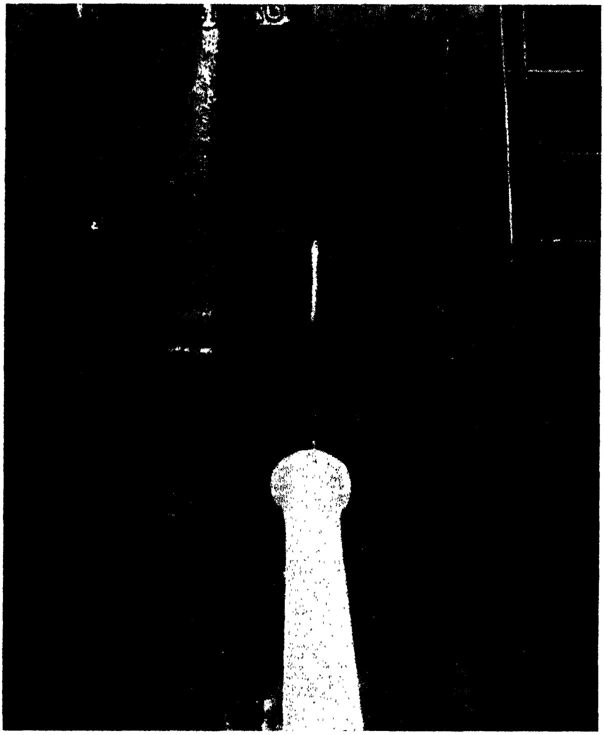


FIG. 177.—Pilger Process. View shows the tube leaving the mill. Also the rolls, and the mandrel can be seen.

Seamless tubes of small diameter are produced from larger tubes by passing through a reducing mill consisting of roll stands up to eighteen in number lying in compact formation one behind the other. In this operation the diameter of the tube is reduced whilst the wall thickness is unaffected.

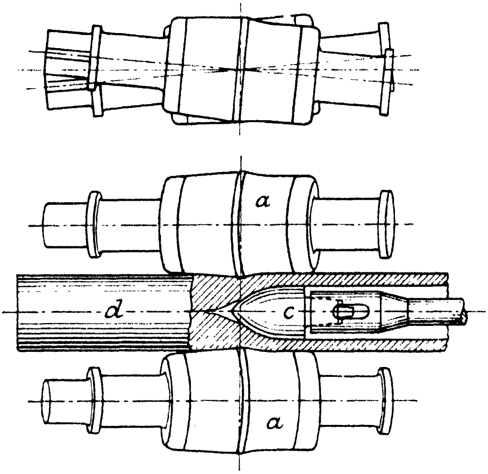


FIG. 178.—Method of piercing the ingot between inclined rolls.

COLD WORKING

Rolling strip and sheet. Greater accuracy of dimensions is obtained by cold rolling and is applied to thin sheet for motor-car body construction, and strip for making punched articles such as pen nibs, hack-saw blades, clock springs, etc.

The rough-rolled steel is first pickled in dilute hydrochloric acid or sulphuric acid to remove the scale of oxide formed during earlier hot rolling. The removal of scale is necessary to avoid rolling in and producing defective surfaces on the cold-rolled product. The scale Fe_3O_4 is not actually dissolved by the acid in the pickling process, but the penetration of the acid underneath the scale liberates hydrogen by attack on the steel. The gaseous reaction loosens and removes the scale. A small amount of organic " inhibitor " is preferably included in the pickling baths to prevent severe attack upon the steel and to minimise pitting. After pickling the work is washed in water, then in milk of lime to remove the last traces of acid, then finally machine-cleaned and dried. The pickling operations for sheets are usually performed in vats placed side by side. Strip in the form of coiled rolls is, in modern mills, pickled in continuous lines, being mechanically uncoiled at one end and recoiled at the other after passing through a battery of tanks.

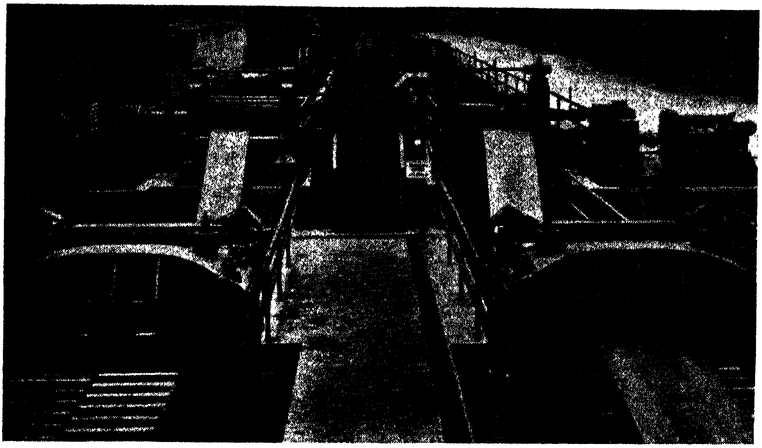


FIG. 179.—Continuous Strip Pickling Lines.
(*Courtesy—Messrs. Wellman Smith Owen Engineering Corpn., Ltd.*)

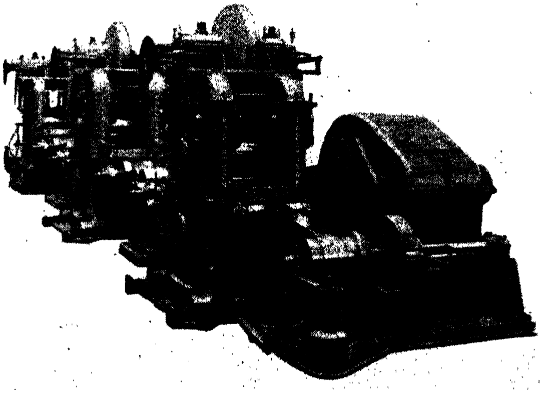


FIG. 180.—Continuous Three-Stand Four-High Rolling Strip Mill. Finishing speed 350/700 f.p.m.
(*Courtesy—Messrs. W. H. A. Robertson and Co., Ltd.*)

Because cold rolling produces hardening almost proportional to the amount of deformation, the steel must be in a soft condition prior to rolling and is therefore annealed. Softening by annealing is especially desirable when dealing with high carbon steel and alloy steel; indeed, it may be necessary to anneal alloy steels several times before the rolling is completed. Annealing is carried out in sealed boxes containing cast-iron turnings or drillings which minimises oxidation of the surface of the steel.

The rolling is performed in two high single-stand mills, four high-tandem mills, four high single-stand reversing mills, or multi-roll mills. The tandem mill has a high output, and will roll tin plate at speeds up to about 3800 ft. per minute. The two-high mill has the disadvantage that the pressure developed on the rolls causes them to deflect slightly, and for this reason there is a minimum thickness to which sheet can be rolled. The working rolls of the four-high and the multi-roll or cluster mill are supported by other rolls to prevent this deflection, and mills using as many as ten supporting rolls are used which make possible the production of strip rolled down to a thickness of $\frac{1}{100}$ mm.

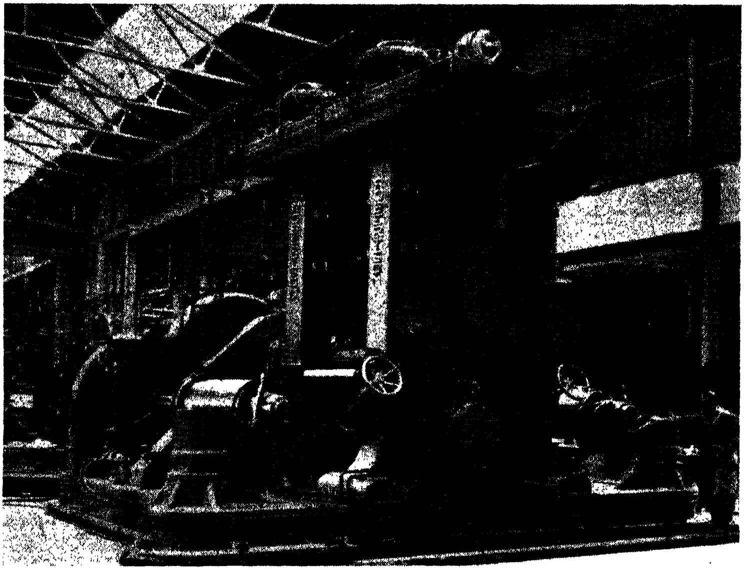


FIG. 181.—A Four-High Cold Rolling Mill for Strip.
(*Courtesy—Messrs. W. H. A. Robertson and Co., Ltd.*)

Drawing of rod. The steel for cold drawing in the form of hot-rolled bar is first pickled to remove scale. The diameter of the steel is reduced by pulling through a tapered die. The machine used for this purpose is known as a draw bench (Fig. 183). It consists of a bench along which a carriage is driven along the whole length, attached to a power-driven chain running over a sprocket wheel turned slowly by gearing. At the other end of the bench the chain passes over an idle sprocket. One end of the bar to be reduced is pointed by mechanical hammers or special forging blocks termed swages. Alternatively a pushing mechanism (pointing head) may be incorporated in the machine and which grips the bar and pushes it through the hole in the die a sufficient distance for the draw head to grip it and pull it through. The die is secured in the rigid upright stand at one end of the bench, and, as the pointed end of the bar is passed

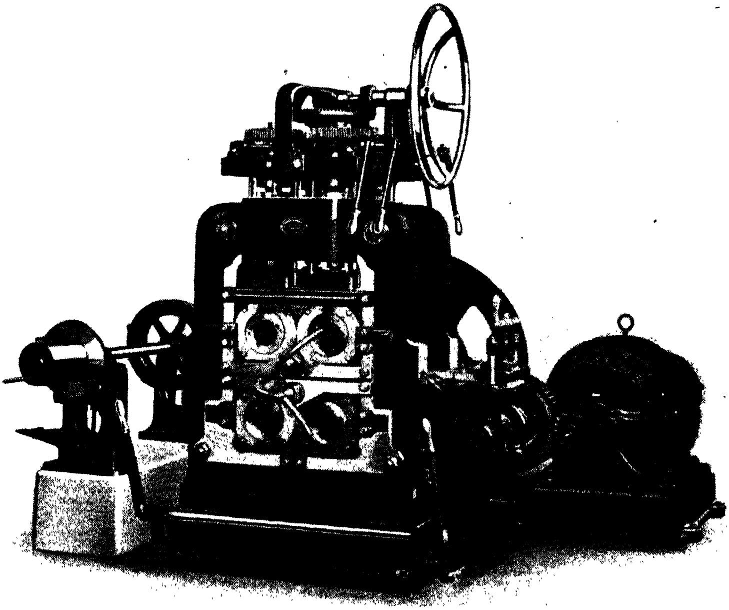


FIG. 182.—A " Cluster " Mill for Rolling Fine Gauge Strip.
Working rolls 5 in. dia. 12 in. face.
Support rolls 10 in. dia. 12 in. face.
(*Courtesy—Messrs. W. H. A. Robertson and Co., Ltd.*)

through, it is gripped by wedges in the carriage or draw head. The forward movement of the chain provides the necessary power for the pulling operation.

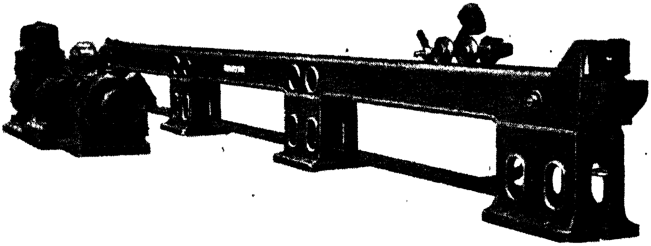


FIG. 183.—A High-Speed Drawbench.
(*Courtesy—Messrs. W. H. A. Robertson and Co., Ltd.*)

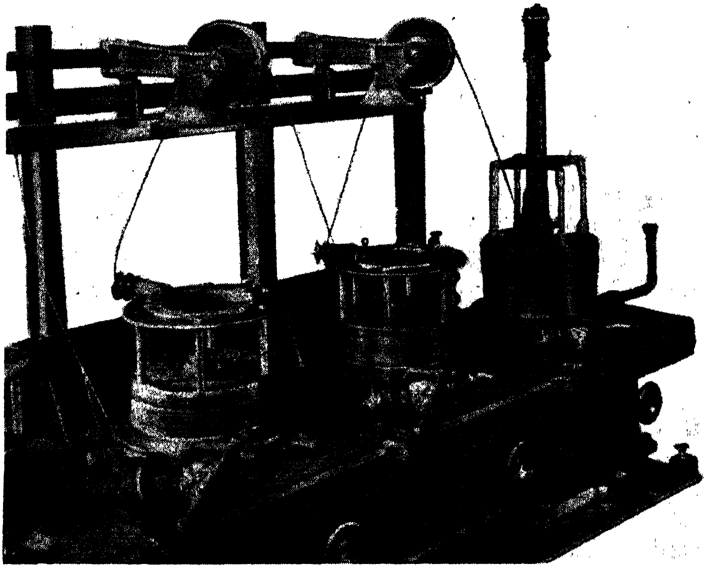


FIG. 184.—" Close-up " of a Four-Die Machine for Wire Drawing from 5 S.W.G. Hot-Rolled Steel Wire Rod.
(*Courtesy—Messrs. W. H. A. Robertson and Co., Ltd.*)

To facilitate drawing, to improve the finished surface, and minimise wear on the die a lubricant is used in the drawing operation. Usually the lime used to neutralise any residual pickling acid is allowed to remain and dry on the bar, and this is said to assist in lubrication. This film is, however, insufficient alone, and is supplemented by passing the bar through a container of grease or a jet of soluble oil.

Drawing of wire. The drawing of wire is similar in principle to the drawing of bar. The steel takes the form of a specially prepared coil wound on a drum. Good quality steel is essential, otherwise the product may be defective. The pointed end of the material is passed through the die and clamped to a power-driven drum which revolves and draws the wire through.

The most simple machines for wire drawing employ one die or draw plate possessing a number of holes of different sizes.

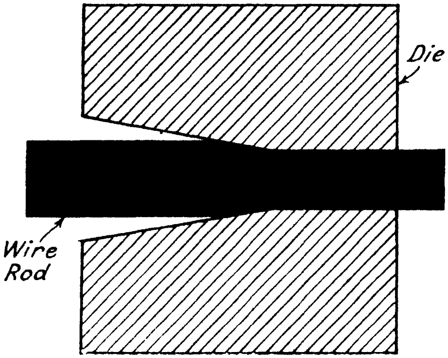


FIG. 185.—Section of Die.

Any one of these tapered holes can be used, depending upon the size of the stock and the amount of reduction required. If further reduction is necessary the wire is drawn again through a smaller die and rewound. The amount of draught may be from about 20 to 25 per cent, although the first pass is the most critical and usually involves rather a less reduction in section than subsequent passes.

The modern tendency is to use continuous wire-drawing machinery. The material is drawn simultaneously through a series of dies following one another in line. Since the strength of the wire emerging from the last die is insufficient to draw it through the complete train of holes, power-driven drums are placed between each die, the wire being wound several times round each drum. Each drum runs at a faster rate than its predecessor to take up the elongation of the wire and allow for any slipping. Although more time is taken in the initial threading up of the series of dies, the method ultimately gives greater speed and output than the single-hole process.

The drawing dies are made from wear-resisting material such as chilled cast iron, carbon tool steel, alloy steel, and more recently from tungsten carbide. The last-mentioned material possesses the advantage that, owing to its increased hardness as compared with other types, gives less friction with less power consumption, longer life and better surface finish to the wire.

The speed of wire drawing varies considerably, being controlled by the carbon content of the steel, its structural condition, original diameter and amount of draught required, but ranges from about 75 to 1500 ft. per minute. With each pass the steel becomes work hardened with increase in tensile strength, decrease in elongation and reduction of area values, and it becomes more difficult to draw. The grain size is also made smaller. Reheating at various temperatures after working results in a softening of the steel, with a regain of some ductility, and loss of strength, although reheating in the lower temperature range up to about 200°C. gives a slight increase in strength. Annealing above the critical points completely softens the steel, and when an ultimate large reduction in section is required in drawing it is often necessary to anneal at intervals, protected from oxidising influences. In many instances it is considered better to commence the drawing operation with steel of large grain size because this condition will permit a greater reduction in diameter than that of small grain size, and without detrimental effect on the properties of the wire, since the grain size is broken down during working.

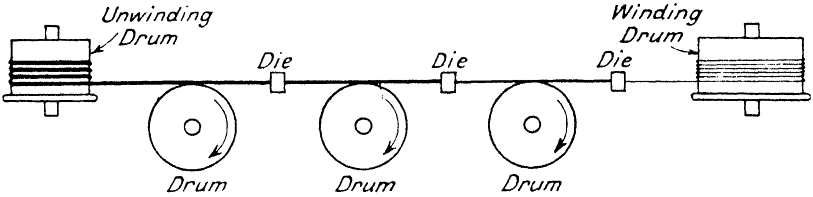


FIG. 186.—Principle of Continuous Wire Drawing.

To enable them to withstand a greater amount of cold work, the medium and high carbon steels are often heated in the region of 1000°C. and cooled in air or molten lead. By this treatment, known as " patenting," a coarse sorbitic structure is promoted, and which may be associated with well-dispersed ferrite in medium carbon steels. Steels approaching eutectoid composition are cold drawn to yield a tensile strength of 80 to 95 tons per sq. in., and these wires are used in the production of wire ropes ; whilst wires for pianos may be severely cold worked to a tensile strength of well over 100 tons per sq. in.

Cold pressing. Steel sheet is used extensively for pressing cold between dies to produce a variety of parts for automobile construction, railway work, seamless hardware, barrows, elevator buckets, and a host of other miscellaneous articles. A blank of soft sheet steel is placed on a die recessed to correspond with the shape of the article it is desired to produce. The contour of the die may be flat, conical or curved. A punch, also suitably shaped but of slightly smaller area than the recess in the die, is attached to the press, and forces the sheet into the die and causes it to flow and conform to the desired shape. A suitable lubricant is applied to prevent, as far as possible, metal-to-metal contact. The edges of the die are radiused and polished to facilitate the sliding of the sheet into it, and also to minimise scoring of the surface of the work.

The motion of the punch is controlled by machines employing a crank and connecting rod actuating a cross-head or slide ; or screw, cam, rack and pinion.

The material used should be of first-class quality to produce smooth pressings free from defects. Rolled-in scale or slag causes serious blemishes. Large crystal grain structures on the surface of the sheet, which may be due to decarburisation, or sheet with general excessive grain size, are likely to give pressings with a rough surface. The distribution of pearlite is also important, and it is desirable that it is present in an evenly distributed condition, since segregates and elongated masses running in parallel directions give loss of ductility.

During cold pressing the steel is considerably work hardened and the usual slight heterogenity of sheet steel often causes surface blemishes in the form of a linear pattern of long wedge-shaped marks due to slight variations in work hardening where these markings occur. These markings are termed " stretcher-strains " and their occurrence in practice is minimised by passing and slightly cold working the sheet through a kind of levelling machine consisting of a series of slightly staggered rollers, and then using in the press soon after this operation.

Deep drawing of steel sheet is a method of pressing, employing a draw ring through which the punch forms the steel into a variety of shapes. During drawing the shaping of the metal is accompanied by a reduction in the sectional thickness of the material owing to the space between the tools being less than the thickness of the metal entering this space.

Cold drawing of tubes. The rough tube or billet for cold drawing is prepared by a hot process, pickled to remove scale, and pointed as in the drawing of rod. Three methods of drawing the tube may be employed.

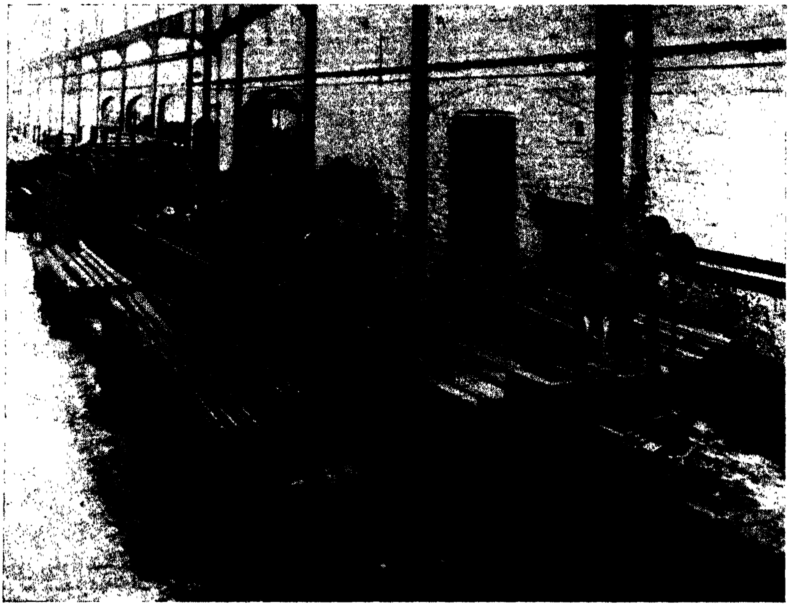


FIG. 187.—Cold Drawing of Tubes.

The first is used chiefly for thick-walled tubing, where the internal dimensions are not required to be strictly accurate, and where a smooth internal surface finish is not necessary. The rough tube is drawn through a die without the use of a mandrel.

In the second method the rough tube is drawn through the die and at the same time over a short hardened steel mandrel attached to a rod. The considerable friction set up between the tube walls, die, and mandrel, varies with the size and wall thickness of the tube, and determines the amount of reduction which can be made at each pass. The mandrel supports the walls of the tube during drawing, gives a smooth surface to the interior, and gives accurate internal diameter and wall thickness. The method is limited to the production of tubes above ¼ in. or so in diameter, since it is difficult to use a mandrel and rod of very small size.

Another method is to fix the tube over a mandrel which takes the form of a long steel rod, and draw both together through the die. The internal diameter of the tube becomes the diameter of the rod, whilst the wall thickness of the tube is reduced as both are drawn through the die. The tube is then removed from the rod by reverse rolling through grooved rolls, by circumferential or spiral rolling, or by other methods. The rolling slightly enlarges the tube to facilitate its removal from the rod.

The method is extensively employed for the making of small diameter tubes, and for thin-walled tubes of medium size where the friction encountered in the second method would cause injury.

EFFECTS OF MECHANICAL WORKING

When metal is hot worked and finished just above the critical temperature, strength and ductility is increased by reducing the size of the crystals, and the closing up and elimination of blow holes. The adhesion of the crystals is increased, for they are broken up and intimately mixed together, and also the cleavage planes are broken along which they would normally yield when stressed. The metal is therefore more dense and the specific gravity is increased. Hardness is also increased if the working is continued below the critical point, but the ductility is adversely affected.

Cold working gives greater strength, a harder material, and more accurate finish as to size than any form of hot working. It produces a very fine grain, and if cold-worked steel is annealed just below the Ac_1 point, the fine grain is retained whilst it has greater strength and ductility than hot-worked material. Cold-worked steels are subject to the phenomenon of "strain-ageing," a change in mechanical and physical properties when the steel has been allowed to stand for extended periods of time, resulting in an increase in hardness, and a loss in ductility and impact values. The brittleness so induced by " strain-ageing " can be removed by sub-critical annealing treatment.

The bright surface produced by cold working often enables steel to be used for shafting and articles for plating without preliminary machining or polishing.

CHAPTER 7

CARBON AND ALLOY STEELS

WE have, in Chapters 1 and 6, dealt briefly with the manufacture and mechanical working of steel, and it now remains to consider the principal types and properties of the many different steels available for engineering purposes. The chief characteristic which distinguishes steel from the other ferrous materials is the available combination of great strength, ductility and toughness. By the use of a considerable choice of alloying elements, different heat treatments, various forms of mechanical working, a very wide range of mechanical properties is obtained, tensile strengths ranging from about 20 tons per sq. in. for low-carbon steels, 115 tons per sq. in. for heat-treated alloy steels, and over 150 tons per sq. in. for cold-drawn high-carbon wire as used for pianos. Grades of steel are available having properties especially adapted for resistance to corrosion, abrasion, high-temperature service, and very hard heat-treated materials for use as cutting tools.

CARBON STEELS

The carbon steels, apart from the usual small amounts of normal elements, phosphorus, manganese and sulphur, contain no intentionally added alloying elements. They contain carbon ranging from 0·05 to 1·5 per cent. As the carbon content increases, the strength increases, there is an increase in yield strength but not strictly in proportion, the elongation and reduction in area decreases, and the hardness increases. The ability of the steel to harden on quenching from above the critical point becomes more pronounced with increase of carbon. In general, the impact resistance is greatest in the lower carbon steels, but it does not always follow that one which shows the best ductility on elongation and reduction in area has the best impact value, as it is dependent, to some extent, upon other factors such as general composition and physical condition. The following table gives some indication of the mechanical properties of hypo-eutectoid steels.

Carbon per cent	*Yield point tons per sq. in.*	*Tensile strength tons per sq. in.*	*Elongation per cent on 2 in.*	*Reduction of area per cent*	*Brinell hardness*
0·10	14–17	24–27	30–36	46–60	100–120
0·20	17–21	27–30	27–35	45–56	111–126
0·30	19–22	29–34	18–27	28–45	126–150
0·40	20–22	34–40	15–20	18–30	150–180
0·50	21–23	38–45	11–16	14–18	190–210
0·60	—	45–50	9–11	9–14	200–225
0·75	—	50–55	6– 9	7– 9	225–255
0·85	—	48–54	4– 6	4– 7	250–270

It is possible to assess roughly the carbon content by the microstructure of the material in the annealed condition. Very low carbon steels consist of practically all ferrite grains with a few small areas of pearlite. As the carbon content increases more pearlite becomes evident until when eutectoid composition is reached the steels are totally pearlitic. Further increases of carbon introduce increasing amounts of cementite in a matrix of pearlite.

Also the microstructure can be roughly forecast from the following simple calculations when the carbon content is known :—

Hypo-eutectoid steels.

$$\text{Per cent free ferrite} = \frac{0{\cdot}89 - \text{Carbon content}}{0{\cdot}89} \times 100$$

$$\text{Per cent pearlite} = \frac{\text{Carbon content}}{0{\cdot}89} \times 100$$

or 100—per cent free ferrite.

Hyper-eutectoid steels.

$$\text{Per cent pearlite} = \frac{6{\cdot}67 - \text{Carbon content}}{6{\cdot}67 - 0{\cdot}89} \times 100$$

$$\text{Per cent free cementite} = \frac{\text{Carbon content} - 0{\cdot}89}{6{\cdot}67 - 0{\cdot}89} \times 100$$

or 100—per cent of pearlite.

Effects of elements normally present. *Manganese* is an essential constituent of steel in the role of a deoxidiser and promotes soundness and freedom from blow holes. It combines with sulphur to form manganese sulphide. Any of the element in excess of that necessary for the purposes of deoxidation and combining with the sulphur, is mainly in solution in the ferrite and imparts to the steel a greater degree of toughness along with increased tensile strength. A proportion of the manganese combines with the carbon to form manganese carbide which becomes associated with the carbide of iron and forms part of the pearlite. This, of course, has some influence upon the composition of the eutectoid so that steels containing manganese exhibit more pearlite than those very low in manganese and of the same carbon content. Carbon steels normally contain up to 1·2 per cent manganese, and, when exceeding that amount, may be considered to be alloy steels.

Silicon is another element also always present in small amounts ranging from traces up to 0·30 per cent. It is combined with the ferrite and in these small quantities has no appreciable effect on the mechanical properties. Steel castings generally contain 0·25 per cent or more, as it has beneficial effects on the cast structure (see p. 203).

Sulphur is an unavoidable impurity, and except in special circumstances it is with benefit kept as low as possible, 0·06 per cent and below being the desired maximum in constructional steels, because it is generally injurious to the properties. When present in excess, it is liable to segregation, and tends to make the steel " hot-short " and introduces difficulties into forging, particularly when the brittle iron sulphide is present. Even when there is sufficient manganese to combine with the sulphur, it still impairs the mechanical properties, but in this respect much depends upon the amount and the manner of distribution of the manganese sulphide. Manganese sulphide is plastic at working temperatures and tends to become elongated into fibres in the direction of working in a similar manner to slag in wrought iron (Fig. 190).

Phosphorus likewise is an unavoidable impurity and is undesirable because it causes " cold-shortness " or brittleness at ordinary temperatures and is therefore detrimental in steel for cold working. It combines with iron to form iron phosphide, which, unless present in excess, is dissolved in the ferrite and cannot, when present in normal amounts, be observed in the structure. It is liable to segregation and the maximum phosphorus content in structural steels is regarded as about 0·06 per cent.

Uses of carbon steels. The steels containing up to 0·3 per cent carbon are generally known as mild steels, and included in this class are those containing less than 0·2 per cent carbon, often termed "dead mild" steels. The mild steels, whilst being lower in tensile strength than those of higher carbon content, have greater ductility, greater shock resistance, and, because they are easily rolled into all types of sections and sheets, they are used extensively in constructional work. Black mild steels are hot rolled and are covered with a thin film of oxide. Bright mild steels are cold worked and are largely free from surface oxidation.

The low carbon steel is often used for cold working in a condition known as "rimmed," this being steel which is not "killed" or deoxidised before pouring into ingots. A killed steel is one which is completely deoxidised so that when poured into ingot form, no gas is evolved on freezing and the solidification shrinkage forms a hollow and tapering pipe-like concavity, starting at the top and extending some way down the axis of the ingot. Any portion containing pipe is cut off and discarded because the cavity will not weld up during rolling. It is possible to control to some measure the extent of the pipe by suitable mould shape, feeding heads and pouring temperature.

Rimmed steel has a shell or rim of metal which freezes quickly against the ingot mould, whilst the remaining liquid metal, because it is not killed with the usually degassing agents, contains dissolved gases which are released on cooling into a number of blow holes. The gases evolved and trapped on freezing compensate for the normal shrinkage and the piping is largely eliminated. As the gases are non-oxidising, the holes are not scaled but are clean voids and in the hot rolling of the ingot they are closed and the steel is welded solid. Unlike killed steel, rimmed steel is more free from non-metallic inclusions (the products of deoxidisation) and for cold forming this is a decided advantage as surface defects are greatly minimised.

Rimmed steels are always low in carbon, contain little silicon and can often be identified from killed steel which usually has a silicon content of 0·15 per cent or more.

The following table gives some indication of the uses of steels with various carbon contents.

Carbon per cent	*Uses*
0·05–0·09	High permeability steel for electrical purposes. High conductivity wire, castings for electrical

PLATE VI.

FIG. 188.—Cast Steel 0·45 per cent carbon. × 100 Dias.

FIG. 189.—Mild Steel 0·2 per cent carbon. Cold-drawn. × 100 Dias.

FIG. 190.—Free-Cutting Steel containing approx. 0·2 per cent sulphur. Note elongated sulphide in direction of rolling.

	machinery, dynamo rotors, pole pieces, crane magnets.
0·05–0·15	Hot- and cold-rolled sheet and bars. Cold-rolled strip for tin plate. Wire, tubes, nails, rivets. Case-hardening steel for core of maximum ductility.
0·12–0·18	General purpose case-hardening steel. Boiler and ships plates.
0·15–0·20	Constructional steel in all types of rolled sections, channels, angles, etc. General engineering mild steel castings.
0·20–0·30	Shafting, connecting rods, case-hardening steel for core strength as in roller and ball bearings.
0·30–0·40	Medium strength forgings and castings. Higher strength shafting for rotors, gear wheels, etc.
0·40–0·50	High strength forgings. Axles.
0·50–0·75	Smiths' tools, hammers, die blocks, cylinder liners. Steel for surface hardening. Rails. Cast steel hammer and press tools, anvils.
0·60–0·85	Wheels for railways, tyres, cold chisels.
0·80–1·1	Vehicle and general purpose springs, ball races, woodworking tools.
1·05–1·40	Drills, cutters, taps, reamers and many other kinds of metal-cutting tools. Razors.

Carbon tool steels. Hyper-eutectoid steels are used extensively for tool steels as the high carbon content gives good hardenability when quenched. Oil quenching is mostly employed owing to the tendency of the steels to crack with the more drastic quenching in water. High manganese aggravates the cracking tendency and is usually kept below 0·5 per cent. Hyper-eutectoid steels in the cast state contain free cementite as a cellular pattern in the form of a network round the pearlite grains. This structure is destroyed by working and annealing at temperatures just above the critical point and is thereby modified to give rounded particles of cementite in a pearlite matrix, and which is the best structure for hardening.

In the hardening operation the steels are heated to above the Ac_1 point (usually 740–760°C.) and quenched. The ideal structure of the hardened steel is that showing small spherical particles of carbide in a martensite matrix, one which gives the greatest hardness, maximum toughness, and the least tendency to cracking. Cracking, distortion and decarburisation are the chief troubles encountered in hardening. To obtain the best results the steel should be uniformly heated and held at the quenching temperature just long enough for the heat to be uniformly soaked. Excessive soaking periods give rise to excessive decarburisation and scaling causing a soft outer layer, coarsening of the grain with brittleness, and some decrease in wear resistance. The coarse, brittle martensite caused by overheating may give rise to both surface and internal cracks.

The shape of the tool is important and those of intricate shape should be heated slowly through the critical range to avoid distortion. Wherever possible, sharp angles in any recesses of the tool should be avoided, as they tend to become the starting point for cracks. Cracking of high carbon steels during quenching frequently occurs where a thin section adjoins a thicker one, and water quenching should not be employed when a suitable hardness can be obtained by oil quenching. Cracking and distortion can often be minimised by filling in sharp recesses and holes with fireclay or some other refractory material.

After hardening, tool steels are usually given a low-temperature tempering treatment to relieve hardening strains, and to increase toughness. In general the longer the period at tempering temperature the greater the extent of the strain relieving, and, compatible with the desired hardness, it is better to temper for a longer time at a lower temperature than a shorter time at a higher one.

Some tools are self-tempered, when the cutting edge only is required in the hardened condition. The procedure is to plunge the cutting end into the quenching medium and move about until quite cold. It is then cleaned rapidly with emery or a soft stone in order to present a bright non-oxidised surface, then the heat from the still hot shank is allowed to flow back until the correct temper colour is obtained and finally the tool is quenched right out.

When finish-grinding a hardened tool, it should be done carefully and with light pressure, since very small surface cracks may develop which result in the chipping of the cutting surfaces in service. Also the cutting surfaces must be as smooth as possible if the maximum life is to be obtained.

Free-cutting steels. Low carbon steels tend to tear and machine with a rough surface at high speeds and it is generally difficult to obtain clean, fine threads on threaded articles. The machining properties of mild steel can be improved by normalising or other heat treatment to increase the hardness. The machineability of dead mild steels is improved by the introduction of elements or inclusions to cause brittle and smooth chips and yet at the same time not to have too abrasive an action on the tools. Manganese contents up to 1·2 per cent effect considerable improvement, and phosphorus and sulphur contents up to 0·15 per cent have been allowed in free-cutting bars for machining, but owing to the excessive embrittling effects of phosphorus on steel, sulphur is now the chief element employed. British standard specifications for free-cutting steels specify between 0·2 and 0·3 per cent sulphur. The sulphide particles are not particularly hard, and when evenly distributed they do not unduly wear the cutting edge of the tool. The free-cutting steels are used for threaded and smoothly machined parts not to be used for severe service. They may be used for certain case-hardening applications, but their main use is as general screw stock for nuts and bolts and for machining in automatic machines.

In recent years, the use of lead has been developed in the production of free-machining steels. Those containing up to 0·2 per cent carbon may be lead bearing and contain from 0·15 to 0·35 per cent lead. It acts in a similar manner to sulphur, but it has the advantage that it is in a very fine state of dispersion, the lead-bearing particles are ultra-microscopic and its deleterious effects on the mechanical properties of the steel are consequently less.

ALLOY STEELS

Many alloying elements are added to steel. Some may contain a single alloying element, some two and others three or more to form rather complex materials. The alloys may be in the form of solid solutions with the iron, and usually combined with some of the carbon to form carbides.

General effects of alloying elements in steel. Since the alloying element combines with the carbon to form carbides, and sometimes to form double carbides of the alloying element and iron, the quantity of carbon required to form pearlite is generally less in alloy steels. For instance, a slowly cooled steel containing about 1·4 per cent chromium and 0·7 per cent carbon would be pearlitic in structure.

The temperature of the critical change points are affected, so that the heat-treatment temperatures are often different from those of carbon steels.

Alloying elements obstruct or retard the austenite-pearlite change on cooling, thus causing a lowering of the A*r* critical range. As a result, alloy materials are more easily hardened and often permit of a lower quenching temperature than is required for carbon steels. The uneven hardness found in articles of heavy section, due to the effects of mass, is minimised, and leads to greater uniformity of structure throughout.

The lowering of the critical points and the retarded transformation period allow martensitic structures to be obtained by milder forms of quenching such as in oil or even by cooling in air.

Some steels containing large proportions of alloying elements may have their A*r* points so depressed that they are obtained in the austenitic condition at ordinary temperatures. Steels of this type are known as austenitic, and have the property of being highly resistant to corrosion and/or abrasion.

Chromium steels. Chromium as an alloying element is often used in conjunction with other elements, but there are many instances where the use of a simple chromium steel offers distinct advantages over plain carbon steels. Chromium alloys readily with iron and will combine with the carbide of iron to form double carbides of iron and chromium, which are hard and promote wear resistance. They are also stable under the influence of heat. With a similar carbon content steels containing chromium are more pearlitic than non-alloy steels ; they are harder, and have increased yield point and tensile strength, generally at some expense of ductility, although small quantities up to 1 per cent of the element increase the tensile strength noticeably, with little loss of ductility. Steels containing 0·30 to 0·45 carbon with these lower chromium contents are used for axles, crankshafts, gears, connecting rods and other machinery parts.

The element raises the critical points on heating, but when rapidly cooled they are depressed, and because the transformation of the austenite is retarded, the heat-treated chromium steels are harder than carbon steels, and accompanied by a greater depth of hardening. They are normally fine grained but are subject to rapid grain growth when overheated, or when held for extended periods at heat-treatment temperatures.

Steels containing 1·2 to 1·6 per cent chromium and carbon in the order of 1 per cent are used where resistance to wear by attrition is desirable, and they find application for ball bearings and parts for grinding mills.

Nickel steels. Nickel when added to steel enters principally into solution in the ferrite. The range of nickel varies in the low nickel steels from 0·5 to 5·0 per cent. In medium and low carbon steels it tends to produce a fine-grained ferritic structure and has also some influence in refining the pearlite, increasing strength and toughness without decreasing ductility. Hardness is also increased to a lesser degree. The 3·0 to 3·5 per cent nickel steels are the most common, having a carbon range of 0·2 to 0·5. Since there is a tendency for nickel to graphitise the carbide when the steel is heated, 0·75 to 0·90 per cent manganese is usually present to render the carbide more stable. These steels have a good resistance to fatigue. Nickel lowers the critical points with increasing nickel contents. Grain growth at heat-treatment temperature is less than with carbon steels and consequently overheating is not so harmful. To obtain the greatest hardening effects they are heated well above the critical point, but since the temperature of the critical points is lowered by the element the heat-treatment temperatures are similar to those of carbon steels of equal carbon contents.

The amount by which the critical points are lowered depends upon the percentage of nickel present. With 10 per cent of the element they are depressed to such an extent that the structure is martensitic with normal cooling regardless of the carbon content, whilst above 25 per cent nickel the structure is austenitic.

The effects of oil hardening and tempering on $1\frac{1}{8}$ in. diameter steels with similar carbon contents but with various percentages

	Per cent carbon	*Per cent nickel*	*Tempering temperature*	*Yield point tons per sq. in.*	*Max. stress tons per sq. in.*	*Elongation per cent on 2 in.*	*Reduction of area per cent*	*Izod impact ft. lb.*
Carbon steel . .	0·39	—	585°C.	32·6	47·1	25·0	63	46
0·5 per cent nickel steel	0·41	0·51	600°C.	35·1	50·1	23·0	57	43
1·0 „ „ „	0·41	0·86	600°C.	40·0	52·6	22·5	59	56
3·0 „ „ „	0·42	3·02	600°C.	54·7	60·6	19·5	57	57
3·5 „ „ „	0·43	3·38	600°C.	55·9	61·9	21·0	60	64

of nickel is well illustrated by the figures, due to Jones,[1] given in the table on the previous page.

Nickel steels are used for structural purposes, drop forgings, axles, shafting, gears, pinions, castings and forgings for locomotives and automobiles.

Those of 25 to 30 per cent nickel content are austenitic even when slowly cooled, are non-magnetic, have low coefficient of expansion, and are resistant to corrosion especially by sea water. They often contain a little chromium and 1 per cent or more of manganese. Their properties make them suitable for such applications as turbine blades, gas engine valves and magneto spindles.

Nickel lowers the coefficient of expansion of steel as the nickel content increases until when about 35 to 36 per cent of the element is present, it is negligible. An alloy of this composition is known as Invar, which, after ageing, remains constant in length at varying temperatures and is therefore very usefully employed for standard measuring tapes, pendulums, and scientific instruments.

Permalloy, an alloy with very high magnetic permeability in weak magnetic fields, contains 78·5 per cent nickel with the remainder essentially iron. It is used extensively in telephony and telegraphy engineering, including submarine cables.

Nickel-chromium steels. By the introduction of the two elements nickel and chromium together, their combined effects produce a class of steel of great importance for general engineering work. These steels are very adaptable to heat treatment, and the possible variation of the percentage of the two elements, along with different heat treatments, give a very wide range of mechanical properties. Nickel-chromium steels are tough, strong and hard. The solution of the nickel in the ferrite provides the toughness, the chromium carbide the hardness, whilst both together increase the strength. The ductility and shock resistance promoted by the nickel is retained whilst the chromium increases resistance to abrasion. The grain-growing tendency during heat treatment usually found in steels containing chromium as a single alloying element is counteracted by the nickel.

The steels vary in composition between 1 and 4·5 per cent nickel, 0·5 to 1·5 per cent chromium, and 0·25 to 0·55 per cent

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[1] *Iron and Steel Industry*, December, 1936.

carbon. The proportion of nickel to chromium is usually between five and two to one.

Steel for forgings contains about 0·3 per cent carbon, 1·0 to 3·5 per cent nickel, and 0·5 to 1·0 per cent chromium. Those containing more than 1·0 per cent chromium are not so easily worked.

The steels are heat treated by quenching from 850°C. when they contain 1·0 per cent nickel, to 820°C. when containing 3·5 per cent. For engineering parts which are to be machined tempering temperatures range between 500 and 680°C. Gears and parts for hard wear are tempered at about 250°C.

Nickel-chromium steels suffer from " temper-brittleness " when cooled slowly or in air from the higher tempering temperatures or when they are tempered in the range of 250 to 400°C. This brittleness is not revealed in the elongation or reduction of area values, but it has a serious effect upon the impact value. Normally the impact value rises steadily when a hardened steel is tempered at increasing temperatures, but in the case of the nickel-chromium steels there is a reduction of impact resistance in the above temperature range reaching a minimum value at about 350°C., after which it increases again. The steels are therefore not tempered in this temperature range. When cooling from higher tempering temperatures this type of brittleness is largely obviated by quenching in water or oil, or by the introduction of 0·2 to 0·7 per cent of molybdenum.

The following mechanical properties are obtained in some nickel-chromium steels, oil hardened and tempered at about 600°C.

Per cent carbon	*Per cent nickel*	*Per cent chromium*	*Per cent manganese*	*Yield point tons per sq. in.*	*Max. stress tons per sq. in.*	*Elongation per cent*	*Reduction of area per cent*	*Izod impact ft. lb.*
0·35	1·50	0·75	0·50	42	50	24	64	76
0·30	3·08	0·80	0·60	53	59	22	59	66
0·35	3·50	0·75	0·55	56	62	21	58	63

The nickel-chromium type are used for all kinds of engineering forgings, stampings, and castings for automobiles and general machinery parts, including crankshafts, axles, connecting rods, gears, etc. Those containing the lower percentages of nickel and chromium find some application as constructional steels.

Air-hardening steels. These are martensitic when cooled in air and give a Brinell hardness of 500 or more. They contain 0·35 per cent carbon, 4·0 to 4·5 per cent nickel, 1·0 to 1·5 per cent chromium, and often molybdenum in quantities up to 0·65 per cent. The air-hardening property depends upon the depression of the A*r* critical point which becomes lower as the initial temperature from which the steel is cooled is increased, but generally 820–840°C. is the heating range employed. The A*r* critical point is then about 400°C.

Hardening by air cooling has the advantage that a minimum of distortion takes place which allows the bulk of the machining to be carried out before hardening. The effect of mass is very small, and the hardness and structure is uniform throughout the section. Mechanical properties in the air-cooled condition are in the order of 115 tons per sq. in. tensile strength, 90 tons per sq. in. yield point, 10 per cent elongation, and an Izod impact of 15 to 30.

The steels are used in the form of forgings and drop forgings, gears, pins, and other machinery parts demanding high strength and resistance to abrasion.

Molybdenum steels. The addition of molybdenum to carbon steel has a considerable effect on the mechanical properties and even in small amounts increases the hardness on quenching. It raises the yield point, tensile strength and gives greater resistance to shock. Its beneficial effects are most pronounced when it is used in conjunction with other elements.

The development of the use of molybdenum as an alloying element has been very marked in recent years, since it is found that the amounts of molybdenum required in combination with other elements is of the comparatively low figure of 0·25 to 1·0 per cent, and at the same time the amounts of other alloying elements may also be low. Molybdenum-bearing steels are therefore capable of being used as substitutes for those containing considerable proportions of other elements, notably nickel.

The molybdenum-bearing steels have great toughness and the property of hardening to greater depths than many other alloy steels. Molybdenum confers an improved creep resistance at moderately elevated temperatures, and chromium-molybdenum steels in particular find application in high-temperature steam service where such steels are free from embrittlement after prolonged exposure to service conditions.

Below are given some common combinations of molybdenum with other alloys in steel along with representative approximate compositions and mechanical properties after hardening and tempering at about 600°C.

Type	*Approximate composition*	*Yield point tons per sq. in.*	*Max. stress tons per sq. in.*	*Elongation per cent*	*Izod impact ft. lb.*
Chromium-molybdenum	C 0·35, Cr 1·0, Mo 0·35	60	65	19	50
Manganese-molybdenum	C 0·35, Mn 1·4, Mo 0·35	54	63	21	65
Nickel-chromium-molybdenum	C 0·35, Ni 1·4, Cr 1·0, Mo 0·3	50	60	19	55

Molybdenum is sometimes used along with a small percentage of nickel because these steels, like the chromium-molybdenum type, retain their strengths well at moderately high temperatures.

The manganese-molybdenum variety are lower in cost and, in addition to their generally good mechanical properties, are especially characterised by excellent fatigue and shock resistance.

The nickel-chromium-molybdenum steels are used for similar purposes to the nickel-chromium type, and they give a very wide range of mechanical properties by various heat treatments and are used for machinery parts working under severe conditions of stress combined with shock. They are eminently suitable for parts of tractors and excavating machinery.

Manganese steels. There are two types of manganese steel in commercial use, the pearlitic and the austenitic.

The former contains 1·3 to 1·8 per cent manganese and up to 0·45 per cent carbon. One containing 1·5 per cent manganese and 0·25 per cent carbon has a similar tensile strength to a 0·40 per cent carbon steel. The reduced carbon content gives a marked increase in toughness. A 1·5 per cent manganese steel with 0·45 per cent carbon is harder and stronger and still possesses a considerable degree of toughness. The pearlitic manganese type are more free machining than the lower manganese mild steels.

Manganese lowers the critical A*r* point and in the pearlitic steels markedly improves the mechanical properties of hardened and tempered steel. In the fully tempered condition they have great resistance to shock and it is not uncommon to find the Izod impact figure in the order of 90 to 100 ft. lb. As they readily respond to heat treatment, a milder form of quenching is employed. Those containing about 0·8 per cent carbon and 1 to 2 per cent manganese are largely non-shrinking after heat treatment, are more true to size after treatment than carbon steels, there is less danger of warping and of cracking, and steels of this type are suitable for gauges and precision cutting tools.

When the manganese content reaches 10 per cent or more, the critical points are so depressed that the structure is austenitic at ordinary temperatures. The steels of this class are the most important of the manganese steels, and usually contain 12 to 13 per cent manganese, 0·3 to 0·5 per cent silicon, and 1 to 1·25 per cent carbon. They are non-magnetic, fairly soft in that they can be dented by a blow from a hammer or chisel, but have the peculiar property that they are most difficult to file or machine. The Brinell hardness number ranges from about 200 to 240. The comparative softness is due to the austenitic condition, but the local surface working caused by the action of a file or cutting tool is sufficient to convert the surface to hard martensite. The material is therefore highly resistant to abrasion. It can be hot worked by forging and rolling. Owing to the machining difficulties, parts in manganese steel are used in the form of forgings and castings and finishing is carried out by grinding.

In the cast condition austenitic manganese steel is rather brittle, due to some segregation of hard carbides of manganese and iron at the austenite grain boundaries. It is never annealed since it is then very brittle. The best mechanical properties are obtained by heating to 1000°C. and quenching in water, which has the effect of taking the carbides into solution during heating and the rapid cooling prevents their re-separation. Steel in the water-toughened condition will give a tensile strength of 55 to 60 tons per sq. in., 35 to 40 per cent elongation and a Brinell hardness of about 200.

The good combination of mechanical properties and the resistance of the steel to wear by abrasive and pounding actions makes it especially suitable for use in dredger buckets, grinding plates, jaws for crushing machinery, railway curves and points, mining machinery, conveyor parts, gears, etc. Its resistance to machining accounts for its use in vaults and safes because it cannot easily be drilled.

Vanadium steels. Plain vanadium steels are used only to a very limited extent in constructional work. Vanadium helps in producing a clean steel on account of its deoxidising action, and dissolves both in the ferrite and the pearlite. Its most marked beneficial effect is found when alloyed with other elements such as chromium, nickel and manganese.

Chromium-vanadium steels give high elastic limit with good ductility, shock and fatigue resistance. They are readily heat treated. Those containing 1·0 per cent chromium, 0·15 per cent vanadium, and 0·5 per cent carbon are used as spring steels. With a slightly lower carbon and slightly higher chromium content the material is suitable for valve springs.

Silicon steels. Silicon dissolves readily in the ferrite of steel and is always found in castings, generally between 0·20 and 0·5 per cent, since it is used for deoxidation purposes and the excess has the effect of refining the weak, coarse and brittle Widmanstätten structure typical of cast steel. The element is sometimes added in greater quantities than the above for strengthening purposes, but usually in conjunction with other alloying elements.

The silicon-manganese steels find use in the manufacture of leaf and coil springs, because the two elements together give toughness and resistance to fatigue. These properties are retained at moderately elevated temperatures. Silicon raises the critical points and gives rise to tendencies towards grain growth. The heat treatment is carefully carried out at temperatures approaching 900°C., quenched in water or oil and tempered to give a Brinell number between 350 and 430. The composition varies between 0·35 and 0·60 per cent carbon, 1·5 to 2·0 per cent silicon and 0·7 to 1·0 per cent manganese, the lower carbon steels being used for water hardening and the higher carbon steels for oil hardening.

Tungsten steels. Tungsten occurs as the simple carbide WC, tungstide of iron Fe_2W, or as a double carbide of iron and tungsten. The constitution of the steels depends upon the amount of carbon present in addition to the amount of tungsten. Tungsten increases the strength, hardness and the hardening power when the steels are quenched. With low carbon contents they are pearlitic and those with 0·45 per cent carbon and 0·6 per cent tungsten have been successfully used for springs. When the tungsten is high the double carbide appears and the hardness and brittleness of the steel is greatly increased.

Steels containing 1·0 to 1·2 per cent carbon, and 1·0 to 2·0 per cent tungsten, are used for cutting tools and are hardened by water or oil quenching.

Tungsten raises the critical points and, for hardening, the steels are heated to well above the temperatures used for carbon steel of corresponding carbon contents. On cooling, the critical transformations are so sluggish that the austenite to pearlite transitional changes are largely obstructed, giving rise to pronounced air-hardening tendencies. The tungsten steels are less affected by decarburisation during hardening and working than carbon steels and are less affected by incorrect heat treatment. The martensite in a hardened tungsten steel breaks down at a higher reheating temperature than other steels, thus increasing the usefulness of the material in cutting operations at elevated temperatures.

" Mushet " steel, produced many years ago by an investigator of the same name, was the first to give high hardness values by air cooling. It contained about 2 per cent carbon, 2 per cent manganese and 7 per cent tungsten. It gave good service when employed in cutting tools working at high speeds and at elevated temperatures and eventually led to the development of the modern high-speed steels. A steel of similar composition but of a lower manganese content is still used for certain drawing dies. To produce effective hardening, steels of the high carbon and high tungsten type are cooled from about 1000°C.

One with approximately 6 per cent tungsten and 0·65 per cent carbon has good magnetic properties, and in the hardened condition is used for permanent magnets.

Cobalt steels. Between 5 to 15 per cent of cobalt added to a 1 per cent carbon steel gives a magnet steel which is superior in magnetic properties to the tungsten type. The cobalt forms carbides with the carbon which are rendered more stable by the inclusion of a fair proportion of chromium. Some magnet steels contain both cobalt and tungsten.

Cobalt is also used in the "super" type of high-speed steel.

Alloy case-hardening steels. *Nickel* is alloyed with steel for case-hardening purposes in the range of 3 to 5·5 per cent. It tends to decrease the rate of diffusion of the carbon during carburising, so that rather longer periods of contact with the carburising medium are given as compared with carbon steels to obtain a similar depth of case, but this may be counteracted to some extent because higher carburising temperatures can be applied with less harmful effects. The restraining influence of the nickel on grain growth is advantageous since a much finer-grained core is obtained. The core is tougher and stronger than that obtained with a carbon steel. The lowering of the critical temperatures and the critical hardening speeds allows a milder form of quenching, thus reducing the amount of distortion. Nickel case-hardening steels are used for machinery parts such as ball and roller bearings, owing to their good strength, toughness and resistance to wear when under compression and rolling actions. The core strength ranges from about 45 to 55 tons per sq. in.

Nickel is sometimes partly substituted by molybdenum, giving a composition of 1·5 to 2·0 per cent nickel and 0·2 to 0·3 per cent molybdenum.

Nickel-chromium. Chromium increases the strength of the core and counteracts any graphitising tendency of the nickel during case-hardening treatments. A very strong case is obtained and the ductility and shock resistance are not materially reduced. The greatest advantage of nickel-chromium steels is that a case of increased hardness and wear resistance is obtained, and consequently a less deep case may be employed for many purposes. The composition ranges from 0·08 to 0·2 per cent carbon, 3·0 to 4·5 per cent nickel, 0·6 to 1·4 per cent chromium, and 0·3 to 0·5 per cent manganese. They consist of two main types, the 3 per cent nickel and the 4½ per cent nickel, giving a core strength of between 55 and 85 tons per sq. in. The lower chromium contents of the above range are usually associated with the lower nickel contents.

Molybdenum is often present in the 4½ per cent nickel type in the order of 0·15 to 0·35 per cent. These steels are useful for parts of heavy and varied section and where conditions of stress are combined with shock as in gears for severe duty. The core is of uniform structure, strong, tough and hard.

The following are the carburising and heat-treatment temperatures usually applied to the chief types of nickel and nickel-chromium steels.

Type	*Carburise at °C.*	*1st Heat treatment*		*2nd Heat treatment*	
		Temperature °C.	*Air-cool, oil or water quench*	*Temperature °C.*	*Air-cool, oil or water quench*
3 per cent nickel	900–950	860–880	Air, oil or water	760–780	Water or oil
5 per cent nickel	880–930	830–870	"	740–780	Oil
Nickel - chromium (3 per cent Ni)	900–950	860–880	"	760–780	Water or oil
Nickel - chromium (4½ per cent Ni)	880–930	830–870	Air or oil	760–780	Oil

Nickel-chromium steels are usually given a final tempering at a temperature of 200°C. to relieve hardening strains.

Nitralloy steels are a class of steels which are used in connection with "nitriding" or nitrogen case hardening. They are rather complex in composition and contain essentially chromium, aluminium and molybdenum. The carbon content is rather higher as compared with the ordinary case-hardening type.

The steel is, before nitriding treatment, quenched from about 900°C. and tempered at 600°C. to promote a sorbitic structure which remains the core structure since the interior is unaffected by the treatment. The parts to be case hardened are machined, and all traces of oil and grease removed. They are then placed in a gas-tight box made of non-scaling alloy steel unaffected by ammonia, and which is provided with inlet and outlet tubes through which ammonia gas is passed from cylinders. Small parts are placed in layers separated by nickel wire-netting to allow free circulation of the gas. The box is introduced into an electric furnace heated uniformly to 500°C. A stream of ammonia flows through the box and, in contact with the steel, splits up into nitrogen and hydrogen. The nitrogen thus freed is very active and penetrates the surface of the steel to form hard nitrides chiefly with the aluminium. Chromium contributes to the hardness to a certain extent and also tends to flatten out the steep hardness gradient below the surface and reduces the risk of spalling. Molybdenum gives good mechanical properties to the core by its refining action.

The case is comparatively shallow—about 0·5 mm. for a 40-hour soaking period, up to about 0·85 mm. for a 100-hour soaking period. It is, however, extremely hard and often exceeds 1050 Vickers hardness, and it exhibits a needle-like structure similar to coarse martensite.

The advantages of nitrogen case hardening as compared with the carburising methods are that the increased hardness of the case give a greater reduction of wear. The hardness is retained on heating to 500°C. There is no scaling, very little warping or distortion, since the temperature employed is low and the steel is not quenched after nitrogen treatment. Nitrided steel is free from internal stresses. Parts may be finish machined before treatment with an allowance for a very small amount of growth. The process is simple and clean.

The disadvantages are that there is not the depth of semi-hard material which is present in ordinary case-hardened steel between the case and core, that is to say, the hardness gradient from case to core is steep. The material is more expensive, but the low-labour costs make the process cheaper when treating numbers of small parts, but for larger articles it is much more expensive.

Certain chromium-molybdenum steels are suitable for nitriding when only a moderately hard case of 900 Vickers is required.

The following are typical compositions for nitriding :—

Type	*C per cent*	*Si per cent*	*Mn per cent*	*Cr per cent*	*Al per cent*	*Mo per cent*	*Ni per cent*
Chromium - aluminium - molybdenum	0·40	0·25	0·5	1·7	1·1	0·2	0·3
Chromium-molybdenum	0·30	0·25	0·5	3·0	—	0·5	0·1

High-speed steels. High-speed steels are rather complex in composition and contain at least three alloying elements, the chief one being tungsten. There are roughly three types—the

14 per cent tungsten, the 18 per cent tungsten, and the 18 per cent tungsten which also contains cobalt and is usually known as " super " high-speed steel, owing to its suitability for particularly heavy duty. The first two are usually hardened by oil quenching, but the " super " steel is air hardening and can be suitably hardened by cooling in air blast. The tools made from high-speed steels are capable of retaining a sharp cutting edge and giving long life at high speeds and elevated temperatures. The compositions of the three types are :—

	C *per cent*	*Si* *per cent*	*Mn* *per cent*	*W* *per cent*	*Cr* *per cent*	*V* *per cent*	*Co* *per cent*
14 per cent tungsten —14/4/1	0·6 –0·7	0·2–0·3	0·15–0·3	13–15	4–4·5	0·5–1·0	—
18 per cent tungsten —18/4/1	0·65–0·8	0·2–0·3	0·1 –0·2	18–20	,,	1·0	—
Cobalt— " super "	,,	0·2–0·35	,,	,,	,,	,,	4·6

To produce a tool, the material must be easily machineable, and to render it suitable for this purpose it is annealed in a non-oxidising atmosphere at about 850°C. and, on account of its air-hardening tendencies, slowly cooled.

The chief essential requirements in high-speed steel are hardness, resistance to wear, red hardness and a certain amount of toughness. The hardness is promoted by the solution of sufficient carbide to give martensite when quenched, and the presence of chromium and cobalt assist in this direction. The resistance to wear is provided by the remaining carbide particles which are out of solution, the chief element contributing towards this property being tungsten, which produces an extremely hard and wear-resisting form of carbide. The carbides are present in the microstructure as bright rounded particles. The red hardness is governed by the resistance of the material to a tempering or softening action because the breakdown of the martensite takes place at higher temperatures than those met with under working conditions. Toughness is controlled by several factors such as

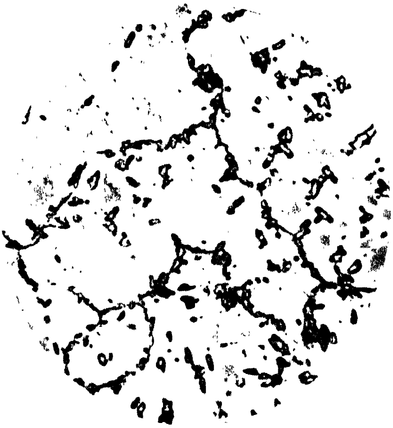


FIG. 191.—Austenitic Manganese Steel. As Cast. × 50 Dias.

The microstructure consists of a matrix of austenite with granules of pearlite-carbide constituent distributed at the austenite grain boundaries and interdendritically. Ghosts of the dendritic structure are visible on the austenite grains.

FIG. 192.—Austenitic Manganese Steel. Water toughened. × 30 Dias.

The microstructure consists wholly of austenite grains. The grains colour differentially on etching and also show ghosts of the dendritic structure.

FIG. 193.—Austenitic Manganese Steel. Hardened by cold working. × 30 Dias.

(*Figs.* 191–193 *kindly supplied by Messrs. Hadfields, Ltd.*)

This photomicro illustrates the microstructure at and immediately below the working surface of a crusher jaw after service.

Comparison with the structure of the unworked steel illustrated in Fig. 192 shows that the cold working has resulted in a slight deformation of the austenite grains situated on the surface accompanied by a copious production of strain lines in all the grains to a considerable depth below the surface.

This effect is accompanied by a considerable increase in hardness, the maximum effect being at the surface where the D.P.H. is 512/532. Further hardness tests show D.P.H. values of 450 and 412 respectively at depths of 2 m/m and 4 m/m below the surface.

X-ray examination of cold-worked austenitic Mn steel has indicated the virtual absence of alpha iron, and magnetic tests show only traces of magnetism to result from cold working. In these respects Mn steel austenite is more stable than and differs from other austenitic ferrous alloys which, after cold working, contain considerable amounts of alpha iron and are appreciably magnetic.

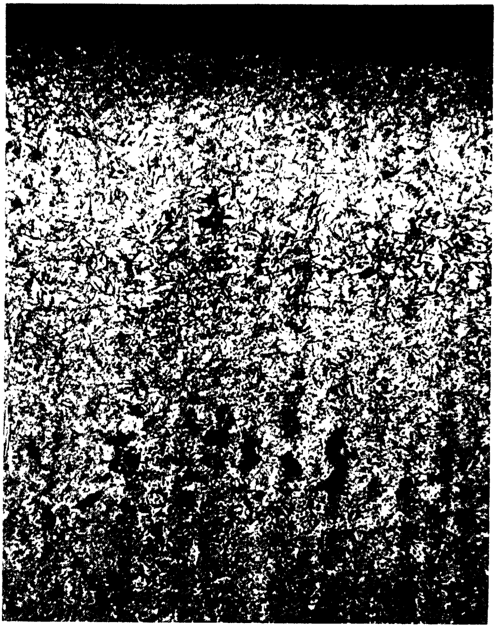


FIG. 194.—$4\frac{1}{2}$ per cent Nickel-Chromium-Molybdenum Case-hardening Steel. As Case hardened. × 100 Dias.

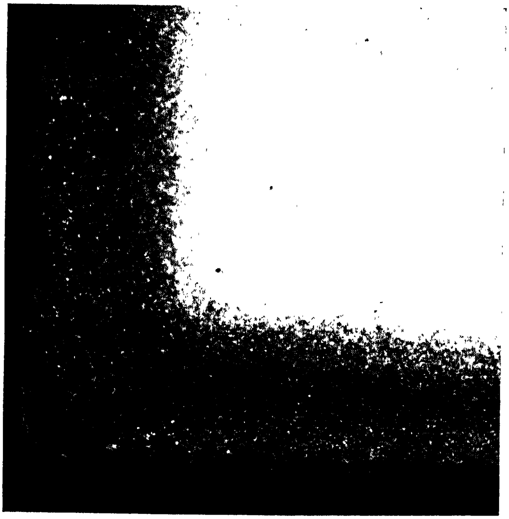


FIG. 195.—Nitrided Case. 3 per cent chromium-molybdenum steel. × 50 Dias.

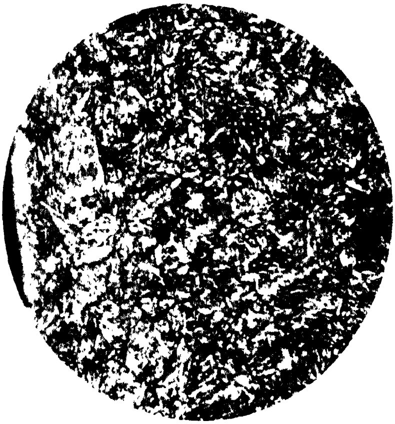


FIG. 196.—Nitrided Case. 3 per cent chromium-molybdenum steel. ×300 Dias.

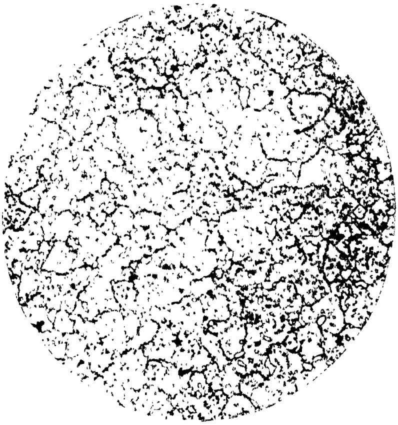


FIG. 197.—18-4-1 High-Speed Steel. Correctly hardened. ×250 Dias.

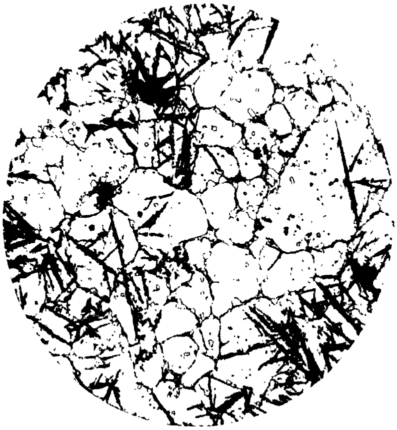
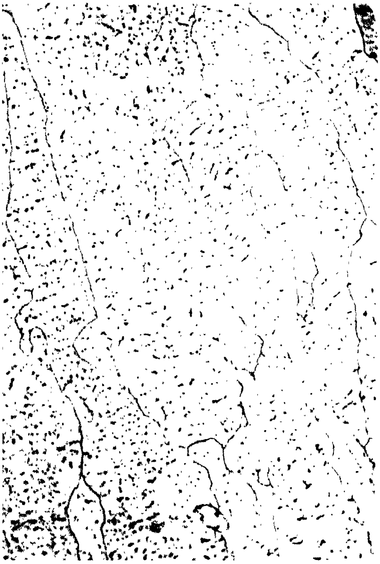


FIG. 198.—18-4-1 High-Speed Steel, Overheated. ×250 Dias.

PLATE X.



. 199.—18/8 Chromium-Nickel Stainless Steel. As Cast. × 100 Dias.

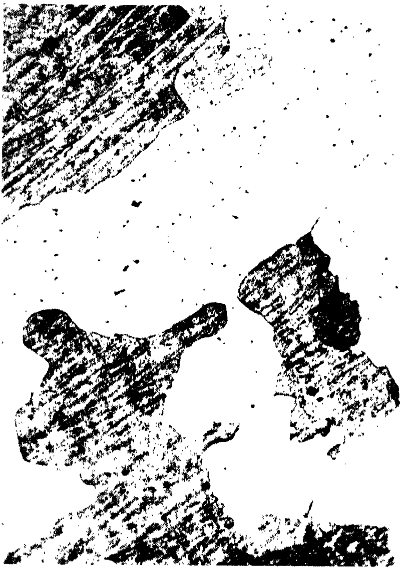
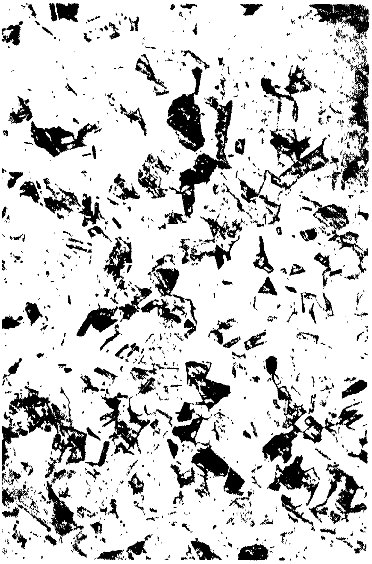


Fig. 200.—18/8 Chromium-Nickel Stainless Steel. Air cooled from 1150°C. × 100 Dias.



. 201.—18/8 Chromium-Nickel Stain-
:ss Steel. Rolled bar air cooled from
050°C. × 100 Dias.

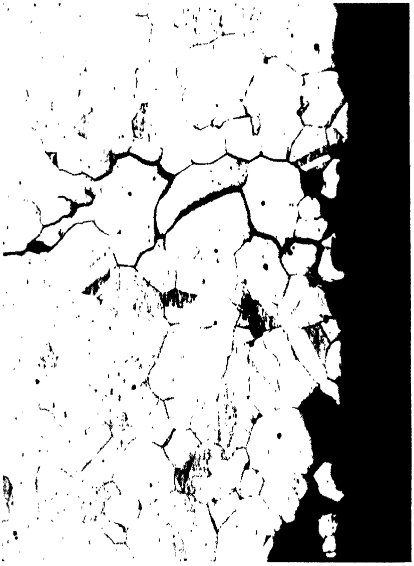


Fig. 202.—18/8 Chromium-Nickel Stainless Steel. Intercrystalline Corrosion. × 100 Dias.

correct composition of the material, grain size, quenching temperature, and tempering temperature.

The hardness of high-speed steel increases with the quenching temperature up to a peak between 1200 and 1300°C., after which the hardness falls with further increases of temperature due to the introduction of increasing amounts of austenite in the structure. Excessively high temperatures introduce large grain size with the attendant brittleness usually found in such structures.

During the hardening operation the steel is with advantage first warmed on a hot plate or on the top of the hardening furnace, then preheated in a separate furnace chamber before heating in the actual hardening chamber. These precautions are taken owing to the changes of volume which take place in the steel as it passes through the critical change point, and it is necessary to heat slowly through or near to this point at about 850°C. so that the change takes place as evenly as possible throughout the mass, minimising the tendency for cracking. When the material has reached the temperature of the preheating chamber it is transferred to the hardening chamber which is maintained at the required quenching temperature. As grain growth takes place above 850°C. the steel is heated rapidly, and for this purpose it is a decided advantage to use a furnace having adequate thermal capacity and of sufficient size to prevent chilling back, and consequently obviating the considerable period of time to reheat to the desired hardening temperature. Before quenching, the steel is held at the hardening point for the shortest possible period. In present-day practice, controlled atmosphere furnaces are preferred, to minimise oxidation and decarburisation of the surface. Quenching is carried out in air, oil or molten lead, choice depending largely upon the type of steel, the sectional thickness and the design of the tool.

In the hardened condition the structure consists of martensite and austenite with carbide particles distributed throughout. Tempering has the effect of breaking down the austenite into further martensite, giving slightly increased hardness and greater wear resistance. This tempering effect produces what is known as " secondary hardness " and the operation is carried out by heating the steel for 1 to 2 hours at 500 to 600°C. or by multiple tempering in separate periods of 1 hour or so. By the latter method a slightly softer material may be produced, but it is advantageous for internal stress relief. The heat developed in tools in service may sometimes be found to be sufficient to convert the austenite to martensite in the outer layers. When tempering temperatures of 600°C. are exceeded the hardness falls rapidly.

Carbide tool steels. In recent years a number of alloys for cutting tools have been developed, most of them consisting chiefly of tungsten carbide, usually associated with varying amounts of cobalt. Other elements are also sometimes present and the compounds are cemented together to give a material of great hardness, exceeding 1100 Vickers, and capable of cutting hard metals at high speeds. The alloys are expensive and tools consist of carbon steels tipped with the material. These tipped tools are used in high-speed lathes, milling cutters, drills, and the alloys are often used for wire-drawing dies. They may be used for the machining of white-irons, chilled rolls, and it is possible to machine with them glass porcelain and austenitic manganese steel. The alloys are sold under such trade names as Widia, Carballoy, Akrit, Diamondite, Elmarid, and Cutanit. The approximate compositions of some of the alloys are given below.

	C per cent	*W per cent*	*Co per cent*	*Cr per cent*	*Ni per cent*	*Mo per cent*
Widia .	5·7	87·4	6·1	—	—	—
Akrit .	2·5	16·0	38·0	30·0	10·0	4·0
Diamondite	3·9	95·7	—	—	—	—
Elmarid .	5·9	83·0	4·5	—	—	—

CORROSION AND HEAT-RESISTING STEELS

It was thirty years or so ago that the corrosion-resisting properties of steel containing substantial proportions of chromium were first recognised. The first stainless steels were used for cutlery and contained about 13 per cent of chromium. The growing demand in recent years for fabricated parts and castings to resist oxidation and creep at elevated temperatures, and to withstand the corroding action of acids, alkalis and salts at both normal and elevated temperatures has led to the rapid development of a large variety of corrosion and heat-resisting steels for various conditions of service. Chromium and nickel are the predominating elements along with suitable proportions of molybdenum, tungsten, titanium, copper or silicon for special applications.

12 to 15 per cent chromium type. The plain chromium stainless steels are still widely employed, the chromium being between 12 and 15 per cent with carbon contents ranging from less than 0·1 per cent to 0·5 per cent. They are suitable for use under mildly corrosive conditions, oxidising acids, and for steam service. The low carbon variety are ferritic, practically non-hardening and can be hot and cold worked into various shapes.

The steels with 0·30 to 0·35 per cent carbon are used for cutlery and can be readily hardened. As the carbon content is increased, they become stiffer to work. When the highest hardness is required for ball bearings and cutting tools, use is made of the higher carbon variety which can be hardened to 550 Brinell.

Chromium raises the critical points and the steels are hardened by oil quenching from 950 to 1000°C. and are fully tempered on reheating to about 750°C. The lower carbon materials are generally used in the annealed or fully tempered condition. Higher carbon steels used for wear resistance or cutting purposes are only lightly tempered after hardening and are martensitic. The tempering temperatures employed are usually below 250°C. for relieving hardening stresses. The hardness of a quenched stainless steel is not greatly affected on reheating until a temperature of 500°C. is reached, after which the hardness falls rapidly with further increase of temperature to a minimum at 750°C.

The steels resist oxidation up to about 700°C., but are not particularly strong at elevated temperatures, although they are superior to mild steel in this respect. Those containing higher carbon are not satisfactorily welded owing to their air-hardening tendencies, and those with low carbon contents which do not materially air harden, suffer from grain growth after welding, which cannot be removed by further heat treatment.

16 to 20 per cent chromium type. This steel, with 0·15 to 0·20 per cent carbon along with about 2 per cent of nickel, gives improved corrosion and heat-resisting properties. It has good strength and impact resistance, is more responsive to heat treatment, contains more martensite on quenching, and gives a hardness in the order of 400 Brinell. It has distinct air-hardening properties which render it unsuitable for welding, except, perhaps, with an 18/8 rod, after which it should be annealed at temperatures of 650 to 680°C. It is most resistant to corrosion in the quenched and fully tempered condition, and is suitable for applications in the manufacture of food products, fruit juices, handling steam, and for contact with salt water and spray.

Austenitic stainless steels. This group is made up of steels of various compositions, the most noteworthy being the 18 per cent chromium—8 per cent nickel type, commonly known as 18/8. The carbon content is usually less than 0·15 and the general range of composition is between 15 and 20 per cent chromium and 7 and 10 per cent nickel. The steel is used under highly corrosive conditions in chemical plant, in the manufacture of foodstuffs, in equipment for paper mills, dairies, textile dyeing and photographic work; and for generally handling alkaline liquids, sea water, organic acids, high-temperature steam and many other chemicals. It is also used extensively for non-tarnishing ornamental work such as taps, handles and sanitary fittings.

Other elements are often added in comparatively minor quantities to confer upon the material specially enhanced resistance to certain acids and chemicals; and to generally inhibit intercrystalline corrosion and brittleness to which 18/8 is liable after heating to temperatures between 650 and 900°C. If carried out prior to any corrosive attack the embrittlement can be corrected by quenching from 1050 to 1100°C., but the treatment does not prevent recurrence upon further exposure in the embrittlement range. The addition of tungsten, titanium and columbium give greatly increased resistance to intercrystalline corrosion. The presence of titanium and tungsten provides complete immunity from this type of corrosion even under the most drastic conditions of service,[1] and without any softening treatment after welding, or other heating within the usually harmful temperature range.

The addition of molybdenum to 18/8 effects a specially good resistance to acetic acid, sulphite liquors and bleaches, acid sulphates, etc.

A steel containing 12 to 14 per cent chromium and up to 20 per cent nickel, along with 4 per cent each of molybdenum and copper gives the highest possible resistance to acids, particularly sulphuric acid.

The austenitic steels are non-magnetic and do not harden

[1] Hatfield, *Iron and Steel Industry*, July, 1936.

CORROSION-RESISTING STEELS.[1]

Typical compositions						*Condition*	*Mechanical properties*				
C	*Cr*	*Ni*	*W*	*Ti*	*Mo*		*Yield point tons per sq. in.*	*Max. stress tons per sq. in.*	*Elongation per cent on 2 in.*	*Reduction of area*	*Brinell hardness*
0·15 max.	12–15	—	—	—	—	Hardened and fully tempered	15–25	30–40	30–40	50–60	140–180
0·20–0·35	12–14	—	—	—	—	Do.	25–35	40–50	20–30	50–60	200–240
0·15	16–20	1·5–2·5	—	—	—	Hardened and tempered	35–50	50–60	15–25	40–60	240–280
0·15 max.	18	8	0·5–1·0	0·5–1·0	—	Fully softened	16–20	40–50	35–40	40–50	160–200
0·07 max.	18	8	—	—	2·4–4·0	Do.	15–18	35–45	40–60	40–60	150–180

HEAT-RESISTING STEELS

Typical Compositions					*Condition*	*Mechanical properties*				
C	*Cr*	*Ni*	*W*	*Si*		*Yield point tons per sq. in.*	*Max. stress tons per sq. in.*	*Elongation per cent on 2 in.*	*Reduction of area*	*Brinell hardness*
0·1–0·5	12–14	—	—	—	Hardened and tempered	15–40	30–60	20–40	40–60	140–280
0·1–0·2	25–30	0–5·0	—	1·0–2·0	Softened	20–35	30–45	15–25	30–50	150–220
0·5 max.	12–16	25–35	0–4·0	1·0–2·5	Do.	30–40	50–60	20–30	40–50	180–270
0·2–0·4	19–26	7–13	0–4·0	1·0–2·0	Do.	22–35	45–60	20–35	35–55	190–260
0·4 max.	20–25	20–25	—	1·0–2·0	Do.	22–35	40–55	30–50	40–60	180–260

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[1] From Hatfield, *Iron and Steel Industry*, July, 1936.

on quenching, and quick cooling or quenching from 1050 to 1100°C. is only employed to soften them or produce the best condition for corrosion resistance. They are readily hot worked at about 1150 to 1200°C., and are very responsive to all kinds of cold working.

Heat-resisting steels. These steels are designed to resist oxidation and creep in high-temperature service and, in addition, they often have excellent resistance to a large variety of corrosive influences. They mostly contain at least 1 per cent of silicon which also increases the resistance to oxidation and corrosion.

The chromium steels of the 12 to 14 per cent type resist oxidising gases and sulphur-rich gases at high temperatures up to 700°C. but show no particular merit for mechanical strength at high stresses at elevated temperatures. Those containing 25 to 30 per cent chromium with small percentages of nickel to increase toughness are suitable for high-temperature service up to about 900°C. where no special mechanical strength is required, as in annealing boxes, furnace doors, etc.

The chromium steels with high percentages of nickel give greatly improved strength at elevated temperatures. They are austenitic and ductile at ordinary temperatures and are generally used in the softened condition obtained by cooling in air from about 1050°C. Their resistance to oxidation is good at temperatures ranging from 900 to 1100°C. and they are used for mechanical stoker parts and rollers, rails, chains, dampers, etc., in furnaces.

The tables give the compositional range and mechanical properties of a few important corrosion and heat-resisting steels.

FACTORS CONTROLLING SUITABILITY OF STEELS FOR VARIOUS REQUIREMENTS

Grain size. The grain size of steel has an important bearing on its properties. The importance of its effects and its control has been recognised in the United States for a considerable time, and is now having close attention in this country, and in recent years steels with controlled grain size have been regularly made.

The production of fine-grained steel depends upon correctly controlled melting practice in the first instance, followed by the addition of a suitable amount of aluminium in excess of that required to complete deoxidation, after preliminary deoxidation with silicon or manganese. Fine-grained steels can be produced only when a procedure is followed which results in thorough deoxidation, and consequently fine grain cannot be produced in rimming steel or semi-killed steel.

Fine grain confers a number of desirable properties. Investigators in this country [1] have found that the effect of fine grain is to give for a steel of similar analysis a slight reduction in the yield stress and maximum stress ; there is a slight increase in ductility and a considerable increase in toughness as shown by the Izod test. Fine-grained steels distort less on hardening, have less tendency to cracking, and are less brittle than coarse-grained steels, but there is a little reduction of hardness penetration which can be largely balanced by increasing the manganese content slightly. For a given hardness, fine-grain steels are tougher.

The chief beneficial effect of fine grain size is that, whereas grain growth in steel which has not been treated for controlled grain size may begin at temperatures below 800°C., a controlled fine grain will not begin to grow until 1000°C. has been reached —a temperature which is in excess of that employed for heat-treatment operations for all except highly alloyed steels. Grain growth, however, is comparatively rapid once this temperature is exceeded, but by reheating to the usual normalising temperature the " inherent " grain size is restored.

Grain size, which may be defined as " the number of grains per unit area of cross-section," is standardised in the U.S.A., and steel is classified according to nine A.S.T.M. numbers, ranging from 0, 1, 2, and so on to 8. The tedious operation of counting the grains is obviated by comparison with a chart illustrating standard grain sizes.

The McQuaid-Ehn method of determining the grain size consists of pack-carburising a specimen for 8 hours at 927°C., cooling slowly at a standard rate, and measuring the grain size microscopically in the hyper-eutectoid zone where the grains are outlined by a network of cementite.

Other considerations. A review of carbon and alloy steels would not be complete without some brief reference to the suitability of various steels for different duties and the factors which control their suitability. As we have seen, the engineer has a very wide choice of materials, ranging from the simple mild

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[1] Swinden and Bolsover, *Iron and Steel Industry*, October 1, 1936.

carbon steels to the highly alloyed and sometimes complex wear, corrosion and heat-resisting types.

Although alloy steels are superior to mild steel for quite a number of purposes, mild steel has advantages over alloy steels for many applications. For instance, the good ductility combined with its well-defined yield point are valuable properties in that they considerably reduce local concentrations of stress. The steel has also a high damping capacity, so that for some duties carbon steel may be more suitable than alloy steel.

Correctly heat-treated carbon steels in small masses give satisfactory hardness for many purposes, but when compared with the alloy steels for hardening, they are somewhat lower in ductility for a given hardness than most alloy steels. There is a limit to the hardness obtainable with carbon steels without reducing the ductility and impact value to a dangerous extent. The air-hardening steels, however, even when hardened to give tensile strengths in excess of 100 tons per sq. in., still retain considerable ductility and shock resistance. Hardened alloy steels give greater depth of hardening, are more even in structure, and hardness throughout, especially in thicker sections.

For resistance to scaling and creep at elevated temperatures, also for use under corrosive influences, carbon steels are of little use and resort is made to the various alloy steels, particularly the austenitic type.

The following factors are considered when deciding upon steels for various duties :—

(1) The tensile strength.

(2) Ductility. For some purposes this is more important than tensile strength.

(3) The shock resistance as indicated by the Izod or other impact value, since good strength and ductility does not always ensure that the steel has ability to withstand repeated shock, and for many purposes the Izod value should be stipulated.

(4) Fatigue values, which are largely related to the tensile strength.

(5) Hardness and resistance to wear—often required with a combination of other properties mentioned above. Hardening ability.

(6) Resistance to heat and scaling. Strength and resistance to creep at elevated temperatures.

(7) Corrosion resistance.
(8) Suitability for case hardening.
(9) Machineability.
(10) Grain size, which affects some of the properties mentioned above.

CHAPTER 8

CAST IRON

THE term cast iron is applied to a series of alloys of iron, carbon and silicon, although, in addition, various quantities of other elements such as manganese, phosphorus and sulphur are always present.

Until recent years cast iron has been regarded as a hard brittle material with limited applications, and only used extensively for purposes where strength and shock resistance are not important. Metallurgical and chemical control, and also development of testing methods have brought about a complete revolution in the mechanical properties of ordinary cast iron. Furthermore, the use of special alloying elements, heat treatment and improved melting technique have led to the production of cast iron with tensile strengths exceeding 70,000 lb. per sq. in. In view of the great improvement effected by technical development, cast iron parts are finding increasing introduction into engineering for high-duty purposes such as camshafts, crankshafts and brake drums for automobiles.

The constitution of cast iron. In the iron-carbon equilibrium diagram, cast irons are found to be iron-carbon alloys containing more than 1·7 per cent carbon. Cast irons also contain silicon in varying proportions, and the amount of silicon present affects the final structural composition of the completely cooled iron. It tends to promote separation of carbon from cementite during cooling after solidification of the molten metal; and generally, after complete cooling, cast irons contain some carbon in the free state, usually referred to as graphitic carbon.

When the iron contains insufficient silicon to promote graphitisation of the cementite, the formation of its structural components on cooling is relatively simple. Referring again to Fig. 136, we find a point (c) representing a composition of 3 per cent carbon in iron at a temperature of 1500°C. On cooling, austenite begins to separate from the metal and continues to do so until the eutectic temperature is reached at B. The eutectic containing 4·3 per cent of carbon consists on solidification of cementite and austenite. On further cooling the primary austenite formed according to AB, because it contains 1·7 per cent carbon, rejects cementite along line EL as with the steels, and on reaching eutectoid temperature at L becomes cementite and pearlite. The austenite of the eutectic behaves in a similar manner. The final structure, which is typical of a white cast iron, consists entirely of cementite and pearlite, and resembles that of hyper-eutectoid steel except that the proportion of cementite is much greater.

When silicon is present in greater amounts than that found in white iron, graphite separates from the cementite which forms on cooling from the eutectic temperature, and the resulting irons are more or less grey in fracture due to the graphitic carbon. With irons of the same carbon content the higher the percentage of silicon the greater the separation of graphite. The graphite formed between eutectic and eutectoid temperatures is known as "primary" graphite, and takes the form of curly flakes. Depending upon the silicon content and cooling rate, the cementite, which should form the carbide plates of the pearlite, also decomposes into iron and graphite, the graphite flakes forming at this temperature being much finer and shorter and often termed "secondary" graphite. The quicker the cooling rate the less the separation of graphitic carbon.

The chief factors which influence the final structural composition are therefore silicon and carbon contents and cooling rate, but sulphur and manganese in normal amounts also have a minor effect. The changes which take place during the cooling of cast iron are seen to be of a somewhat complicated character, and for the sake of simplicity we may regard cast iron as an iron-carbon alloy in which the carbon is present in either one or two forms. It is present as all combined carbon in white iron, all graphitic carbon in exceptional cases where the silicon content is high and the cooling rate very slow, or present partly as combined carbon and the remainder as graphitic carbon. In the last case, cooled cast iron may be simply regarded as a steel containing some free carbon in the form of graphite and in which the combined carbon content may be taken as the carbon content of the steel. Thus by reference to the iron carbon constitutional diagram we find that there are several basic structures found in cast iron :—

(1) White iron—Carbon all combined—Cementite and pearlite.

(2) Grey cast iron—Carbon all graphite—Graphite and ferrite.

(3) Grey cast iron—combined carbon less than 0·89 per cent—Graphite, pearlite and ferrite.

(4) Grey cast iron—combined carbon approximately 0·89 per cent—Graphite and pearlite.

(5) Grey cast iron—combined carbon above 0·89 per cent—Graphite, cementite and pearlite.

In the last example, when the combined carbon content is considerably in excess of 0·89 per cent, we have the mottled irons which are partly white and partly grey in fracture.

Pig iron. For the production of iron castings, large quantities of pig iron form the whole or a proportion of the charges for remelting in the cupola or other types of furnace. As already indicated in the first chapter, there is a wide variety of pig irons available of different compositions and can be obtained from the same types of iron ore, by adjustments to the burden of the blast furnace. The silicon contents of pig iron usually decrease as the crystalline fracture becomes more close, until the lowest silicon is found in white irons, whilst the sulphur content increases as the silicon decreases. The increase in combined carbon content and decrease of graphite occurring in the change in fracture from open grey to white, are accompanied by a slight fall in the total carbon and manganese contents. This is illustrated in the following table :—

	Silicon	*Sulphur*	*Manganese*	*Total carbon*	*Combined carbon*	*Graphitic carbon*	*Phosphorus*
Glazed or silvery	over 4·0	0·015	0·47	3·50	traces	3·50	Low in hematite irons.
No. 1 .	3·5	0·018	0·45	3·70	0·10	3·60	
No. 2 .	3·2	0·020	0·45	3·70	0·20	3·50	High in basic irons.
No. 3 .	2·8	0·040	0·43	3·65	0·35	3·30	
No. 4 .	2·3	0·060	0·38	3·55	0·60	2·95	
No. 5 .	1·9	0·100	0·35	3·30	0·80	2·50	
Mottled .	1·3	0·250	0·32	3·10	1·50	1·60	
White .	0·8	0·320	0·28	2·90	2·90	traces	

Depending upon the type of iron ore used, the series of pig iron may be high or low in manganese and phosphorus.

Irons low in sulphur and phosphorus are known as hematite pig irons, whilst those high in phosphorus and manganese and low in silicon are known as basic pig irons.

Siliceous or glazed pig iron is chiefly used for blending with other grades of iron to increase the silicon content of the remelted mixture.

No. 1 iron is soft and grey, dark in colour and with a coarse highly crystalline fracture. The carbon existing in the form of large flakes of graphite, breaks up the continuity of the metal matrix, and the iron is consequently mechanically weak.

No. 2 iron has a closer crystalline grey fracture, is harder and stronger than No. 1, and is used alone or along with No. 1 for the production of light castings.

No. 3 iron is still closer, with graphite in smaller flakes. It is fairly hard and strong, and is used extensively in foundry work to form a proportion of the furnace charges for a wide variety of castings.

No. 4 quality, being close and dense, is used in the production of larger castings, also engineering grey iron castings of high quality where the demand is a combination of strength, hardness and toughness.

No. 5 iron is very finely crystalline and grey in fracture. It is used for forge purposes, for the production of chilled castings, and may be blended by remelting with more open irons.

Owing to their hardness, brittleness, and unmachineability with ordinary tools, mottled and white irons are used in foundry work to a much less degree than the other grades, but they do find application for articles where resistance to abrasion is the primary factor, as in chilled rolls, plough shares, crusher heads, grinding balls and stars for use in tumbling barrels for the cleaning of rough castings. They are also used in malleable iron annealing cans for cheapness and a certain amount of heat resistance.

As the grades of iron become progressively lower in silicon and carbon contents, they become less fluid when molten.

There are in addition to the normal types of hot blast pig irons produced in the blast furnace, other types made by rather different methods, having different properties, and used for special purposes.

The pig irons known as cold-blast irons are smelted in small furnaces using a colder blast. The resulting irons are lower in carbon content, closer and stronger, and used in the production of high-strength castings.

Refined irons are made in cupolas and sometimes other melting furnaces by melting mixtures of hematite irons, medium phosphorus irons and steel scrap, and are usually close grained and homogeneous in structure. Like cold-blast irons they often form a proportion of charges melted for the founding of high-strength iron castings.

Effects of normal elements in cast iron. *Carbon.* There are two forms of carbon found in cast iron, namely, combined and graphitic carbon, the total of these being known as the *total carbon* content. An increase in the amount of total carbon lowers the melting-point of iron and increases the fluidity, but because high total carbon is usually associated with a high proportion in the form of graphite there is often a corresponding decrease in strength.

Graphitic carbon has its greatest effect in lowering the strength of iron when it is in the form of large flakes which break up the continuity of the metallic matrix, and therefore larger planes of weakness are present. The lower the amount of graphitic carbon, the less abundant the flakes and usually they are smaller in size. Graphitic carbon in ordinary irons aids machineability, for it is soft in character and acts as a lubricating agent for the tool.

Combined carbon exists as carbide of iron in a similar manner to which carbon exists in carbon steel, that is, as cementite Fe_3C, or as a constituent of the pearlite. The strength of cast iron depends to a great extent on the quantity and fineness of the pearlite, and therefore combined carbon increases the strength in proportions ranging up to 1 per cent, after which there is a slight decrease, with increase of brittleness. The hardness is increased progressively with increasing combined carbon content, until with the appearance of free cementite when the combined carbon exceeds 0·9 per cent, the iron becomes difficult to machine with ordinary tools. Irons or castings exhibiting chill have higher combined carbon content where the intensity of the chilling is greatest.

Silicon dissolves in the ferrite of iron, and is the predominant element in determining the relative proportions of combined and graphitic carbon. Therefore, with other conditions being equal, the higher the silicon, the greater the relative amounts of graphite precipitation, less combined carbon, with an increase in softness, ease of machineability, but with a loss of strength. In excess of the quantity of silicon required to displace all of the combined carbon, a silvery fractured iron with graphite in a hard weak and brittle matrix is produced.

Sulphur. In the absence of sufficient manganese to neutralise its deleterious effects, sulphur increases the stability of the iron carbide and inhibits graphitisation, thereby increasing chilling and embrittling effects.

Manganese is found in ordinary cast irons between the range of 0·4 and 1·2 per cent. Within this range it increases tensile strength slightly, reaching a maximum with about 1 per cent of manganese and the tendency is for the iron to be harder and finer in grain. Its chief and most important function in cast iron is to counteract the undesirable effects of sulphur by promotion of manganese sulphide which is definitely less harmful than if the sulphur is present as iron sulphide. To ensure that the bulk of the sulphur is present as manganese sulphide, the theoretical amount of manganese required is approximately 1·7 times the sulphur content. Usually, however, the practice is to maintain an excess of at least 0·2 per cent manganese above that theoretically required to form manganese sulphide with the sulphur, in order to ensure that the full benefits of manganese in the other respects are utilised.

Manganese sulphide is recognised in the micro-structure as small rounded inclusions blue-grey in colour.

Phosphorus is present in cast iron as iron phosphide, which is a constituent of the iron—iron phosphide eutectic in grey irons and the iron—iron phosphide—cementite eutectic in mottled and white irons. The eutectic has the relatively low melting-point of 960°C. and consequently higher phosphorus irons have greater fluidity. Owing to this increased fluidity iron with a phosphorus content in the region of 1 per cent is used for castings of thin and intricate section, with which difficulty would be experienced using low phosphorus irons. The phosphide eutectic is hard, brittle, wear-resisting, and increasing amounts decreases machineability. Since 1 per cent of phosphorus occupies 10 per cent by volume in the form of eutectic, its proportion in cast irons used for purposes where shock resistance is important should be kept to a minimum. In high phosphorus irons the eutectic often appears in the form of a network; also with heavy sections and slow cooling, segregations or local differences in distribution are often found, particularly near the middle of the section where the eutectic, being of low melting-point, tends to be driven inwards as solidification of the iron proceeds from the outside.

Metal mixtures for melting. By making the correct choice of pig irons, scrap, and other materials including scrap steel, and mixing in suitable proportions for remelting, a wide variety of irons of different properties are obtained, from relatively weak and fluid irons for thin ornamental and domestic work, to high strength irons for severe engineering service. These may be roughly classified into four groups.

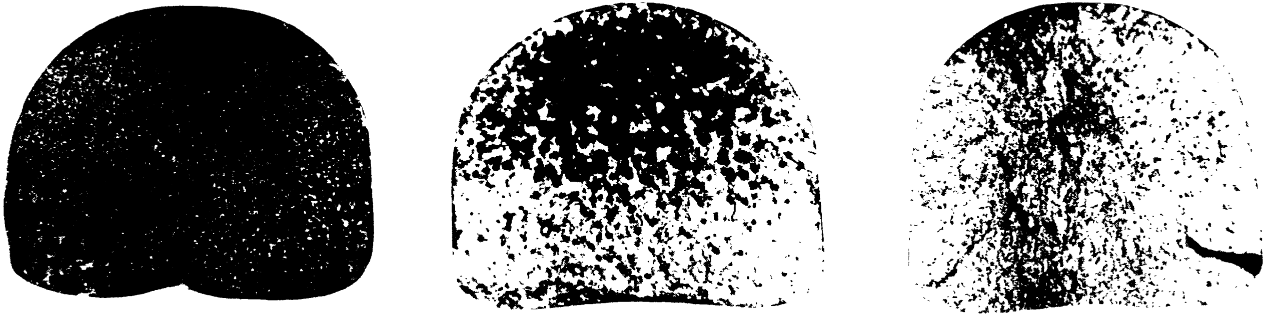
(1) For thin ornamental work, radiators, stoves, hardware, rainwater goods and other light castings, the open and soft No. 1 and 2 phosphoric irons are commonly used along with cheap cast-iron scrap. The carbon and especially the silicon contents are generally higher in iron for these castings, to promote the necessary softness and greyness in the thin sections encountered.

(2) For general castings of thicker section where somewhat higher strength is required, such as valves, pipes, fittings, pulleys, flywheels, and so on, more combined carbon is desirable. The silicon content of the charges is reduced by the inclusion of some No. 3 foundry pig iron, and if lower phosphorus is desired a proportion of medium-phosphorus pig is added.

(3) Close-grained irons used in medium engineering castings are produced from low phosphorus charges containing proportions of steel scrap and the closer grained grades of pig iron, in order to induce a lower total carbon content, giving strong fine-grained and tough metal. This type of metal, often with the inclusion of special alloying elements, is used for the casting of cylinder blocks, heads, brake drums, pump castings, compressor parts, etc.

(4) For large engineering castings including hydraulic work, machine tool parts, heavy high duty cylinders, close-grained hematite or semi-phosphoric types of pig of fairly low silicon content are blended with proportions of steel and good quality scrap. The inclusion of steel assists in maintaining a lower total carbon content, to give a fine-grained iron of necessary strength and a homogeneous texture.

In computing charges accurately to give a cast iron of desired analysis and physical properties, all the raw materials for remelt-



(a) Close Grey

(b) Mottled

(c) White

FIG. 203.—Pig-Iron Fractures.

PLATE XII.

FIG. 204.—Coarse Graphite in Cast Iron.
Unetched. × 100 Dias.

FIG. 205.—Fine Graphite in Cast Iron (Inoculated Type),
Unetched. × 50 Dias.

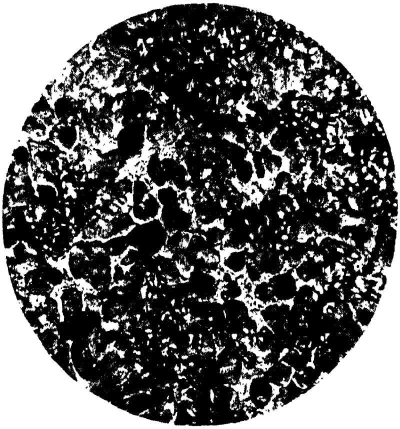


FIG. 206.—Medium Phosphorus Iron.
Approx. 0·7 per cent phosphorus.
Phosphide eutectic is the constituent forming the light network.
Etched. × 50 Dias.

FIG. 207.—Showing the appearance of the phosphide eutectic.
Etched. × 300 Dias.

FIG. 209.—Soft Cast Iron containing 0·45 per cent combined carbon. Note the presence of ferrite (white). Etched. × 200 Dias.

FIG. 210.—Pearlitic Cast Iron containing 0·5 per cent chromium and 0·70 per cent combined carbon. Etched. × 300 Dias.

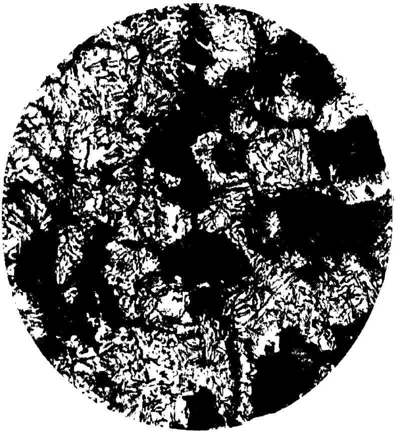


FIG. 211. — Cast Iron containing approximately 1·2 per cent molybdenum. Etched. × 200 Dias.

PLATE XIV.

FIG. 213.—Hardened Cast Iron (3 per cent nickel). Etched. ×200 Dias.

(Martensite plus a little graphite.)

FIG. 214.—Annealed Cast Iron, 1-in. Section, heated for 1 hour at 820° C. and air cooled. Etched. ×200 Dias.

(Ferrite, graphite, and phosphide eutectic.)

FIG. 215.—Chilled Cast Iron from a Chilled Roll. Etched. ×50 Dias.

(Cementite (light) and pearlite (dark).)

Facing page 225.]

ing are checked for composition by chemical analysis, and it is from these analyses rather than from the fractures of the ingredients that the proportions of raw materials required are calculated. The cupola is by far the most extensively used furnace, although the other melting units mentioned in Chapter 1 are used in special circumstances. In calculating the metal charges, allowances are made for possible oxidation losses in the cupola, and should any analysis obtained from a spoon sample indicate any deviation from the desired analysis during the melting operation, the composition of the subsequent metal tapped may be corrected by addition of the requisite quantities of ferro-alloys of manganese and silicon. Metal charges are usually computed to include a small addition of speigeleisen or ferro-silicon (40 per cent Si) in the form of lumps or briquettes, the quantities of which may be increased or decreased as the necessity arises, during long periods of melting or for the next day's operations.

The table on page 226 gives an approximate indication of the range of analyses and physical properties found in irons for various purposes, along with simple mixtures which may form the basis of the charges for producing them.

Often the process of desulphurising is applied to high-quality cast irons for engineering service, the sulphur content being considerably reduced by the addition of sodium carbonate to the molten metal in the ladle.

Shrinkage in cast iron. When cooling from the molten state the volume of the metal decreases in stages with falling temperature, this effect being known as shrinkage. There are three varieties of shrinkage as follows :—

(1) Liquid shrinkage which occurs during cooling from the casting temperature to the initial freezing point of the iron. The volume contraction is a definite constant for each unit fall in temperature. Normally this loss of volume is made up in a casting by excess metal being fed by gravity from molten metal in the down runner and pouring basin of the mould.

(2) Solidification shrinkage is the contraction in volume as the metal passes from the molten to the solid state. The specific gravity of molten cast iron is about 6·65 and solid cast iron 7·1. The transition from molten to solid takes place from the outside inwards, so that the contraction gives rise to shrinkage cavities in the middle of the section, these defects

being particularly found in castings of non-uniform section with attendant uneven rates of cooling, causing directional or dendritic crystallisation resulting in porosity in the thickest section. The graphite which forms near the freezing temperature provides partial compensation for solidification shrinkage, and it follows that an iron predisposed to graphitisation will exhibit less of this type of shrinkage, but more with irons containing substantial amounts of combined carbon.

	Group 1	*Group* 2	*Group* 3	*Group* 4
Total carbon	3·2–3·6	3·0–3·4	2·9–3·2	2·8–3·2
Combined carbon	0·2–0·4	0·4–0·55	0·6–0·8	0·7–0·85
Silicon	2·3–2·8	2·0–2·3	1·5–2·0	1·0–1·5
Sulphur	0·05–0·08	0·06–0·10	0·06–0·10	0·08–0·10
Manganese	0·4–0·6	0·5–1·0	0·6–1·0	0·6–1·0
Phosphorus	1·0–1·6	0·5–1·0	0·3–0·5	0·2–0·5
Structure	Chiefly ferrite with some pearlite. High graphitic carbon.	Ferrite-pearlite graphite. More pearlite. Less graphite and in smaller flakes.	Chiefly pearlite with perhaps a little ferrite. Less graphite and in finer flakes.	Pearlite with fine graphite.
Tensile strength tons per sq. in.	9–12	12–15	15–20	17–22
Transverse strength tons per sq. in.	19–23	23–26	26–31	28–34
Brinell hardness	160–200	180–210	200–230	210–240
Possible mixture	50 per cent open 1 or 2 high P iron. 50 per cent cheap "bought in," scrap along with wasters from foundry, runners, etc.	25 per cent open high P pig. 25 per cent No. 3 med. P pig. 50 per cent scrap including returned runners, etc., from foundry.	35 per cent No. 3 med. P pig. 15 per cent No. 4 or 5 med. P pig. 5–10 per cent steel scrap. 40–45 per cent good quality cast iron scrap, including returned runners, etc., from foundry.	20 per cent No. 3 hematite. 25 per cent No. 4 or 5 med. P pig. 15–25 per cent steel scrap. 30–40 per cent good quality cast iron scrap, including returned runners, etc., from foundry.

In foundry work these cavity defects are usually corrected by incorporating suitable reservoirs (termed feeders or shrinkheads) in the system of runners (gating) of the mould to supply more molten metal to the troublesome area as solidification proceeds. Correction can also be made by the insertion of metal chills in the mould where the heavy section occurs, so that the induced rapid rate of solidification allows insufficient time for the shrinkage to take place.

(3) Solid shrinkage is the solid and final contraction in volume on cooling from solidification temperature to normal temperature, and forms the basis of the pattern-maker's allowance for shrinkage. This is normally $\frac{1}{8}$ in. per ft. for grey cast iron, and about $\frac{1}{4}$ in. per ft. for white iron.

The " Keeps Test " provides a means of measuring the linear shrinkage of cast iron. A test bar 12 in. in length and of $\frac{1}{2}$ in. square section is cast. On cooling, the bar is placed between a suitably mounted yoke with jaws 12 in. apart, and the contraction is determined by placing a tapered and graduated feeler gauge into the space caused by the contraction, and located between one end of the bar and the corresponding jaw of the yoke.

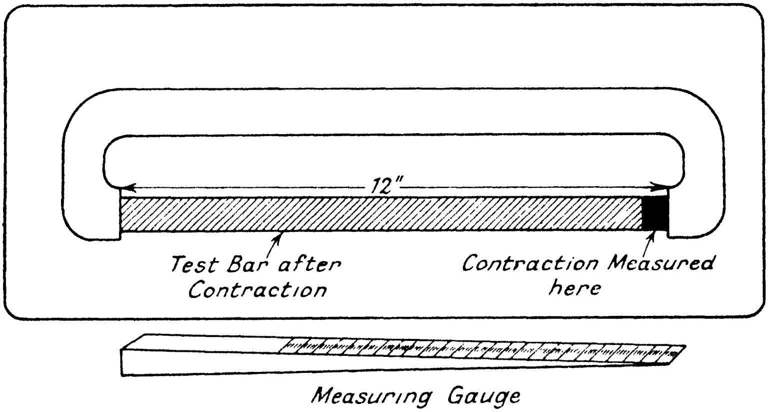


FIG. 208.—Apparatus for Keeps Test.

Growth of cast iron. Growth is the permanent increase in volume which occurs when certain types of grey iron are subjected to repeated cycles of heating and cooling. In extreme cases the increase in volume may be as much as 50 per cent. Growth seriously lowers the strength of cast iron and causes brittleness.

Growth in its initial stages is expansion caused by graphitisation of the carbide or cementite. The second cause is intergranular oxidation due primarily to the penetration of hot gases by way of the graphite flakes, giving internal oxidation of the iron and its constituents, especially silicon. On heating to red heat, oxidising gases enter at the sides of the graphite flakes producing sheaths of oxide round them, and eventually this passage becomes blocked with oxide so that on continued heating the growth becomes much slower. On cooling the oxide layers associated with the graphite crack and tend to disintegrate, producing new passages into which the oxidising gases may enter. With further reheating more oxidation and more growth take place.

Irons higher in silicon, with their more open grain and larger and more abundant graphite flakes, are more prone to growth than low-silicon irons with dense structures.

Growth is restrained by certain alloying elements, notably chromium, on account of the more stable character of the carbide when these elements are present.

High-strength cast irons. High-strength cast irons, sometimes known as high-duty cast irons, are special irons with superior properties, and produced by a number of methods. Strict attention is paid to control of the quantity, condition and distribution of the graphite, and to the promotion of a fine pearlitic or sorbitic matrix. Irons falling within this class contain low carbon, low phosphorus, correctly balanced silicon contents, and very often the inclusion of definite quantities of the more expensive alloying elements.

In the cupola, high-strength iron is made by the melting of charges containing high proportions of good quality steel scrap, with a suitably low coke bed. A dense coke is used which minimises the amount of carbon pick-up. The casting temperature of the metal is also a factor which determines the strength of the iron from the cupola, and should be poured as hot as possible to give the best graphite structure. Cupola-melted iron superheated in the electric or rotary furnace (duplexing) further improves the strength of the metal by refinement of the graphite structure, although the actual pouring temperature for the best results is not the maximum possible in these furnaces, but the extra benefit in graphite structure refinement is obtained by allowing the superheated metal to cool to about 1550 to 1450°C. before pouring.

A process which is finding increasing favour is that known as inoculation. An iron is melted having a composition which, when cast in the normal manner, would give a white fracture on cooling, but the addition of relatively small amounts of certain materials to the molten iron causes precipitation of graphite and a strong dense grey iron of low silicon content is produced. Those materials which have the most drastic effect on graphitisation are ferro-silicon, ferro-silicon with nickel shot as in Ni-Tensyl,[1] or calcium silicide as in Meehanite.[1] Tensile strengths in the order of 25 tons per sq. in. are obtained, and which can be further improved by suitable heat treatment. Titanium is sometimes added as either ferro-titanium or ferro-silicon-titanium. The inoculating effect of titanium is somewhat milder than that obtained with the other materials, but it serves a dual purpose as it deoxidises in addition to graphitising.

Another form of inoculation sometimes used is to mix molten irons from two cupolas. In one is melted metal charges containing high proportions of steel scrap along with some pig iron rich in silicon, giving a hard iron with low carbon and fairly low silicon contents. A soft mixture containing normal amounts of silicon and carbon as used for general foundrywork is melted in the other. A predetermined amount of soft iron is poured into a ladle containing a suitable quantity of the molten hard iron. The resultant iron from this mixture has a close and uniform structure with a tensile strength of about 18 to 22 tons per sq. in. and good machineability.

The Lanz Perlit method of producing high-strength castings employs the pouring of a low silicon iron into a sand mould which has been preheated to a given temperature, usually in the region of 400°C. The iron when poured into a cold mould would show a white or mottled fracture, but the slower rate of cooling induced by the hot mould gives an iron with a close grey structure and which is pearlitic in character. Castings of uneven section are obtained remarkably uniform in hardness, and having good growth-resisting properties.

The introduction of various amounts of alloying elements, such as nickel, chromium, molybdenum, vanadium and copper, is made to produce certain high-duty irons, frequently having other special properties including wear, corrosion and heat resistance.

Effects of alloying elements. Alloying elements are added to cast iron to improve its mechanical properties by modifying the condition of the matrix. Usually the amount of carbon required

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[1] Manufactured under patent.

to form pearlite is less in irons containing alloying elements, the matrix is generally tougher and harder, and the graphite finer. For most purposes, castings are made in non-alloy iron, and resort is only made to alloy additions when special physical requirements are to be met, and even then care and discretion is necessary if economic benefit is to be gained by their use.

Nickel is perhaps the most common alloying element used and normally added to grey iron and in proportions of 0·25 to 4·0 per cent. It has a graphitising effect about one-third as effective as that of silicon, and its addition is made at the expense of silicon. For example, to produce a 1·2 per cent nickel iron of equal graphitising tendency as a 2 per cent silicon non-alloy iron, 1·6 per cent of silicon should be associated with the nickel. Nickel reduces chilling effects, softens iron in thin sections, and equalises to a great extent hardness values in castings of varying section. It reduces cracking in castings of thin section, also reduces shrinkage, and tends to minimise porosity in heavy sections. It promotes a fine pearlitic structure with fine graphite flakes, resulting in a slight increase in strength; but for the purpose of increasing strength alone, nickel additions are not justified economically.

Chromium has the opposite effect to silicon, as it strongly suppresses the formation of graphite, that is to say, it forms carbides. The addition of a predetermined amount of chromium has a similar effect to the subtraction of a corresponding amount of silicon. The carbides promoted by chromium are much more stable than the carbides in chromium-free iron, and are resistant to graphitisation under the application of heat, rendering chromium irons less partial to growth. Chromium increases strength, hardness and chilling effect in cast iron. Its presence in quantities approaching 1 per cent, introduces machining troubles unless the hardness induced is offset by additions of other elements.

Nickel and chromium are often used together to obtain the benefits gained by the use of each, whilst at the same time their disadvantages are neutralised. The ratio used is usually 2½ to 3 parts of nickel to 1 of chromium in a range of selected quantities to suit various purposes, up to 3 per cent and 1 per cent respectively. The industrial applications of nickel chromium cast irons are for castings of greater toughness, hardness, strength and wear resistance, without material sacrifice of machining properties.

Molybdenum is used as an alloying element for cast iron, either alone, or along with others such as nickel and chromium. In the lower range of additions the element forms solid solutions with ferrite, but as the amount of molybdenum is increased it has definite double carbide-forming tendencies which become pronounced as the molybdenum content exceeds 1·2 per cent (Fig. 211). With additions up to about 1·5 per cent tensile strength, transverse strength and deflection are improved. It promotes uniformity of structure and hardness in thick sections, although its general effect is to increase hardness. Shock resistance is considerably improved, and with a content of about 0·5 per cent molybdenum the impact value is approximately double that of molybdenum-free iron. Owing to its high cost, molybdenum is used with discretion, and in special circumstances for engineering purposes where the benefits obtained justify the extra cost. The technique of its use has been developed to an appreciable extent in the U.S.A.

Nickel-molybdenum irons sometimes find application in the manufacture of brake drums, pressure and machine-tool castings, and drop-forging dies ; and chromium-molybdenum irons in cylinder blocks and heads.

Vanadium is the most powerful of the carbide-forming elements. Increasing quantities progressively increase hardness with corresponding increase in strength, but the strength increase is greater when vanadium is used in conjunction with other elements such as chromium, copper, nickel, and molybdenum. The carbides are stable at elevated temperatures which give vanadium-containing irons the property of heat resistance.

Some applications are for mill rolls, grate bars, forming dies, etc.

Copper dissolves in iron in proportions up to about 3 per cent and has a slight graphitising effect. It has only a moderate effect in improving the strength of cast iron. It slightly softens the matrix of close, hard and phosphoric grey irons, and the author has found that the presence of around 1 per cent aids machining. Its chief effect is in increasing resistance to atmospheric corrosion and mildly corrosive salt solutions.

Heat-resisting cast irons. Although a close-grained iron resists heat better than one with open grain, in general the most highly resistant are those which contain stable carbide-forming elements such as chromium and vanadium.

Irons containing chromium in relatively small amounts are heat resisting due to the prevention of graphitisation under the influence of heat, and for this reason chromium is used in white iron annealing boxes or cans. For severe high-temperature service over considerable periods of time, irons containing between 24 and 35 per cent chromium and 1 to 2 per cent carbon are extremely resistant to growth and oxidation, those of higher chromium content being immune to oxidation at temperatures approaching 1100°C. The structures of these irons are ferrite-carbide.

Certain types of austenitic cast iron offer excellent heat resistance, amongst which should be mentioned " Ni-resist " and " Nicrosilal." The former has the approximate composition of total carbon 2·5, graphitic carbon 1·7, nickel 16, copper 7, silicon 1·1, and chromium 3·5 per cent; having a fine graphite structure in an austenite matrix. " Nicrosilal " contains approximately total carbon 1·8, combined carbon 1·5, nickel 18, silicon 5·5, and chromium 2 per cent, and has a very fine graphite structure with chromium carbides in an austenite matrix. The tensile strengths of these irons, 15 to 25 tons per sq. in., compare favourably with those of high-duty cast irons.

" Silal," a heat-resisting iron, containing about 6 to 8 per cent silicon and 2·25 per cent carbon, was developed by the British Cast Iron Research Association. It consists structurally of very fine graphite in a ferrite matrix. It is suitable for service at temperatures up to 850°C., but, owing to its rather brittle nature, the material is not used under conditions of stress.

The production of castings in heat-resisting irons is expensive on account of the high price of some of the alloying materials involved, but this increased cost over other types of iron is usually compensated for by the greater length of service obtained, less frequent replacement, and lower maintenance costs. Alloy heat-resisting irons are extensively used for fire bars, annealing boxes, manifolds, stoker and furnace components.

Wear-resisting cast irons. In the ordinary non-alloy types of cast iron the relative amounts of ferrite and pearlite, or pearlite and cementite, affect the wear resistance. It usually follows, therefore, that increasing amounts of pearlite give a harder and more wear-resisting material in grey iron; whilst similarly increasing amounts of cementite at the expense of pearlite give irons which are whiter and harder. The hardness of ordinary cast iron varies from about 140 Brinell for ferritic irons to about 440 for white iron. Alloying elements such as nickel, chromium and molybdenum increase the amount of wear resistance of pearlitic cast irons and has led to their use in automobile engineering in the form of cylinder blocks, brake drums, brake shoes, etc.

White irons either unalloyed or containing small percentages of chromium to harden the carbide, have many uses, including the manufacture of crushing machinery, chilled iron rolls and plough points. The higher the carbon, the harder the iron owing to the greater amount of massive cementite, but the brittleness is proportionately increased. Further improvement in resistance to wear is effected by the promotion of a martensitic matrix, with or without the presence of troostite. This can be accomplished by heat treatment. Alternatively, for maximum wear resistance, drastic quenching in heat treatment with its attendant disadvantages of extreme brittleness can be avoided by the addition of suitable quantities of alloying elements, to allow harder and martensitic structures to be formed by milder quenching or by simply cooling in a normal manner.

Cast irons containing about 3 per cent nickel are martensitic on quenching in oil, and with a nickel content of 4½ per cent they are martensitic in the cast state. To obtain maximum hardness, chromium or other carbide-forming elements are added to counteract the graphitising tendencies of the nickel.

The " Ni-hard " type of low silicon irons (0·4 to 0·8 per cent silicon) with nickel contents ranging from 1 to 5 per cent and chromium from 1 to 2 per cent, give a wide choice of combinations for the production of wear-resisting irons. In these irons carbon has some influence upon the properties. With 3·2 to 3·6 per cent carbon the highest hardness values are obtained, whilst lower carbon contents from 2·7 to 3·2 per cent give increased toughness with a slight decrease in hardness.

High hardness values are also obtained by the use of manganese and molybdenum together as alloying elements in cast iron containing 1 per cent or so of silicon. Manganese contents exceed 2 per cent, with 1 to 3 per cent of molybdenum.

Typical applications of wear-resisting cast irons are for shot- and sand-blast machines, grinding machinery, fan blades for pulverised fuel, conveyor and sand mill parts.

Corrosion resistance. Corrosion is caused by either chemical action, electrolytic action and more often a combination of both. Corrosion by chemical action is by direct attack such as in rusting, or comparatively rapid solution of the metal when in contact with acids. Electrolytic corrosion may be due to contact with other more or less electro-negative substances ; or in these days of electrification, to the influence of stray or outside currents.

The extent to which the iron is chemically homogeneous also has some influence on the resistance to corrosion, so that, generally speaking, close-grained irons in which the graphite is fine and evenly distributed are considered to be superior in this respect than the open graphitic irons. The austenitic cast irons with their homogeneous matrix are highly resistant to many corroding influences.

Surface defects such as shrinks, inclusions, and blowholes act as centres, and have the effect of accelerating corrosion. Increasing temperature which generally speeds up the chemical action naturally increases the rate of corrosion. (Of course there are exceptions to this rule, especially in the case of water and certain salt solutions, because the increase in temperature decreases the solubility of oxygen in the water. Since the presence of excessive dissolved oxygen in water is often responsible for the corrosion of cast iron the removal of oxygen by heating the water will minimise further corrosion.)

The improvements in corrosion resistance brought about by small additions of alloying elements to cast iron, or the control of the condition of the graphite are only of a minor character. Copper additions assist in combating mild corrosive influences, but it is only when irons contain high proportions of silicon or chromium ; or are made austenitic by substantial additions of certain other alloying elements, that they have the greatest resistance to attack from a greater variety of acids and solutions.

The acid-resisting high silicon irons containing 12 to 16 per cent silicon have been used for many years in the chemical industry, and appear to be the best all-round materials for resistance to most acids and solutions, being practically unattacked by sulphuric, nitric, hydrochloric and acetic acids, whether concentrated or dilute, and hot or cold. They are not, however, suitable for substances such as bromine, caustic solutions and hydrofluoric acid ; also their chief disadvantages are hardness, brittleness and low-strength values.

Cast irons containing 2 per cent or so of carbon, and chromium in percentages ranging from 15 to 35, may also be used in contact with a number of corrosive chemicals, but they are not in general so resistant as the high silicon irons, neither is their range of application so wide. They offer good resistance to sulphurous gases.

The most popular type of corrosion-resisting materials are those of austenitic structure. Nicrosilal and Ni-resist, which have previously been described as heat resisting, are also corrosion resisting, especially Ni-resist. Whilst Nicrosilal resists many types of chemical attack in addition to being highly heat resistant; when corrosion resistance is required, Ni-resist (Nimol) is recommended. The alloys overcome the disadvantages of the 12 to 16 per cent silicon irons, in that they are easily machineable and take a high finish. They also give definite elongation values in the order of 1 to 3 per cent, and consequently these alloys are tough and have a good resistance to shock.

Corrosion-resisting cast irons are used in chemical plant, electrical gear, laundry and food-preparing machinery.

Introduction of the alloys. *Nickel.* For ladle additions in not too great an amount, the nickel in the form of shot is introduced to the metal stream in the spout, preferably through a funnel devised to ensure a steady and uniform addition, thorough solution, and good mixing in the ladle. When higher percentages of nickel are required, and the supply of molten nickel-alloyed iron is to be continuous, the alloy may be added to the charges in the form of ingot or nickel-containing pig iron.

Chromium and vanadium are not so readily dissolved in molten iron. Small ladle additions can be made with ferro-alloys, although precautions are necessary against losses due to incomplete solution. The iron must be hot, and the alloy well stirred and mixed into the metal for complete solution. The most satisfactory method is to make the addition in the form of chromium or vanadium-bearing pig iron.

Molybdenum may be introduced as a ladle addition via the spout in the form of ferro-molybdenum (55 to 75 per cent Mo). Calcium molybdate may also be used.

Copper readily alloys with molten iron. For small batches of metal, it may readily be introduced into the ladle of iron as the ladle is filling; or when a continuous supply of copper-containing iron is required, copper bolts, plate or other forms of scrap can be added to the charges.

Silicon is usually incorporated in the charges as ferro-silicon, of which there are several grades of different silicon contents.

Manganese is available for additions in the form of spiegeleisen (20 per cent Mn) or ferro-manganese (80 per cent Mn) containing about 5 to 7 per cent carbon and the balance chiefly iron.

For irons containing high proportions of alloying elements, as in the austenitic irons, where large additions of alloying elements to the ladle are not practicable due to the drastic cooling effects on the molten metal, specially chosen alloy pigs or other alloys such as Monel metal are used in the charges.

Heat treatment. Heat treatment may be divided into four distinct procedures, each treatment being intended to serve a particular purpose.

(1) Low-temperature treatment for the relief of internal stress in castings. Many types of castings, particularly those with sudden changes of section, also those of the plate, spoked-wheel or hollow-cylinder types, contain on cooling from casting temperature, internal stresses which may sooner or later result in cracks or complete fracture, either before or after the part has been placed into service. Although prevention of internal stresses is better than cure, by allowing the casting to remain in the mould until completely cool, by strict attention to design of the casting and the gating of the mould, it is not always possible to avoid its presence.

There are two methods of stress relieving generally employed. One, which is old fashioned and rapidly disappearing from use, is often known as " ageing." The casting is allowed to " weather " at normal temperature for very long periods, usually extending into years. There is no question that this method does result in stress relieving to some degree, but it suffers from the great disadvantage of the time factor, and even then there is always the uncertainty whether the relief of stress has proceeded to the desired extent.

The more satisfactory, quicker and modern method is to heat the casting in a furnace, preferably of the muffle type, at a slow and uniform rate to a temperature of between 425 and 500°C., for periods ranging from 30 minutes to 6 hours, depending upon the design and size of the casting. The maximum results are obtained when they are soaked for a period of several hours at the chosen temperature. The castings are allowed to cool slowly in the furnace, those of heaviest section requiring the slowest cooling rates, for it will be appreciated that quick rates of cooling after treatment would, to some extent, defeat the purpose of the treatment by introducing temperature gradients in the castings during cooling, and which would, of course, reintroduce further internal stresses. The low-temperature treatment outlined above has little effect on the hardness, strength, and structure.

(2) Quenching and tempering treatment to introduce predetermined hardness and strength. As with steel, the constitutional changes taking place on heating cast iron are reversed on cooling. There are, however, other factors which influence the structure when iron is heated. When heated to temperatures above the Ac_1 point, in addition to the pearlite change, a portion of the graphite is redissolved. Rapid cooling by quenching tends to retain the redissolved graphite in solution in the austenitic or martensitic form. The size of the graphite and the condition of the matrix play a part in determining the potential hardness of a cast iron when quenched. Fine graphite dissolves with much greater ease than coarse graphite, and consequently higher hardness values are obtained with irons containing finer graphite. Hardening can readily take place with even ferritic irons, in addition to those with pearlitic and cementite-pearlite structures, provided that the graphite is sufficiently fine. In white irons, hardness can be increased from 400 to 650 Brinell by quenching.

Prior to quenching, the castings are heated uniformly and relatively slowly to the quenching temperature, and maintained at that temperature until the heat has penetrated uniformly. Quenching is usually carried out in oil (water being too drastic for most purposes, causing quenching cracks). Hardening will take place on quenching from above the Ac_1 point but, for the best results, temperatures of 850 to 875°C. are employed. Quenching without tempering results in a considerable loss in strength which can be regained and often substantially increased above the original by tempering at temperatures of 300 to 400°C. As with hardened steel there is a steady decrease in hardness with increasingly higher tempering temperatures.

The alloying of the carbide stabilising elements, nickel, chromium, and molybdenum in suitable amounts affects the temperatures of the critical points, permitting slower critical hardening speeds and less drastic quenching treatments. Nickel and chromium contents in the order of 3 per cent and 1 per cent respectively give irons having pronounced air-hardening tendencies.

Heat-treated irons have been used with success in the automobile industry for cylinder liners, camshafts, piston rings, etc.

(3) Annealing treatment as an aid to machineability, and to remove local hard spots or hard skins due to chilling. In the treatment all or part of the free cementite, or the cementite of the pearlite may be removed, resulting in a casting which is either completely or partially softened.

As previously explained, graphite is redissolved on heating to above the critical Ac_1 point. Now when the iron is slowly cooled, this graphite is again precipitated, along with a precipitation of additional graphite which would normally exist in the carbide of the iron in the cast state. The iron after relatively slow cooling is therefore more ferritic and contains more graphite than the iron in the original cast condition. With correct soaking times at the chosen temperature, and suitable cooling rates, the carbide may be completely decomposed into ferrite and graphite, such irons exhibiting structures of phosphide eutectic and graphite in a ferrite matrix (Fig. 214, facing p. 225).

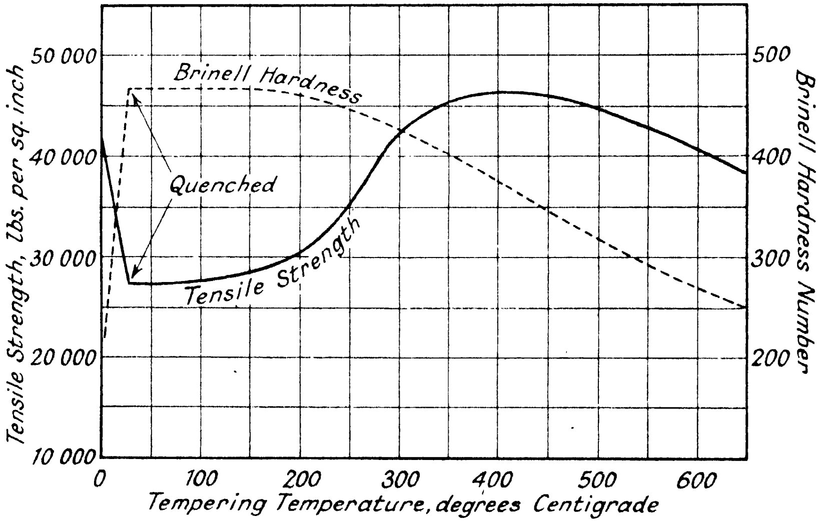


FIG. 212.—Hardening and Tempering Curves.

The usual annealing temperatures for ordinary grey iron are 760 to 820°C., and the time about 1 hour for every inch of section, but it is often necessary to employ somewhat higher temperatures for irons containing small amounts of the carbide stabilising alloying elements. An ordinary grey cast iron of 1½ in. section containing percentages of about 2·1 silicon, 3·2 total carbon, 0·6 combined carbon and 0·85 phosphorus, with a Brinell hardness of 225 to 230, will, after soaking for 1½ hours at 820°C. and cooling over a period of 3 to 4 hours, be reduced in hardness to a Brinell of 150 to 160.

There is usually a loss in strength in addition to the softening effect, but this is not consistent in amount, and will vary according to the composition and the initial physical condition of the iron. Retention of strength after annealing treatment appears to be most marked with irons of lower silicon and carbon contents, whilst iron cast in permanent moulds usually shows an increase in strength.

(4) The specialised heat treatments of Shorterising and nitriding can be applied to cast iron in a similar manner as to steel.

Flame hardening or Shorterising gives cases of suitable thickness and hardness.

Nitriding is used to surface harden certain machined castings to 800 to 950 Brinell. The alloy irons employed are of the low carbon variety (approximately 2·6 per cent carbon) and contain up to 1·5 per cent each of chromium and aluminium, often along with a little nickel to induce toughness.

Machineability of cast iron. The chemical composition, structure and physical properties extend over a wide range and, because machineability is dependent upon these factors, cast iron varies from a very easily machined material to one of the most difficult. Since these three factors are closely related, machineability may be assessed and classified according to the structure of the iron. The most easily machineable, permitting high speeds, and giving the greatest tool life are the annealed non-alloy grey cast irons consisting of silico-ferrite and graphite.

Increasing amounts of pearlite with its laminations of hard carbide decreases machineability. Upon the appearance of massive free cementite, when the combined carbon is in excess of eutectoid proportions as in mottled irons, machining is only carried out at greatly reduced speeds. Graphite in iron is an aid to machining owing to its softness, and to its tendency to act as a lubricant for the tool.

White irons containing no graphite but consisting of pearlite and cementite are the most difficult to machine. Where machining of white iron (Figs. 215 and 219) is necessary, as in the case of chilled rolls, it is done at very slow speed, and usually with special alloy carbide-tipped tools. The lower the total carbon content of white irons, the less difficult it is to machine them owing to the reduced amount of cementite.

Generally speaking, the addition of alloying elements to cast iron results in an increase of hardness with a corresponding decrease in machineability. It is often found, however, that the refining influence on the graphite and matrix by small alloy additions permits machining by ordinary methods, of hardnesses above the limits of machineability of non-alloy irons.

Phosphorus in small amounts, evenly distributed, have not a serious detrimental effect on machining properties, but when present in such quantities that a network or segregates are formed, tool life is appreciably affected.

The degree of finish on the machined surface is influenced by a large number of factors other than metal condition, including the design of the tool, depth of cut, speed of cutting and so on. The character of the surface finish obtained in machining grey cast iron under suitable conditions is controlled largely by the hardness of the metal, and the size, quantity and distribution of the graphite. Rough machining of coarse-grained irons containing coarse graphite will usually give surfaces containing small pits caused by the tearing out of small particles of iron. Completely annealed irons with an abundance of graphite will exhibit machined surfaces with a more matt appearance than irons containing appreciable amounts of carbon in the combined form. Fine-grained high-strength irons containing fine graphite give surfaces of a smooth and dense appearance. They also allow more successful machining of fine sharp-tipped threads, for such threads machined in coarse-grained irons and those containing large graphite particles, tend to become rough and broken.

Irons containing hard spots or areas will show bright surface areas where the local hardness is experienced.

Specifications and tests. British Standard Specifications cover tensile and transverse tests. Two specifications are employed, one for general grey iron, and the other for high-duty iron. The round test bars are cast to a standard diameter to represent the cross-sectional thickness of the casting. The test bar is cast with a good surface finish, free from flaws, and tested in transverse between standard spans on the testing machine, and the deflection of the bar just prior to fracture is measured. Tensile test

Abstract—B.S.S. No. 321—1938

GENERAL GREY IRON CASTINGS, GRADES A AND C

Standard diam. of test bar	Distance between supports	*Transverse test*						*Tensile test*		
		Grade A			*Grade C*			Gauge diam. of test piece	*Min. ultimate tensile stress*	
		Min. breaking load on standard diam.	*Corresponding transverse rupture stress*	*Min. deflection*	*Min. breaking load on standard diam.*	*Corresponding transverse rupture stress*	*Min. deflection*		*Grade A*	*Grade C*
in.	*in.*	*lb.*	*Tons per sq. in.*	*in.*	*lb.*	*Tons per sq. in.*	*in.*	*in.*	*Tons per sq. in.*	*Tons per sq. in.*
0·6	9	530	25·1	0·08	420	19·9	0·06	0·399	12·5	10
0·875	12	1185	24·2	0·11	960	19·6	0·09	0·564	12	10
1·2	18	1950	23·0	0·17	1600	18·9	0·14	0·798	11	9
1·6	18	4280	21·4	0·12	3650	18·2	0·10	1·128	10·5	9
2·1	24	6660	19·6	0·15	6020	17·8	0·14	1·596	10	9

Abstract—B.S.S. No. 876—1938

HIGH-DUTY IRON CASTINGS, GRADES 1, 2 AND 3

andard am. of st bar	Distance between supports	*Transverse test*									*Tensile test*			
		Grade 1			*Grade* 2			*Grade* 3				*Min. ultimate tensile stress*		
		Min. breaking load on standard diam.	*Corresponding transverse rupture stress*	*Min. deflection*	*Min. breaking load on standard diam.*	*Corresponding transverse rupture stress*	*Min. deflection*	*Min. breaking load on standard diam.*	*Corresponding transverse rupture stress*	*Min. deflection*	*Gauge diam. of test piece*	*Grade* 1	*Grade* 2	*Grade* 3
in.	*in.*	*lb.*	*Tons per sq. in.*	*in.*	*lb.*	*Tons per sq. in.*	*in.*	*lb.*	*Tons per sq. in.*	*in.*	*in.*	*Tons per sq. in.*	*Tons per sq. in.*	*Tons per sq. in.*
0·875	12	1270	25·9	0·11	1420	28·9	0·12	1620	33·0	0·13	0·564	15	18	22
1·2	18	2120	25·0	0·16	2370	28·0	0·17	2630	31·0	0·18	0·798	14	17	20
1·6	18	4800	24·0	0·13	5400	27·0	0·14	6000	30·0	0·16	1·128	13	16	19
2·1	24	8000	23·6	0·17	8850	26·1	0·19	9850	29·1	0·21	1·596	12·5	15	18

SUMMARY OF TESTING REQUIREMENTS

bars are machined to standard dimensions to bear some relation to the original dimensions of the transverse test bar, and turned from the broken halves.

Other common properties of cast iron. *Compressive strength* is regarded, next to transverse and tensile strength, as the most important property. There does not appear to be any direct relationship between tensile strength and compressive strength. It is about 4 times the tensile strength for the weaker irons, and 3 times for high-strength irons.

Shear strength is sometimes valuable for giving an indication of the local strength of a casting. Again there is no direct relationship to tensile strength, being about 1 to 1·6 times the tensile strength, the wider ratios applying to the weaker irons.

Endurance limit. Recent work carried out by various investigators shows that the ratio of fatigue strength to tensile strength is roughly 0·40 to 0·57, giving for grey irons fatigue strengths of between 4 and 11·5 tons per sq. in.

Impact. Owing to the comparatively brittle nature of cast iron, the standard methods of testing cannot generally be employed. The close-grained irons with greater plasticity, and which give greater deflection values, are usually more resistant to shock.

Tensile strength at elevated temperatures. Short-time tests show that cast iron loses little of its strength up to the temperatures of about 425°C. Above 475°C. there is a considerable loss of strength which continues with increasing temperatures. These temperatures do not apply of course to certain alloy cast irons, with which strength is retained at higher temperatures.

Specific gravity varies with the quality of the metal, from about 7·0 for a common coarse-grained iron, to 7·4 to 7·6 for high-duty irons, and 7·7 for white iron.

CHAPTER 9

MALLEABLE CAST IRON

MALLEABLE cast iron may be described as an intermediate product between ordinary cast iron and mild steel or wrought iron, having a fair amount of ductility and therefore having more resistance to shock than cast iron, but having less ductility than mild steel.

There are two types of malleable iron, namely, white-heart originating from the experiments by Réaumur in Europe in 1722, and blackheart developed by Boyden, an emigrated Englishman in America, about one hundred years later. These names have arisen from the appearance of the fractures of the finally annealed material. When fractured, whiteheart exhibits a dull grey appearance similar to steel, merging into a bright and somewhat crystalline centre or core, whilst black-heart is uniformly black in texture excepting for a slightly lighter rim seen on the extreme edge.

BLACKHEART MALLEABLE IRON

The metal mixture for the production of blackheart malleable is computed from pig iron, scrap, steel scrap, and ferro-alloys, to give a white iron free from primary graphite when poured into castings. Melting is carried out in either the acid open hearth, air furnace, rotary, electric furnace or cupola. Until recently the cupola has not been considered as being a satisfactory melting unit for blackheart malleable iron, but with strict metallurgical supervision it is possible to obtain a material having good physical properties, but somewhat inferior to that obtained from the other melting units mentioned above.

Although the base hard iron is in all instances white and brittle before the malleablising annealing process, the carbon-silicon ratio can be so balanced that the range of composition is greater than with whiteheart. The silicon and carbon contents of black-heart malleable iron produced in the cupola are rather different from those of metal produced in other furnaces. The total carbon content of the iron is usually considerably higher in cupola-melted material, and to avoid the presence of primary graphite in the castings, this high carbon value is offset by a lower silicon. The following gives the approximate compositional range of blackheart, the higher carbon, higher sulphur, higher manganese, and lower silicon values being found in the cupola-melted material.

Total carbon . . .	2·20 to 3·20	per cent
Silicon . . .	0·50 to 1·10	,,
Sulphur . . .	0·03 to 0·20	,,
Manganese . . .	0·20 to 0·55	,,
Phosphorus . . .	0·05 to 0·20	,,

In order to ensure a completely white fracture in the hard iron, it is often the practice to pour test pieces from time to time, which are allowed to cool comparatively slowly in an open sand mould, then in air to a temperature below 700°C., and the cooling finished by quenching in water. The bars being brittle, are readily fractured and, from the white condition or the amount of grey mottles found in the fracture, it is possible to assess roughly the suitability of the metal for the size of castings to be poured. Also the fracture of the test bar gives some indication of the correct mixing of the charges, and whether any alteration to the charges is required, particularly in the case of cupola metal. It is, of course, essential that accurate checks by chemical analysis are carried out at intervals. It is vital that the castings are free from primary graphite, as its presence persists during annealing and is a source of mechanical weakness in the finished product. As the effect of mass has a great influence on the cooling rate and the amount of graphite precipitation during cooling, it is usual to pour castings of thick section with iron lower in silicon or carbon than that used for the production of thin castings.

After fettling and cleaning, the castings are placed in round, square or rectangular white-iron cans, which are with advantage flanged at the top and built into a tier several high, up to a height of 6 or 7 ft., depending upon the height of the annealing furnace. Underneath the bottom can a robust stool with good strong legs is used which serves two purposes, firstly to facilitate the handling of a full tier of castings by allowing the prongs of the lifting gear on a petrol or electric truck to pass underneath, and secondly, to enable the hot furnace atmosphere to circulate underneath the bottom can of the tier. An older method, particularly with ovens of the " beehive " type, is to support the tier on bricks and pack the cans in the oven. After the anneal, removal of the bricks from one side then allows the tier to fall, and the annealed castings are unloaded at the oven.

Different types of castings require different means of packing before annealing. Thin and intricate castings are packed in some inert material such as burnt sand or ground slag in order to prevent warping under heat. More robust products may be loaded into cans without packing material, providing that sound cans and lids are used. It is essential that the furnace atmosphere, which may at times be of an oxidising nature, should not come into direct contact with the castings. To minimise this danger, a liberal application of strong wet luting mixture, which may consist of fine sand and intimately mixed clay, is well rubbed into the joints formed by the bottom of each can on the rim of the one directly underneath. A sound and well-fitting lid covers the top can of the tier, which in turn is rendered absolutely airtight with an application of luting mixture.

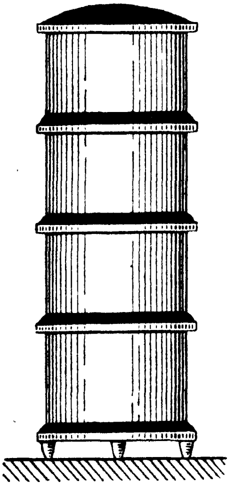
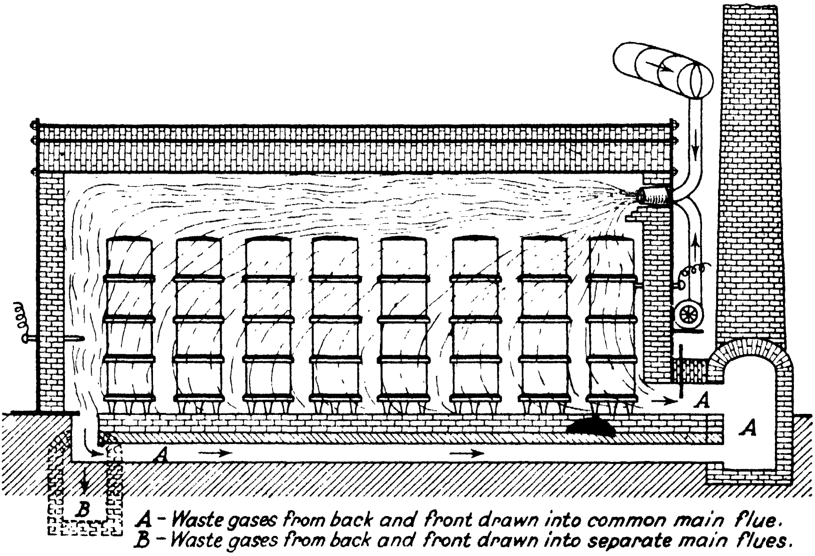


FIG. 216.—Illustrating the Arrangement of a Tier of Cans.

An annealing furnace of the batch type consists of a firebrick chamber, the size depending on the quantity of castings to be annealed. The flues for conducting away the products of combustion may be constructed in the floor of the furnace, the floor also consisting of firebrick. The walls and roof are completely encased with a layer of light insulating brick. Burners for the fuel may be located in the roof or walls, the position depending upon the shape of the furnace and the type of fuel used. Firing may be carried out with pulverised coal, gas, fuel oil or lump coal in a grate. Access to the inside of the furnace is made possible by a well heat-insulated door.

For the best results a soft-rolling flame is usually maintained during the whole firing operation. This is produced by using the minimum amount of air in excess of that required to effect combustion of the fuel. In addition, it is essential to have as part of the air used, an adequate amount of natural draught through the furnace to allow flexibility of flame control, carefully exercised by suitable flue dampers—too much draught being likely to cause a rather fierce flame which may result in hot spots or zones.

During the whole annealing process the temperature is strictly maintained by the use of reliable temperature recorders and indicators. Fuel low in sulphur content is preferred, as any sulphur dioxide which may reach the castings in excessive amounts promotes oxide-sulphide penetration at the grain boundaries at the edge of the casting, giving danger of peeling (Fig. 227).



A - Waste gases from back and front drawn into common main flue.
B - Waste gases from back and front drawn into separate main flues.

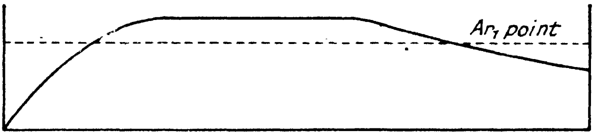
FIG. 217.—Typical Batch Annealing Furnace.

A modern development in annealing is to employ a continuous tunnel type of equipment where the castings are passed through the furnace temperature zones on a series of cars. The hard castings enter in the white state at one end and are withdrawn annealed at the other.

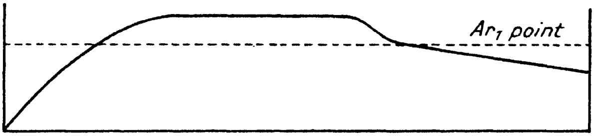
The annealing process. The annealing of blackheart malleable iron consists of three essential stages.

(1) A period in which to raise the furnace to a predetermined temperature known as the " at heat " temperature,

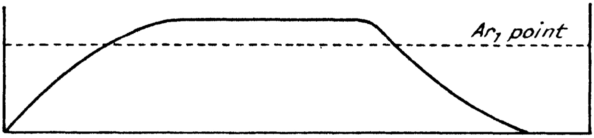
generally between 850 and 950°C., the choice of which depends upon the desired class and quality of the product, and also to a great extent upon the average composition of the metal. The temperature gradient is not forced but at such a rate that heating is uniform throughout the furnace. The rate of heating is also controlled of course by the size and capacity of the furnace and, with large furnaces holding 40 tons or more of metal, the time required may be in the region of 36 to 40 hours or more. The rate of heating, then, to the " at heat " temperature is as gradual as to ensure thorough and uniform heat penetration of the mass of product in the furnace.



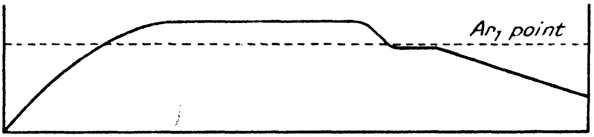
(1) Normal Anneal: Natural slow cooling.



(2) Normal Anneal: Cooling quick but retarded through critical temp.



(3) Quick cooling through critical temperature: Pearlitic Malleable



(4) Temperature held just below the critical: Pearlite Spheroidised

FIG. 218.—Graphs of Typical Annealing Cycles.

(2) The next stage is to maintain the furnace at the required temperature for a sufficiently long period to promote and complete what is known as first-stage graphitisation. This operation is the breaking down of the massive cementite or carbide

PLATE XV.

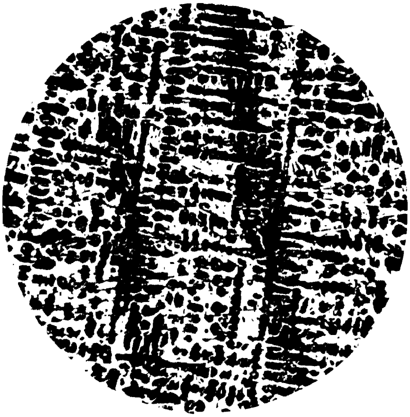


FIG. 219.—White Iron before annealing.
Etched. × 50 Dias.
(Cementite and pearlite.)

FIG. 220.—Blackheart Malleable Iron.
Unetched. × 50 Dias.
(Ferrite and graphite.)

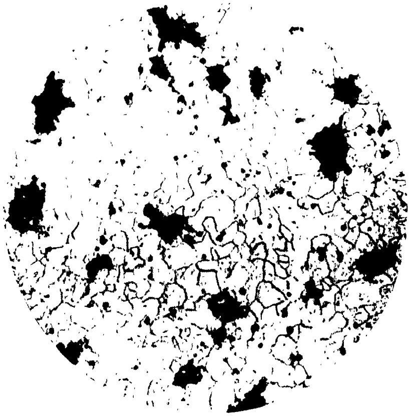


FIG. 221.—Blackheart Malleable Iron.
Etched. × 100 Dias.
(Ferrite grains and graphite.)

PLATE XVI.

FIG. 222.—Defective annealing. First stage graphitisation incomplete—some cementite still remains.

Etched. × 50 Dias.

FIG. 223.—Pearlitic Malleable Iron. Second stage graphitisation incomplete.

Etched. × 350 Dias.

Similar structures may be obtained by—

1. Quick cooling through Ar_1 point.
2. Incorrect analysis.
3. Alloying elements.

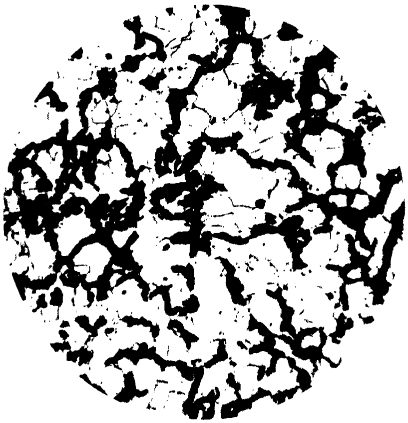


FIG. 224.—Annealed Structure of Blackheart Malleable Iron containing primary graphite before annealing.

Etched. × 100 Dias.

(Primary graphite and ferrite.)

PLATE XVII.

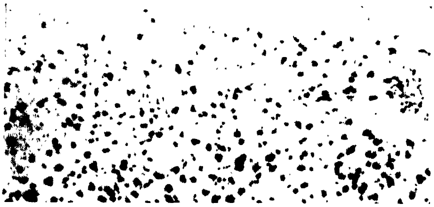


FIG. 225.—Blackheart Malleable Iron. Decarburised.
Unetched. × 20 Dias.

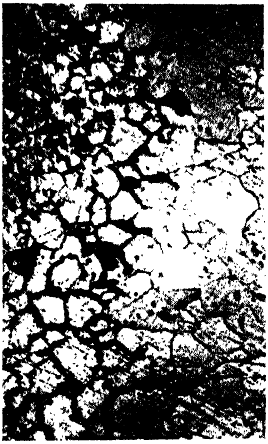


FIG. 226.—Blackheart Malleable Iron. Decarburised, also showing oxide penetration.
Etched. × 100 Dias.

FIG. 227.—Sulphur Print.
× 2 Dias.

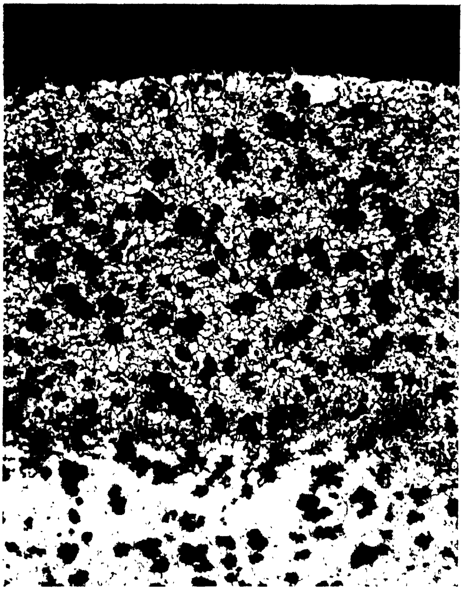


FIG. 228.—Showing sharp line of separation between affected rim and core.

Etched. × 25 Dias.

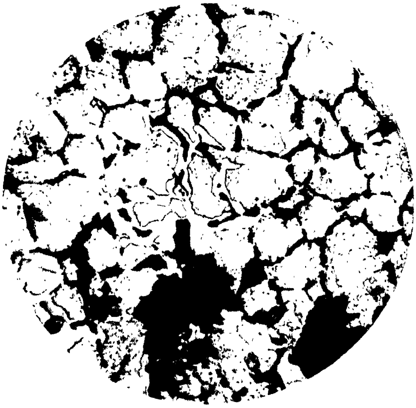


FIG. 229.—Showing sulphide network at grain boundaries.

Etched. × 150 Dias.

FIGS. 227, 228 and 229.—Structures of a Blackheart Malleable IronTest Bar annealed, using pulverised coal fuel rich in sulphur.

of iron, which is the hardest structural chief constituent of white iron. The length of time required for this purpose depends upon the temperature used. The higher the temperature, the more rapid the reaction. At 850°C. the period required is about 60 to 70 hours, whilst at 950°C. the reaction may be complete in about 30 to 36 hours.

A finer-grained metal is obtained by the use of lower temperatures, but the time factor involved is a great disadvantage in mass-production work. With metal of suitable analysis, reasonably fine-grained fractures can be obtained with moderately high annealing temperatures, although excessively high temperatures tend to give poor coarse-grained metal.

(3) The third and final stage of the annealing process is the cooling down period, during which second-stage graphitisation takes place. When the furnace has been maintained at heat for the required time, the fuel is shut off, any dampers closed, and all openings to the atmosphere are filled up with refractory material, thereby completely insulating or sealing off the furnace. The rate of cooling is extremely important, especially in the range 700–730°C., and care is necessary to ensure that it does not exceed 7° per hour through this range, and preferably less. Some furnaces may be so small that the natural cooling rate is in excess of that desired, but it may be retarded by relighting the furnace when it has reached a temperature of 730°C. and gradually reducing the fuel supply so that it takes up to 10 hours for the temperature to fall from 730 to 690°C. With the larger types of furnace this procedure is usually unnecessary as the cooling rate is naturally slow due to the larger bulk contained therein, but nevertheless the cooling rate is carefully observed at the critical period as a precaution against leaking flues or faulty heat insulation.

The structural composition of fully annealed blackheart malleable iron is a matrix of ferrite to which the iron owes its ductility, and fine evenly distributed particles of free carbon in the form of black rosettes known as "temper carbon." Ferrite is carbonless iron in which is dissolved the silicon and most of the manganese.

Theory of annealing. When the white iron is heated above the critical point, the pearlite is transformed to austenite with a carbon content of about 0·9 per cent. As the temperature is increased the austenite absorbs carbon from the cementite, the saturation depending upon the temperature. When the desired annealing temperature has been reached, maintaining at this temperature results in the austenite precipitating some of its carbon in the free state as very small particles of graphite, not in the form of flakes as in ordinary cast iron but as rounded particles (Temper carbon). From this point onwards two reactions take place.

Whilst free carbon is being precipitated from austenite thereby reducing the carbon content of the austenite, this loss is made good by solution of carbon from the cementite. Whilst the annealing temperature is maintained, the reactions continue until equilibrium has been reached when the structure of the iron consists of nodules of free carbon and saturated austenite. Continued holding at this temperature then produces no further precipitation of graphite.

At lower temperatures less carbon is required to give saturation of the austenite, so that when the metal is slowly cooled more free carbon is rejected until the recalescence point is reached. At this stage the austenite holds in solution about 0·45 per cent carbon.

If continued cooling is comparatively rapid, the remaining carbon is present as pearlite on reaching normal temperature, so that the final structure consists of temper carbon nodules surrounded by areas of ferrite (bull's-eye structure) in a matrix of pearlite. This quicker cooling through the critical temperature finds application in the production of the pearlitic malleable irons.

By cooling very slowly through and 20° or so below the critical temperature at a rate not exceeding 7° per hour, or by holding just on or just below the critical temperature for a few hours, the remaining carbon dissolved in the austenite will graphitise completely, giving the normal structure for blackheart malleable iron consisting of nodules of temper carbon in a matrix of ferrite (Fig. 221, facing p. 248).

Effects of common elements. *Carbon* in well-annealed material greatly influences the strength and ductility. Since the structure is a ferrite matrix with carbon modules dispersed throughout, greater carbon contents by virtue of the larger number of nodules, break up more the continuity of the ferritic matrix, and therefore the iron is generally less strong and ductile.

Silicon. The silicon content is governed by the size of the casting as previously indicated, and the carbon content. Higher carbon contents are better when associated with lower silicon contents. Increased silicon favours graphitisation and tends to promote more rapid annealing.

It has recently been discovered that ladle additions of very small amounts of tellurium (0·002 to 0·015 per cent) to the molten metal ensures an iron completely free from primary graphite.[1] The addition is effective when silicon contents are abnormally high, the result being that it is possible to pour heavy and light castings from metal of the same composition. The higher silicon allowed accelerates graphitisation in the annealing process and permits a somewhat shorter anealing cycle.

Sulphur has a strong restraining effect on graphitisation during annealing and is kept as low as possible.

Manganese must be present in sufficient quantity to minimise the deleterious effects of sulphur, that is, at least 1·7 times the sulphur content, which is the theoretical requirement to convert the sulphur to manganese sulphide. General practice is to use quantities in excess of this, the excess manganese required increasing with the sulphur content. Too great an excess, however, retards graphitisation to some extent during annealing, and will be dealt with further under the section dealing with pearlitic malleable iron.

Phosphorus has little or no effect under 0·20 per cent as it dissolves in the ferrite, but in excess of this amount insoluble free phosphide areas appear in the matrix, and is detrimental to the physical properties of the annealed product.

Chromium has a drastic effect in retarding graphitisation during annealing, even when present in small quantities. It is desirable that the chromium content does not exceed 0·05 per cent. As most pig irons and steel scrap contain varying amounts of chromium, it is necessary that great care is taken in the choice of raw materials.

Copper is not present in the iron in any substantial quantities as an impurity. When intentionally added in quantities approaching 1 per cent it tends to graphitise the hard iron, and irons of given silicon and carbon content tend to be more grey with the presence of copper than without. In general, irons containing additions of copper require a slightly lower silicon content, and promote a slight saving in annealing time due to acceleration of

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[1] **Process covered by Patent.**

graphitisation. The mechanical properties and corrosion resistance are slightly improved.

WHITEHEART MALLEABLE IRON

The melting of iron for the production of the whiteheart variety is usually carried out in the cupola. The metal melted must be low in silicon and phosphorus, and therefore the molten metal must leave the cupola sufficiently hot to have the necessary " life " or fluidity to successfully run castings of thin section.

For the charges, steel scrap, hematite pig iron or refined iron, foundry scrap, runners, etc., are mixed in such proportions as to give a white iron having the following range of analysis :—

Total carbon	2·8 to 3·2	per cent
Silicon	0·5 to 0·8	,,
Manganese	0·2 to 0·5	,,
Sulphur	0·15 to 0·30	,,
Phosphorus	0·06 to 0·10	,,

The hard white iron tapped from the cupola should contain no primary graphite, that is to say, all the carbon should be present in the combined form. Any graphite in the hard iron persists throughout the annealing process, and its presence in the finished product constitutes a source of mechanical weakness.

As in the case of blackheart malleable iron, castings of thick section are poured with iron lower in silicon, and whiter in test block fracture than that used for castings of thin section. Iron containing about 0·8 per cent silicon is used where possible for castings of thin section, ranging to approximately 0·5 per cent as the casting size increases.

After fettling and cleaning, the castings are packed in cans and surrounded with hematite iron ore low in sulphur content. During use, the ore, chiefly ferric oxide Fe_2O_3, is converted to the magnetic oxide Fe_3O_4, and it is general practice to mix used and new ores in the proportion of approximately five to one owing to the excessively rapid oxidation when all new ore is used. The reason for this will be apparent later.

The annealing temperature for the whiteheart material is usually higher than for blackheart. The period of heating is also longer but is determined by the size and thickness of the castings, and being considerably longer for thicker castings.

The reactions which take place during annealing are up to a point similar to those which take place in the blackheart process. On the surface of the metal, however, the austenite is impoverished in carbon due to oxidation by the iron ore, and as the austenite tends to maintain its saturation of carbon, migration of carbon takes place from the centre of the casting to the outside. It will be seen, therefore, that the oxidising conditions affecting the surface promote a concentration gradient of carbon from the surface to centre. Away from the surface material, graphitisation proceeds to some extent as in the blackheart process, but when decarburisation has proceeded to such a degree that there is no cementite left, the austenite then slowly tends to dissolve the already precipitated graphite. The migration of carbon then becomes so slow that it is overbalanced by decarburisation, and if the time of annealing or the proportion of used ore to new is not carefully regulated according to the sectional thickness of the castings, oxidation of the surface of the iron takes place.

Except in the case of castings of thin section, there is usually some temper carbon and pearlite in the centre. In the thin castings, owing to complete diffusion and oxidation of the carbon, complete decarburisation takes place giving a ferritic structure throughout, showing only ferrite grains in the etched condition with a little manganese sulphide.

It will be seen, therefore, that if the ore mixture is too strong, having too great a proportion of new ore, the rate of oxidation of the carbon in the outside layers exceeds the rate of diffusion of the carbon from the centre to the outside. In consequence some oxidation and penetration of oxide into the grain boundaries of the ferrite takes place, often resulting in scale formation on the outside of the casting.

Effects of common elements. These are much the same as for blackheart malleable iron excepting for chromium. Chromium is permissible in rather greater amounts than in blackheart, indeed its presence is beneficial in quantities up to about 0·1 to 0·2 per cent as it causes the carbon to separate out in small nodules and has a toughening effect, but more than this quantity reduces the rate of decarburisation and should be avoided.

Properties of malleable iron. Whiteheart malleable iron has a higher yield point than blackheart, and slightly better corrosion resistance. Owing to a practically continuous ferritic structure and absence from graphite particles on the pickled or polished surface, it electroplates and galvanises better than blackheart. With completely annealed product the material may be heated as for welding, also for straightening of distorted castings, and normalised without fear of producing the brittleness which occurs in blackheart when heated above the critical temperature, due to re-solution of some of the carbon.

With blackheart malleable iron, on reheating to approximately 900°C., the carbon modules are to some extent redissolved, and cooling in air produces a hard material with a white fracture. It has been found that excessive local heating produced when fettling an annealed casting on a grinding wheel, is sometimes sufficient to produce hard spots.

Blackheart malleable iron by reason of re-solution of carbon when heated, lends itself to heat treatment, and when quenched from red heat is capable of hardening and exhibiting a martensitic structure. Tensile strengths of 60 tons per sq. in. may be obtained, but with a considerable loss of ductility. Tempering is possible on the hardened material as in the case of steel, but ductility is not restored to the same extent until fully tempered at temperatures near to the Ac_1 point. On the fully tempered material the tensile strength still exceeds that of the original untreated material. Fig. 233 shows the structure obtained by such a treatment giving a ferrite-sorbite matrix, the sorbite being the fine half-tone areas round the graphite nodules. Lesser degrees of tempering produce more sorbite.

Like steel, blackheart malleable iron may be austempered. It can be carried out by two methods—heating the fully annealed material to about 900°C. and quenching in molten lead; or alternatively, by applying various annealing periods to the hard unannealed material and quenching direct from the annealing temperature. The iron is allowed to remain in the molten lead for 1 hour or more, after which time equilibrium is attained. The latter method produces a material with greater hardness, but the tensile strength and impact resistance are somewhat lower than obtained by reheating the fully annealed material. Varying physical properties are also obtained by using different temperatures for the molten lead. By austempering, the tensile strength may be doubled, giving a hardness approaching 400 Brinell with fairly good shock resistance and a little elongation.

Specialised treatments which show promise of successful development and increased application are those of case hardening by cyanide, and by surface flame hardening.

The former process is more applicable to whiteheart material, as the resolution of carbon in blackheart at the case-hardening temperature gives a brittle core when the material is quenched. With whiteheart material, if well decarburised during annealing, the case-hardening and quenching treatment will have little effect on the core. The castings are treated for about 30 minutes in a cyanide salt bath at a temperature exceeding 900°C. and quenched in oil. A treatment which will give a more ductile core especially if not completely decarburised in annealing is to cool in air from the carburising temperature, reheat to about 780 to 800°C. and quench in oil.

Flame surface hardening is only truly applicable to blackheart malleable iron owing to lack of carbon in the surface of whiteheart, for resolution. The heating flame is followed by a water jet and, since the heating is only local, the inside of the casting is unaffected whilst a good wear resistance is given to the surface.

Mechanical tests and specifications. The test requirements of the two materials differ as regards elongation and bend test, as it is recognised that blackheart is more ductile on account of being more homogeneous throughout the section.

	Whiteheart	*Blackheart*
Tensile strength .	20 tons per sq. in.	20 tons per sq. in.
Elongation . .	5 per cent on 2 in.	7·5 per cent on 2 in.
Bend test . .	45 degrees	90 degrees

B.S.S. 309–310.[1]

The tensile test bar is normally 0·564 in. in diameter with a gauge length of 2 in. For the bend test a square bar $\frac{3}{8}$ in. thick is employed and tested cold round a radius of 1 in.

Both materials have good machining properties, a rate of approximately 90 ft. per minute being specified in each case. Usually, blackheart machines better than whiteheart, especially when whiteheart is completely decarburised, in which condition the material tends to tear when high speeds are used, whereas the temper carbon in blackheart tends to act as a lubricant for the tool and promotes a smooth-machined surface.

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[1] To be revised in the near future.

Pearlitic malleable irons. One of the simplest methods of producing pearlitic malleable iron is to cool quickly from the annealing temperature. It may be also produced by subsequent heat treatment of the normally annealed product.

Alloying elements may be introduced into the mixture, which have the effect of retarding graphitisation. The most use is made of those elements which will retard second-stage graphitisation, that is, the final graphitisation which takes place during slow cooling through the Ar_1 point.

Such elements are chromium, manganese, molybdenum, nickel, and, to a lesser extent, vanadium.

Chromium may be introduced in quantities up to 0·4 per cent. Except when the chromium is present in relatively small quantities, some free cementite exists showing that first-stage graphitisation has not been completed, but this constituent is small in size and spheroidised, so that the shock resistance of the material is not impaired to the same extent as when the cementite exists in larger areas. The remainder of the matrix is largely composed of fine pearlite with a little temper carbon.

Manganese is introduced in quantities of about 0·5 per cent above that normally found in malleable iron. It is milder in its restraining effect on graphitisation than chromium. First-stage graphitisation at the " at heat " temperature is usually complete, and the structure of this type of material consists of temper carbon in a matrix of well-defined laminated pearlite with a little ferrite.

Molybdenum has found applications ranging in additions of about 0·2 to 0·5 per cent. Its action in retarding graphitisation is greater than that of manganese but less than that of chromium.

Vanadium, even in very small quantities, has a drastic effect in preventing decomposition of carbide, and usually some cementite of a massive nature is retained, resulting in a rather brittle material. It, however, increases wear resistance.

Nickel additions are made ranging from small quantities up to about 1½ per cent. It is milder in its restraining influence on carbide decomposition than the other alloying elements, and the pearlite matrix is often associated with considerable amounts of ferrite. This pearlite-ferrite structure has the effect of giving reasonable ductility and good resistance to shock, along with a substantial strengthening effect and higher yield stress value. The nickel-containing pearlitic malleable irons are sensitive to

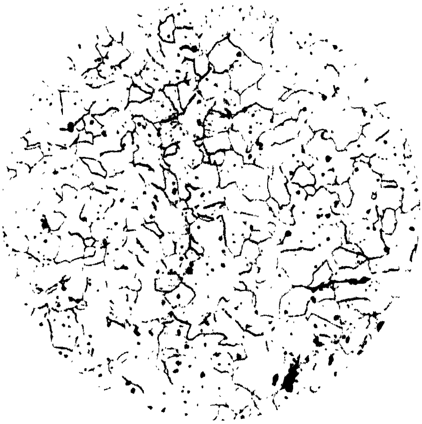


FIG. 230.—Structure near the surface of a Whiteheart Malleable iron casting.
Etched. × 100 Dias.

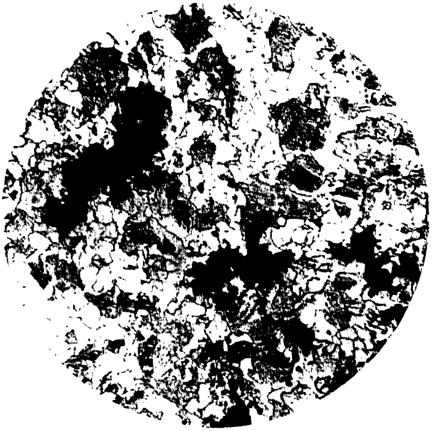


FIG. 231.—Structure near the centre of a Whiteheart Malleable iron casting.
Etched. × 100 Dias

PLATE XX.

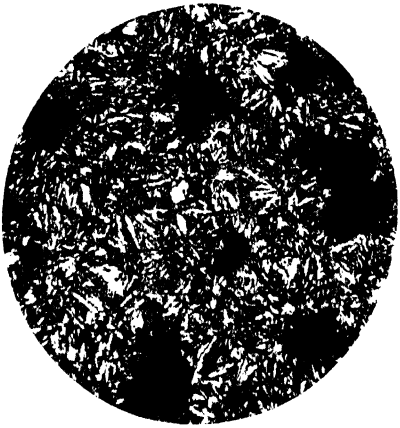


FIG. 232.—Blackheart Malleable Iron. Water quenched from 950° C.

Etched. × 100 Dias.

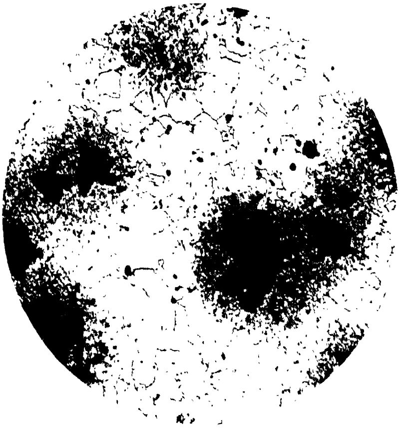


FIG. 233.—Blackheart Malleable Iron. Oil quenched from 900° C. and tempered at 630° C.

Etched. × 100 Dias.

(Note sorbitic areas round temper carbon nodules.)

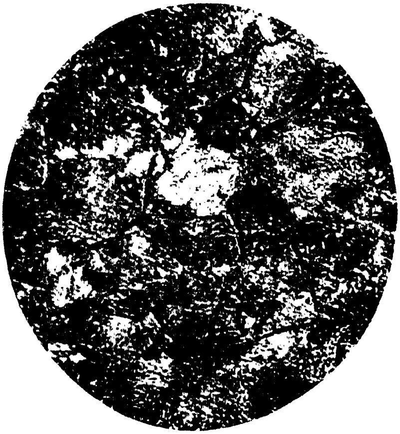


FIG. 234.—Blackheart Malleable Iron. Austempered.

Etched. × 500 Dias.

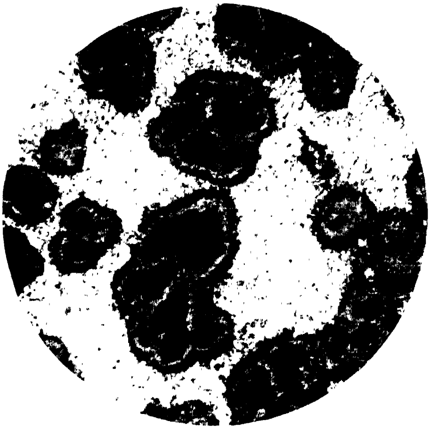


FIG. 235.—Flame-hardened Blackheart Malleable Iron.

Etched. × 100 Dias.

FIG. 236.—Flame-hardened Blackheart Malleable Iron.

Etched × 500 Dias.

(Note martensitic structure round what remains of the temper carbon nodules.)

heat treatment and tensile strengths in the order of 50 to 60 tons per sq. in. are obtained, also Brinell hardnesses of 340 to 360 with an elongation of about 1 per cent. As with the quenched steels ductility can be noticeably increased with increased tempering temperatures.

With many of these pearlitic malleable irons, rapid cooling from the annealing temperature, followed by a treatment of several hours just below the Ar_1 temperature produces an iron which is not strictly pearlitic, but where the laminated carbide which is found in pearlite has taken the form of small rounded particles, that is to say, spheroidising has taken place. Irons of this type are considered as being superior to the straight pearlitic malleable irons owing to the better elongation values obtained, whilst the tensile strength is not affected. The following range of mechanical properties can be obtained in pearlitic malleable iron by use of either short cycle annealing, heat treatment, alloy additions, or alloy additions with heat treatment. In general those giving the highest strength have the lowest elongation and highest hardness.

Tensile strength . . .	30 to 60 tons per sq. in.
Yield point	18 to 40 ,, ,,
Elongation	1 to 18 per cent on 2 in.
Brinell hardness . . .	150 to 350

Uses of malleable cast iron. Malleable iron is used where the high ductility of mild steel is not necessary, but where a stronger and less brittle material than cast iron is desired. It finds a wide application in the automobile industry for a number of small parts used in frames, wheels, brakes, etc., and for hubs, transmission gear housings and steering gear housings. There is also a large demand for castings to be used in agricultural machinery. Other uses are for pipe fittings, plumbing supplies, household hardware, burners, stoves, electrical and power equipment, railway work and many other purposes in a wide range of industries.

The pearlitic types of malleable iron are finding increased application in some instances as a substitute for steel, especially where toughness and resistance to shock is desirable and where high ductility is not necessary. Such products are elevator parts, chain links, sprockets, machine tool parts, conveyor links, etc.

CHAPTER 10

NON-FERROUS METALS AND ALLOYS

THE non-ferrous branch of metallurgy covers a wide range of metals and alloys, with a very comprehensive range of properties. Non-ferrous metals and their alloys are used in all branches of engineering, including electrical, automobile, marine, aircraft, chemical, in connection with steam plant, and also for domestic applications.

COPPER

Copper is a soft malleable metal, salmon-pink in colour, and its application either as copper or alloys of copper cover an enormous field in engineering industries. A great amount of copper is used in the electrical industry owing to its high electrical conductivity. Also large quantities are used in general engineering in the form of tubes, wire, rod, strip and sheet, and also in cast forms.

Copper is readily cold worked during which hardening takes place, and a fairly large range of mechanical properties is obtained by various degrees of working. Work-hardened copper can be softened by heat at temperatures upwards of 200°C. Copper and its alloys are easily jointed by brazing and welding.

Other mechanical properties are given below :—

	Tensile tons per sq. in.	*Elongation per cent.*	*Brinell hardness.*
As cast . .	8–11	25–30	40
Annealed . .	14–16	40–60	45–55
Cold worked . .	18–30	2–25	75–100

Small additions of other elements are often added to give copper specific properties ; for example, silicon may be alloyed in small quantities up to 0·2 per cent, when the tensile strength is increased without seriously affecting the electrical conductivity. For these reasons it is often alloyed with copper for telegraph and telephone wires.

The inclusion of small quantities of berylium is notable in that it increases the tensile strength of hard-drawn copper, making available material with tensile strengths of about 90 tons per sq. in. along with good fatigue and corrosion-resisting properties.

Effects of other impurities in copper. *Arsenic* increases the tensile strength and is used in quantities of 0·3 to 0·5 per cent. It raises the temperature at which the softening of hard-drawn copper takes place, tends to counteract the embrittling effects of excessive oxygen contents, and the tendency to crack when subjected to reducing conditions. Arsenical copper, sometimes called " tough copper," is therefore employed for loco fire-boxes, boiler tubes, bolts and rivets.

The other impurities listed below have deleterious effects on the physical properties of copper, and it is therefore desirable that their quantities are kept as low as possible.

Iron forms brittle solid solutions.

Antimony injures the cold-working properties.

Phosphorus is often used as a deoxidant, but, when present in excess, causes brittleness and seriously impairs the electrical conductivity.

Bismuth forms a eutectic with copper which has a very drastic influence on the properties. The eutectic tends to collect at the grain boundaries, causing brittleness and decreased cold-working properties. In view of the low melting-point of the eutectic, the tensile strength of copper containing bismuth is very low, and especially when used at temperatures above normal. Even very small amounts in the region of 0·002 per cent have a very harmful effect.

THE STRAIGHT BRASSES

Brasses are essentially alloys of copper and zinc. The addition of zinc to copper has the effect of lowering the melting-point of the alloy from that of copper to that of zinc. The alloy becomes stronger with percentages up to about 45 of zinc, and more ductile up to 30 per cent zinc.

Alpha brasses. These contain up to 39 per cent zinc and consist of a single solid solution. The colour varies from copper coloured to yellow as the proportion of zinc increases. The alloys are cored in the cast state, the dendrites being removed by annealing. They are very readily cold worked, this condition being easily recognised by the presence of strain lines, and after annealing by well-defined twinned crystals.

A popular brass within this range is 70/30 (70 per cent copper, 30 per cent zinc), giving maximum ductility withstanding a remarkable degree of cold work without fracture, and which is extensively used for condenser tubes, cartridge cases and other products which are deep drawn or stamped to shape. The effects of cold work are removed by annealing at 500 to 600°C., at which temperature they are fully annealed, giving the maximum ductility.

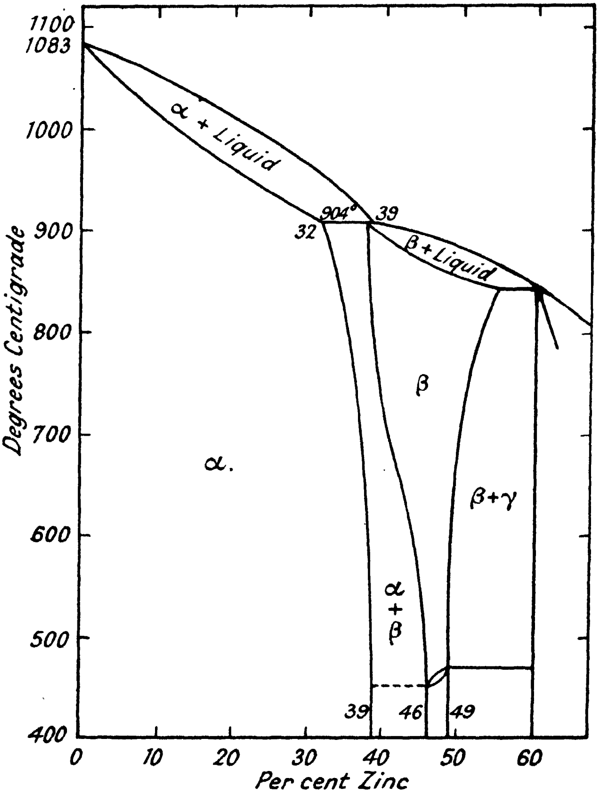


FIG. 241.—Equilibrium Diagram for Alloys of Copper and Zinc.

The alpha brasses amongst certain other non-ferrous alloys, due to internal stresses in worked articles, tend to suffer from intercrystalline cracks after being in service for some time. This effect is known as " season cracking." The trouble may be prevented by heating the material to a little under 300°C., a temperature where the structure and other properties are not affected.

A useful test which may be applied to indicate whether the material is in a state of internal stress and liable to season cracking, is to immerse it in dilute nitric acid followed by a 1 per cent solution of mercurous nitrate containing a little nitric acid. If the material is internally stressed, cracks will usually appear in about 30 seconds.

The alpha brasses are not normally hot worked. Typical mechanical properties of 70/30 brass are :—

	Tensile tons per sq. in.	*Elongation per cent*	*Brinel hardness*
As cast	15	40–50	55–65
Cold worked . . .	25–30	5–10	140–200
Cold worked and annealed .	18–22	55–65	60

Alpha-beta brasses. These contain between 46 and 49 per cent zinc, and are of importance because they come within the range where is found the best combination of strength and ductility. The structure consists, on normal cooling, of two constituents, the alpha and beta solutions. The beta solid solution is richer in zinc, and its quantity increases with the zinc content of the alloy. Reference to the equilibrium diagram will show that quicker cooling or quenching arrests the amount of alpha constituent, and by quenching from above certain temperatures depending upon the composition of the alloy it may consist entirely of beta. Owing to the brittleness of the beta constituent alloys containing less than about 60 per cent copper cannot be cold worked successfully, but the plasticity introduced over a wide range of temperatures renders these brasses very suitable for hot working and extrusion. They are harder than alpha brasses, machine very easily, have a marked resistance to corrosion, and in the cast state have a tensile strength of 22 to 25 tons per sq. in., 30 to 45 per cent elongation and a hardness of 90 to 100 Brinell.

Beta brasses. These contain between 46 and 49 per cent zinc, and are less ductile than the other brasses, and, as their composition is confined to narrow limits, care is necessary in their preparation so as to exclude brittle gamma constituent which appears when excess of 49 per cent zinc is present. The alloys have a pronounced resistance to corrosion, and may be used in marine work where ductility is not of primary importance.

Beta-gama brasses. These contain more than 49 per cent zinc. Owing to their low melting-point they find application in brazing, but, on account of brittleness, they are of little use for any other purpose.

Effects of other elements in brass. *Lead* is added to brass to promote easy machining and give a good finished surface on the material, and is generally present in stock used for machining in automatic machines. Lead does not dissolve in brass but exists as globules of free lead. If evenly distributed throughout, it does not greatly affect the general properties of brasses until 2 per cent is exceeded, after which it impairs the strength and ductility. Its presence in excess has a harmful effect on mechanical working properties.

Tin is only slightly soluble in alpha brasses, and as it increases resistance to corrosion by sea water, it is introduced in the region of about 1 per cent into 70/30 and 60/40 brasses, to which are given the names Admiralty Brass and Naval Brass respectively. Tin slightly increases the strength of brass when present in this amount.

Admiralty Brass, like ordinary 70/30, is readily cold worked, and in this condition a tensile strength of 40 tons per sq. in. may be obtained along with 10 per cent elongation. Amongst a wide variety of uses, it is employed for condensers, surface heaters and coolers.

Naval Brass is not so ductile in the cold state, but it is readily hot worked and used in the form of bolts, spindles, tubes and sheet. In the annealed state the average tensile strength is about 26 tons per sq. in. with an elongation of about 30 per cent.

HIGH-TENSILE STRENGTH BRASSES

High-tensile strength brasses are produced by the addition of other elements to brasses, generally those containing between 53 and 60 per cent copper. Some elements such as lead retain their identity in the alloys, but others form special structural constituents or enter into solid solution. The alloying elements are either added singly or in various combinations. The more common elements found together are iron, aluminium, tin, and manganese. Silicon and nickel are employed less frequently. There are many excellent high-strength brasses computed from combined additions of these elements, a number of the alloys produced being proprietary.

Each element has a definite influence on the structure of brass, exerting a similar effect to zinc additions but in varying degrees. Each of the common elements has been given by Guillet, a zinc equivalent value, so that if the composition of the alloy is known it is possible to forecast its structural constitution. The approximate zinc equivalent values are as follows :—

Silicon	10
Aluminium	6
Tin	2
Magnesium	2
Lead	1
Iron	0·9
Manganese	0·5
Nickel	—1·2

For example, 1 per cent of aluminium has a similar effect to 6 per cent zinc, whilst 1 per cent nickel acts in a similar manner to 1·2 per cent copper. To enlarge on the first example, a brass containing 38 per cent zinc would normally give an alpha structure, but when 1 per cent aluminium is present also, the equivalent zinc content would be approximately 44 per cent resulting in an alpha-beta structure.

Tin. In castings, owing to its limited solubility, an excess of tin gives a separate tin rich constituent which is harder than the matrix of the alloy. There is a slight increase in tensile strength with the presence of quantities approaching 1 per cent, but if serious loss of ductility is to be avoided this amount should not be exceeded. It is usually found in high tensile brass in the order of 0·5 to 1·0 per cent on account of its promotion of increased corrosion resistance.

Iron is encountered in most high-tensile brasses. It is soluble to a limited extent only, and, when present in amounts exceeding about 0·35 per cent, a separate iron-rich constituent appears, bluish in colour and rather harder than the matrix. Its chief function is a considerable refinement of structure, but when present in excess (upwards of 3 per cent) corrosion-resisting properties are somewhat impaired. The normal additions do not appreciably affect tensile strength and ductility values, but they improve forging properties.

Manganese is almost invariably found in high-tensile brasses. When only present in small proportions, its function is as a deoxidiser and assists in the production of sound castings, in addition to correcting the tendency of some brasses to crystallise with large grain size. Manganese increases the amount of iron which will dissolve in brass, and increases the resistance to corrosion and erosion.

It has a pronounced resistance to corrosion by sea water, and Manganese Bronze, a 60/40 alloy containing up to 2 per cent manganese with small proportions of other elements, is therefore used extensively for propellers, rudders, valve parts and ships' fittings.

The element forms a solid solution with brass. It increases the strength with up to 4 per cent, and the elongation with up to 6 per cent manganese.

Aluminium has the greatest effect in increasing strength and hardness, with a progressive decrease of ductility. Additions of about 3 per cent to 60/40 brass increase the tensile strength in the cast state to 40 tons per sq. in. or more, increasing hardness from 90 to about 160 Brinell, and reducing elongation by 30 to 50 per cent.

It is used in casting brass in amounts up to 2 per cent, although larger amounts are found in certain proprietary alloys. Aluminium additions improve the resistance of brass to oxidation by the formation of a protective film of aluminium oxide which inhibits further attack.

Nickel, when added in small amounts, has little effect on strength and ductility, but as the quantities are considerably increased, there is some increase in strength.

Copper-nickel-zinc alloys containing from 10 to 30 per cent nickel have a pleasing silvery appearance, giving a combination of tensile strengths up to 30 tons per sq. in. and up to 40 per cent elongation. The alloys become more white as the nickel content is increased, and they all take a bright finish. In general these alloys contain copper and zinc in the proportion of a little over 2 to 1, the remainder being nickel. The name usually applied to the alloys is " nickel-silver " although " nickel-brass " is a more correct term. The alloys are mostly made up of the alpha solid solutions, heavily cored in the cast state, and they may be annealed and cold worked. Alpha-beta alloys are hot worked successfully, and an alloy of the approximate composition of 40 per cent copper, 45 per cent zinc and 10 per cent nickel is readily extruded into sections for architectural and ornamental purposes.

PLATE XXII.

FIG. 237.—Cold-worked 70/30 Brass, showing presence of strain lines. × 100 Dias.

FIG. 238.—Cold-worked and annealed 70/30 Brass, showing twinned crystals. × 50 Dias.

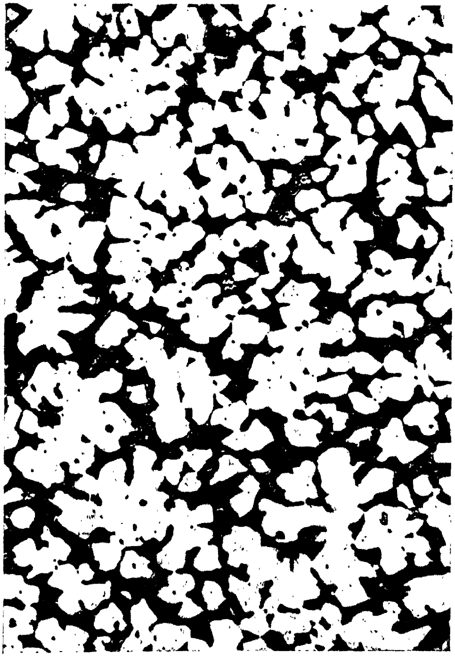
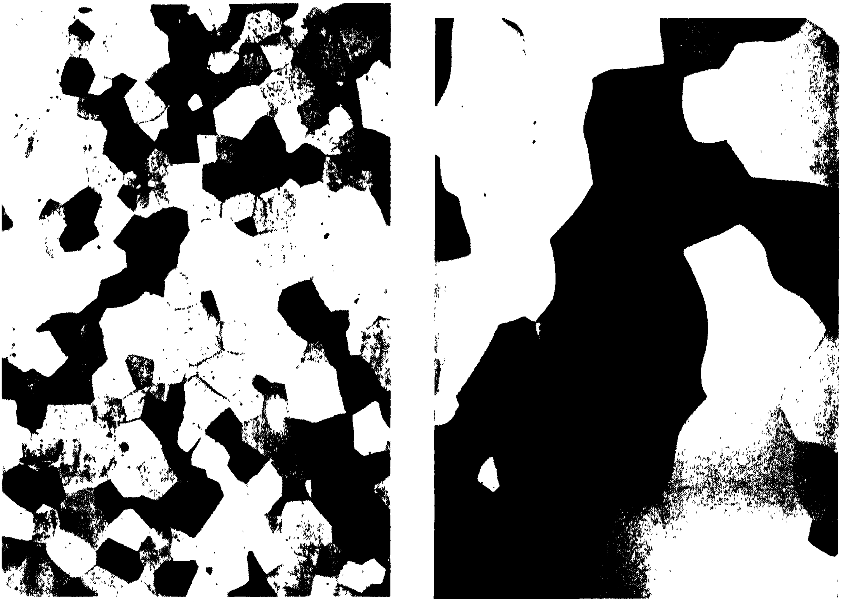


FIG. 239.—Leaded 60/40 Brass extruded and annealed at 620°C. × 100 Dias.

(Micro kindly prepared and supplied by Messrs.

PLATE XXIII.



(a) (b)

FIG. 240.—" Beta " Brass.

(a) Extruded.
(b) Cast.

Etched. × 10 Dias.

(*Kindly supplied by the Delta Metal Co., Ltd.*)

FIG. 242.—85/5/5/5 Gunmetal in unetched condition, showing free lead finely dispersed. × 50 Dias.

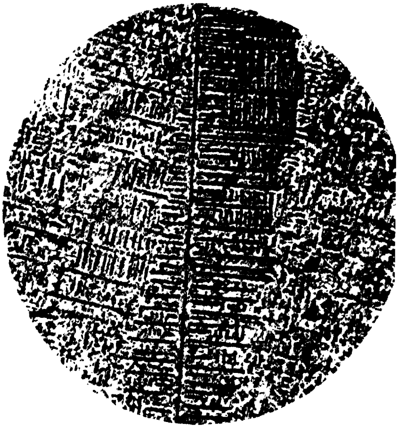


FIG. 243.—85/5/5/5 Gunmetal (etched) showing cored or dendritic structure × 25 Dias.

FIG. 244.—Phosphor Bronze. 88·5 Cu, 11 Sn, 0·5 P. Etched. × 100 Dias.

FIG. 245.—Manganese Bronze. Alpha beta cast structure. Etched. × 10 Dias.

PLATE XXV.

FIG. 246.—Nickel Bronze. 53 Ni, 33 Cu, 12 Sn. Cast state, and showing heavy coring. Etched. ×50 Dias.

FIG. 247.—Cast Aluminium Bronze. 9·5 Al. Alpha-beta structure. Etched. × 150 Dias.

(*Micro kindly prepared and supplied by Messrs. McKechnie Bros., Ltd.*)

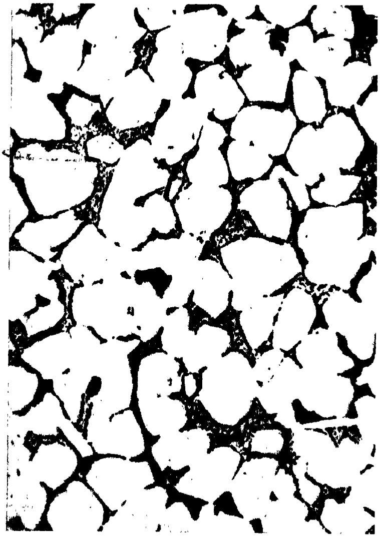


FIG. 248.—Aluminium Bronze. 9·5 Al. Extruded rod from a cast billet. Brinell 95. Etched. ×150 Dias.

(*Micro kindly prepared and supplied by Messrs. McKechnie Bros., Ltd.*)

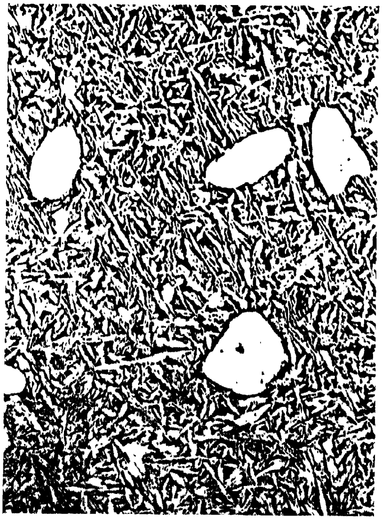


FIG. 249.—Aluminium Bronze. 9·5 Al. Quenched from 940°C. Alpha needles in a beta matrix. Brinell 121. Etched. ×150 Dias.

(*Micro kindly prepared and supplied*

Some uses of the nickel silvers are for fittings on cars, railways, for sanitary appliances, valves, ornaments, jewellery, tape and wire for electrical purposes.

Silicon. This element is only used to a limited extent, chiefly owing to its high zinc displacement value, and its tendency to oxidation during melting of the brass, giving rise to oxide inclusions. Silicon, however, is finding increased application in the higher copper content brasses, which are not really high-strength brasses, and will be dealt with later.

BRONZE

Bronze may be defined as an alloy of copper and tin.

Alpha-bronzes with tin contents up to 6 per cent have similar properties to the corresponding copper-zinc alloys, cored in the cast state, and homogeneous solid solutions obtained on annealing. Tensile strength is rather higher than that found with the corresponding copper-zinc alloys.

With increasing amounts of tin in cast bronzes, a second constituent appears which is harder and more brittle than the matrix. Use is made of this constituent in alloys containing 10 to 18 per cent tin, by occasional application for bearings. The other straight bronzes have only a limited field of application, the phosphor bronzes and gunmetals being more popular.

Phosphor bronzes. The phosphor bronzes are alloys of copper and tin with the inclusion of phosphorus in amounts up to 1 per cent. The phosphorus forms a hard and brittle eutectic with copper, appearing in the microstructure as light-coloured areas distributed in the softer matrix. There are two general classifications :—

(1) Those containing less than 7 per cent tin, and from 0·1 to 0·3 per cent phosphorus. They are malleable, readily cold worked, having an average tensile strength of 25 to 30 tons per sq. in. and 12 to 18 per cent elongation. Their chief uses are for valve and pump spindles, boiler fittings, etc., where strength, ductility and corrosion resistance are desirable.

(2) Those containing 10 to 13 per cent tin and 0·3 to 1·0 per cent phosphorus. These alloys have a low coefficient of friction, good hardness and wear resistance, which makes them suitable for heavy-duty bearings and gears. The mechani-

cal properties vary widely with the composition, particularly the elongation.

The tensile strength varies according to other conditions, but, in general, test results range from 10 to 14 tons per sq. in. tensile strength, and 2 to 10 per cent elongation. It retains its strength moderately well at high temperatures, 8 to 10 tons per sq. in. being obtained at 400°C.

Silicon bronzes. This type of alloy is an acid-resisting bronze and includes the well-known "Everdur." The silicon content ranges from about 1 to 5 per cent along with approximately 1 per cent of manganese. The alloys often contain also 1 to 1·5 per cent iron, up to 2 per cent tin, and 5 per cent zinc, the remainder being copper.

The wrought alloy is lower in silicon than the cast alloy and is generally in the range of 1 to 3·5 per cent, when the material readily worked by forging, rolled into rods and sheet, and drawn into tubes and wire. Working may be carried out either hot or cold. Cold working increases the tensile strength and it is possible to obtain by severe cold working, values in the order of 70 tons per sq. in. The alloys give good strengths at elevated temperatures, 16 tons per sq. in. being obtained at 400°C. Some typical mechanical properties are :—

	Yield point tons per sq. in.	*Ultimate tensile stress tons per sq. in.*	*Elongation per cent on 2 in.*
Cast . .	13·5	22·5	24·0
Hot rolled .	21·0	33·0	55·0

The alloys are resistant to attack by many mineral and organic acids, salts, dyes and fruit juices. They are used for handling corrosive liquids, parts for pickling equipment, pipe fittings and pump units.

Gunmetals. These are bronzes to which certain proportions of zinc are added, often both lead and zinc. Both these metals form cheaper substitutes for tin. Zinc acts as a deoxidant in the bath of metal by preferential formation of zinc oxide instead of tin oxide. It hardens bronzes and tends to counteract the softening effect of any lead which may have been added to promote easy machining.

Gunmetals contain small particles of a hard tin rich constituent, the quantity of which increases with the tin content of the alloy and also with quicker cooling, and has the general effect of decreasing ductility and increasing wear resistance. Annealing between 600 and 700°C. causes this constituent to be absorbed in the alpha matrix, and ductility is considerably increased.

Gunmetals are used chiefly in the form of pressure-resisting castings for use with liquids, steam or air.

Perhaps the best known gunmetal is that containing 88 copper, 10 tin, and 2 per cent zinc, and which is known as Admiralty Gunmetal. It is harder and more corrosion resisting than the other types, and has the following approximate range of properties—18 to 19 tons per sq. in. tensile strength, 20 to 25 per cent elongation and 74 Brinell. After annealing at 650 to 700°C., this metal shows 50 to 100 per cent increase in ductility, and becomes suitable for hot working.

Alloys with lower tin and higher zinc contents have greater ductility, are easier to work with in the foundry, and give less trouble due to porosity. The addition of small percentages of lead gives easy machining. Although slightly inferior in some respects to the 88–10–2 alloy, a number of alloys within the following range are satisfactory for pressure work :—

Copper . . .	84 to 90 per cent
Tin	4 to 8 ,,
Lead . . .	1 to 7 ,,
Zinc . . .	4 to 7 ,,

giving tensile strengths of 16 to 18 tons per sq. in., 25 to 45 per cent elongation, and 45 to 60 Brinell hardness.

A composition of 85 copper, 5 tin, 5 zinc, and 5 per cent tin, often referred to as "Ounce Metal," is used for low pressure steam valves, fittings, etc. It is a fluid metal when molten, easily handled in the foundry, and in the cast state will give 16 to 18 tons per sq. in. tensile and 25 to 35 per cent elongation.

COPPER-NICKEL ALLOYS

Copper and nickel form a simple continuous series of solid solutions, each being completely soluble in the other in all proportions. The melting-points of the alloys rise progressively with increasing nickel contents, from that of copper at 1083°C. to that of nickel at 1455°C. The alloy becomes lighter in colour with increasing amounts of nickel until, when 15 per cent is present, the alloy is steely white. Nickel improves the strength, hardness, corrosion-resisting properties, and its ability to retain mechanical properties at high temperatures.

Nickel alloys are all cored in the cast state, it being possible to remove this structure by annealing, although prolonged treatment may be necessary with alloys of high nickel content. They are readily both hot and cold worked and may be drop forged. When cold worked and afterwards annealed, well-defined twinned crystals are formed.

The chief copper-nickel alloys are :—

(1) Nicro-copper containing 2 per cent nickel which is sometimes used in railway work and for other applications where mild corrosive influences are present, and at slightly elevated temperatures. It is extensively used in the form of tubes for boilers and flues. In the annealed state it will give a tensile strength of about 15 tons per sq. in. with an elongation of 50 per cent. A tensile strength of about 10 tons per sq. in. is obtained at 350°C.

(2) Cupro-nickel containing 20 per cent nickel. The alloy is white in colour and used for ornamental purposes, condenser tubes, bullet envelopes, and many other forms of cold pressings and stampings. The alloy is easily workable, very ductile and is not subject to season cracking after cold working. In the annealed condition it has a tensile strength of about 20 tons per sq. in. with approximately 50 per cent elongation. A tensile strength of about 17 tons per sq. in. is obtained at 400 to 450°C.

The 70/30 copper-nickel alloy, owing to its high resistance to sea water and also its good ductility, is widely adopted for marine condenser tubes. It gives a tensile strength of about 22 tons per sq. in. in the annealed condition along with up to 50 per cent elongation. A tensile in the order of 20 tons per sq. in. at 400 to 450°C. is obtained.

(3) Monel metal containing about 30 per cent copper, 67 per cent nickel, 0·5 to 1·25 per cent iron and up to 2 per cent manganese, is produced by smelting direct from Canadian ore containing similar proportions of nickel and copper as is desired in the resultant alloy. The amounts of other elements vary, normally ranging up to 3·0 per cent iron, up to 3·0 per cent manganese along with smaller proportions of silicon,

sulphur, carbon and phosphorus. The alloy has good strength and ductility and also the valuable property of excellent corrosion resistance to many chemicals, organic acids and all alkalis. It is highly resistant to the corrosive action of superheated steam and retains its strength and toughness at high temperatures, about 28 tons per sq. in. being obtained at 400 to 450°C.

It is not resistant to corrosion by nitric acid and sulphurous acid, also oxidising salts such as sulphates and chlorides of iron and copper. It is not suitable for handling molten metals such as lead and zinc.

Monel metal is readily forged and hot rolled at temperatures between 1000 and 1175°C. It can also be rolled into sheets, rod, wire, etc., after which it shows a great increase in strength. It may be soldered, brazed, and welded either by the electric or acetylene processes.

The alloy is used for many kinds of corrosion resistant castings, valves, valve trimmings, cocks and pipe fittings for handling steam, and for pump impellers and casings. It is also used for chemical process work such as the manufacture of caustics, textile and dyeing equipment, and water-softening plant.

Monel metal gives in the hot-worked condition a tensile strength of 30 to 35 tons per sq. in., elongation of 20 to 40 per cent, and a Brinell hardness of approximately 130.

Recent years have seen the introduction of modifications of Monel metal brought about by additions of aluminium and silicon. The alloys become heat-treatable by precipitation hardening, that is to say, there is a precipitation during cooling through the lower temperatures or by tempering a quenched alloy, of very fine particles of a constituent incorporating the added element, and which is normally soluble at the higher temperatures.

Monel K contains about 2·75 per cent aluminium which renders the material heat treatable to give mechanical properties comparable with many alloy steels, whilst retaining the corrosion-resisting properties of ordinary Monel.

Alloys containing 2·5 to 3·75 per cent silicon have increased hardness and strength, and have better frictional or non-seizing properties than ordinary Monel metal, which makes them suitable for certain bearings and for faces of gate valves.

The silicon alloys are divided into two grades, Monel H and Monel S,[1] the former having approximately 2·5 to 3·0 per cent silicon and employed for castings where hardness and strength must be associated with considerable ductility. Monel S containing about 3·75 per cent silicon, having increased strength and a Brinell hardness in the order of 300 or more is low in ductility, and, whilst it has excellent non-seizing characteristics, it is not recommended for parts where dynamic loading is experienced. It is used in the cast and heat-treated forms only.

(4) Nickel-copper-tin alloys containing 52 to 54 per cent nickel, 32 to 34 per cent copper, and 11 to 13 per cent tin along with smaller but definite proportions of iron, manganese and phosphorus. The addition of tin to copper-nickel alloys progressively increases hardness, resistance to wear and corrosion, with decrease of ductility. The alloys are heavily cored in the cast state, with typical mechanical properties of 40 tons per sq. in. tensile strength, 1 to 3 per cent elongation, and 240 Brinell. The alloys find application in trimmings for valves, discs and seatings, and for high resistance to corrosive attack at high temperatures.

(5) Copper-nickel alloys containing 40 to 45 per cent nickel, amongst which are Constantan and Eureka, are readily cold worked and have a high electrical resistance. They are used in electrical engineering for rheostats and base-metal thermocouples.

(6) Nickel-chromium alloys, such as the 80/20 type, possess high resistance to oxidation, very high electrical resistance, and good mechanical properties at elevated temperatures. They are used extensively as resistors in electric furnaces, in the construction of electric heaters of all types, for annealing boxes, etc.

(7) Nickel-chromium-iron alloys strongly resist oxidation up to 1100°C. and have good mechanical strength at high temperatures. They are used to a large extent for recuperator tubes, pyrometer sheaths, annealing boxes, etc. Inconel, an 80/14/6 alloy highly resistant to heat and corrosion, is used in certain types of food processing equipment, exhaust manifolds, and tubular electric heating elements for cookers, etc.

(8) Nickel-iron alloys of approximately 80/20 composition

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[1] Covered by British Patents.

such as Permalloy and Mumetal have, after suitable heat treatment, high magnetic permeabilities and low hysteresis loss. They are used in the form of castings, forgings, rod, wire and tape, for electrical instruments, current transformers and submarine cables.

COPPER-ALUMINIUM ALLOYS

These are known as aluminium bronzes although, strictly speaking, they are not bronzes at all, as they contain no tin.

The alpha alloys contain up to 9·8 per cent aluminium, but the aluminium content in commercial alloys is in general below 7·5 per cent. They possess considerable strength, a notable feature being their low yield points which give rise to exceptional elongation values. They exhibit a rich golden colour. They are readily cold worked with an improvement in strength and hardness, but with a loss of ductility. Reheating to above 300°C. considerably softens the cold-worked alloy, and annealing at 650°C. completely restores the ductility whilst retaining a tensile strength in excess of the unworked material.

Typical mechanical properties in the cast state are yield point 5 to 7 tons per sq. in., tensile strength 18 to 22 tons per sq. in., and elongation 65 to 75 per cent.

The alpha alloys are used widely for decorative purposes and in the form of seamless tubing, wire, etc.

The alloys containing between 9·0 and 11·0 per cent of aluminium are important alloys in engineering. They may contain nickel, or nickel and iron in small percentages. The alloys containing up to 3·5 per cent of iron are used for die castings. For forgings and stampings nickel and iron are present either separately or together in proportions of up to 6 per cent of each. Both elements increase the tensile strength.

The alloys containing between 9·8 and 11·8 per cent of aluminium respond readily to heat treatment. It will be seen from the thermal equilibrium diagram that the normally cooled alloys of this composition consist of α and δ constituents. The composition is, in general, preferred nearer to 10 per cent aluminium on account of the decreased ductility of the alloys with the higher aluminium contents.

In the cast state slowly cooled the structure bears a similarity to that of medium carbon steel. On heating into the β region at about 850 to 900°C. and quenching in water, a structure of martensitic appearance is obtained consisting of a β matrix retained by quenching and in which is distributed a mass of fine needle-shaped crystals of the α constituent. In the quenched condition there is a considerable increase in strength and hardness with a loss of ductility. Reheating or tempering breaks up this structure and leads to the introduction of small particles of the δ phase intimately mixed with α to give the appearance of sorbite, when the hardness and tensile strength introduced by quenching is reduced along with increase of ductility, the amount of alteration depending upon the reheating temperature.

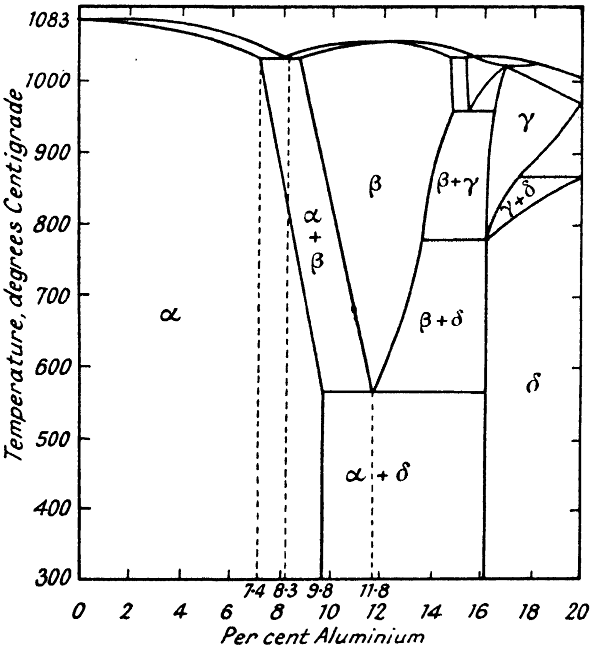


FIG. 250.—The Copper-Aluminium Equilibrium Diagram.

The alloys in the range of 9·0 to 11·8 per cent aluminium also have good resistance to corrosion, especially by many organic acids. In engineering they are used for parts requiring strength and where steel would be unsuitable. They are adapted for use in various forms of gears, die castings, and other castings to withstand hydrostatic or steam pressure. A strength of about 30 tons per sq. in. is maintained when subjected to temperatures

PLATE XXVI.

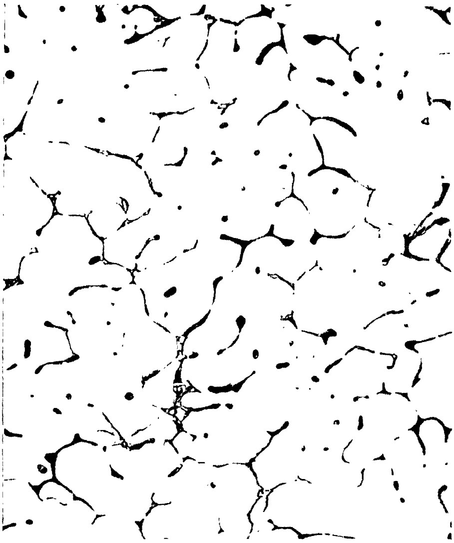


FIG. 251.—Duralumin as cast. Etched 30 secs. in $12\frac{1}{2}$ per cent NaOH, $CuAl_2$ shows black and α(MnSi) outlined and unattacked. × 350 Dias.

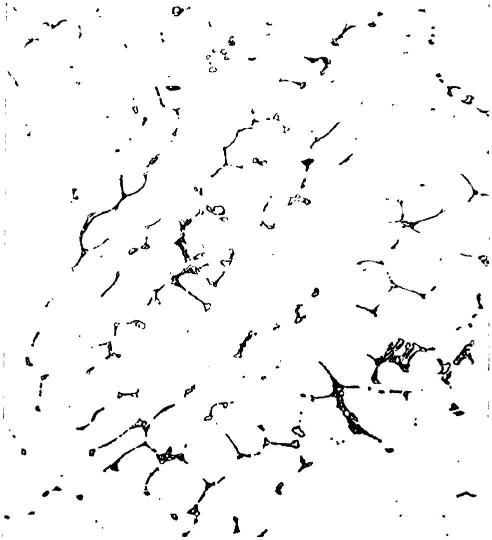


FIG. 252.—As above but after solution heat treatment. (20 mins. at 495°C. Quenched.) Etched 30 secs. in $12\frac{1}{2}$ per cent NaOH, $CuAl_2$ all in solution, α(MnSi) outlined and unattacked. × 350 Dias.

(Both photomicrographs kindly supplied by The British Aluminium Co., Ltd.)

PLATE XXVII.

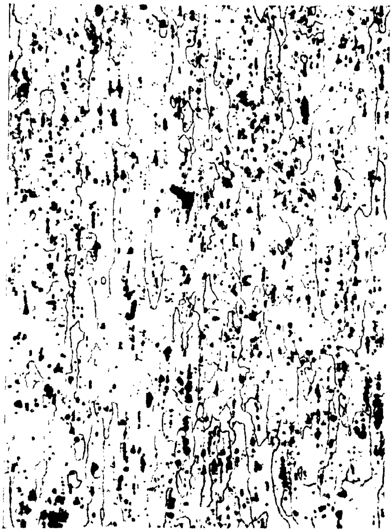


FIG. 253.—" Duralumin B " sheet. Longitudinal section. × 100 Dias.

FIG. 254.—Longitudinal Section of " Duralumin B " extrusion. × 200 Dias.

FIG. 255.—" Y " Alloy Solution treated and then precipitated for 450 hours at 285° C. During the extended treatment the precipitate, which is normally ultramicroscopic, is easily visible at the magnification of 500 Dias.

(*The above three photomicrographs kindly supplied by Messrs. James*

PLATE XXVIII.

FIG. 256.—Sand-cast 12 per cent Silicon-Aluminium Alloy. Unmodified. Almost eutectic composition. × 100 Dias.

(*Courtesy—Messrs Light Alloys Ltd.*)

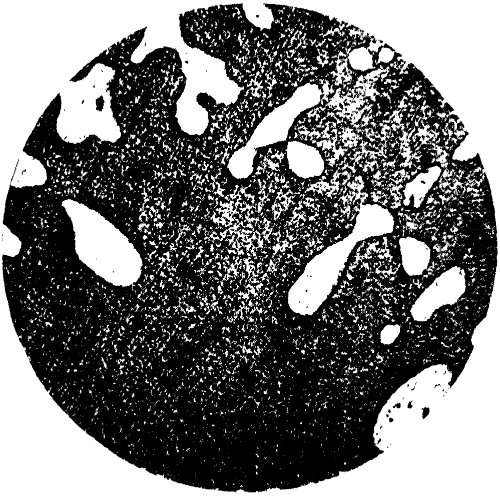


FIG. 257.—Sand-cast 12 per cent Silicon-Aluminium Alloy. Modified. Showing greatly refined eutectic structure along with some excess aluminium above eutectic composition. × 100 Dias.

(*Courtesy—Messrs Light Alloys Ltd.*)

PLATE XXIX.

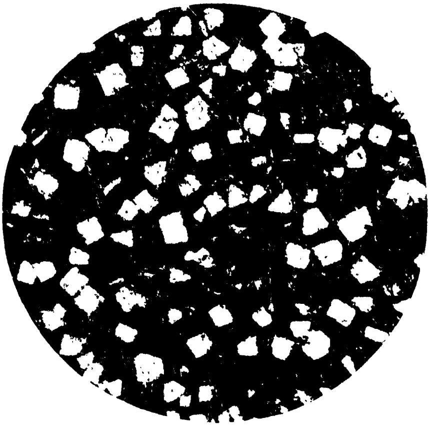
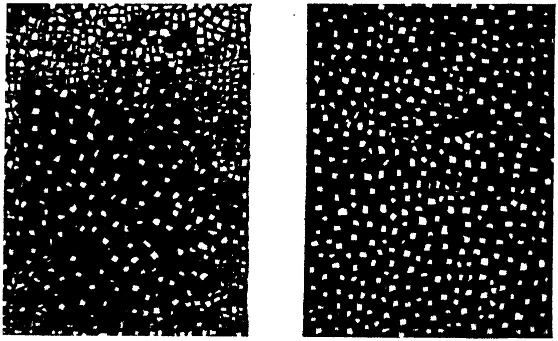


FIG. 258.—Babbit Metal. × 100 Dias.



(a) (b)

FIG. 259.—Sketch illustrating flotation of cuboids in Babbit Metal.

(a) Bad flotation.
(b) No flotation.

(*See page* 282)

of between 260 and 300°C. Aluminium bronzes have good machineability, but rather more difficult than the normal type of brasses and bronzes. They may be forged, rolled or extruded, at temperatures between 850 and 900°C.

The following data is typical of a heat-treatable aluminium bronze :—

Condition	*Yield point tons per sq. in.*	*Ultimate tensile stress tons per sq. in.*	*Elongation per cent on 2 in.*	*Brinell hardness*
Cast . . .	12	32	21	100
Quenched from 900°C. . .	22[1]	43	4	250

The 10 per cent aluminium alloys containing 1 per cent or more of nickel are sometimes used as exhaust valve seats for internal combustion engines.

ALUMINIUM AND ITS ALLOYS

Aluminium and alloying elements. Aluminium is a comparatively soft metal with a silvery white appearance, has a specific gravity of 2·68, and is a good conductor of heat and electricity. It melts at 659°C. In the cast state its mechanical properties are rather poor, having a tensile strength of only 6 or 7 tons per sq. in. It is ductile and malleable, flowing easily under pressure so that it can be rolled into thin sheets or drawn into fine wire.

Cold working considerably increases the tensile strength whilst subsequent annealing reduces it to approximately the value of that of the cast material, but with an improvement in ductility. Pure aluminium machines badly tending to tear and consequently it is difficult to produce fine threads. It is readily attacked by caustic alkalis and salt solutions.

Because the mechanical properties of aluminium are greatly improved by the alloying with it of suitable proportions of other elements, pure aluminium is seldom used for structural purposes. The amounts of alloying elements used to effect these

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[1] 0·1 per cent proof stress.

improvements are relatively small, and, in some instances, they themselves have also a low specific gravity, so that the general lightness of the alloys are little if at all increased. The chief elements used in the production of the light aluminium alloys are copper, magnesium, manganese, silicon, iron, nickel, zinc and titanium. The alloys so produced are usually divided into two principal classes, the casting alloys and the wrought materials. Although all alloys are usually cast in the first instance the former type are those which are cast approximately to the size and shape of the desired component on which no further working operations are necessary other than machining. The latter type are the alloys, often unsuitable for producing the article direct by casting processes, but first cast into the form of ingots or billets and followed by working to the desired shape by forging, hot or cold rolling, extrusion, or by drawing.

The resistance of aluminium and its alloys to corrosion is improved by anodic treatment. This treatment is an electrolytic process in which the article is made the anode in an acid electrolyte bath, the acids chiefly used being dilute chromic and sulphuric. The cathode may be of carbon, lead, stainless steel or other materials to suit the type of electrolyte employed. When an electric current is applied, the oxygen liberated at the anode oxidises the aluminium to produce an adherent film of oxide which greatly enhances the corrosion resistance of the alloy. The film has the property of reacting with certain dyes, and is sometimes employed to give coloured finishes.

Some alloys have pronounced age-hardening properties, that is to say, if heated to about 500°C. and quenched in water or oil the properties are not immediately materially altered, but after a short time the hardness and strength increases relatively rapidly and then more slowly until a maximum is reached after 4 or 5 days. When the alloys are to be worked, working is best carried out immediately after quenching while they are still in the soft condition. The soft state after quenching may be retained by storing at a low temperature, usually[1] −5°C. to −10°C. Refrigeration is particularly applied to rivets for aircraft construction, and also to strip and sheets.

In certain alloys the ageing is only slight at normal temperatures after quenching. These alloys are artificially aged by reheating to a definite temperature between 130 and 200°C. and for a

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[1] W.L.A.D.A. Information Bulletin No. 3.

definite time, according to the composition and the properties required. The hardening after quenching can be accelerated by artificial ageing in alloys which age harden naturally, although the practice is not in general recommended.

Although there has been some difference of opinion regarding the exact cause of age hardening, it is generally accepted that the intermetallic compounds, notably $CuAl_2$ and Mg_2Si, are taken into solution on heating to a temperature between the solidus and the limit of solid solubility in the equilibrium diagrams of the systems. Quenching from this temperature retains the compounds in solid solution. These operations are known as " solution treatment." The solid solution so produced is not stable and the dissolved compounds precipitate in a finely dispersed state and are normally ultramicroscopic. The precipitation may take place at ordinary temperatures or it may require further low-temperature treatment often referred to as " precipitation treatment." As precipitation proceeds it is accompanied by a marked alteration in the properties of the alloy.

Duralumin. This type of alloy was first developed in 1909 and to-day is still one of the most extensively used aluminium alloys. The general range of composition is copper 3·0 to 4·5 per cent, manganese 0·4 to 1·2 per cent, magnesium 0·4 to 1·0 per cent, iron 0·4 to 1·0 per cent, and silicon 0·5 to 1·0 per cent. The specific gravity is about 2·82.

It is not a satisfactory alloy for castings on account of the difficulty in obtaining pressure tightness and is therefore essentially a wrought alloy. Large quantities are used in aircraft and automobile engineering in the form of forgings, stampings, bars, sheet, tubes and rivets. To obtain in a suitable condition for cold working the alloy is softened by annealing at 360 to 400°C. It is readily forged on heating to about 500°C.

The Duralumin alloys are readily hardened by solution treatment followed by natural ageing. They also retain their strengths moderately well at elevated temperatures, 20 tons per sq. in. being obtained at 200°C.

Condition	0·1 *per cent proof stress*	*Ultimate tensile stress*	*Elongation per cent on 2 in.*	*Brinell hardness*
Annealed . .	8	19	22	65
Quenched and aged	16	26	20	100

Y alloy. This is an alloy with a copper content similar to that of Duralumin but with increased magnesium (about 1·5 per cent) and with the inclusion of approximately 2 per cent nickel. It hardens readily, employing a solution treatment temperature a little higher than Duralumin, and is naturally aged. It can be used either in the form of castings or forgings. The corrosion resistance is rather superior to that of Duralumin and it has good machining properties. It has good strength at elevated temperatures—somewhat better than Duralumin in this respect. These properties have led to its extensive use for pistons in aero and automobile engines, cylinder heads, etc.

Condition	0·1 *per cent proof stress*	*Ultimate tensile stress*	*Elongation per cent on 2 in.*	*Brinell hardness*
As cast (sand cast) .	10	11	1	90
Quenched and aged	14	15	1	105

R.R. alloys. These are a series of high-strength alloys containing in general smaller percentages of copper than Y alloy and the Duralumin type alloys. They contain nickel, a rather higher percentage of iron than most light aluminium alloys, and also a small amount of titanium for deoxidation and grain refinement purposes. In the series perhaps the most widely employed material is R.R. 56 having the range of composition of copper 1·8 to 2·5 per cent, nickel 0·6 to 1·4 per cent, magnesium 0·65 to 1·2 per cent, iron 0·6 to 1·2 per cent, titanium 0·05 to 0·15 per cent, and silicon 0·55 to 1·25 per cent. The mechanical properties are :—

Condition	0·1 *per cent proof stress*	*Ultimate tensile stress*	*Elongation per cent on 2 in.*	*Brinell hardness*
Annealed .	7–11	16–19	16–22	70–80
Solution treated and aged .	21–23	27–30	10–15	121–138

The R.R. alloys are hardened by solution treatment for 2 to 6 hours at 520 to 535°C., quenched, and artificially aged for periods and temperatures ranging from 5 to 20 hours and 130 to 180°C. They retain their strengths well at comparatively elevated temperatures about 14 tons per sq. in. being obtained at 300°C.

They are available for use in extruded and all wrought forms and employed for connecting rods, crankcases and all kinds of constructional parts in aircraft.

Aluminium silicon alloys. The general range of silicon content is 5 to 13 per cent. The alloys are lighter than the aluminium copper alloys owing to the low specific gravity of silicon (2·3). They are divided into two classes.

The 5 per cent silicon alloy is popular in the U.S.A. It has excellent casting properties, freedom from hot-shortness, and is extensively used for permanent mould and die castings. It has good corrosion-resisting properties. The mechanical properties are in the order of 10 tons per sq. in. tensile strength with 6 per cent elongation, and in a good permanent mould casting the elongation will exceed 10 per cent.

The other class of aluminium-silicon alloy has a silicon content in the range 10 to 14 per cent. These alloys have the low specific gravity of 2·65 and are used in the form of castings for highly stressed parts and to a lesser extent in the form of extrusions and rolled sections. Amongst the light aluminium alloys, these are the most resistant to corrosion and they retain their strengths well at moderately high temperatures, rendering them suitable for marine purposes where a light alloy is required and for certain moving parts of internal combustion engines. The castings have a notable freedom from porosity and hot-shortness. Because of the high degree of fluidity when molten, castings of intricate and thin section are readily produced when other aluminium alloys would not be suitable. The castings are dense, may have considerable variation in section with the minimum amount of cracking and will withstand fluid pressure without leakage. The alloy is also used for die-casting purposes.

The 10 to 14 per cent silicon alloys are recommended for anodic treatment and are used in architectural work, ornamental work, panels and doors, and general light marine construction.

A considerable amount of grain refinement is effected by a process known as " modification," which consists of the addition of small amounts of about 0·06 per cent by weight of metallic sodium to the molten metal just prior to casting. Other materials may be used to obtain the same effect, amongst which are potassium, fluorides of sodium and potassium, and the alkaline earth metals. The grain refinement brings about also an improvement in the mechanical properties.

Condition	0·1 *per cent proof stress tons per sq. in.*	*Ultimate tensile stress*	*Elongation per cent on 2 in.*	*Brinell hardness*
Sand cast . .	4·0	11	8	55

Certain aluminium silicon alloys are rendered heat-treatable by the addition of hardening alloys such as magnesium and copper. An example of such an alloy is Loex[1] containing 0·5 to 1·0 per cent copper, 0·75 to 1·25 per cent magnesium and 1·5 to 2·5 per cent nickel. The alloy has a low coefficient of expansion, good thermal conductivity and strength. It is very suitable for use as a piston alloy. Typical mechanical properties are :—

Condition	0·1 *per cent proof stress tons per sq. in.*	*Ultimate tensile stress tons per sq. in.*	*Elongation per cent on 2 in.*	*Brinell hardness*
Sand cast and heat treated	10·5	11·5	0·5	140

Aluminium magnesium alloys. Magnesium with a specific gravity of only 1·74 increases the lightness of aluminium alloys and is present in quantities of 1 to 10 per cent, and provides a number of useful alloys both of medium and high strength. The alloys are adaptable for anodic coatings. In general, increase of magnesium results in an increase of strength.

The alloys containing 3 to 6 per cent magnesium and 0·25 to 0·75 per cent manganese (D.T.D. 165) are casting alloys with good corrosion resistance. They are used both for sand and chill castings and give a minimum tensile strength of 9 tons per sq. in., 10 per cent (min.) elongation and 58 Brinell hardness.

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[1] British Patent No. 334656.

Another casting alloy (D.T.D. 300), containing 10 per cent magnesium in the sand-cast condition gives at least 16 tons per sq. in. and 7 per cent elongation.

A general-purpose wrought alloy is B.S.S. L44, readily extruded, cold worked, welded, and has good corrosion resistance. The range of composition is 1·0 to 3·0 per cent magnesium, 1·5 per cent (max.) manganese, 0·5 per cent (max.) chromium and 0·35 per cent (max.) nickel, along with small quantities of silicon, iron and titanium. In the softened state it gives a tensile strength of more than 11 tons per sq. in. and upwards of 18 per cent elongation.

The alloys containing 6 to 10 per cent of magnesium are high-strength alloys resistant to corrosion, and, after annealing, can be readily pressed, spun, and cold rolled into sheets. They are forged at about 400°C. The specific gravity is 2·63. The mechanical properties are 20 to 23 tons per sq. in. tensile with 15 to 20 per cent elongation in the annealed condition, whilst cold work will increase the tensile strength to 25 to 28 tons per sq. in. with a considerable decrease in ductility.

Aluminium-copper-zinc alloys. Originally this type of light alloy contained proportions of zinc up to about 14 per cent. Owing to the relatively low melting-points they are capable of running castings of thin and intricate section such as gear boxes, crankcases and brake shoes. The high zinc alloys, although they give fair mechanical properties " as cast," tend to be " hot-short " and are weak at high temperatures.

A more popular alloy for this class of work contains lower percentages of zinc with the inclusion of some silicon. A typical composition is 7 per cent copper, 3 per cent zinc and 2·5 per cent silicon, and which gives mechanical properties of approximately 11 tons per sq. in. and 2 per cent elongation. The alloy is useful for the production of die castings.

MAGNESIUM BASE ALLOYS

The series of magnesium base alloys are manufactured in this country under the trade names of Magnuminium and Electron. Unlike aluminium, pure magnesium metal has little application in engineering, but, by alloying small proportions of other elements with it, principally manganese, aluminium and zinc, a valuable light engineering alloy is obtained. The total alloy additions range up to 12 per cent and, since the specific gravity of magnesium is only 1·74, that of the finished alloy is still low at about 1·8. The mechanical properties of most magnesium alloys can be considerably improved by heat treatment.

Manganese improves the corrosion resistance but effects little improvement on the mechanical properties.

Aluminium is the element chiefly responsible for strength and ability to withstand heat treatment.

Zinc also improves the strengths of the alloys but is always associated with aluminium to promote ductility. In general the zinc content is somewhat lower in the wrought alloys.

Silicon is always present in the small amount of 0·2 to 0·4 per cent as insoluble Mg_2Si, which, when solution treated and precipitated, increases hardness.

Other minor quantities of alloying elements are often present for special purposes. Calcium and cerium have been found to increase the strength of the wrought alloys, general mechanical properties at elevated temperatures and lead to some grain refinement. Cadmium in suitable small proportions also improves the strength. Copper and nickel do not improve the mechanical properties, and, because they tend to decrease corrosion resistance, they are kept to a minimum.

In addition to castings, magnesium alloys can be used in the form of forgings, extruded sections and tubes, rolled sections and sheet. The alloys are usually worked hot at about 300 to 400°C. Cold working can be applied to sheets, but to a limited extent only.

The heat-treatable alloys are solution treated for at least 16 hours at about 435°C. Those requiring subsequent precipitation treatment are then reheated to 200°C. for 8 hours or more. There is available a wide range of magnesium base alloys, but the table on page 281 gives the composition and mechanical properties of typical examples.

The alloys are corroded by acids and chlorides, but are resistant to alkalis. They can be protected against corrosion to some extent by dipping in solutions of dichromates, although this treatment alone does not render them immune to attack from such agents as sea water, but it often forms a foundation for an application of lacquer or enamel.

The magnesium alloys machine excellently, and with a sharp tool high speeds can be used. The high conductivity of the metal and the low pressure required for cutting prevents local

Specification	*Condition*	*Al*	*Zn*	*Mn*	*Proof stress tons per sq. in.*	*Ultimate tensile stress tons per sq. in.*	*Elongation per cent on 2 in.*	*Brinell hardness*
D.T.D. 59A (casting alloy)	Sand, die, and pressure die casting.	(*max.*) 8·5	(*max.*) 3·5	(*max.*) 0·5	4·5–5·5	9–11	3–5	50–60
	Solution treated				4·5–5·5	14–16	9–14	50–60
D.T.D. 136A (casting alloy)	Sand, die, and pressure die casting.	9–11	(*max.*) 3·5	(*max.*) 0·5	4·5–5·5	8–10	1–3	55–65
	Solution treated and aged.				7–9	15–17	1–3	75–85
D.T.D. 259 (wrought alloy)	Bars, rods, tubes, sections, sheets.	(*max.*) 11	(*max.*) 1·5	(*max.*) 1·0	9–12	18–22	12–16	55–60

heating. Machining is carried out dry. Fine chips and borings readily take fire and should not be allowed to accumulate near to the work, as the friction of a blunt tool may provide sufficient heat to ignite fine turnings. Coarse turnings and chips are not usually dangerous.

On account of their lightness magnesium base alloys have a wide field of application in engineering where a light and strong component is required. They are employed particularly in aircraft construction, both in cast and wrought forms, for forged airscrews, for crankcases, under-carriage members, landing wheels, petrol and oil tanks, and various kinds of interior fittings.

WHITE METAL ALLOYS

These alloys are of low melting-point, having either a zinc, lead or tin base.

The former are used chiefly for die-casting and contain up to 4 per cent copper and aluminium. The melting-point of these alloys is about 380°C. They give tensile strengths up to 20 tons per sq. in. with 5 per cent elongation, a Brinell hardness of 60 to 85, good impact resistance and good machineability. Their uses include die-cast parts for carburettors, small machine gears, and other general-purpose parts not requiring contact with salt water, alkalis or continuous exposure to steam.

Tin and lead base metals are essentially bearing alloys. Both contain antimony, an element which gives rise to hard crystals embedded in the soft matrix of the alloy. In use, the soft matrix wears away slightly to yield a series of microscopic channels round the hard particles, forming an effective irrigation system for the lubricant. The hard particles in the form of cuboids are easily distinguished in the microstructure.

The *Tin Base Alloys* are known as Babbit metals containing varying amounts of antimony up to 15 per cent. The antimony-tin alloys form a single solid solution up to 8 per cent antimony, above which a further and separate solid solution appears richer in antimony. It is this second solid solution which forms the hard-wearing constituent of the alloy. The cubes are relatively light, and, in a slowly cooled alloy, they tend to segregate and float to the top of the casting or ingot, giving an heterogeneous structure. This flotation can be minimised by quick cooling or by the general practice of including in the alloy up to 5 per cent of copper to form a further solid solution with the tin. This solid solution, containing copper, solidifies at a higher temperature (366°C.) than the remainder of the alloy and in the form of a network which entraps the cuboids as they in turn begin to solidify at 264°C. Finally the tin-rich matrix solidifies at 238°C. The alloys are not cast at a higher temperature than necessary if the best properties are to be obtained.

The Babbit metals have good compressive strength, low coefficient of friction and good shock resistance. They are used extensively in aircraft, automobile, electrical, and general engineering for big-end bearings for connecting rods, shaft bearings ; or for bearings generally where high speeds, heavy loads and rather severe service conditions are encountered (*see* Plate XXIX).

The *Lead-Base Alloys* are softer and more plastic than the tin-base alloys. Lead forms a eutectic alloy with antimony in the proportions of 13 per cent antimony and 87 per cent lead. Increase of antimony above 13 per cent leads to the formation of cuboids of metallic antimony which are the hard-wearing constituent of the bearing material. The alloys are rather inferior to the tin base alloys when used under severe service conditions, but they may be used in high-speed service under lighter pressure.

The *Lead-Tin Bearing Alloys* are those which have the lead and tin contents arranged to suit various service conditions such as heavy pressure and medium speed, medium pressure and high speed, or both medium pressure and speed. They usually contain about 1·5 per cent of copper to minimise segregation.

Fusible alloys. These are the low melting-point alloys produced by combining various proportions of bismuth, lead, tin and cadmium.

Tinmans' solder is a lead-tin alloy of approximately eutectic composition and it therefore melts easily, is very fluid, and solidifies quickly soon after being applied to the joint.

Plumbers' solder contains more lead and begins to freeze when the molten alloy has cooled to the liquidus at about 240°C. On continued cooling solid particles of lead in excess of the amount required for lead-tin eutectic composition continue to be formed until the eutectic temperature is reached at about 180°C. The solder thereby keeps in a more or less plastic state through the range of 60°, and it is this long range of solidification which enables the plumber to wipe and shape the joint.

The alloys of still lower melting-point are used when a soft alloy of very low melting-point is required for special purposes, such as certain metal pattern work. Bismuth expands slightly on solidification, which gives some of the fusible alloys the property of being non-shrinking.

Some alloys containing substantial quantities of lead are employed for electrical fuse wires.

The following table gives the compositions and melting-points of some of the many fusible alloys available :—

	Bismuth per cent	*Lead per cent*	*Tin per cent*	*Cadmium per cent*	*Melting-point °C.*
Plumbers' solder .	—	67	33	—	240–180
Tinmans' solder .	—	33	67	—	180
Rose's alloy . .	50	28	22	—	100
Wood's alloy . .	50	24	14	12	71
Lipowitz's alloy .	50	27	13	10	60

NON-FERROUS AND LIGHT ALLOYS MELTING FURNACES

The majority of the melting furnaces for non-ferrous metals and alloys are of the crucible type in which the metal is considerably or completely protected from contamination by the products of combustion. When very large quantities of metal are required at a time for heavy castings, the use of an open hearth or reverberatory furnace may be necessary, a practice having the disadvantage that the products of combustion are in direct contact with the metal with consequent deterioration in quality and loss of metal by oxidation, but where a sufficient number of crucible furnaces are available and can be used simultaneously, the required amount of molten metal can be made up by combining the melts. Furnaces may be heated either by coke, gas, oil or electricity, and are of several basic types : Lift-Out, Tilting and Bale-Out furnaces. Plumbago and silicon carbide crucibles are used, and are designed to give maximum refractoriness and heat conductivity together with resistance to flux and slag erosion, and oxidation. Crucibles range in sizes up to 15 cwt. brass, and 10 cwt. aluminium capacities.

FIG. 260.—Forced-Draught Furnace in Pit. Coke fired.
(*Courtesy—Morgan Crucible Co., Ltd.*)

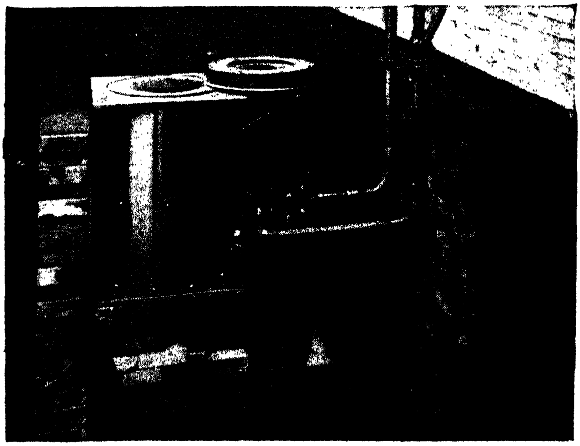


FIG. 261.—Pit Type Gas-Fired Furnace.
(*Courtesy—Morgan Crucible Co., Ltd.*)

Lift-out furnaces. This type of furnace is suitable in cases where small quantities of a variety of alloys are required, and is therefore generally the most popular type for small and medium-sized foundries handling a range of alloys.

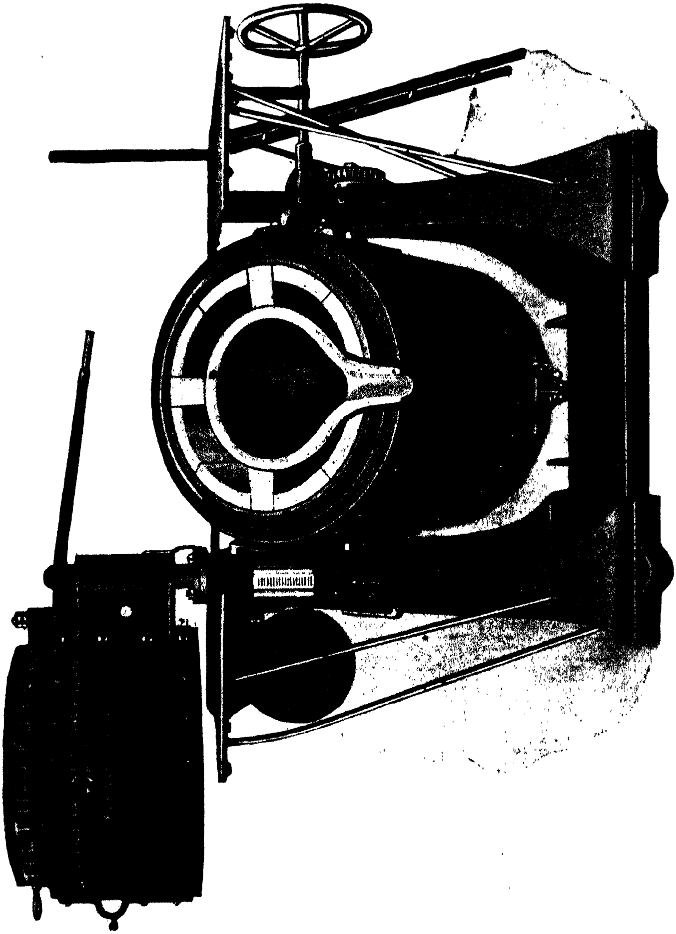


FIG. 262.—Coke-fired Tilting Furnace. Central axis pattern in pouring position. (*Courtesy—The Morgan Crucible Co., Ltd.*)

Coke firing is most commonly employed, but the use of oil and gas is rapidly increasing.

The crucible, ranging up to about 400 lb. capacity, is housed in a shell built up with iron or steel plates fixed together and lined with good-quality firebrick and insulation, the whole being generally set below floor level. The space between the crucible and furnace lining forms the combustion space. Coke furnaces may be natural or forced draught, provided in the first case by a suitable chimney stack, and in the latter case by a high-speed fan supplying air to a closed ashpit. Oil and gas furnaces are of the forced draught type, blown by air at ¾ lb. per sq. in. supplied by a high-speed fan.

The crucible is lifted from the furnace by means of steel tongs, placed in a shank and carried direct to the moulds for pouring.

Tilting furnaces. This type is more suitable for handling larger quantities of metal with greater efficiency and lower labour costs. It is therefore the most usual type for larger foundries and is used extensively for the mass production of medium and heavy castings, billets, strip and ingot.

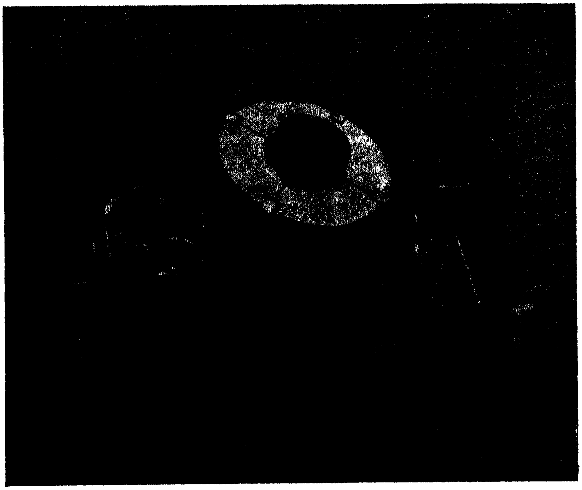


FIG. 263.—Gas-fired Tilting Furnace. Central axis design.

(*Courtesy—The Morgan Crucible Co., Ltd.*)

Oil and gas are becoming the more popular fuels due to their greater cleanliness and ease of working, although coke firing is still used to a considerable extent in the smaller sizes.

Tilting furnaces are arranged either for central axis pour, in which case the metal is poured into a ladle for transfer to the moulds, or with lip-axis pour for supplying metal direct to billet and ingot moulds. The former type of furnace is the more common and is a good deal cheaper, due to the absence of counterbalance weights for the latter design. It is usual for the tilting to be operated by hand although power tilting can be utilised.

The standard type of crucible for the smaller sizes of central axis-design oil and gas furnaces, pours right over the top of the furnace. This arrangement, in which the muffle ring for the supercharge and the pot are made in one piece, is preferred to the older spouted crucible with separate muffle ring, as it gives easier setting of the pot, complete protection of the metal from furnace gases, freedom from metal spillage into the combustion space, and the opportunity, if desired, of charging more than the nominal capacity of the crucible. Spouted crucibles have to be employed in lip-axis furnaces which would otherwise not retain

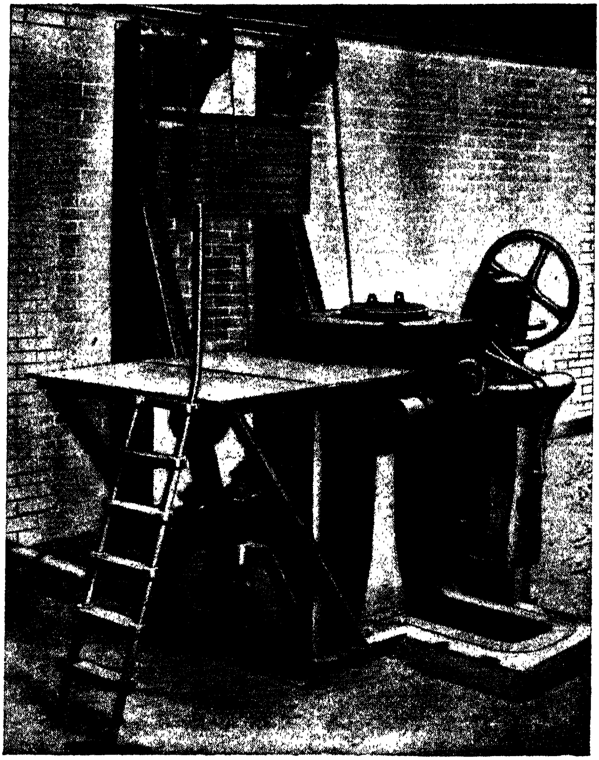


FIG. 264.—Oil-fired Tilting Furnace. Lip-axis design.
(*Courtesy—The Morgan Crucible Co., Ltd.*)

the constant position of pour. Spouted crucibles are also used in coke furnaces. Most coke furnaces are made with a separate swinging preheater section, but gas and oil furnace casings are made in one piece as no provision has to be made for coking up—the oil and gas furnaces are, therefore, more efficient from the aspect of heat losses.

Bale-out furnaces. This type of furnace is used in the main for aluminium and bronze die-casting, although large units are made for ingotting scrap aluminium. The furnace is of the stationary type and uses a wide shallow basin from which the charge can be easily emptied by ladling out. For die casting, it is required to maintain a molten bath of metal at a constant temperature, and for this reason oil and gas are almost exclusively used, giving easier temperature control. The furnace is intended chiefly for maintaining metal and, due to the shape of the basin, it is not quite as economical a unit for plain melting as the types previously described.

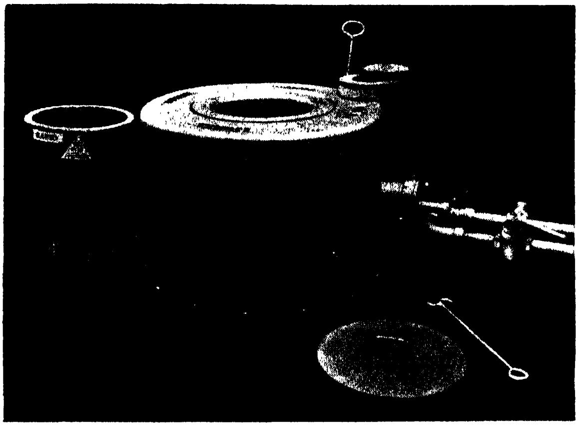


FIG. 265.—" Bale-Out " Type, Oil-fired Aluminium Melting and Maintaining Furnaces.

(*Courtesy—The Morgan Crucible Co., Ltd.*)

Electric furnaces. These are used to a lesser extent than the tilting furnaces previously described and are mainly used for specific purposes. The most generally used is the induction type, chiefly the Ajax-Wyatt low-frequency induction furnace. It is a tilting furnace ranging in standard capacities from about 6 to 22 cwt. and finding especial favour in the production of non-ferrous ingots, in which connection the modern shop contains a number of furnaces fed by overhead cranes and pouring direct into ingot moulds. The moulds are fixed on turntables arranged in a suitable position directly in front of the furnaces.

The principle of the furnace is shown in Fig. 267, in which B is a copper coil acting as the primary of a transformer. The secondary winding is provided by molten metal which completely fills a V channel below the main charge. Due to the superheating of the metal in the V channel by the induced currents, it circulates in the direction shown by the arrows resulting in rapid melting of the main body of metal A. Convection, " pinch " and " motor " effects, all due to electrical forces, result in evenly heating, circulating and thoroughly mixing the molten charge. There are no crucibles used in the furnaces but they are lined by ramming a specially compounded refractory material into position round formers. These linings give an excellent life. During melting, metal losses are low owing to accurate temperature control and even heating. The furnace is cheap to operate, reliable, clean in operation, but it suffers from the disadvantage

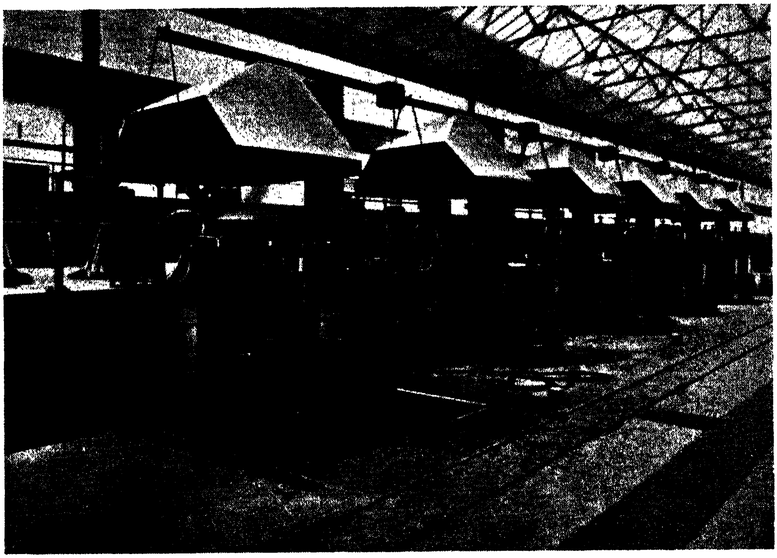


FIG. 266.—Battery of Ajax-Wyatt Furnaces.
(*Courtesy—Electric Furnace Co., Ltd.*)

that it is always necessary to leave the V channel full of molten metal in order to start the next heat. This means that between working periods it is necessary to leave a small amount of power in circuit to maintain the metal in the secondary V circuit in a molten condition. Difficulties may also arise when it becomes necessary to frequently change from one type of metal mixture to another.

The Ajax-Northrup high-frequency furnace, previously dealt with in Chapter 1, is also used to some extent for melting non-ferrous alloys, for intermittent working and where frequent changes of mixtures are necessary. Under these conditions it is more economical in operation than the Ajax-Wyatt furnace. For continuous production on one type of mixture the Ajax-Wyatt is more economical.

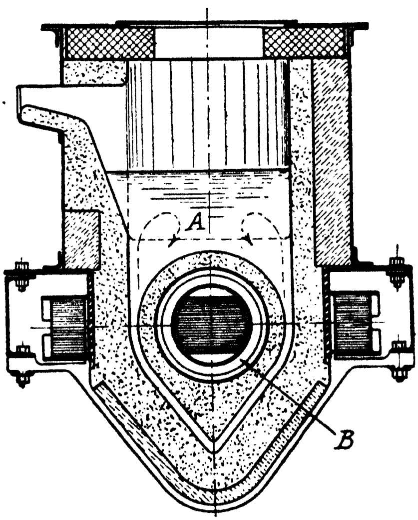


FIG. 267.—Diagram of Ajax-Wyatt Furnace.

The Electric Rocking Arc furnace has found considerable favour in the U.S.A. for use with non-ferrous alloys, and is now being used in this country to a limited but increasing extent, and with success. The melting is very rapid, and, since the melting chamber is almost sealed during melting, the furnace atmosphere is non-oxidising. Metal losses through oxidation are therefore low.

Furnace atmosphere. The atmosphere of the furnace controls to a considerable extent the quality of the metal and particularly the melting loss. When melting bronzes or gunmetals containing substantial amounts of tin, the atmosphere is preferably slightly oxidising owing to the deleterious effects of the gases absorbed should the atmosphere be reducing. In the case of alloys containing high proportions of zinc, zinc is very readily oxidised to zinc oxide, and results in a considerable metal loss in an oxidising atmosphere. The losses, then, can be minimised by employing an atmosphere which is slightly reducing.

Gas and oil-fired furnaces are advantageous when atmosphere control is desirable, in that they permit, by regulation of the air and fuel supply, a control of combustion conditions, and often the appearance of the flame will serve as a guide.

Protection of the surface of the metal can be afforded by a covering of certain fluxes during melting.

MELTING AND COMPOUNDING NON-FERROUS ALLOYS

Straight brasses. The alloys are usually melted under charcoal, the copper being melted first. When considerable quantities of scrap metal are used, it is an advantage to use borax as a flux. When the copper is melted, the zinc is added gently piece by piece. The copper should not be too hot at this stage, otherwise the addition of the zinc is accompanied by a violent hissing noise, a vivid light, and copious white fumes. The resultant metal may then be of poor quality, with high zinc losses. The zinc is added by means of tongs, stirred in with a mixing bar, or the melt plunged with a special plumbago plunger. The melt may be deoxidised with a small amount of manganese-copper containing about 30 per cent manganese. The slag and flux is skimmed off and the metal poured.

Complex brasses. Some charcoal is first added to the crucible of the furnace. The copper is charged in and melted. The other metals are added in the order of their decreasing melting-points. Some of the special elements, having higher melting-points than copper, are introduced in the form of " key " metals or " hardeners." Manganese has already been mentioned as being available in the proportion of 30 per cent in manganese-copper. Nickel may be added in the form of 50-50 cupro-nickel. Iron may be introduced in the form of ferro-zinc containing about 5 per cent iron, or, in some instances, be added directly as thin gauge iron to the molten copper, but the copper should be hot enough to effect solution.

Manganese bronze may be included in this category. The copper is melted first, then the iron is added and well mixed in, followed by the required amount of manganese-copper, and then the zinc. It is good practice to pour a small test piece in a metal mould before pouring the heat. When this is fractured, it is possible from the crystalline appearance of the fracture to assess roughly the zinc content, and therefore its suitability for pouring.

Bronzes and gunmetals. The metal should be melted under charcoal which has previously been well heated to drive off moisture and traces of volatile matter. The metal should also be melted as rapidly as possible to avoid gas absorption from the atmosphere, which should be maintained slightly oxidising. As usual with the other copper alloys, the copper is melted first, then the zinc added, then the lead, if any, and finally the tin. A flux covering of glass is sometimes used throughout the melt. The melt is deoxidised just prior to pouring by stirring in about 1 oz. of 10 per cent phosphor copper for each 100 lb. of metal. The metal should be poured immediately it is mixed, and should not have to wait longer than is necessary for the best results.

Phosphor bronze. Is similar in preparation to gunmetals and straight bronzes, but a small allowance is made when computing the charge, for a small loss of phosphorus.

Aluminium bronze. The alloy is melted under charcoal, and borax is sometimes used as a flux. The copper is melted first, then the iron is added. The aluminium is added last, preferably in the form of 50-50 copper-aluminium pig.

Nickel alloys. Manganese ore (manganese dioxide) is used as a flux and is placed at the bottom of the crucible before any metal is charged. If the alloy is to be one of high nickel content, nickel shot is charged and melted first, but if the nickel is of lower content, cupro-nickel is used. If iron is required in the mixture it is added next in the form of ferro-copper. Any other metals are added in order of melting-point. The melt is deoxidised with a little metallic silicon, and the deoxidation may be perfected by plunging beneath the surface ½ to 1 oz. of magnesium per 100 lb. of metal either in the form of magnesium metal or as magnesium-copper. Iron pick-up from the tools can be minimised by using tongs or stirring rods coated with some refractory material.

Nickel silver. When melted under reducing conditions nickel silver has a strong tendency towards gas absorption, resulting in gas and non-metallic inclusions being the cause of defective castings. The metal is therefore melted under oxidising conditions. No charcoal is used in the process but it is necessary to have a flux protection. The fluxes used are either broken glass, borax, borocalcite, and often manganese ore is employed. Sulphur is injurious to the alloy and it is therefore essential to use fuel low in sulphur content. Cupro-nickel 50-50 shot is melted first, then is added the copper, and then the zinc. If other metals of lower melting-point than zinc are desired in the alloy, they are added afterwards. A final 3 to 5 per cent of the total zinc charge is added to compensate for oxidation losses. The melt is deoxidised with about 0·05 per cent magnesium, or with small amounts of manganese-copper or phosphor-copper.

Silicon bronzes. No charcoal is used, glass is employed as a flux, and the furnace atmosphere is slightly oxidising. The mixture is made up from copper, manganese copper, and 10 per cent silicon-copper. When zinc is desired to be present in the alloy, it is added last. Stirring should not be excessive but just sufficient to ensure thorough mixing. When the whole heat is molten the slag can, with advantage, be thickened up with a little dry silica sand. A little phosphor-copper added just prior to casting assists in deoxidation. The metal should be poured immediately the required temperature has been attained.

Note. In all the foregoing alloys, if any scrap of similar composition to the finished alloy is to be included as part of the charge, whether in the form of wasters, runners, etc., it is introduced early in the melt, usually immediately after the first major metal of highest melting-point.

White-bearing metals. When producing the lead base type, the lead is melted first, the antimony is next stirred in by adding small pieces a little at a time, and finally the copper. The copper is easier to add in the form of a copper-tin-antimony hardener.

When making the tin base alloys or Babbit metals, perhaps the most satisfactory method is to first of all make up an antimony-copper-tin hardener from the weighed ingredients. To do this the copper is melted first and the antimony added in small pieces and a little at a time until melted. Then a proportion of the tin is added. The melt is now poured into small ingots. The remainder of the tin is now melted, and the hardener prepared as above is added to it and stirred well.

Aluminium alloys. The aluminium alloys are usually melted in crucible furnaces, care being taken to avoid contact of the flame with the molten metal. This assists in minimising pick-up of gases which, when released on solidification, introduces porosity. Graphite and iron crucibles are used, the former being employed for mixtures like the high silicon alloys in which iron content must be minimised. Iron pots are frequently cleaned and given a wash on the inside with some protective material. In melting, scrap is charged first to provide a pool of molten metal for the ingots which follow. The copper in the form of 50 : 50 copper-aluminium alloy is charged with the aluminium ingot. The other alloying elements are added in the form of key metals, that is, they are associated with aluminium in suitable amounts and the order of charging is usually silicon, iron, manganese, nickel and magnesium. Zinc, when required in the alloy, is the last to be introduced, is quietly stirred in, and, as usual, a small allowance made for oxidation and volatilisation losses. The bath is deoxidised with a little magnesium gripped by tongs and immersed below the surface of the molten metal. It is not usually necessary to use a flux if melting is carefully carried out, but when fair amounts of scrap or secondary metals are used in the charge, fluxes such as zinc chloride and ammonium chloride can be used with benefit. Undue agitation during handling and pouring is avoided to minimise oxidation and trapped air in castings.

Magnesium alloys. The metal is melted in a mild steel or preferably a heat-resisting steel pot. Magnesium is very easily oxidised and the choice of flux is important. One lighter than the metal is used, and also one which thickens as it reacts and so forms a hard crust on the surface of the metal. The materials employed as fluxes are usually magnesium fluoride, potassium or sodium chloride, and anhydrous magnesium chloride mixed in various proportions. At the beginning of the melt a thin flux, consisting of about 60 per cent magnesium chloride and 40 per cent sodium chloride, is added to the ingot metal and scrap. During melting, the flux removes the oxides and becomes more viscous and dense, and, on stirring, it sinks to the bottom of the crucible. More flux is added to make good the loss, and eventually a point is reached where it remains fluid and floats on the metal, and it is then known that the refining is complete. A thicker flux is now added, composed of 30 per cent magnesium fluoride and 70 per cent magnesium chloride, which forms a hard crust on the surface of the metal, and which is pierced when the heat is ready for pouring. The casting temperature is approximately 720°C., but for the finest-grained material a superheat temperature of 100 to 200°C. above this is employed, and the metal allowed to cool again before casting. The flux covering is strictly maintained during this period.

Pouring of magnesium alloys should be slow and uniform, and the stream of metal protected from oxidation by dusting sulphur on to it as it leaves the ladle.

Quality of cast metals. To produce the best quality of metal and the soundest castings, much depends on proper melting and temperature control.

Strict attention must be paid to melting conditions, to have the correct atmosphere and the correct flux covering. The metal should be melted as rapidly as possible to avoid excessive pick-up of gas, and it should not be heated (with perhaps the exception of magnesium alloys) to a higher temperature than is necessary prior to pouring. Unlike other liquids, whose capacity for dissolving gases decreases with rise of temperature, molten metals dissolve increasing quantities as the temperature rises. A molten metal, then, which has been overheated, will often produce a casting containing fine blowholes due to the liberation of the dissolved gases during solidification. Care is generally taken to ensure that fluxes and covering materials for the bath of molten metal are dry, also that the ladles used for taking and pouring the metal from furnace to casting are also well dried, these precautions helping to minimise gas pick-up.

In the case of most non-ferrous alloys, the casting temperature is very important and is somewhat dependent upon the size of the article to be cast, one of thin and intricate section requiring a higher casting temperature than a heavier casting. If the metal is cast very hot, the resulting casting will have a very coarse crystalline fracture often exhibiting sponginess, this undesirable structure being due also to prolonged cooling, because the refractory mould is also locally overheated and heat transference is slow. The mechanical properties of such metal are low, and in thick sections there will be a tendency to segregation of any low melting-point constituents. The casting is usually more rough in appearance with high-pouring temperature, and particularly with the very fluid alloys such as the phosphor bronzes where the metal tends to penetrate between the sand grains. On the other hand, the metal should not be poured so cold that " cold-shuts " are formed, that is, defects caused when the streams of metal in the mould are not sufficiently fluid to combine to form a sound joint. These cold-shuts can often be distinguished by a fine line on the surface of the casting, but sometimes they are not located until a casting is subjected to fluid pressure, air pressure, or other tests.

The melter can often judge the temperature of the metal by its appearance and brightness, and, in the case of brasses, by the evolution of white and dense fumes which increase in quantity as the temperature of the metal rises. Temperature control by the use of a pyrometer is, however, most desirable if consistently good results are to be obtained, because pouring temperatures can then be standardised for any particular mixture, and any type and size of casting.

The metal should be treated just before pouring with the appropriate deoxidiser in the correct amount, care being taken not to add too great an excess.

The following table gives the approximate average pouring temperatures for the most common non-ferrous metals and alloys, and it should be borne in mind that the temperature may range from about 30° below to 70° above that given, according to the sectional thickness of the casting.

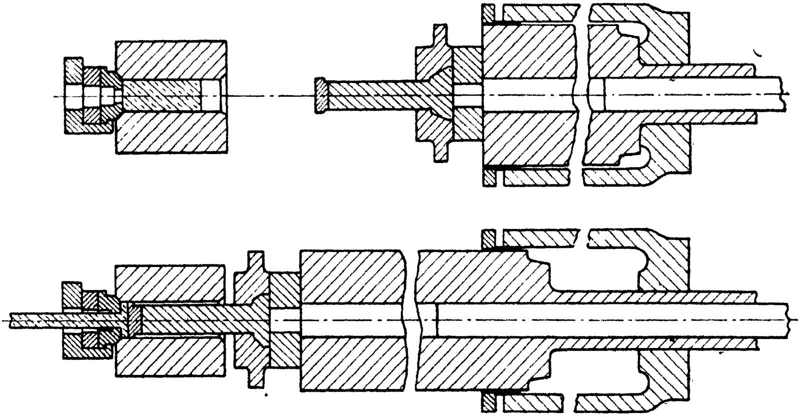
Metal or alloy	*Approximate average pouring temperature °C.*
Aluminium	730
Aluminium alloy (Y and R.R. types)	720
Aluminium silicon alloys (10 per cent Si)	690
Magnesium base alloys	720
Admiralty gunmetal	1150
85–5–5–5 gunmetal	1120
Brass 70–30	1100
Brass 60–40	1000
Copper	1150
Aluminium bronze	1160
Phosphor bronze (10 per cent Sn)	1080
Manganese bronze	1000
Silicon bronze	1140
Ni–Sn–Cu alloys (Nickel bronze type)	1350
Monel metal	1530
Nickel silver	1300
Babbit metal	440

FIGS. 268 and 269.—Two views of a 2000-ton Hydraulic Horizontal Extrusion Press fitted with internal mandrel-moving cylinder, for the production of solids and tubes.

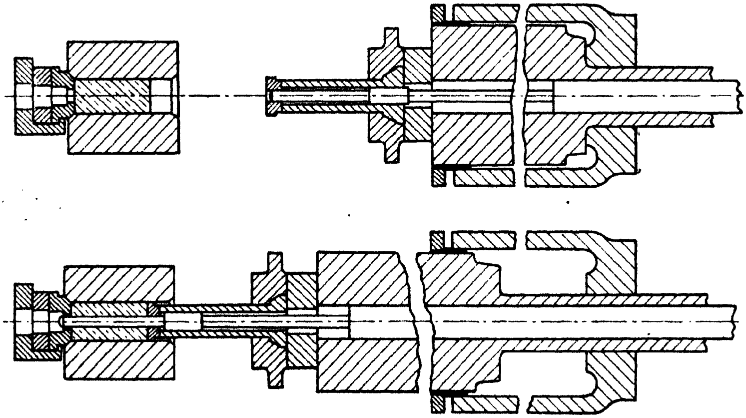
(*Courtesy—Messrs. Fielding and Platt, Ltd.*)

EXTRUSION

The mechanical working of non-ferrous metals is in many respects very similar to the working of steel, but whilst the operation of extruding sections is very limited in the case of steels, a large amount of non-ferrous metals are extruded, and, by the process, a large variety of sections, including hollow tubular shapes, are produced.



(A) Extrusion of Solids



(B) Extrusion of Tubes

FIG. 270.—**Diagrammatic Layout of Extrusion Processes.**

(Drawing by Messrs. Fielding and Platt, Ltd.)

Unlike drawing, which is the operation of elongating metal by pulling through a die, extrusion consists of pushing through a die. The extrusion press consists essentially of a container for the billet, a die securely fixed at one end of the container, a pusher rod and a hydraulic cylinder and ram.

The billet of metal is placed into a reheating furnace until it has attained the desired temperature and is of uniform heat throughout. The temperature is important, since if it is too high, the metal is too plastic, extruded too easily, and the work done upon the metal will not be sufficient to give the necessary strength. On the other hand, if the temperature is too low the metal will be insufficiently plastic and may give difficulties in extrusion. The billet is taken to the press, placed in the heated container, the hydraulic pressure is applied when the ram slides forward and brings the pusher rod into contact with the billet, compressing it and causing it to completely fill the container. Further forward movement of the ram forces it through the die. Solid sections are shaped only by the plastic metal conforming to the shape of the die, but when making certain hollow sections, both a die and a mandrel are employed.

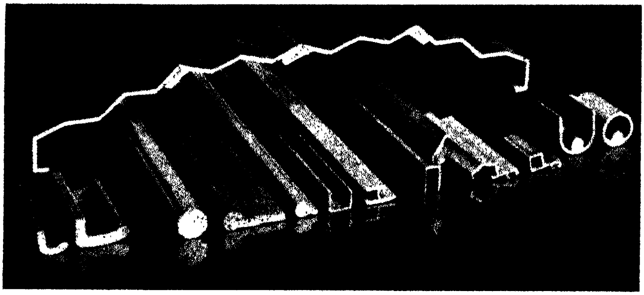


FIG. 271.—Typical Brass and Copper Extruded Sections.
(*Courtesy—Copper Development Association.*)

Extrusion of tubes. The billet must be clean and free from defects. It is sometimes bored with a drill, as the presence of the hole reduces the pressure on the mandrel bar, when piercing. The billets are reheated before extruding, in a furnace close to the press. In the case of 70–30 brass for condenser tubes a temperature of about 800°C. is employed. The billet is placed in the gas-heated container of the press and is brought into contact with the extrusion die, the press ram is drawn back and a guide bush and pressure plate placed in position in the container. The piercing mandrel actuated by an internal cylinder is brought up to enter the guide bush and further advanced until it contacts the hot billet, which has the effect of compressing the billet before actual piercing starts and causing it to completely fill the container. The mandrel is forced by the internal ram through the billet until it enters the die. The main ram then pushes the metal at a pressure approaching 3000 lb. per sq. in. over the mandrel and through the die, thus forming the tube.

DIE CASTING

Die casting is a method of mass-producing castings by introducing metal into permanent moulds of such a type that they can easily be assembled and taken to pieces. The moulds or dies are usually constructed from cast iron or steel, and for the best length of service, chrome-vanadium steel is used. The halves of the dies are located together with dowel pins, and firmly closed with either screw clamps, or wedges, or swinging catches, etc. Holes, certain recesses, and slots are formed in the castings by removable steel cores which are inserted before each pour and withdrawn when the casting is ejected. All cores, usually of special steel, are fitted with handles on the outside of

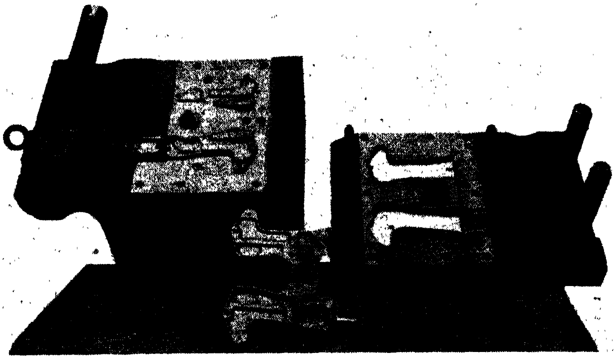


FIG. 272.—Halves of a Die for the production of a Die Casting.

(Courtesy—Messrs. Fox and Offord, Ltd.)

the die to facilitate removal and replacement with each pouring operation.

Two general methods of introducing the metal into the mould are used. One is termed " gravity die casting " where the metal is poured into a hole at the top of the mould, and thence through gating to the mould cavity, and gravity is then the only force which carries the metal into the recesses of the die. The dies are usually preheated prior to receiving the molten metal.

The other method " pressure die casting " employs mechanical or air pressure to force the metal into the dies. The pressure process is more rapid, lending itself to machine production, gives a superior finish with a greater degree of dimensional accuracy than is obtained with gravity casting.

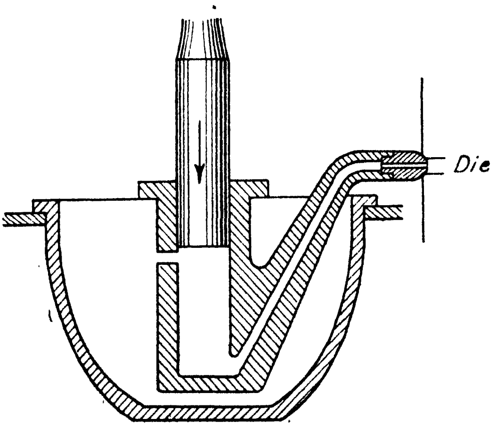


FIG. 273.—Pot and Plunger Method.

The alloys usually die cast are those of the low melting-point white metals with lead, tin or zinc base; brasses, aluminium bronze, aluminium alloys, and magnesium base alloys.

Pressure castings are mainly produced in machines, some of which have been developed to such a state of efficiency that opening and closing of the die, inserting and withdrawing cores, and ejecting the finished casting is performed mechanically. In most instances the dies are water cooled.

A simple type of machine suitable for the production of castings in zinc or other low melting-point alloys is that employing the " pot and plunger " principle. The cylinder and plunger are fixed in a melting-pot containing the molten metal. The apparatus, in broad principle, can be compared with a straight-sided teapot where the die is attached to the spout and a well-fitting plunger replaces the lid. When the plunger is at the top of its stroke, metal enters the cylinder through a hole which is normally covered by the plunger when making its downward stroke. The metal is forced through a stout tube branching upwards from the bottom of the cylinder, through a nozzle and into the die. The cylinder is again filled with metal when the plunger, on its upward stroke, moves above the entrance hole. Plungers on small machines may be hand-operated, whilst large plungers are operated by compressed air.

The Gooseneck machine consists of a vessel shaped as in the diagram and is held in a melting-pot, and by a pivoting mechanism the nozzle can dip into the reservoir of metal and take up a fresh charge. The nozzle is brought to fit firmly with the entry into the die. Air pressure is used ranging up to about 500 lb. per sq. in., depending upon the size of the machine, etc., and its action on the surface of the metal contained in the gooseneck, forces the molten metal into the die.

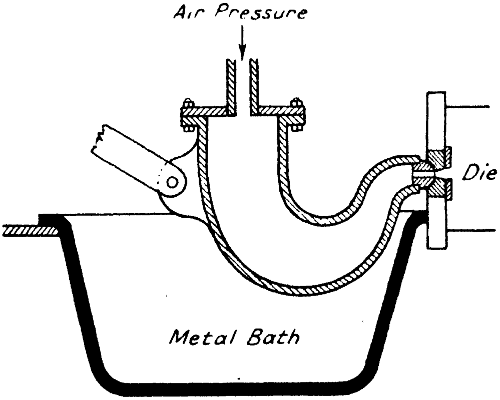


FIG. 274.—Gooseneck Method.

Other methods of die casting use hydraulic pressure and especially find application in the production of brass die castings. In one method the metal is taken from a separate furnace and poured through a hole in the plunger end of a cylindrical container. A hydraulic ram pushes the plunger forward into the cylinder and, after covering the hole, the plunger forces the molten metal into the die cavity. In another method, the metal in a plastic state, at a temperature between the liquidus and the solidus, is introduced into a chamber. A plunger is brought quickly into operation which squeezes the metal into the die.

Generally speaking, die castings are considered to be superior in finish to sand castings, they give a greater dimensional accuracy, the metal is more dense, due to the quick rate of cooling, and there is a minimum of machining; in fact, articles with a cast thread can be successfully produced. The die castings produced in hydraulic machines are particularly sound and dense, and have a high degree of surface finish.

CHAPTER II

WELDING, GALVANISING, CENTRIFUGAL CASTINGS, CHILLED CASTINGS, POWDER METALLURGY

WELDING

IN recent years great strides have been made in the technique, scope and application of welding. Since the subject is now a very large one, space permits of only a generalised summary of welding processes.

Welding was the term originally applied to the joining of metals by heating to a state of plasticity or incipient fusion, and necessarily followed by the application of pressure. The term now also embraces the procedure of melting the surfaces for joining with the addition of a molten filling material (from a welding rod) to form the joint, both by gas-welding and electric-arc methods, the operations being independent of pressure. Metals are also joined by electrical resistance methods whereby the heat developed by the resistance of the material to the electric current provides the necessary heat and is accompanied by the application of pressure to aid the formation of the joint.

The methods of welding, therefore, may be roughly classified into two groups :—

(1) Those where the localities to be joined are heated to a state of plasticity or incipient fusion, accompanied or followed immediately by the application of pressure.

(2) Fusion methods.

Incipient fusion. *Forge welding.* This is the oldest form of welding. The parts are heated to a suitable temperature and the joint made by hammering or rolling. The blacksmith heats his materials in a fire and hammers the ends together, often using sand as a flux.

Electrical resistance welding. (*a*) *Spot.* This is a method used for the joining of sheets or plates. The parts overlap and are gripped between heavy electrodes. As the current is passed local heating of the sheets to a state of plasticity takes place, resulting in a spot weld. This method of welding is useful for the production of temporary joints.

(*b*) *Seam.* This is similar in principle to spot welding but is a continuous process employing circular electrodes in the form of wheels. The sheets to be joined are passed between the wheels, one of which is driven and the other free to rotate. The electric current heats the moving sheet metal to a state of plasticity, and with the aid of the pressure from the revolving wheels, the sheets are bound together in a continuous weld.

(*c*) *Butt.* Lengths of rod, bar, tube or wire are placed end to end. An electric current is passed through the work and the resistance to the current heats the ends to a plastic state. By increasing the pressure, a weld is formed.

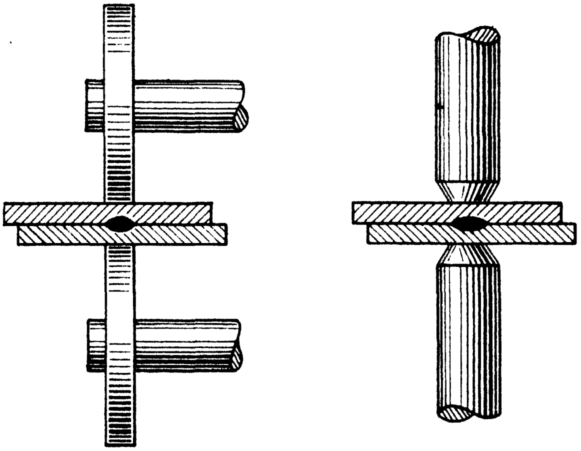


FIG. 275.—(a) Diagram illustrating method of Seam Welding. (b) Diagram illustrating method of Spot Welding.

(*d*) *Flash.* This is also a butt weld which, amongst other shapes, is applied to sheets and tubes. The parts to be welded are placed end to end with a narrow air gap between them so that with the passing of the current an arc with a "flashing" action is struck and any uneven edges are burned away. The current is broken when the edges attain welding heat, and the pieces are forced together with sudden application of pressure to form a strong weld.

Complete fusion. *Gas.* The best welds are obtained by joining clean prepared surfaces, and, since the heating prior to joining tends to promote an oxide film on the work and rod, particularly when dealing with aluminium alloys and aluminium bronze, a suitable flux is applied. This melts at a temperature considerably lower than the actual welding temperature, and combines with oxide formed during the preheating of the metal and formation of the weld to form a fluid slag, and so the oxide is removed. Also the protection which the flux affords to the metal inhibits oxidation, and sometimes, to a certain extent, volatilisation of low melting-point constituents in some alloys. Fluxes are obtained from manufacturers, ready mixed in correct proportions for any particular application.

The surfaces to be joined are melted by a flame from a gas torch. The gases most commonly used are mixtures of oxygen and acetylene. They enter the torch from cylinders or generators, and are mixed there in readily controlled proportions to give a flame either oxidising, neutral or reducing, the character depending upon the composition of the materials being welded. The oxy-acetylene torch gives temperatures up to 6000°F. and quickly melts any of the ordinary metals. A filler rod is used along with the correct type of flux, which is best applied on the end of the rod. In the welding operation the end of the filler rod is held close to the work and melted by the heat of the flame. The molten metal from the rod flows into the prepared joint between the pieces being welded, and the fusion between this and the base metal creates a strong weld.

Welding rods, with certain specific exceptions, have a composition similar to that of the metals being welded, although in some instances the rod is somewhat richer in the elements having a tendency to volatilisation in the process.

Carbon Arc. This is the oldest electric welding process where an arc is struck between a graphite electrode and the work. The heat generated melts the surfaces to be welded. A filler rod can be used by melting the end in the arc.

Metallic arc. This method of welding, along with spot welding, now covers the greater proportion of the welding industry. It is chiefly used for steel, and in this respect is the most widely used fusion process. It is also used, but to a lesser extent, for welding a wide range of non-ferrous metals, including alloys of copper, aluminium and nickel.

The method is similar to the carbon arc, but the electrode is a metal rod of suitable composition which serves also as a filler rod. The heat generated by the arc melts the end of the electrode, which is usually coated with a suitable flux to protect the metal from oxidation, etc., while it is being deposited on the joint. The flux coating also has the effect that it assists in stabilising the arc. At the same time the heat of the arc, in addition to melting the end of the electrode, locally fuses the surface of the work being welded and both metals become intermixed in the weld. The deposition of the metal from the electrode is continuous and at a uniform rate.

Atomic hydrogen arc. An arc is formed between two tungsten electrodes carried in a holder in the form of a torch. By means of a supply tube attached to the torch, a stream of hydrogen is passed through the arc whereby the molecules of gas are broken down into the atomic state. As the atomic hydrogen leaves the arc, the atoms recombine into molecules producing an intensely hot flame (about 7000°F.) in contact with the work, and thus the heating is localised. Due to the envelope of burning hydrogen, the welding atmosphere is reducing.

Thermit welding. This is a process sometimes used for the repair of large iron and steel castings or mild steel forgings. A mould is formed round the parts to be joined, and above is placed a quantity of Thermit powder, consisting of an intimate mixture of powdered aluminium and iron oxide. The parts to be welded are preheated. When the mixture is fired, the iron oxide is reduced to the metallic state, and the reaction, being highly exothermic, forms molten iron at a very high temperature. The molten iron runs into the mould and combines with the preheated surfaces to produce the weld.

$$Fe_2O_3 + 2Al = Al_2O_3 + 2Fe$$

Brazing. Brazing is similar to a soldering operation, but the materials used to form the joint are of higher melting-point and possess considerable strength. The alloys used for brazing are usually alloys of copper and zinc, and are applied with a suitable flux, and with a blowpipe flame of lower temperature than used in welding.

Welding of wrought iron and steel. *Mild steel.* Gas welding of wrought iron and mild steel requires a good quality filler rod low in sulphur and phosphorus. Wrought iron and mild steel weld with ease, but the higher carbon hypo-eutectoid and the hyper-eutectoid steels present difficulties such as hardening brought about by quick cooling; and decarburisation when the oxidised carbon may give trouble with porosity. A rod similar in composition to the base metal is used, usually without flux, and with a neutral or slightly oxidising flame.

For metallic arc welding of mild steel the electrodes are coated with a combination of such materials as lime, silica, rutile, ferromanganese, powdered aluminium, etc. In addition to fluxing and deoxidising actions the coating has the effect of stabilising the arc.

The structure and general properties of the welds can be improved by hammering whilst hot, or by normalising.

Alloy steels. Many alloy steels can be successfully welded by the correct choice of welding rod or electrode.

Gas welding of low alloy steels can be carried out with special mild steel welding rods, but these rods are a little higher in carbon content than the ordinary mild steel (very low carbon) rods used in the welding of mild carbon steel. These rods usually contain greater amounts of manganese and silicon than ordinary rods, e.g. carbon 0·25 per cent, manganese 1·5 per cent, silicon 0·4 per cent; and give satisfactory results as there are usually sufficient amounts of alloy elements picked up in the weld metal from the parent metal. It is often necessary to preheat the work a little, but general procedure depends upon the type of steel and other considerations.

Steel containing 3 per cent nickel can be used for welding most types of low alloy steel, but this type of rod is usually applied to the building up of worn nickel-steel parts, such as shafts, than to the general fusion welding of steels lower in nickel content.

Stainless steels are welded with 18/8 and other austenitic steel rods. Air-hardening steels of the martensitic type are difficult to weld. The austenitic stainless steels are welded successfully with a high nickel-chrome rod, with flux applied to the underside of the work, but heating in the range 650 to 900°C. greatly reduces their corrosion resistance due to the deposition of complex carbides at the grain boundaries, and the material becomes brittle after being subjected to various corrosive influences. This phenomenon is known as "weld decay." It has been found that additions of suitable proportions of titanium, columbium, etc., to the steel during manufacture, provide proof against the defect.

The metallic arc welding of low-alloy and high-alloy steels has presented major problems which have partly been solved in recent years. The aim in metallic arc welding of the low-alloy steels is the reduction of the hardening at the fusion zone of the welds. Arc-welded metal cools more quickly than oxy-acetylene welded metal, and absorbs more nitrogen. The nitrogen absorption, and consequently the hardness and brittleness, is reduced by employing special coatings on the electrodes. Electrodes which in effect are mild steel, with coatings which also introduce slight alloying in the weld metal, are used in arc welding these steels. Preheating of the steel to prevent cracks and hardening of the weld is often necessary.

The high-alloy steels, including armour steels, are arc welded with austenitic electrodes of the nominal 18/8 and 25/20 chromium-nickel types, the main reason for their use being the prevention of " hard cracks " in the fusion zone of the parent steel. Either the nickel and chromium is kept high in the core wires and/or elements come over from the electrode coating, to deal with dilution, so that the weld metal is stable in its austenitic structure.

Stainless steels welded by the metallic-arc method also suffer from " weld decay " unless proofed against this by the addition of the appropriate alloys. Austenitic electrodes are used either of the 18/8 chromium-nickel types or with higher contents of these elements.

Irrespective of the welding method, steels not proofed against " weld decay " should, after welding, be heated to between 950 and 1100°C. and water quenched if they are intended to withstand corrosive influences, but the shape, size, etc., of the part does not always permit this treatment.

Cast iron. With the use of a suitable welding rod cast iron is readily welded. In gas welding, the rods also consist of cast iron relatively high in silicon and reasonably low in manganese. The castings are preheated before welding in order to minimise cracking. Because heating to welding heat takes graphite into solution, it is necessary to cool slowly and reprecipitate the graphite in order to produce an easily machineable weld. A neutral or sometimes slightly reducing flame is used, with a flux consisting chiefly of sodium carbonate and bicarbonate, along with 10 to 12 per cent borax, and often about 5 per cent of fine silica.

Cast iron can also be welded by the metallic arc process using a coated mild steel electrode, or a steel base electrode containing silicon. A disadvantage is that the weld metal is hard, due to carburisation, that is, taking into solution some of the carbon from the cast iron.

Malleable iron castings. Well-decarburised whiteheart malleable iron can be satisfactorily welded with mild steel filler rods.

Other types of malleable iron are not usually gas welded by using iron or steel filler rods, owing to re-solution of temper carbon at high temperatures. The carbon remains in solid solution on cooling the weld, thereby destroying the malleability. A satisfactory weld may be produced by employing one of the low melting-point proprietary bronzes. The parts or castings are preheated and the essential features are that the surfaces to be welded must be clean and free from oil or grease, given an application of flux and then " tinned " with the bronze before actually welding. The tinning operation is important in producing a tenacious weld, since no actual fusion takes place between the iron and the bronze. Flux is used continuously during welding, and also a slightly oxidising flame.

Bronze welding is used in some instances for the welding of cast iron.

Copper and its alloys. Owing to its high conductivity, copper must be well preheated before welding. As copper readily absorbs gases, rods containing small percentages of phosphorus are used, in which the phosphorus functions as a deoxidant, minimising blowholes resulting from the liberation of the gases during solidification. The properties of the weld are improved by hammering and annealing at 500 to 600°C.

In dealing with brass, a filler rod is used of similar composition to that of the parts, and containing small amounts of aluminium for de-oxidation purposes. The weld in a 60/40 brass is improved by hammering hot; but in the case of 70/30 brass it is hammered cold and afterwards annealed to reduce the hardness introduced by hammering.

Copper-nickel alloys are easily welded, using a similar rod to the parent metal, along with a flux. Oxy-acetylene welding requires a neutral flame, with a minimum sulphur content in the gas mixture.

Filler rods for bronze are likewise much the same in composition as the parts for welding, with the inclusion of small amounts of phosphorus and aluminium. The weld is, with advantage, annealed.

For the carbon arc welding of phosphor bronzes and low-copper brasses, a silicon-bronze rod, containing about 3 per cent silicon, gives good results.

A neutral flame is desirable for copper and slightly oxidising for brass and bronze. Fluxes for copper and its alloys may be mixtures of sodium chloride, borax, boracic acid and powdered glass.

Aluminium bronze is one of the most difficult alloys to weld on account of the refractory oxide films formed on the surface of the heated metal, and which are difficult to slag off with flux. It can be welded using special fluxes, and aluminium bronze or other special bronze rods. Reasonably good results are possible by the carbon arc method, using a silicon bronze filler rod.[1]

Aluminium alloys. These alloys are welded chiefly by oxy-gas, although metallic-arc and spot-welding methods are used very much also. The alloys of the non-heat-treatable types are those most easily welded.

Aluminium oxidises readily and its oxide fluxes with difficulty with the common fluxing reagents. The usual flux mixture contains chlorides and fluorides of sodium, potassium and lithium, and small proportions of potassium bisulphate. The flame used in gas welding is soft and neutral in character, and generally the parts are preheated. Welding rods may consist of pure aluminium or of alloy material. For use with heat-treated base metal, rods of silicon-aluminium alloy are used with advantage owing to lower contraction. It is often the practice in welding sheet metal to use welding rods cut from the parent metal. Owing to the corrosive nature of the flux the weld is given a thorough washing in hot water. The properties of the weld are improved by breaking up the cast structure by hammering followed by low-temperature annealing.

In metallic arc welding the electrode wires consist of aluminium, aluminium-silicon alloy or other special alloys, and it is usually desirable that the weld be of similar composition to the base metal, though in practice this is very difficult in many cases. The electrodes are specially coated with a flux which, in addition to its normal fluxing reactions, serves to stabilise the arc.

Magnesium alloys. The welding rod is of similar composition

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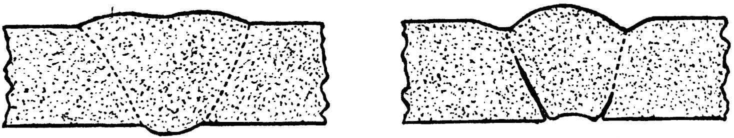
[1] Vreeland, *Metal Industry*, February, 1944.

to that of the parent metal, employing similar technique to the welding of aluminium and its alloys. The special flux used is also corrosive, and is thoroughly washed from the weld.

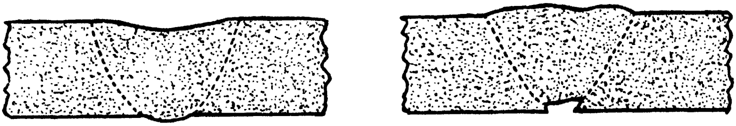
A process, known as Heli-Arc Welding, has been recently developed in the U.S.A. for the welding of magnesium base alloys. A stream of pure dry helium is passed through a direct current arc struck between the work and a tungsten electrode, and a filler rod of suitable composition fed into the arc. It is claimed that welding can be carried out without the use of a flux.

Inspection of welds. *Visual examination for surface defects.* The observable defects may vary somewhat for various metals and for various welding processes and techniques, but careful examination will often indicate correct or incorrect welding conditions such as overheating and excessive gassing as shown by rough, burnt or blistered surfaces; and insufficient fluxing and fusion. Spattering in arc welding indicates incorrect arc conditions, whilst some of the observable defects in spot welding are heavy surface indentation, surface burning and cracks.



Satisfactory weld.

Showing insufficient fusion, undercutting, and concave defect.

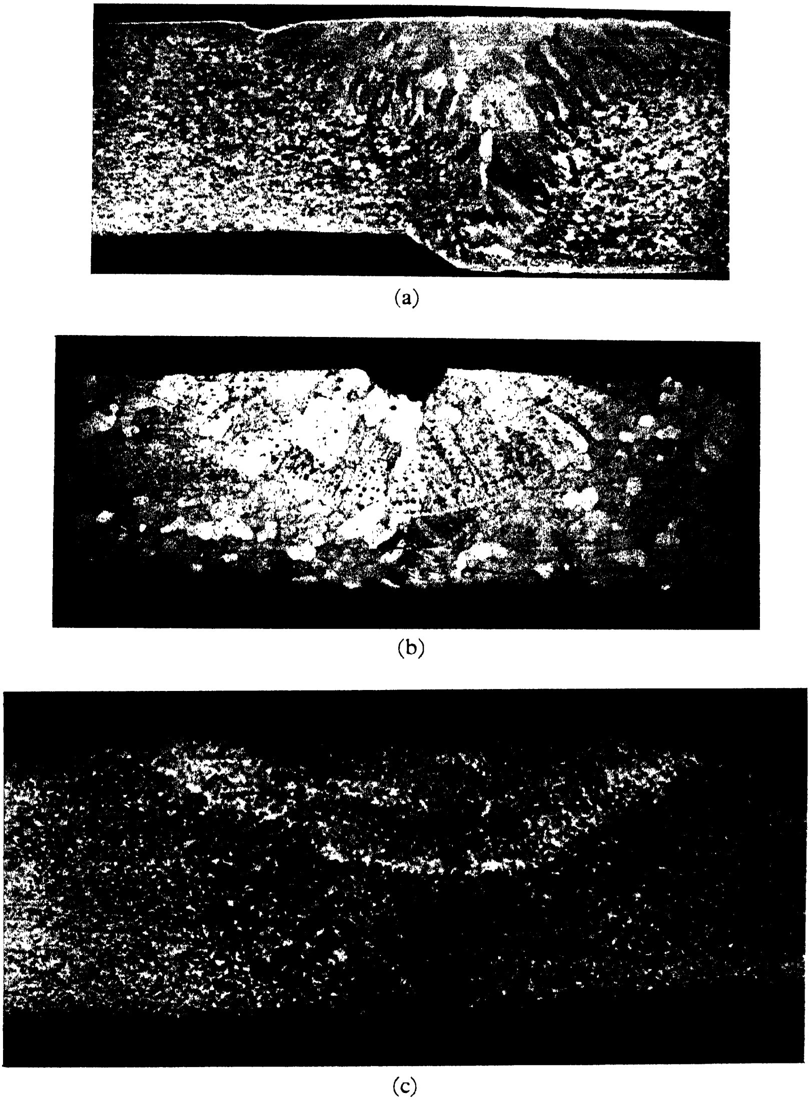


Insufficient weld metal, No reinforcement.

Insufficient penetration.

FIG. 276.—Diagram showing typical defects.

In fusion welding, the appearance of weld metal on the underside of the work does not always signify that there is satisfactory penetration, as weld metal will often run through the joint without complete fusion throughout. A weld should be free from undercutting of the parent metal adjacent to it, and should not be concave on the underside. The weld should be slightly built up above the parent metal to allow for trimming by grinding, etc.



(a)

(b)

(c)

FIG. 277.—Macrostructures of Welds.

(a) Weld in commercial purity aluminium by " step-back " technique, a method where a second layer is deposited before the flux or the first weld metal, half-filling the vee, has solidified. Good weld, metallurgically, there being no porosity or inclusions. Slight tendency to undercut.

(b) Weld in pure aluminium. Welded in two separate runs. Porosity in the second layer.

(c) Slag entrapment in a mild steel weld.

((a) *and* (b) *by courtesy of the Institute of Welding Research Council.*)

PLATE XXXI.

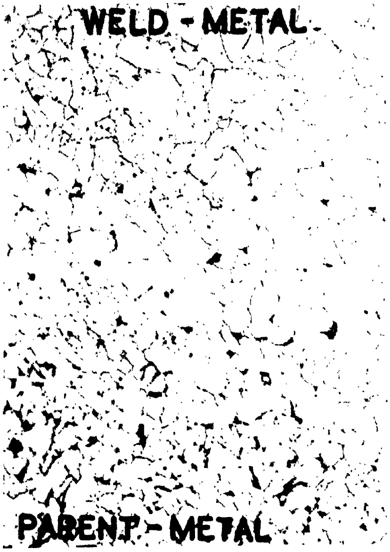


FIG. 278.—Satisfactory Fusion Weld in mild steel made by the oxy-acetylene method. × 100 Dias.

FIG. 279.—Gas Cavities and Slag inclusions in mild steel weld. × 50 Dias.

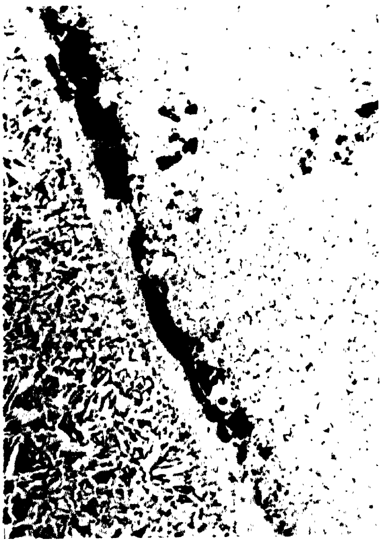


FIG. 280.—Lack of fusion, porosity and decarburisation in mild steel weld. × 50 Dias.

FIG. 281.—Lack of fusion and entrapment of oxide along fusion face of mild steel weld. × 100 Dias.

(*The above micros kindly supplied by the British Oxygen Co., Ltd.*)

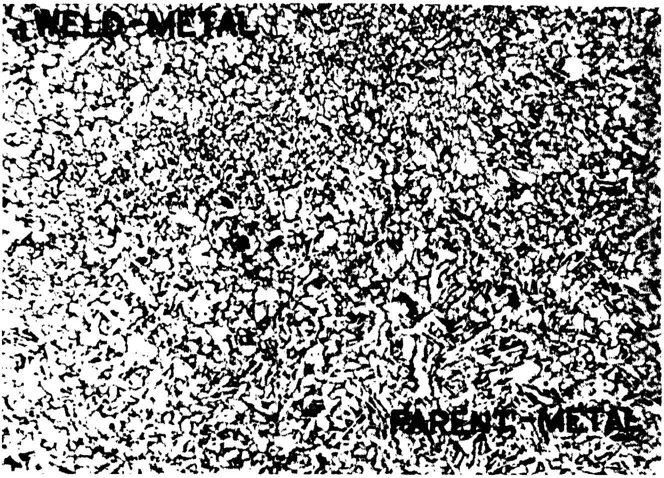


FIG. 282.—Satisfactory fusion weld in mild steel made by the oxy-acetylene method. · 50 Dias

FIG. 283.—Intergranular oxide films and cavities in oxidised weld. × 100 Dias.

(The above micros kindly supplied by the British Oxygen Co., Ltd.)

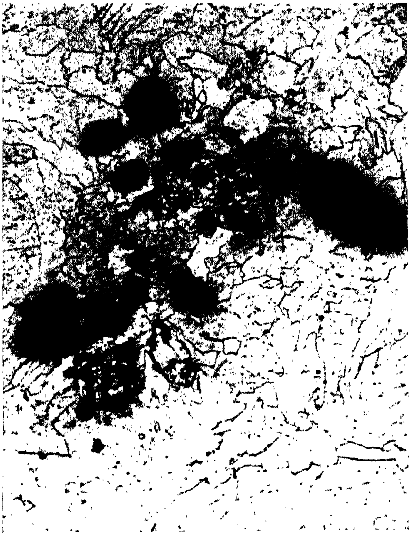


FIG. 284.—Gas cavities in mild steel weld.
50 Dias.

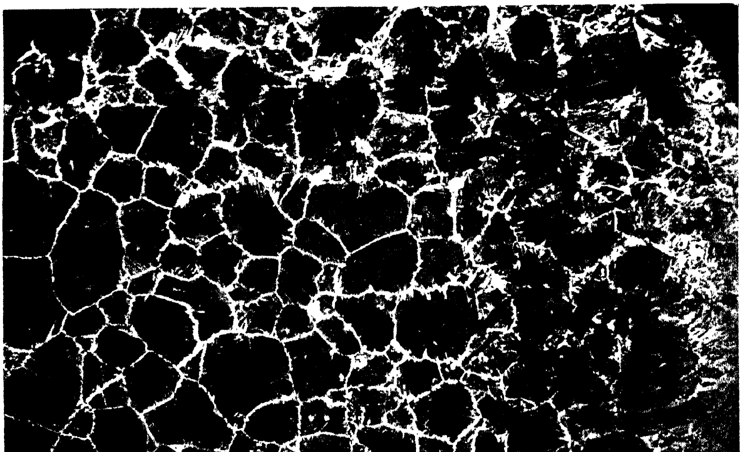


FIG. 285.—Showing excessive carburisation and porosity in mild steel weld.
×30 Dias.

(*The above micros kindly supplied by the British Oxygen Co., Ltd.*)

Detection of cracks. The surface is smeared with thin oil and allowed to stand for a few minutes. The oil is carefully wiped off with a rag and finely powdered chalk is applied and smoothed over the surface. The oil, which ultimately seeps out of the crack, will show on the chalk.

The electro-magnetic crack detector is a piece of apparatus which provides a reliable method of detecting cracks in iron and steel. The part under test becomes magnetised and the lines of force are broken by the fracture or crack. The presence of the cracks is revealed by applying a special ink to the part, or spraying with a dry detecting powder.

Mechanical tests. Most of the usual mechanical tests are applied, but choice of test depends upon the specific service application of the part. Bending is a test which is much applied. Tensile and elongation tests also provide valuable information, but, as they are destructive, they are chiefly limited to sample pieces. They do, however, indicate whether similar results can be reproduced by similar welding operations on the actual articles. The fracture may occur in the weld or the parent metal, and examination of the pieces gives data as to which is the stronger. If failure occurs at a low stress between the weld and the parent metal, inadequate fusion may be indicated by the appearance of the fracture, which is often partly that of the smooth prepared surface. When failure occurs in the weld itself, visual examination of the fracture will often reveal the general quality of the weld as regards porosity, blowholes, slag and cracks.

Microscopic examination. This will show the difference in quality between the weld and the parent metal, the extent of the fusion between them, the presence of porosity, overheating, small blowholes, cracks, slag, and oxide inclusions. It will also indicate change of composition or structure, for example, decarburisation in iron and steel, loss of zinc in brass, etc.

X-ray examination. This is a non-destructive method of examination for porosity, voids, cracks, poor fusion and inclusions.

Pressure tests. These are essential in welded articles subject to gas or fluid pressure in service. The articles are tested by immersion in water or painting with a penetrating liquid. With high-pressure and larger vessels, hydrostatic tests should be employed.

GALVANISING

Galvanising is the process of the formation of a permanent zinc coating on wire, sheet, castings and other articles, usually applied to ferrous materials for the purpose of making them resistant to corrosion and rusting, particularly atmospheric corrosion.

Hot galvanising. This is the method chiefly employed. In this process the articles are immersed in a bath of molten zinc, together with the use of a flux. The fluxes used are zinc chloride and ammonium chloride, but the double salt zinc ammonium chloride is the one most generally favoured.

The articles are first of all pickled in dilute sulphuric or hydrochloric acid of strengths ranging from 5 per cent to almost 10 per cent, in order to remove scale. To inhibit attack on the metal during pickling, small additions of certain organic chemical mixtures, most of them proprietary, are made to the bath. These materials are known as restrainers.

In the case of castings the adhering sand is removed by immersing for a suitable period in dilute hydrofluoric acid before entering the other acid pickle bath. After each pickling operation the work is given a thorough washing in a vat containing running water.

In the earlier methods of hot galvanising, which are still used to-day to some extent, the flux is floated on top of the molten zinc and the work is passed through the layer of flux. The flux absorbs and removes any moisture left on the articles after pickling, so that the metal comes into contact with the molten zinc in an absolutely dry condition. It keeps the metal free from oxide and dissolves all other contaminations. The flux is liable to decomposition through loss of ammonia, but this loss may be reduced by the addition of small quantities of glycerine.

The more modern tendency is to use mechanised galvanising plants where the flux is made into a solution of about 1·2 specific gravity, and contained in a heated vat (often referred to as lye bath). The articles on hooks or contained in metal baskets are suspended from a continuous conveyor chain and pass slowly through the flux solution. They are then passed on the same conveyor through a heated drying chamber and then drawn slowly under the surface of the molten zinc contained in a long rectangular steel tank (kettle), situated on the other side of the drying chamber. As the pieces are withdrawn from the zinc the conveyor system may come into contact with a mechanical shaking device which removes drops of excess molten zinc. Afterwards they are passed under a water spray or cooled in a tank so that they are reasonably cool to handle. The temperature of the zinc (spelter) bath is maintained at 440 to 450°C., often by the use of automatic temperature controllers which regulate the firing when the temperature drops below or rises above the set figure.

In galvanising, the amount of iron salts entering the spelter bath is kept to a minimum, as they combine with the zinc to form hard iron-rich crystals. These, being very slightly heavier than the molten spelter, sink to the bottom of the bath, necessitating periodical removal of the layer. This iron zinc compound is commonly termed " dross." Dross formation, which is a wastage of zinc, is minimised by thoroughly washing the work after pickling, so that practically no iron salts enter the lye bath, to be carried through the drying chamber into the molten spelter. As a precautionary measure it is sometimes the practice to dip in a hot weak lye solution which, in addition to preheating, washes off any residual iron salts before the articles are introduced into the main lye bath. To keep down the acidity of the lye bath a slab of zinc is often introduced to reduce the attack and the formation of iron salts on the work. When, in spite of these precautions, the iron content of the lye bath reaches what is considered to be a dangerous level, it is with advantage discarded, and a new solution made up. Dross formation can also be the result of the spelter bath being run at too high a temperature, whereby the zinc attack on the work and the kettle is increased, and it follows that the life of the kettle will be reduced.

A galvanised coating consists of several zones. Next to the iron base is a thin layer of Fe-Zn alloy rich in iron, then a layer of Fe-Zn alloy less rich in iron, and, on the surface, a layer of pure zinc.

Small additions of aluminium to the bath increase the whiteness of the coating, and improves the general finish. There is a tendency towards rather thinner coatings and a decrease in the Fe-Zn layer between the base metal and coating. The thinner alloy layer gives more flexibility to the coating, which is desirable in wire and sheet materials.

The modern tendency for the treatment of sheets is the employment of galvanising machines. The sheet, on leaving the molten zinc, is passed through well-aligned rollers, which has the effect of squeezing off the excess zinc and at the same time promoting a smooth and even coating.

Prior to galvanising, wire is usually annealed in order to remove the effects of cold working, after which the pickling, drying and galvanising is mechanical and continuous. Since thick coatings are somewhat lacking in flexibility and exhibit a tendency to peeling, the thickness of the coating is reduced by wiping as the wire leaves the zinc bath. The wiping operation consists of passing through a stripping device such as an asbestos loop, a draw plate, or by other suitable means.

Electro-galvanising. As with nickel, chromium and other metals, zinc coatings can be produced by electro-methods, where the energy of an electric current is used for the formation of the coating. The object to be galvanised is prepared by scouring and pickling for the removal of grease and other surface impurities, and then made the kathode of the circuit by introducing into a bath of a zinc salt dissolved in water. Other salts are added to the bath, some to adjust the conductivity, some known as buffer salts which control the *p*H value, and others which influence the appearance of the deposit. A good quality zinc plate acts as the anode. Under the influence of the applied low voltage direct electric current, a smooth and firmly adhering coating of zinc is formed.

CENTRIFUGAL CASTINGS

Centrifugal castings are articles of simple cylindrical or tubular shapes, amongst which may be mentioned bushes, cylinder liners, pipes, rings and wheels. The cylindrical shapes may not always have completely straight contours but they are essentially symmetrical in form. Metal cast by the centrifugal process has enhanced mechanical properties and a better structure than that cast by the usual methods.

Cast iron. Molten grey iron is led down a refractory spout into a rotating mould which is arranged to rotate in a vertical, horizontal or inclined axis. The mould is suitably stopped off at the ends to prevent displacement of the molten metal in the direction of the axis of rotation. The centrifugal forces distribute the metal on the revolving mould surface, where it solidifies into a hollow casting with an external shape to correspond with that of the internal shape of the mould.

The most important application of centrifugal castings in cast iron is the production of pipes for water, gas, and sewage mains.

The Stanton-de-Lavaud machine employs a revolving alloy steel mould surrounded by a water box. The machine is mounted on rollers and is traversed on a slightly inclined bed by a hydraulic cylinder. The molten grey iron is delivered from a tilting hopper hydraulically operated, down a long spout of such a length as to extend practically the length of the mould. A sand core is inserted at the lower end of the mould to form the socket. To commence the pour, the machine is brought up to the top of the track, and then the end of the spout is in a position to run metal into the socket end. When the socket portion is full the machine travels slowly down the incline, and, because the spout is fixed, the centrifugal force throws a continuous spiral of metal on to the inside of the mould, which completely knits together

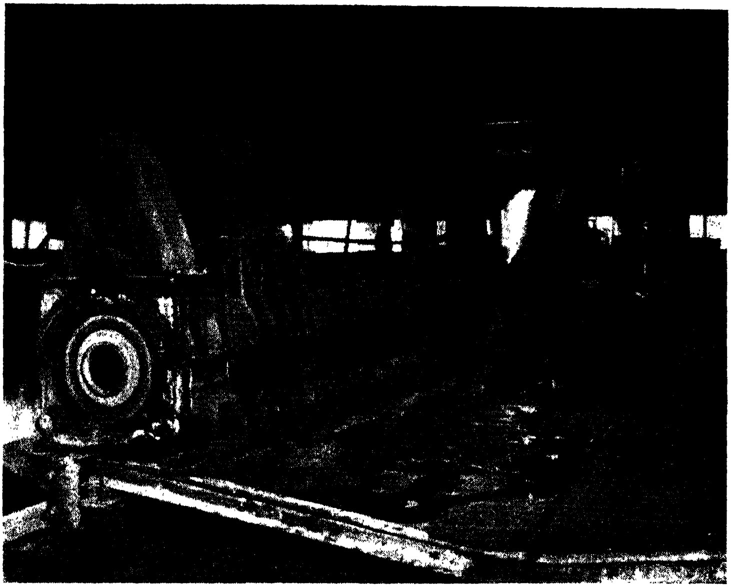


FIG. 286.—The Stanton-de-Lavaud Machine during the pouring operation.

(*Courtesy—The Stanton Ironworks Co., Ltd.*)

to form the pipe. The casting is removed by gripping the socket end with internal grip tongs and traversing the machine up the track. The tilting ladle holds only sufficient metal to pour one casting, and is refilled from a larger ladle before the casting process is completed. The cycle of operations takes from 2½ to 8 minutes, depending upon the size of the pipe.

Pipes cast in metal moulds are somewhat chilled on the outside skin. The amount of chilling is minimised by sprinkling the inside of the mould with powdered ferro-silicon, but the chill is completely destroyed and internal stresses removed by passing the pipes whilst still hot through a normalising furnace fired by producer gas. They first pass through a hot zone of the furnace at one end, and are slowly conveyed through and out of the other at a relatively low temperature. Because the rapid solidification of the metal gives a fine structure with small evenly distributed graphite, the mechanical properties of iron cast centrifugally in metal moulds are much superior to those poured by ordinary methods in sand moulds.

The necessity for annealing is altogether obviated in the centrifugal process employing sand moulds which are rammed up in well-vented circular mould boxes and dried. A socket core is inserted and the mould placed in the casting machine, where it is rotated and the metal poured in from a tilting ladle. The metal is evenly distributed throughout the mould and rapid rotation projects it against the sand wall of the mould. When the iron has solidified the rotary motion is stopped and the mould containing the pipe removed. As a result of the slower rate of solidification and cooling of the casting as compared with the use of metal moulds, the iron remains in a soft condition.

Steel. Centrifugal castings are produced in moulds spinning about a horizontal or vertical axis. Casting about a vertical axis is applied to the production of articles which are generally disc or wheel shaped with a hole in the centre, whilst tubular castings, of various lengths, diameters and thickness, are produced by spinning about a horizontal axis. The molten steel is poured into a refractory trough which is constructed to lead the metal into a spinning mould through an orifice extending through a " stop-off " core at the end of the mould. A further flat core is fixed at the other end to keep the molten steel enclosed. After solidification and cooling somewhat, the castings are removed. The centrifugal force used is considerably in excess of that which is theoretically required to overcome gravity. This is necessary to give a casting of homogeneous metal, and to squeeze out slag particles and non-metallics. The spinning speeds used for steel are rather greater than those used for cast iron and extend to those which give a centrifugal force up to about 70 times that of gravity. The mould materials may be either sand or metal, the choice depending upon several factors.

Metal moulds are used when large numbers of identical castings are to be made for simple tubular products which can be readily withdrawn from the mould, or where a quick cooling rate is required giving a fine grained steel. The sand-lined moulds are used where the molten steel has to flow relatively long distances over the mould surface and when a metal mould would chill the steel too rapidly, or where sharp sectional changes in the casting necessitate the breaking of the mould to remove the solidified casting. Sand moulds are also used when a more even cooling rate and structure are desirable in thick or uneven sections.

Non-ferrous. As with cast iron and steel, there is a distinct improvement in the mechanical properties obtained by centrifugally casting compared with casting in still sand moulds. Cold, slightly preheated, or water-cooled moulds are employed. There is a very marked refinement of structure, due to the combined effects of rapid and uniform cooling, and accompanied by an increase in strength and hardness. When casting alloys having in the molten state constituents of an insoluble or widely different character, there is a tendency for the specifically heavier components to be forced outwards towards the wall of the mould. The heterogenity so introduced in the section is more pronounced the higher the pouring temperature in excess of the melting-point of the alloy, the slower the cooling rate, the greater the solidification range, the greater the dissimilarity in the specific gravity of its constituents, the greater the speed of the moulds, and the thicker the walls of the castings. By the regulation of working conditions the trouble can be minimised and largely overcome.

General applications. Several advantages are offered by the centrifugal method of producing iron, steel, and non-ferrous castings. The use of inside cores is largely eliminated, there is quick repetition of pouring, and, in general, the metal is sound, clean and dense. The use of the method is, however, limited to castings of simple design and is only profitable when large amounts of castings of identical design are to be made, owing to the expense of the equipment required for new jobs.

Wheels may be produced by the centrifugal process, in which case the molten metal first forms the rim, and then in turn fills the cavities for the spokes and hub.

It is also possible to produce compound castings in more than one type of metal. Taking the case of a wheel in which a hard-wearing rim is required—the outside layer of hard metal to form the circumference or tyre may be introduced into the mould first, followed by a softer metal to form the remainder of the casting.

Articles having paraboloidal forms are cast in an inclined or vertical axis.

CHILLED CASTINGS

Sometimes a casting is required to have a hard surface or one that is hard in certain portions where wear resistance is necessary. The hard surface can be produced in any chosen portion by introducing into the mould a dressed cast-iron section known as a chill, and in such a position to correspond with the portion of the casting which is required in the harder condition. The iron used for chilled castings is one which is normally of fine grain, and the silicon and carbon present in such amounts as to give a white iron when quickly cooled. Manganese and sulphur contents also exert some influence on the properties of the casting.

The chills which form part of the mould cool the predetermined portion sufficiently quickly that the carbon is retained in the combined form, and the castings then are composed of a white section at the location of the chill, gradually merging into an intermediate mottled zone, until, in the section most remote from the rapid cooling influence, the iron is grey, close grained and tough.

Chilled iron castings are used where high-unit pressures are imposed on articles such as cams, rollers and wheels. They are also used as tools for deforming soft and ductile metals. Examples of such applications are wire-drawing dies and rolls for rolling mills. Chilling is often applied to castings which, in service, are in continuous moving contact with abrasive materials, notably plough points and shares, sand-blast nozzles and crusher heads.

The depths of chill introduced are mainly controlled and influenced by the chemical composition of the iron, pouring temperature, thickness of the casting in the chilled sections, temperature of the chill, and the size and thickness of the chill. Chromium is sometimes added to the metal to increase the hardness of the chilled portion.

It is the usual practice to pour a test piece to determine the relative amount of chill in the castings. This takes the form of a flat wedge, moulded in sand, and with the bottom of the mould open and resting on an iron slab of suitable thickness for the purpose of chilling. The amount of chill can be measured from the fracture of the broken test pieces. These tests serve both for control and record purposes, and, when the metal is melted in a furnace of the type where it is possible to take a preliminary spoon sample, should the amount of chill be excessive or insufficient, corrections can be made to the bath before pouring the actual castings.

The most important chilled castings are rolls for a variety of purposes, mainly for rolling hot and cold metals, paper, rubber and textile goods. Fig. 287 shows the general principle employed in producing a chilled roll casting. The mould parts and chills (A) are heated in a stove to a temperature of 150°C. to dry them thoroughly. On withdrawal they are assembled, given a light dressing with blacking mixed with water, and cast whilst still hot. The moulds for casting are placed in a pit of suitable depth which gives a more convenient position for pouring, and also any metal which overflows from the extension of the tenon (B) will fall into the pit. The overflow of metal is desirable because it allows hot metal to feed back into the casting while liquid shrinkage takes place during solidification. The metal, which should not be too hot, is led into the bottom of the mould at a tangent. As the molten metal rises in the mould it does so with a gentle, swirling, centrifugal action, taking up any loose material from the mould and chill faces and keeping all dirt and slag on the top. This more or less ensures a sound casting free from blemishing surface defects which would appear on the rolls during machining and dressing.

The thickness of chilled metal in rolls depends upon the purpose for which they are required. Rolls for dealing with metals require a much deeper chill than the type for dealing with paper, rubber sheets and textiles.

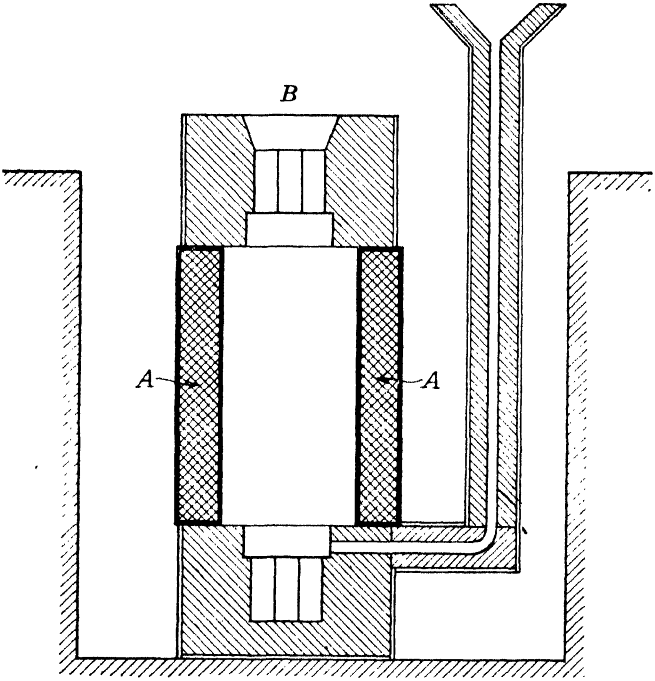


FIG. 287.—Construction of a mould for production of a chilled roll.

POWDER METALLURGY

Articles produced by powder metallurgy methods are made from compressed fine-metal powders. The powder contained in a die is compressed in special presses at pressures ranging from approximately 5 to 50 tons per sq. in., the non-ferrous metals requiring the lower pressures and certain types of ferrous metals the higher pressures. The compacts so produced are then sintered in a furnace for a closely controlled time, and at a temperature below the melting-point of the major constituent. Increase in sintering time and temperature increases the density of the product. The compacts may be repressed to certain shapes by using electrically heated dies and a plunger. Some metals made by powder metallurgy technique lend themselves to cold working.

In general the densities of the products of powder metallurgy are low compared with the cast or wrought metals, also rather weaker and somewhat porous, but the latter property renders some of the products useful for application as bearings owing to oil being held in the pores.

Developments in powder metallurgy technique indicate that in the future they will prove advantageous for other applications. For instance, non-metallic materials may be included in the base metal, such as the introduction of substantial proportions of graphite in bronze bearings, the graphite serving as a lubricant for the bearing.

Other applications are the manufacture of tungsten carbide products for cutting tools, in fact, carbide tool material is made almost entirely by powder metallurgy methods. In the manufacture of these materials the use of specially dry hydrogen atmospheres is necessary during sintering, and the carbides are not necessarily confined to those of tungsten, but may have also proportions of carbides of chromium, titanium, and cobalt.

Electrical contacts may also be manufactured by powder metallurgy, where a hard-wearing constituent is compressed along with the comparatively soft electrically conductive metal, giving a product of prolonged life whilst not impairing its electrical conductivity.

CHAPTER 12

USES OF METALS AND ALLOYS DURING NATIONAL EMERGENCY

DURING the war period the demand for many of the raw materials used for armament and other essential purposes exceeded the normal peace-time consumption, and, since some of the materials were obtained from abroad, the supply was limited by shipping capacity. The position was largely met by stringent economies in the use of materials in limited supply, by rationing, by conserving, and making the best use of the amounts available, by increased attention to the salvage of used material and scrap metals, and by the use of substitutes or alternatives. (*See* postscript.)

Iron and steel. Hematite ores and irons are reserved for purposes where their use is indispensable.

Owing to the effect of high phosphorus content on mechanical strength and porosity of iron castings, particularly in those which are subjected to pressure tests after machining, it has normally been the practice for foundrymen and metallurgists to use iron low in phosphorus, and include in metal mixtures considerable proportions of hematite iron and refined irons. The restrictions in the use of low phosphorus materials for many purposes, make necessary the use of higher phosphorus irons produced from ores mined in this country. In spite of the long standing preference for low phosphorus engineering castings, sound castings can be and are being made in the higher phosphorus material by giving special attention to the control of silicon and carbon contents, whereby the deleterious effects on mechanical properties are considerably counterbalanced. The defect of porosity is largely overcome by adopting improved methods of feeding the casting, close control of pouring temperature, and the correct application of chills in the portions of the mould where the castings are likely to suffer from this defect.

Much economy in vital alloying elements for steel manufacture is effected by the restriction of the number of alloy steel compositions in use. In normal times there are hundreds of various steel specifications in use and these have now been greatly reduced by the preparation of War Emergency British

Standard Specifications by co-ordinating representative bodies. The compositions, although giving a much-reduced choice, adequately cover all the required properties.

Tungsten is one of the alloying elements in severe short supply owing to enemy occupation of territory in the East, and, in order to minimise the consumption of tungsten, a number of high-speed steels have been developed, in which the element is substituted by molybdenum. The type which has been used with the most success is that known as 4/6 molybdenum high-speed steel with a composition of :—

Carbon	0·75 to 0·85	per cent
Chromium	4·0 to 5·0	,,
Tungsten	5·0 to 6·0	,,
Vanadium	1·4 to 1·6	,,
Molybdenum . . .	3·9 to 4·4	,,

Similar hardness values to those of the 18 per cent tungsten type are obtained with the material, but, since it is more susceptible to decarburisation and grain growth, more care is necessary in heat treatment to obtain the best results. The heat-treatment temperatures are a little lower, but, owing to the more rapid grain growth and decarburisation tendencies, the time of treatment should be as short as possible compatible with the desired hardness. The following are the heat treatments applied :—

Annealing . .	875°C. and slowly cooled.
Hardening . .	1175 to 1230°C. and quenched in oil. For more robust tools a slightly higher temperature may be used.
Tempering . .	550°C. for about 2 hours.

Non-ferrous. Owing to the large number of Service, British Standard, and private specifications originally in use, technical co-ordinating departments have prepared specifications which simplify and reduce the number to the minimum necessary to meet all essential requirements. Those of the British Standards Institution and the Directorate of Technical Development cover wrought and cast alloys of the non-ferrous metals. A Services Schedule B.S./S.T.A7, drawn up by various conferring Government Departments, embraces, in cast and wrought forms, copper, aluminium bronze, gunmetal, manganese bronze, silicon brasses and bronzes, zinc brasses and other special-purpose alloys.

In the manufacture of non-ferrous alloys the use of virgin metals is restricted, and economies are effected by using in mixtures a greater quantity of secondary metals in scrap or ingot form. Supplies of tin are strictly controlled, since the bulk of our normal supplies were in the hands of the Japanese. A number of the Emergency Specifications prepared by the British Standards Institution are intended as substitutes to be used, wherever possible, in the place of other alloys containing more tin.

The use of Admiralty gunmetal, 88 Cu 10 Sn 2 Zn, is minimised and replaced by 88 Cu 8 Sn 4 Zn,[1] and even then the use of the alloy is permitted only for special applications such as hydraulic valves working at pressures between 500 and 1000 lb. per sq. in. It is recommended that the 86 Cu 7 Sn 5 Zn 2 Pb [2] be used for general castings for steam service at working pressures above 100 lb. per sq. in. and temperatures up to 500°F., for castings for hydraulic work at pressures of 200 to 500 lb. per sq. in., for highly loaded bearings and for good grade backings for lined bearings. The 85 Cu 5 Sn 5 Zn 5 Pb alloy is recommended for general-purpose castings handling steam up to 100 lb. per sq. in. and at temperatures up to 400°F., and for hydraulic castings operating at up to 200 lb. per sq. in. pressure.

Where it is not strictly essential to employ tin in the alloy, type A and B brasses are to be used. Type A brass [3] is suitable for valves, fittings, taps and sanitary goods working at low pressures (less than 100 lb. per sq. in.). It is not recommended for use at elevated temperatures and under corrosive conditions. Type B brass [4] is intended for general structural and ornamental castings. The tin allowed in the specifications is intended to cover any which may be present in the scrap or other secondary material used in the preparation of the alloys and on no account is any tin intentionally introduced.

The tin containing alloys—phosphor bronze, other tin bronzes and gunmetals—can for certain applications be replaced by silicon bronze [5] containing 1·5 to 5·0 per cent silicon, 1·5 (max.) per cent manganese, 5·0 (max.) per cent zinc, up to 2·5 per cent iron and usually a little phosphorus. The alloy has fluidity comparable with gunmetal. It gives greater shrinkage and more foundry difficulties, but with care to obtain the correct tem-

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[1] B.S. 1022. [2] B.S. 1024. [3] B.S. 1026. [4] B.S. 1028. [5] B.S. 1030.
(War emergency specifications which may now be liable to modification.)

perature gradient in the casting during solidification by employing fillets in the correct places and chills in the mould, and by proper attention to feeding, sound pressure-tight castings are obtained. The alloy has good corrosion-resisting properties.

Economy of tin is also effected by the use of a lower tin phosphor bronze. Although the use of the well-known alloy,[1] containing a minimum of 10 per cent tin and 0·5 per cent phosphorus, is specified for high-duty work, especially for aircraft purposes, a second alloy [2] is used as far as possible for other work and contains between 6·5 and 8·5 per cent tin, 2 and 5 per cent lead and not less than 0·3 per cent phosphorus. The alloy is prepared largely from scrap materials.

Two aluminium bronze alloys [3, 4] are suitable for high-strength and high-temperature service. They are resistant to corrosion by sea water, and can be used for replacing tin-containing alloys for a number of purposes. They are particularly useful for marine engine castings.

In bearing alloys, lead, wherever possible, replaces tin. Owing to the tendency of the lead base-bearing metals to squeeze out, they have their limitations. For high-speed bearings subjected to fluctuating loads, such as in big ends and crankshafts in high-speed internal combustion engines, the tin base alloys are still used. For other bearings working under less severe conditions, other compositions lower in tin, and also lead base alloys are used. For some applications it is possible to economise in tin by using the tin base material in the form of thinner layers on a backing of iron, steel or brass, when no bearing properties are required of the backing. The lower tin gunmetals 86/7/5/2 and 85/5/5/5 can be used as backings for lined bearings where bearing properties are required in the backing material.

For soldering applications, wherever possible, lead is increased at the expense of tin. In some instances the inclusion of bismuth and a small amount of silver is made, together with the reduction of the tin. With suitable proportions of bismuth and silver, an alloy, which is handled like the tinmans' solder, can be obtained. For some purposes lead-antimony alloys, with a little arsenic added, dispense altogether with the use of tin, and, if the composition is approximately that of the lead-antimony eutectic, the

[1] B.S. 1059. [2] B.S. 1061. [3] B.S. 1032. [4] B.S. 1073.

(War emergency specifications which may now be liable to modification.)

B.S.S. No. (*War Emergency*)	88/8/4 *Gunmetal*	88/7/5/2 *Gunmetal*	*Type A brass*	*Type B brass*	*Silicon bronze*	*Aluminium bronze*	*High tensile aluminium bronze*	*Phosphor bronze*	*Leaded phosphor bronze*
ngots . .	1021	1023	1025	1027	1029	1031	1072	1058	1060
astings . .	1022	1024	1026	1028	1030	1032	1073	1059	1061
in . . .	7·5–8·5	6·0–8·0	2·0 (max.)	2·0 (max.)	—	—	—	10·0 (min.)	6·5–8·5
ead . .	0·5 (max.)	1·0–3·0	1·0–4·0	1·0–4·0	—	—	—	0·25 (max.)	2·0–5·0
inc . .	3·5–4·5	4·0–6·0	Balance	Balance	5·0 (max.)	0·5 (max.)	0·5 (max.)	0·05 (max.)	2·0 (max.)
ickel . .	1·0 (max.)	1·0 (max.)	1·0 (max.)	1·0 (max.)	—	1·0 (max.)	3·0–5·5	—	1·0 (max.)
hosphorus .	—	—	—	—	—	—	—	0·5 (min.)	0·3 (min.)
anganese . .	—	—	—	0·25 (max.)	1·5 (max.)	1·0 (max.)	3·0 (max.)	—	—
ilicon . . .	—	—	—	—	1·5–5·0	—	—	—	—
ron . .	—	—	0·75 (max.)	0·75 (max.)	2·5 (max.)	1·5–3·5	3·0–5·5	—	—
luminium .	—	—	0·01 (max.)	0·25 (max.)	—	8·5–10·5	8·5–10·5	—	—
mpurities. .	0·15 (max.)	0·5 (max.)	0·5 (max.)	0·50 (max.)	0·50 (max.)	0·3 (max.)	0·50(max.)	0·5 (max.)	0·5 (max.)
opper . .	Balance	Balance	70·0–80·0	62·0–70·0	Balance	Balance	Balance	Balance	Balance
lt. tensile stress. Sand cast min. Tons per sq. in.	16	14	11	14	20	32	40	12	12
longation per cent min.	12	12	20	12	15	20	12	1·5	3

alloy has a short solidification range and the lowest melting-point of the series at about 245°C. It will solder steel but it is not recommended for use with brass or copper.

Electrical purposes. Nickel is another metal used to a great extent in armaments. In an effort to conserve the element for essential purposes the wide use for electrical resistance wire of the 45 nickel/55 copper alloy, known as Constantan or Ferry, is restricted as far as possible for purposes where alternatives are not at present available. The chief alternatives are stainless iron (12 to 14 per cent chromium), and 80/20 cupro-nickel. The chief differences, as compared with Ferry, are a lower specific resistance for 80/20 and slightly higher for the stainless irons. Cupro-nickel is suitable where a moderate temperature coefficient of resistance is required, and the stainless iron where a high coefficient of resistance is not deleterious for the purpose required. With Ferry it is negligible.

The ductility of 80/20 cupro-nickel compares favourably with Ferry, in fact, it is slightly more ductile. Both substitutes can easily be formed into spirals, although the ductility of stainless iron is somewhat less than that of the other two alloys. The useful, closely adhering oxide coating obtainable with Ferry cannot be produced on either of the substitute materials.

Both substitutes have good corrosion-resisting properties, although 80/20 cupro-nickel is slightly inferior in this respect, but it has sufficient corrosion resistance for normal applications.

Whilst Ferry has good resistance to oxidation up to 400°C., the stainless irons are resistant up to about 750°C.; but the 80/20 cupro-nickel, by reason of its deficiency in nickel, has rather less resistance than Ferry.

The substitutes are used for all kinds of current-control gear, starters, battery charging, light-current equipment, heating units, series resistances for arc lamps, welding equipment, etc.

The uses for which no alternative is satisfactory are for thermocouple wires, thermal overloads, and slide-wire rheostats depending for insulation on the oxide coating between the turns of wire.

POSTSCRIPT

Since the completion of the last chapter hostilities in both theatres of war have ceased, and it is expected that, owing to the resulting changing circumstances, certain specifications and recommendations given will be liable to modification or will be revoked whilst the book is passing through the press, and from time to time. The chapter may in due course be of historical interest only.

V. N. WOOD.

11*th September,* 1945.

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