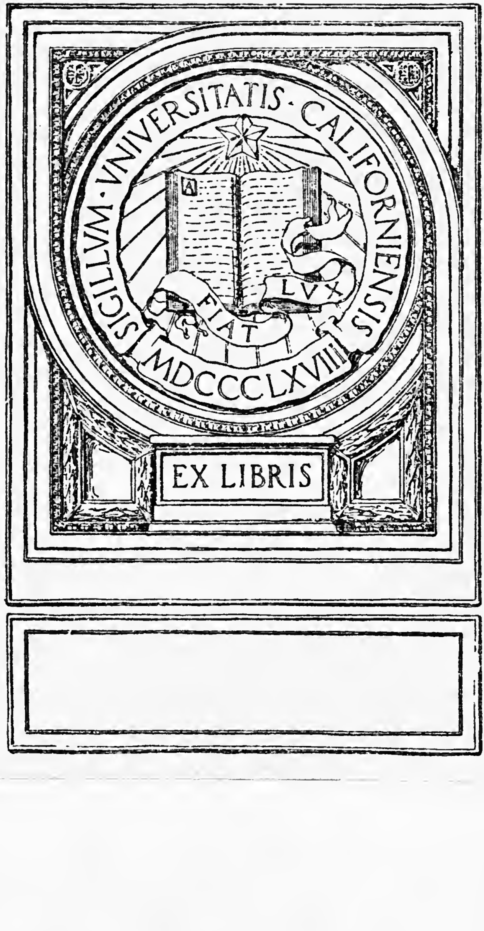
THE MANUFACTURE OF IRON AND STEEL

H. R. HEARSON



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THE MANUFACTURE OF IRON AND STEEL

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AND USERS OF IRON AND STEEL

BY

H. R. HEARSON, M.I.MECH.E.

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PREFACE TO SECOND EDITION

The First Edition has been generally revised, and the chapter on "Heat Treatment of Steel" slightly extended. As this most important operation in the manufacture of steel admits of such a large number of varied applications according to the qualities of steel under treatment, it is considered that the subject is too vast to be more than lightly touched upon within the intended scope of this little volume.

Attention is drawn to the revised note on Titanium (page 90), as this metal is becoming of increasing importance in the manufacture of steel.

H. R. HEARSON.

Late of Ministry of Munitions, Gun Department,
London, 1922.

EXTRACT FROM
PREFACE TO FIRST EDITION

THE object of this book is to give a brief and simple outline of the principle operations in connection with the manufacture of iron and steel. Some information concerning this great industry may be interesting to all, and useful to those commercially connected with iron and steel. Engineering students who have opportunities of seeing iron and steel manufactured may find that this outline will enable them to understand easily the work that is going on, whereby they can then quickly acquire a practical knowledge

Instead of giving all definitions at the beginning, technical expressions are used where necessary, and then defined at the point where it seems most appropriate. Therefore, it is recommended that this book be read through quickly at first, in order to obtain a general idea of its contents.

H. R. HEARSON.

SHANGHAI ARSENAL, CHINA.
November, 1912.

THE MANUFACTURE OF IRON AND STEEL

CHAPTER I

CHEMICAL ELEMENTS IN IRON AND STEEL

An *element* is a substance which cannot be divided into other substances. There are about 80 elements, and more are constantly being discovered. Each metal in its pure state is an element, and no one metal can be changed into another metal. For example, copper cannot be changed into tin or any other metal, tin cannot be changed into copper; but if copper and tin are melted together they form an *alloy* which is brass. This alloy has properties different from either copper or tin.

There are other elements which are not metals, such as carbon, which is the chief component of all substances that are combustible. Coal and wood are composed chiefly of carbon. Oxygen is an element; it is a gas, which, mechanically mixed with nitrogen gas, forms our atmosphere.

A *chemical compound* is a substance formed by the chemical combination of two or more elements. For example, the elements oxygen gas and hydrogen gas combine chemically and form water.

Chemical combination takes place in definite proportions of elements, a definite number of atoms of one element entering into chemical combination with a definite number of atoms of another element.

Each element has a definite value with regard to each other element; the relative values are called the *atomic weights* of the elements.

The atomic weights of oxygen and hydrogen are:—Oxygen, 16; hydrogen, 1. These gases will only unite with each other in the proportion of 16 to 1, by weight. The formula of water is H_2O; this means that it is composed of two parts, by weight, of hydrogen, and one part, by weight, of oxygen; so 2 lbs. of hydrogen will chemically combine with 16 lbs. of oxygen to form 18 lbs. of water. Two lbs. of hydrogen will not entirely combine with 13, 14, or 15 lbs. of oxygen; if, say, 2 lbs. of hydrogen is mixed with 14 lbs. of oxygen, and a lighted match be applied to the mixture, the 14 lbs. of oxygen will combine with $2 \times \frac{14}{16}$ lbs. ($= 1\frac{3}{4}$ lbs.) of hydrogen, and $15\frac{3}{4}$ lbs. of water will be formed: the remaining $\frac{1}{4}$ lb. of hydrogen will be in a free state as a gas. The principal elements, with their symbols and atomic weights, to be considered in the manufacture of iron and steel are:—

	Name.	Symbol.	Atomic Weight.
Metals	Iron	Fe	56
	Manganese	Mn	55
	Aluminium	Al	27·5
	Magnesium	Mg	24
	Nickel	Ni	59
	Chromium	Cr	52·5
	Vanadium	V	51·25
	Titanium	Ti	50
	Tungsten or Wolfram	W	184

Name.	Symbol.	Atomic Weight.
Carbon	C	12
Oxygen	O	16
Hydrogen	H	1
Nitrogen	N	14
Silicon	Si	28
Phosphorus	P	31
Sulphur	S	32
Calcium	Ca	40

Iron (Latin name, Ferrum) quickly combines with oxygen to form *oxide of iron.*

The three oxides of iron are :—

Ferrous oxide.—A chemical compound of iron and oxygen in the proportion of one atom of iron to one atom of oxygen, represented by the formula FeO. If there is any moisture in the air, iron will be attacked by the oxygen, and ferrous oxide or rust will be formed on the iron.

Ferric oxide.—The combination of 2 atoms of iron with 3 atoms of oxygen, represented by the formula Fe_2O_3.

Magnetic oxide.—The combination of 3 atoms of iron with 4 atoms of oxygen, represented by the formula Fe_3O_4.

If ferrous oxide is made to absorb more oxygen, it is converted into ferric oxide.

If ferric oxide is heated, oxygen gas is given off and it changes to magnetic oxide.

Manganese is a metal which is always one of the chemical components of iron and steel. As it easily combines with oxygen, and to some extent with sulphur, it is useful in the manufacture of steel.

Carbon and oxygen enter into chemical combination with each other to form the gas called *carbon monoxide*

(CO), or the gas *carbon dioxide* (CO_2), the usual name of which is *carbonic acid gas.*

When fuel is consumed in a furnace in which there is a plentiful supply of air, the carbon of the fuel combines with the oxygen in the air and forms CO_2; if the air supply is insufficient, the CO_2, on coming into contact with more hot carbon, takes up one more atom of carbon and becomes C_2O_2, or 2CO.

Such chemical actions are conveniently represented by equations:—

$$C + O_2 = CO_2.$$

Carbon and oxygen form carbon dioxide.

$$CO_2 + C = C_2O_2 = 2CO.$$

Carbon dioxide and carbon form carbon monoxide.

All fuel is composed chiefly of carbon, hydrogen, and compounds of hydrogen and carbon called "hydrocarbons."

An element is said to be "oxidised" when it combines with oxygen to form a chemical compound.

A chemical compound containing oxygen is said to be "deoxidised" when it is made to give up its oxygen.

Silicon is easily oxidised. When oxidised it is called *silica*, which has the formula SiO_2. Silica is the most plentiful of all substances.

Pure white sand is an example of silica. All iron ores contain silica, and in the manufacture of iron the silica gives up its oxygen and becomes silicon. The greater part of the silicon is removed, but a portion remains as a component of the iron.

The worst impurities in iron are *phosphorus* and *sulphur.*

Too great a proportion of phosphorus makes iron and steel brittle when cold; it is then said to be "cold short." The only advantages of a high percentage of phosphorus are that in cast iron the metal more easily retains its fluidity while being cast into a mould, so that the castings are clean and smooth; and that in steel the surface can be smooth machined with greater facility.

Too great a proportion of sulphur makes iron and steel brittle when red-hot; it is then said to be "red short."

The separate effects of increased percentages of carbon, manganese, and silicon are briefly:—

Carbon.—Increased tenacity and decreased ductility.

Manganese.—Increased tenacity, decreased ductility, also rise in yield.

Silicon.—Increased tenacity, decreased ductility and rise in yield.

See definitions, page 92.

CHAPTER II

IRON ORES

ORES which are found near the surface of the earth are "quarried," and ores at lower depths are "mined."

Iron ore is made up of oxide of iron and other substances, which in most cases consist chiefly of silica and clay. The "other substances" are the *gangue* of the ore, and the process of smelting separates the gangue from the iron.

The three classes of ores are:—Ferrous ores, ferric ores and ferrous-ferric ores. They all contain phosphorus.

Ferrous ore, of which Cleveland Ironstone is an example, contains iron in the form of ferrous oxide combined with carbon, forming ferrous carbonate (FeO,CO_2).

Ferric ore, such as English *hematite*, red and brown, contains iron in the form of ferric oxide.

Ferrous-ferric ore has the highest percentage of iron; it consists almost entirely of ferrous oxide and ferric oxide. The ore called *magnetite* is the most plentiful of this class, and it is found principally in Sweden.

PREPARATION OF ORES FOR SMELTING

All ferrous ores are heated by the process called *calcination* before being smelted. Calcination changes the ferrous oxide into ferric oxide; carbon dioxide and moisture are driven off and other small chemical changes take place.

Advantages of calcination.—Ferric oxide is easier to smelt in the blast furnace than ferrous oxide, as it does not enter into chemical combination with the silica in the ore.

The driving off of the carbon dioxide has two advantages; by containing a lesser quantity of this gas, the gases generated in the blast furnace burn with a greater heat, and the gases after they leave the furnace are better for producing power in gas engines, etc.

Calcination makes the ore porous, so that it is more quickly melted in the blast furnace by the heat passing more easily through it.

Calcination causes a shrinkage of the ore, but the weight of iron contained in it remains the same; thus a blast furnace can contain a greater weight of calcined ore, and more iron can be smelted.

Brown hematite ores are sometimes calcined to drive off the water and a little carbon dioxide which they contain.

Red hematite ores are not calcined.

Ores may be calcined in open heaps on the ground, but it is more economical in the consumption of fuel and in the labour of handling the materials that calcination be conducted in kilns.

Fig. 1 is a section of a calcining kiln built of steel plates and lined with firebricks. A fire is first lighted at the bottom, and ore and fuel are then charged from the top. The fuel used is small coal, and as there is no forced draught or chimney it burns very slowly. Very little fuel is needed, as additional heat is generated by the chemical action of the ferrous oxide being changed to ferric oxide. The calcined ore is withdrawn through openings between the pillars at the bottom of the kiln.

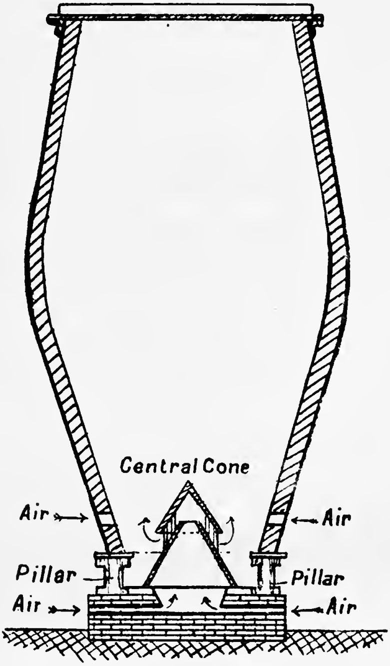

FIG. I. CALCINING KILN

Air is required for the combustion of the fuel and for the oxidation of the ferrous oxide; it is admitted through holes at the bottom, between the pillars, and up through a central cone.

CHAPTER III

THE BLAST FURNACE

The process known as "smelting" is conducted in the blast furnace at a very high temperature. The ore is converted into pig iron, slag and gases. Fig. 2 is a sketch, partly in section, of an iron-smelting blast furnace. It is built of steel plates and lined with firebricks. The whole is supported on cast-iron pillars. Internally, the furnace consists of the cylindrical "well" or "hearth" of brickwork, at the bottom; next to this is the lower cone which is called the "bosh," the upper cone is the "stack."

Ore and fuel are charged from the top of the furnace, and the stack expands in diameter from the top to the bottom to allow them to become loose as they descend.

The furnace is then contracted in diameter by the bosh so that the materials may be held up until the fuel is consumed at the bottom of the bosh. The melted iron and slag continually drop into the well of the furnace, from which they are tapped out.

A furnace is "tapped" by removing a fireclay plug from a hole which is called the "tap hole"; molten iron then flows out.

After smelting, there is a residue from the ore, which is called "slag"; this, being of lower density—that is, lighter—than iron, floats on top of the iron, and it is tapped out of the furnace through a hole called the "slag hole" near the top of the well.

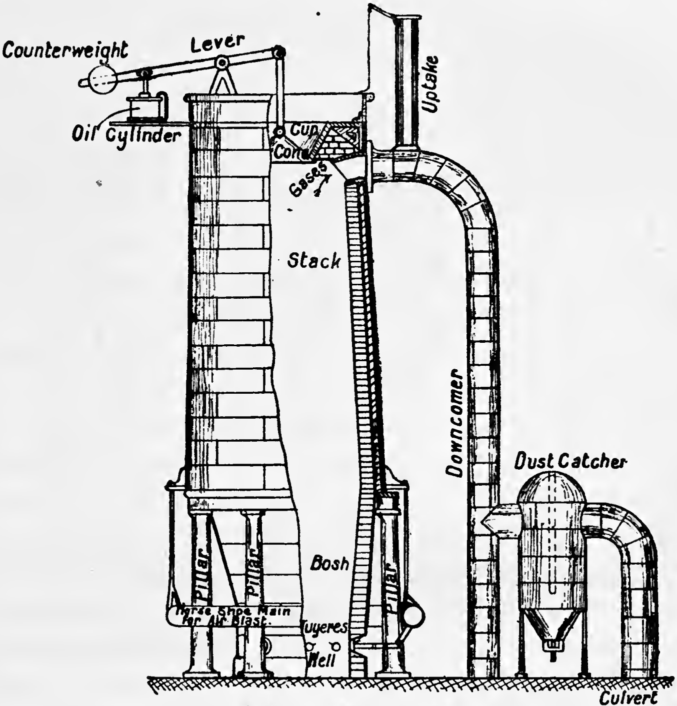

FIG. 2. BLAST FURNACE

The materials are charged into the furnace by means of a *cup* and *cone*. When the lever which supports the cone is released, the weight of the materials causes the cone to descend, and when these are discharged into the furnace the cone is raised by a counterweight at the end of the lever. A rod is connected from the lever to a piston which works in a cylinder containing oil;

a pipe connects the two ends of the cylinder so that oil can flow from one side of the piston to the other. The oil prevents the lever from being suddenly raised or lowered. If the cone closes with a bang on to the cup, the iron castings of which they are made may be cracked.

The *air blast* enters the furnace from the brick-lined *horseshoe main* through *tuyeres* built into the brickwork at regular intervals at the top of the well.

The combustion of the fuel and the reduction of the ore generate a large quantity of gases, which are collected at the top of the stack and passed into a large brick-lined tube called the *downcomer*, thence through the *dust catcher* to culverts which lead them to where they are required for further use.

The dust catcher collects the dust which is blown out of the furnace with the gases; if the gases are to be used in a gas engine it is very necessary that the dust be first separated from them.

As the tuyeres are exposed to the heat of the furnace, means must be taken to prevent the iron of which they are made from melting.

There are many kinds of tuyeres; one kind is shown in fig. 3. This consists of a tapering spiral coil of wrought-iron pipe, 1 inch diameter, with cast iron moulded around it.

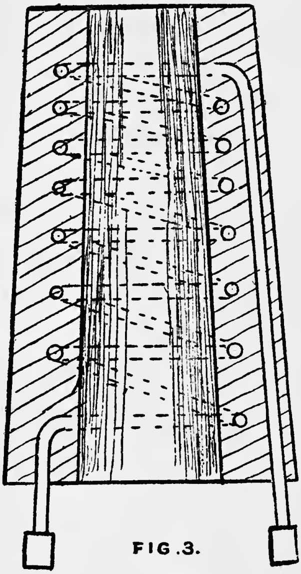

FIG. 3.
TUYERE

When in use, water is made to flow through the coil; the water carries away the heat so quickly that the cast iron cannot melt.

Size of blast furnaces.—Furnaces of large capacity work with the best economy. A high furnace requires less fuel per ton of ore reduced than does a low furnace; but a furnace should not be higher than 90 feet, as, if higher, the fuel will be crushed by the weight of the ore.

The maximum internal diameter at the top of the bosh should not exceed 22 feet; if of greater diameter, the air blast will not get through the burning materials to the centre.

Hot-blast stove.—An economy of fuel is obtained by heating the air before it is blown into the furnace. Fig. 4 is a sectional elevation and fig. 5 is a sectional plan of a hot-blast stove, built of steel plates, lined with fire bricks, and worked on the "regenerative" system. Gases from a blast furnace are ignited in a vertical flue of elliptical section. Divisions are made in the lower part of the flue to split the gases into sheets, so that they burn more readily. To assist combustion, air is admitted just above the gas inlet and mixes with the gases in the flue. Long flames go up the flue, and the hot products of combustion pass down the regenerator to the chimney valve.

The *regenerator* is a chamber filled with checkered bricks; that is, the bricks are laid in such a way as to expose as much of their surfaces as possible to receive and give forth heat, while, at the same time, allowing free passage for gas or for air. When the regenerator has become greatly heated, the gas and air inlet valves and the chimney valve are shut. The air-blast inlet and the hot-blast outlet valves are then opened and cold air from the blowing engine is admitted at the

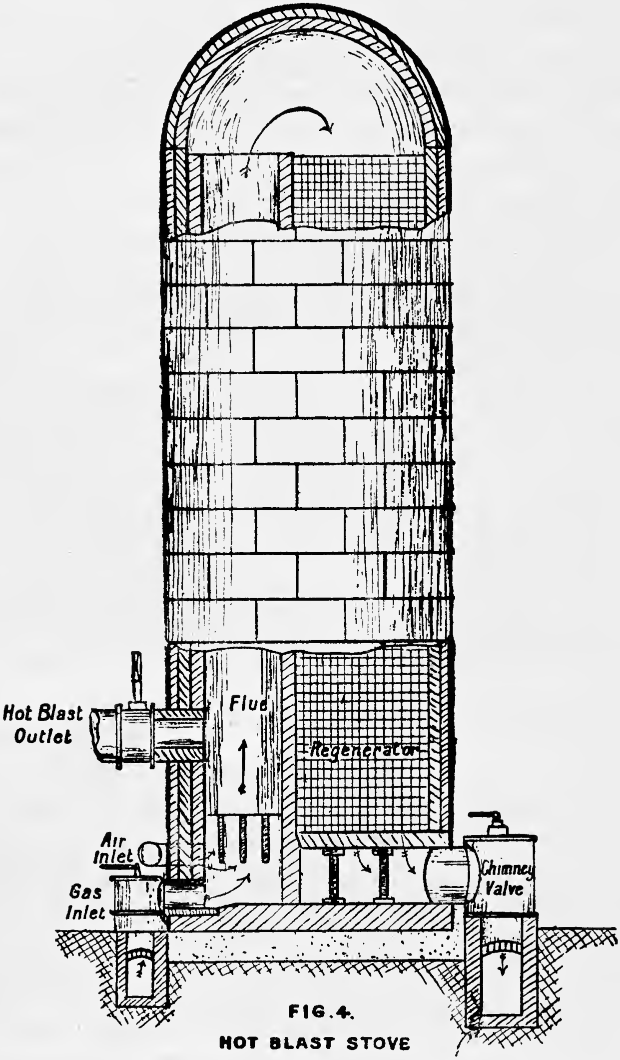

FIG. 4.
HOT BLAST STOVE

bottom of the regenerator. The air passes up between the hot bricks and down the flue to the hot-blast outlet, and thence, at a temperature of about 1500° F., to the blast furnace. In the meantime, the gases from the blast furnace are being burnt in a second hot-blast stove, and when the first stove is cooled down so that the air comes out of it at a temperature of about 1100° F., the valves are reversed. The first stove is then reheated and cold air is heated in the second stove.

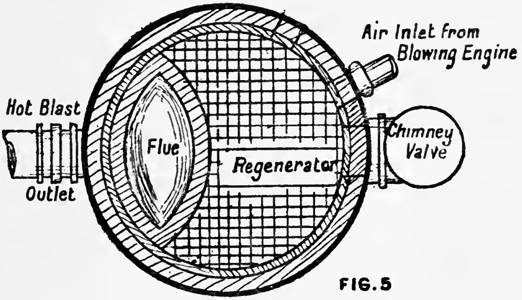

FIG. 5

HOT BLAST STOVE

Hot-blast stoves are worked in pairs or in sets of three.

Blowing engines are large air pumps which compress air and force it under pressure to the air-blast main. They are now generally driven by gas engines, the engines being worked by the gases from the blast furnace.

WORKING THE BLAST FURNACE

Fuel.—Coal or coke is used as fuel according to the prices at which each may be obtained. Bituminous coal is either coking or non-coking. If it is suitable for coking, it is coked for use in the blast furnace. If it is not suitable, it is used without coking. Anthracite coal may also be used. Coke is better than coal as fuel for a blast furnace; it burns with a more intense heat, and it is not so easily crushed as coal is.

100 parts of bituminous coal may have an analysis approximately as follows:—Fixed carbon, 55 parts; hydrocarbons, etc., 35 parts; water, 5 parts; and ash, 5 parts.

Coke is obtained by highly heating bituminous coal without or with very little admission of air. Water and the free hydrocarbons of the coal are driven off. The coke thus obtained contains a greater percentage of carbon than the original coal. Good coke has a silvery appearance. It should be dense, but also porous; that is to say, the pores should be very small, otherwise the coke will not be strong and it will be easily crushed in the furnace. The pores allow the heat to pass through the coke, so that it burns quickly and with an intense heat.

Flux.—A flux is a substance which is added to other substances to cause them to become fluid when heated. It must be of such chemical composition that it will, when heated, enter into chemical combination with the substances which are to be fluxed. It is necessary to form from the gangue a liquid slag which may be tapped from the furnace.

Ores which contain a large percentage of silica require a flux, as silica does not melt at the temperature of the blast furnace.

Limestone is charged into the furnace as a flux; it contains calcic carbonate (CaO,CO_2). The CO_2 at once escapes with the blast-furnace gases, and the lime

(CaO), which is left, chemically combines with the silica to form calcic silicate ($2CaO,SiO_2$), usually called silicate of lime, the melting point of which is below the temperature of the blast furnace.

If alumina (Al_2O_3) is present in the ore with the silica, the addition of limestone as a flux forms a compound silicate of lime and alumina, which melts at a lower temperature than calcic silicate.

Some ores are called "self-fluxing"; this means that they contain a sufficient quantity of lime to combine with the silica.

Other ores contain more lime than is required to assist in the melting of the silica; such ores can be mixed with "non-fluxing" ores, and no limestone flux will be needed. For example, one kind of ore may contain 20 per cent. of silica and alumina and 4 per cent. of lime; this is a non-fluxing ore. Another kind of ore may contain 10 per cent. of silica and alumina and 18 per cent. of lime; this is a self-fluxing ore which contains more lime than is required. If these two kinds of ore mixed together are charged into the blast furnace, they will be self-fluxing.

The *charge* is the total of materials which are put or "charged" into the furnace. The charge consists of the ore, the flux and the fuel; the ore and the flux are the *burden* of the furnace, and the fuel supports the burden. The greater the burden that the fuel is capable of supporting, the greater will be the output of pig iron from the furnace per ton of fuel used.

Reduction of the ore.—When the air blast on entering the furnace meets the burning fuel, the oxygen of the air enters into chemical union with the combustible elements in the fuel and produces a high temperature. CO gas is first produced, and this takes oxygen from the oxides in the ore to form CO_2. The transferring of oxygen is called *reduction*, and the oxide which gives up its oxygen is said to be *reduced.*

Oxide of iron is thus reduced to metallic iron, which melts and drops, together with the molten slag, into the well of the furnace.

The iron is tapped from the furnace every 6 to 8 hours, and the slag is tapped as often as is necessary.

Pig iron.—Iron as it is tapped from the furnace is known as pig iron; it is allowed to flow into moulds made in sand in front of the furnace. Each pig is about 3 feet long and weighs about 120 lbs.

Pig iron contains carbon, silicon, phosphorus and sulphur, which have been taken up in the process of reduction from the materials in the charge. The term "cast iron" should not be confused with pig iron. Cast iron is iron which has been melted in a cupola and cast into some definite shape.

CHEMICAL ACTIONS IN A BLAST FURNACE

The chemical actions may be represented by chemical equations:—

Reduction of ferric oxide:—

Fe_2O_3 + 3CO = 2Fe +
Ferric oxide and carbon monoxide yield iron and
$3CO_2$.
carbon dioxide.

Reduction of manganese oxide :—

$Mn_3O_4 \quad + \quad 4CO \quad =$
Manganese oxide and carbon monoxide yield
$3Mn \quad + \quad 4CO_2.$
manganese and carbon dioxide.

Reduction of phosphorus pentoxide (phosphoric acid) :—

$P_2O_5 \quad + \quad 5CO \quad = \quad 2P$
Phosphoric acid and carbon monoxide yield phosphorus
$+ \quad 5CO_2.$
and carbon monoxide.

The silica is directly reduced by carbon, thus :—

$SiO_2 \quad + \quad 2C \quad = \quad Si \quad + \quad 2CO.$
Silica and carbon yield silicon and carbon monoxide.

The two equations which follow represent the chemical actions which cause the formation of slag :—

$2CaO \quad + \quad SiO_2 \quad = \quad 2CaO,SiO_2.$
Lime and silica yield silicate of lime.
$2Al_2O_3 \quad + \quad 3SiO_2 \quad = \quad 2Al_2O_3,3SiO_2.$
Alumina and silica yield silicate of alumina.

The silicate of alumina combines with six times its weight of silicate of lime to form a compound silicate of lime and alumina; this compound is represented by the formula :—$2Al_2O_3,3SiO_2 + 6(2CaO,SiO_2)$. This is the main composition of some blast-furnace slags, and it consists, approximately, of silica, 38 per cent. ; alumina, 14½ per cent. ; and lime, 47½ per cent.

Uses of blast-furnace slag.—Slag may be used instead of stone for road-making and for railway ballast. It may be made into cement or bricks. Slag wool (an insulating material) is also made from it (see pp. 49, 55, 65).

QUALITY OF PIG IRON

In the selection of a pig iron for any purpose, the quantity of phosphorus which it contains is generally the most important consideration. Nearly all the phosphorus in a blast-furnace charge goes into the pig iron. If a pig iron with a small percentage of phosphorus is required, ore, fuel and flux, which contain little phosphorus, must, if easily procurable, be selected.

The following table shows the composition of some pig irons :—

Component Parts.	Cleveland.	Hematite or Acid Bessemer.	Swedish Magnetite.	Basic Bessemer.
Phosphorus . .	1·60	0·05	0·03	3·00
Graphitic carbon .	3·20	3·42	2·00	0·50
Combined carbon .	0·50	0·46	2·00	2·80
Silicon . . .	2·60	2·20	1·20	0·50
Sulphur . . .	0·08	0·04	0·01	0·07
Manganese . .	0·60	0·47	3·00	2·00
Iron . . .	91·42	93·36	91·76	91·13
	100·00	100·00	100·00	100·00

Grey and white pig iron.—A blast furnace which is working with a light burden, or at a high temperature, generally produces a grey pig iron which contains much carbon and silicon, most of the carbon being graphitic carbon.

If the burden of the furnace is heavy and at a comparatively low temperature, a white pig iron is produced; this contains less carbon and silicon, and most of the carbon is combined carbon.

Carbon is a component of pig iron in two states—as combined carbon and as graphitic carbon. As graphitic carbon it is not in chemical union with any other element in the iron: it is in a free state in the form of flakes. The other chief differences between grey pig iron and white pig iron are:—Grey pig iron contains more manganese and less sulphur, is more fluid when melted, expands when changing from a fluid to a solid, has a coarse grain, and is comparatively soft and tough.

White pig iron becomes of a pasty condition when below its melting-point; this condition is unfavourable for making a clean, smooth iron casting, but it is favourable for "puddling" in the manufacture of wrought iron. White pig iron is fine-grained, hard, and brittle.

To understand what is meant by the "grain" of a metal, break a piece of wrought iron and a piece of porcelain and compare the fractures. The former has a coarse, fibrous grain; the latter has the finest possible grain.

Grey pig iron has a coarse grain, but not a fibrous grain.

BLAST-FURNACE GASES

Great volumes of gases of many different kinds mixed together are generated in a blast furnace.

The following table shows what the gases consist of, and their approximate relative proportions:—

Gas.	Chemical Formula.	Furnace with Coal Fuel.	Furnace with Coke Fuel.
Combustible—			
Carbon monoxide .	CO	28	29
Hydrogen . .	H	6	1
Methane, or Marsh gas	CH_4	5	...
Incombustible—			
Carbon dioxide .	CO_2	9	15
Nitrogen (from the air)	N	52	55
		100	100

The gases after leaving the blast furnace undergo a distilling process called "scrubbing," in order to recover the ammonia and tar contained in them. The scrubbed gases are then used for steam raising by burning them in boilers with special furnaces and long flues: or power is generated by using the gases direct in a gas engine. About three times as much power may be obtained by means of a gas engine as by the use of boilers and a steam engine.

CHAPTER IV

THE MANUFACTURE OF WROUGHT IRON

Puddling.—Wrought iron is produced from pig iron or cast iron by the process of puddling, which is performed in a "reverberatory" furnace. By this process the impurities contained in the iron are almost entirely removed.

The change that has to be made in the composition of pig iron is shown by comparing the composition of Cleveland pig iron, given in the table on page 19, with an analysis of good wrought iron.

Component Parts.	Cleveland Pig Iron.	Wrought Iron Produced.
Phosphorus	1·60	0·16
Graphitic carbon . .	3·20	...
Combined carbon . .	0·50	0·04
Silicon	2·60	0·25
Sulphur	0·08	0·03
Manganese	0·60	0·01
Slag	...	2·66
Iron	91·42	96·85
	100·00	100·00

A purer wrought iron than that shown by the above analysis may be obtained if required.

The change in the composition is effected by the "oxidation" of the impurities. That is, the pig iron is heated to a high temperature so that the oxygen in the air and in the lining of the furnace shall chemically combine with the impurities and separate them from the iron.

The puddling process consists of melting pig iron in a furnace and stirring, or, as it is called, "rabbling" it, so as to bring the whole of the molten metal into contact with the lining of the furnace.

The furnace is lined, bottom and sides, with a material which is called the "fettling." The fettling is composed chiefly of oxides of iron, which, when heated, give up their oxygen.

The oxygen combines with the impurities (carbon, silicon, manganese, phosphorus, and sulphur) in the pig iron, and the solid chemical compounds thus formed enter into the slag.

The gas CO_2, made by the oxidation of the carbon, escapes to the chimney. As oxygen is given off, metallic iron is melted away from the fettling; some of it mixes with the molten pig iron and some goes into the slag. The iron in the charge is thus increased in quantity, and the fettling diminishes; the latter has to be continually renewed.

Oxidation is further assisted by an oxide of iron which is put in with the charge of pig iron, and also by the oxygen contained in the air which enters the furnace.

Fig. 6 is a sketch of a puddling furnace.

Bituminous coal is burnt in a grate at one end, and the flame from it strikes against and heats the sloping roof at the other end. Heat is "reflected" from the roof, and the flame is "beaten back" by the roof on to the pig iron.

This type of furnace is called a *reverberatory* furnace.

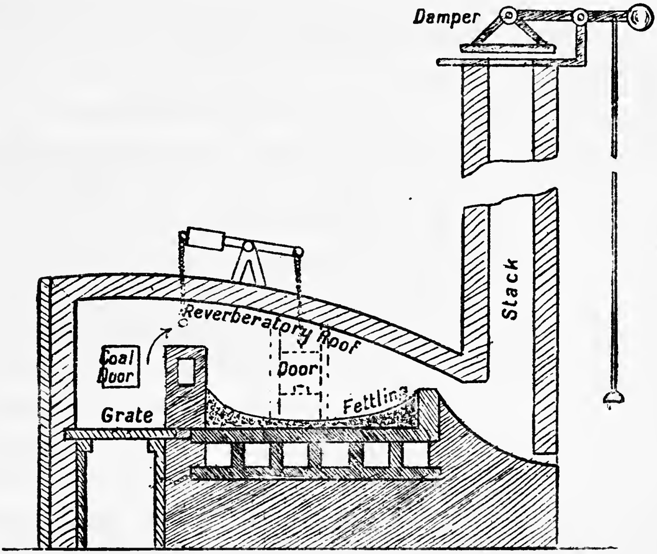

FIG. 6 PUDDLING FURNACE

The word "reverberatory" means "beaten back." The fuel does not come into contact with the pig iron.

Fettling

Some materials used for fettling are:—

Best tap.—The cinder or slag from reheating furnaces which are worked with basic bottoms.

Bull dog.—The cinder or slag from a puddling furnace which has been roasted in a reheating furnace to render it less fusible.

Purple ore, *hematite ore* and *pottery mine* are also used for fettling.

The following table is an analysis of best tap and bull dog:—

Components.	Chemical Formula.	Best Tap.	Bull Dog.
Ferrous oxide	FeO	62·0	4·0
Ferric oxide	Fe_2O_3	27·0	70·0
Manganous oxide	MnO	1·2	0·6
Silica	SiO_2	8·0	24·0
Phosphoric acid	P_2O_5	1·0	0·7
Sulphur	S	0·5	0·7
Lime	CaO		
Magnesia	MgO		
		99·7	100·0

The tops of the iron bed-plates are covered with best tap to a depth of 3 inches. The furnace is then heated sufficiently to cause the best tap to soften, and it is then covered with a 2-inch layer of bull dog or some other kind of fettling. The kind of fettling is selected according to the quality of the pig iron and the quality of the wrought iron which is required to be produced.

Some scrap iron is now thrown into the furnace and raised to a welding heat; it becomes oxidised, and, by means of an iron tool, is pushed about the furnace in order to oxidise the surface of the fettling.

The furnace is now ready for puddling, and pig iron, together with some "hammer scale," is thrown in. The black flakes of ferrous oxide which fall off wrought iron or steel when it is being forged are called hammer scale. During the melting of the pig iron, silicon, manganese and some of the phosphorus are oxidised; these elements leave the pig iron and combine with some of the melted fettling to form the slag. To quicken oxidation, the molten metal is rabbled with an iron tool called a "rabble."

The carbon and most of the remaining phosphorus is now oxidised. CO gas escaping through the molten iron to the surface gives it the appearance of boiling. The CO gas burns with a blue flame, and, taking up more oxygen from the air, passes away as CO_2.

Some slag is now tapped off. Then the temperature of the furnace is reduced so that the iron may become in a pasty condition; that is, not quite fluid. The iron is separated into masses of about 100 lbs. each, rolled into balls, removed from the furnace and hammered under the steam hammer. Hammering expels most of the slag, but not all of it. The balls are shaped into rough oblong blocks called "blooms," which are then taken to the forge rolls to be rolled into bars of different shapes—rounds, squares and flats. If large blooms are required, two balls are welded together under the steam hammer.

CHAPTER V

THE MANUFACTURE OF STEEL

STEEL is a compound of iron and carbon; other elements in small percentages only may be contained in it. The difference between cast iron, wrought iron and steel depends chiefly on the relative amounts of carbon in chemical combination with the iron. The usual percentages of carbon are:—

Metal.	Percentage of Carbon.
Cast iron	3·25
Wrought iron	0·04
Steel, mild, for ship plates and bridges	0·15 to 0·2
Steel, mild, for boiler plates	0·2 to 0·25
Steel, medium (gun steel)	0·3 to 0·4
Steel, hard	0·7
Chisel steel	1·0
Tool steel	1·2
Razor steel	1·5

If steel contains 0·5 per cent. carbon and 0·1 per cent. sulphur, it is red short; if it contains more than 0·1 per cent. phosphorus, it is cold short. 0·03 per cent. of phosphorus renders steel useless for cutting tools.

Manganese considerably mitigates the ill effects of sulphur and phosphorus. If manganese is present in steel, and if the steel is low in carbon, 0·1 per cent. of phosphorus is permissible for some purposes. Good rails may be made of steel containing 1 per cent. manganese and 0·1 per. cent. phosphorus.

Blister steel.—Blister steel is made from long flat bars, about 3 inches wide and $\frac{3}{4}$-inch thick, of the purest wrought iron. The wrought iron is converted into steel by *cementation*, by which process carbon is added to the bars.

Fig. 7 shows a transverse section of cementation furnace. The firegrate extends from the front to the back, and two cementation boxes are placed above, one on each side of the grate. The inner walls and arch are built of firebricks. The cementation boxes, usually about 15 feet long, 4 feet wide, and 3 feet deep, are made of fire-stone slabs cemented together with fireclay. The boxes are packed with alternate layers of charcoal and flat bars; the top and bottom layers are of charcoal. All the bars must have both sides in contact with the charcoal. The top layer of charcoal is covered with "wheelswarf" to prevent access of air to the iron bars. Wheelswarf is collected from the troughs of grindstones. When a tool is ground on a grindstone, steel dust from the tool mixes with the silica dust which is worn away from the grindstone. The heat of grinding causes some of the steel to become oxidised; so wheelswarf is a mixture of steel, oxide of iron, and silica. Wheelswarf melts slightly when the furnace is in operation, and it forms an airtight cover. The cementation boxes must be absolutely airtight. A fire is maintained in the fire-grate so as to keep the bars heated to a bright orange colour from six to nine days, according to the quality of the wrought iron and to the quality of the steel which is required to be produced.

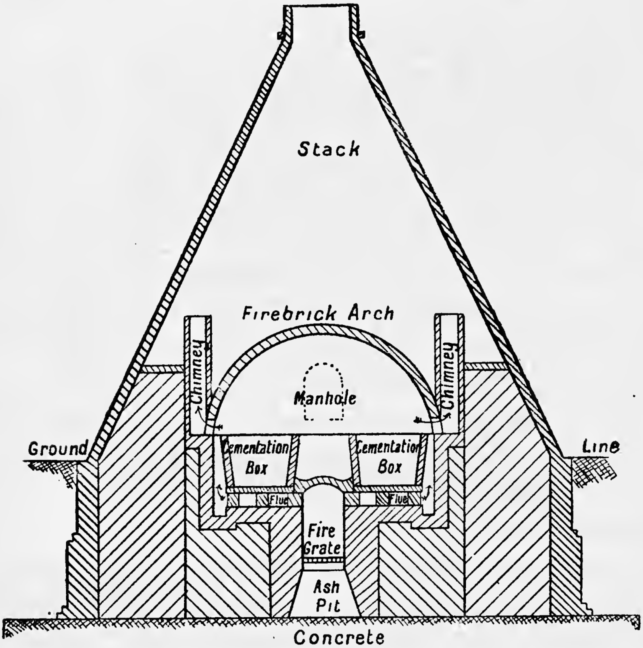

FIG 7. CEMENTATION FURNACE

The effect of the process is to cause carbon from the charcoal to penetrate into the iron bars; this is called "carburisation" of the iron.

When the bars are being packed, a few bars are placed with their ends protruding through slots at one end of the boxes. A bar can be drawn out through the slot, and the slot is then closed up with fireclay.

When the bar is cold, it is broken and the fracture examined to see if carburisation has proceeded far enough; allowance being made for further carburisation of the bars remaining in the boxes during the time of the cooling of the furnace.

The bars were originally fibrous and tough; when taken from the boxes they are brittle and covered with blisters. Hence the name, "blister steel." When broken, the fracture is of a crystal appearance and shows no fibre. The bars nearest to the firegrate are more highly carburised than the others. None of the bars are carburised right through to the centre, so the centre still remains as iron. If air gains access to the bars during carburisation or cooling, the surface becomes oxidised; such bars are known as "aired bars."

Single shear steel is produced by welding together six bars of blister steel and rolling them out to the required shape. This makes a fairly uniform mixture of iron and steel.

Double shear steel is produced by welding and rolling together two bars of single shear steel; the iron and steel are then more intimately mixed. When the bars are raised to a welding heat, they must be protected to prevent a loss of carbon. They are covered with gypsum (calcic sulphate, $CaSO_4$), which melts in the furnace and forms a coating on the bars.

Crucible Cast Steel

Blister steel contains some slag, and the carbon is not evenly distributed throughout its mass. To obtain a homogeneous steel it is necessary to melt the blister steel. Wrought-iron bars may be converted into steel in the crucible by an addition of charcoal or an alloy of iron and carbon; but the *best* qualities of crucible cast steel are made from blister steel. The bars of blister steel are broken into small pieces and melted in a small crucible made of a mixture of different kinds of fireclay. The crucible stands on a disc of fireclay and has a lid of the same material.

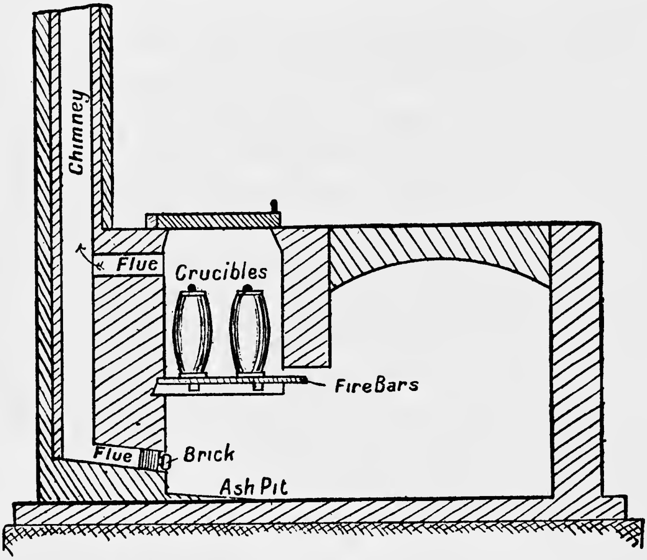

FIG 8. CRUCIBLE STEEL MELTING HOLE

A section of a steel melting hole is shown in fig. 8. Each hole contains two crucibles which are heated in the furnace by coke fuel packed all round them. The temperature of the furnace is regulated by means of a brick placed in the flue at the bottom of the stack. When the brick stops up the flue, a draught of air passes up between the fire bars and through the furnace to the stack. The draught is caused by the air being heated when passing through the glowing coke. If the brick is removed, cold air rushes through the flue to the stack, and the draught is lessened. With less draught the coke burns more slowly and less heat is given forth.

A compound containing manganese is charged into the crucible with the blister steel. When the steel is in the right condition to be removed from the furnace, the crucibles are lifted with tongs, the slag is skimmed off, and the contents poured or "teemed" into moulds. The moulds are of cast iron, each in two halves held together by rings and wedges. The steel may be prevented from adhering to the moulds by previously exposing the inner surfaces of the moulds to the smoky flame of burning coal tar, thus covering the surfaces with a fine deposit of soot.

Considerable experience is necessary in order to be able to judge correctly the temperature at which to teem the molten steel. Steel which is low in carbon requires to be teemed at a high temperature, but as soon as possible after it has become fluid. Steel selected with more carbon than is required in the finished steel requires "killing" or "dead melting"—that is, it is kept in the furnace for some time after it has become fluid, until it has quieted. It should not have any ebullition after it is teemed, or the ingot will be honeycombed (porous).

The steel in the fluid state contains a large quantity of gases; such gases are called *occluded gases.* The greater proportion of these gases should be separated whilst the crucible is in the furnace, instead of after the steel is teemed. If a large quantity of gases separate during solidification, the steel will be porous.

The quieting is effected by the reaction upon the carbon of the iron oxide contained throughout the mass of molten metal; CO gas is formed and escapes. Part of the oxide of iron is reduced and part floats to the surface of the metal. When the evolution of gases ceases, the metal is quiet.

If kept too long in the furnace, the steel will be brittle on account of its having taken up too much silicon from the crucible.

The very small percentages of phosphorus and sulphur contained in wrought-iron bars made from the best Swedish pig iron are not injurious, but the steel unavoidably receives a slight addition of sulphur which is given off from the coke and penetrates through the crucible. The steel, however, takes up some manganese from the compound of manganese charged into the crucible, and this destroys the ill effects of the sulphur.

Ferro-manganese is the compound generally used, the chemical action of which is shown by the following equation:—

$FeO \quad + \quad Mn \quad = \quad Fe \quad +$
Ferrous oxide and manganese yield iron and
MnO.
oxide of manganese.

The oxide of iron rises to the surface of the metal and combines with the silica of the crucible to form manganese silicate. During killing or dead melting, the manganese silicate is acted on by the excess carbon in the steel, and silicon is set free.

$2MnO,SiO_2 \quad + \quad C \quad = \quad Si \quad +$
Silicate of manganese and carbon yield silicon and
$CO_2 \quad + \quad 2MnO.$
carbon dioxide and oxide of manganese.

The silicon enters into the steel and hastens the liberation of the CO_2 gas; so it assists in quieting the metal. A percentage of 0·02 of silicon will not be injurious, but the steel is liable to take up more than this amount during killing. The addition of 0·03 per cent. of aluminium just before teeming has the same effect as silicon in quieting the metal.

The chemical action of the oxide of manganese with the silica of the crucible at the surface of the metal cuts a groove in the crucible, so the charge has to be reduced for the next melting. The first charge is about 60 lbs.; the second 54 lbs.; and the third 48 lbs. These three charges are completed in one day, and a new crucible is required for the next day's work.

Mild Steel

Mild steel is not as pure a steel as tool steel, but it is more suitable for most purposes for which steel is used. Mild steel is crystalline and free from slag; wrought iron is fibrous and contains slag irregularly mixed with it. Mild steel is now much more generally used than wrought iron, because:—it can be produced in larger masses, is more uniform in composition throughout its mass, has a greater tensile strength, and is cheaper to produce. Wrought iron, however, has the advantage that, owing to its fibrous composition, it can endure a great deal of hammering during forging without deterioration. It may also be reheated very many times.

ANALYSES OF MILD STEEL AND WROUGHT IRON COMPARED.		
Component Parts.	Mild Steel.	Good Wrought Iron.
Phosphorus	0·05	0·16
Carbon	0·20	0·04
Silicon	0·02	0·25
Manganese	0·50	0·01
Slag	None	2·60
Iron	99·18	96·85
	99·95	99·91

The *Siemens-Martin* process for the manufacture of steel consists in melting pig iron, or pig iron together with scrap steel or iron, in an "open-hearth" furnace. The silicon and manganese are oxidised. Hematite ore is added to the molten metal, and the oxygen contained in it will oxidise the carbon. The metal in the furnace is then nearly pure iron, and it is converted into medium or hard steel by the addition of spiegeleisen in the furnace. Steel is then tapped from the furnace.

The iron is converted into mild steel by the addition of ferro-manganese in the furnace, or in the ladle, after the iron has been tapped from the furnace. The *Bessemer* process consists in oxidising the impurities in the iron by blowing air through fluid pig iron which has been made to flow into a "converter," and then converting it into steel by the addition of spiegeleisen or ferro-manganese.

The Siemens-Martin process is slower, but it is *more completely under control* than that of the Bessemer, and any grade of steel can be made with more regularity and certainty than by the Bessemer process.

ACIDS AND BASES

The following is a list of some acids and bases which can enter into chemical union with each other so that the resulting compound has a much lower melting-point than either the acid alone or the base alone.

Acids.	Chemical Formula.	Bases.	Chemical Formula.
Phosphoric acid .	P_2O_5	Ferrous oxide .	FeO
Titanic acid. .	TiO_2	Manganous oxide .	MnO
Silica	SiO_2	Lime . . .	CaO
Carbon dioxide, or carbonic acid	CO_2	Magnesia . .	MgO

The union of the "acid" silica with the "base" lime in the blast furnace is an example.

Alumina (Al_2O_3) acts as an acid when lime predominates, and as a base when silica is the chief component.

Acid steel.—The Siemens furnace and the Bessemer converter were formerly lined only with material which consisted chiefly of silica.

Silica is an acid, so is phosphoric acid; therefore, silica will not assist in eliminating phosphorus from iron.

Only pig iron which contains a small percentage of phosphorus can be converted into good steel by the acid process.

Basic steel.—Most iron ores contain a considerable amount of phosphorus, and, as has already been stated, it all goes into the pig iron during smelting. Thus it was necessary to discover some means of eliminating the phosphorus. The discovery of the "basic" process by which phosphorus and sulphur can be eliminated from some kinds of pig iron immensely increased the production of mild steel; as pig iron, formerly useless for steel-making, is now being converted into steel.

CHAPTER VI

THE SIEMENS-MARTIN OR OPEN-HEARTH PROCESS

THE heat in the open-hearth furnace is obtained by the combustion of "producer" gas.

GAS PRODUCER

Small coal is burnt in a producer and converted into gases which can be collected and conveyed to the furnace where they are required to be burnt. The gases generated are carbon monoxide (CO), methane or marsh gas (CH_4), and hydrogen (H); these are all combustible.

A gas producer is shown in fig. 9. It is built of fire-bricks with an outer covering of steel plates. The whole structure is set on pillars over a recess which contains water.

A fire is first lighted at the bottom, and coal is charged into a "hopper" at the top. Fuel is admitted to the producer from the hopper by means of a cup and cone arrangement, as in a blast furnace. The necessary air, generally pre-heated, for combustion is forced in by injecting steam into a pipe with an enlarged entrance. It enters the producer through a steam and air flue and escapes from under a central cone. The central cone holds up the fuel until it is consumed; the ashes drop into the water and are raked out. The gases ascend and are led away by the downtake. Ammonia can be extracted from the gases before they are led away to the furnace to be burnt.

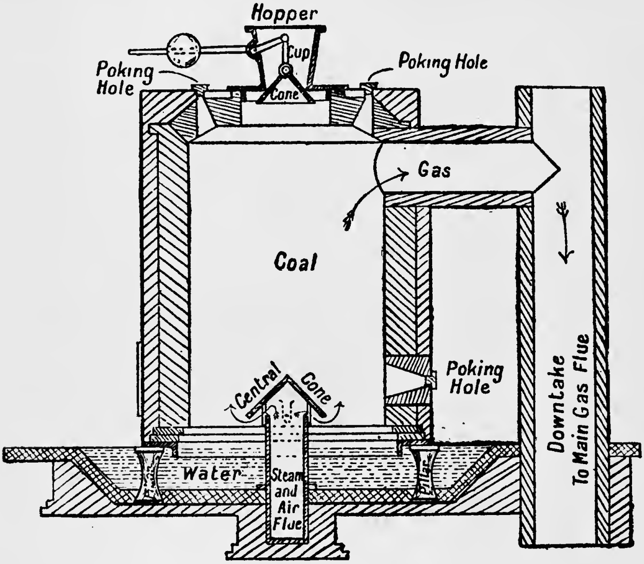

FIG. 9. GAS PRODUCER

The Open-hearth Furnace

Fig. 10 is a vertical longitudinal section of an open-hearth furnace worked on the *regenerative system.* The whole is built of firebrick and strengthened by steel plates and old rails braced together by tie rods. The furnace is built over four arches which are the arches of the *regenerators*, one on each side for gas and one on each side for air. The regenerators are filled with checkered bricks in the same way as in the regenerator

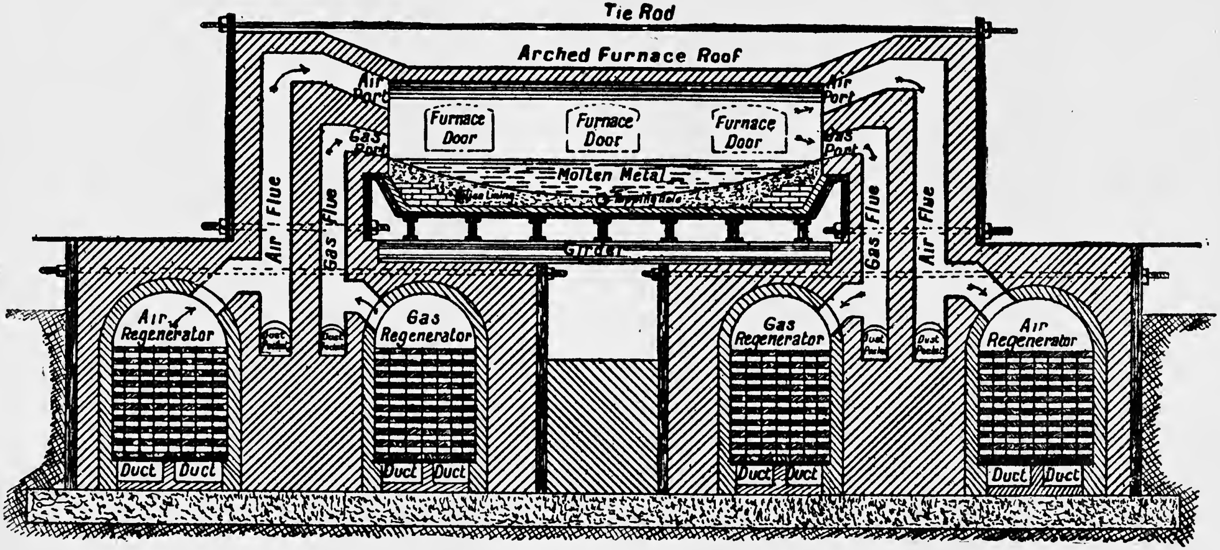

FIG. 10. SIEMENS' OPEN-HEARTH FURNACE

of a hot-blast stove (see page 13). The outer ones are for air and the inner ones are for gas, but it may be arranged that the outer ones are for gas and the inner ones for air.

The gases and air are led from the regenerators by flues to ports in the inner walls of the furnace. There may be one gas and two air ports at each end of the furnace, or two gas and three air ports. The air ports are at a higher level than the gas ports.

The "dust pockets" are for the purpose of collecting the dust (and sometimes slag) blown out of the furnace. If the dust was allowed to go into the regenerators, they would become choked.

When the furnace is at work, the gases from the producer are led through a "duct" in the ground to the bottom of the gas regenerator, and through the regenerator to the gas port, or ports, in the furnace.

Air passes through another duct in the ground to the bottom of the air regenerator, and thence to its ports in the furnace.

The ducts, flues and ports for the gases are quite separate from the ducts, flues and ports for the air, but they are built in exactly the same way on each side of the furnace. The gases and air meet and are ignited in the furnace. As the ports are built with a slope inwards, the flame is directed on to the metal in the furnace.

The products of combustion pass out through the opposite ports at a very high temperature and heat the regenerators on the other side on their way to the chimney.

The arrows in the figure indicate the directions of the gases and air entering the regenerators on the left side and leaving the regenerators on the right side. When the gases and air have travelled in this direction for a certain length of time, say twenty minutes, the regenerators on the right side will have become greatly heated; the gas and air valves are then reversed so as to cause the gases and air to enter the furnace through the opposite ports and in the opposite direction. That is, the gases and air will be made to pass upwards through the regenerators on the right side. The gases and air will be heated by passing between the very hot bricks, and when they ignite in the furnace the flame produced will give a more intense heat than before. In the meantime, the regenerators on the left side are being heated by the outgoing gases.

The valves are at intervals reversed, so that the gas and air regenerators on one side and the gas and air regenerators on the other side are alternately heated and cooled. With each reversal the furnace becomes more highly heated until a temperature is attained which melts the iron.

The roof of the furnace becomes greatly heated and reflects its heat on to the metal. The bricks of the roof are built with an arch to prevent them from falling in.

As the whole structure expands on being heated, the nuts at the ends of the tie rods are gradually screwed back. When steel-making is finished, the furnace is allowed to cool down gradually, and as it cools, the nuts on the tie rods are screwed up. The bottom of the furnace consists of firebricks on steel plates supported by girders.

Lining the Furnace for the Acid Process

The furnace is lined with white or silver sand mixed with a small quantity of ganister. The former is found chiefly in Belgium; it is almost pure silica (silica, 98½ per cent.) and is infusible at the furnace temperature. Ganister is found in large quantities near Sheffield; it contains a less percentage of silica (silica, 94½ per cent.) than white sand, and the other materials contained in it are fusible at the furnace temperature, so it acts as a binding material.

A thin layer of the mixture is laid over the bottom firebricks, and when the heat of the furnace is sufficient, it "frits" (melts slightly) and adheres to the bricks. The mixture is continually added in thin layers until the bottom of the furnace has a thick lining of sand. The grains of sand frit just sufficiently to stick to each other.

Some acid slag is then thrown into the furnace and melted and rabbled over the furnace bottom so as to glaze the surface of the sand. The slag is tapped off.

Charging the furnace.—The furnace is charged with a small quantity of pig iron and, on top of the pig iron, scrap steel or iron. Light scrap should be kept off the bottom and clear of the banks of the furnace, as it quickly oxidises and would cut grooves in the silica lining.

The furnace is not charged to its full capacity until it has been worked for three or four days; it should be kept in continual operation, day and night, until repairs are necessary. A furnace is usually worked continuously for two and a half to three months.

If there is a large quantity of scrap steel to be disposed of, a charge for a 15-ton furnace may be :—8 tons of pig iron, 5 tons of scrap steel, 1½ tons of hematite ore as the oxidising agent, and 2½ cwts. of ferro-manganese at the end of the process to convert the iron into steel.

CHEMICAL ACTIONS IN THE ACID OPEN-HEARTH PROCESS

Good acid open-hearth steel may be manufactured from pig iron containing the following elements :—

Element.	Percentage.
Carbon	3·5
Silicon	2·0
Phosphorus	0·05
Sulphur	0·05
Manganese	0·75

In the acid process neither phosphorus nor sulphur is eliminated. In fact, the percentages are greater in the finished steel than in the original pig iron, as the iron when molten absorbs slight amounts of phosphorus and sulphur from the hematite ore and from the spiegeleisen or ferro-manganese. So phosphorus and sulphur should not be contained in the pig iron in a greater proportion than 0·05 per cent.

The eliminations of the impurities in the charge take place in three stages :—

1. During melting, by the oxidising action of the flames.

2. After melting, by the action of the oxides of iron formed during melting.

3. During boiling, by the action of the oxide of iron added to the charge.

In the first stage, "during melting," about one-half of the silicon and one-third of the manganese are oxidised.

In the second stage, "after melting," nearly all the remaining silicon and manganese are eliminated and the carbon has been diminished. The oxidised products, silica (SiO_2), oxide of manganese (MnO), and some oxides of iron (FeO and Fe_2O_3) go into the slag.

At this point, a hematite ore containing 70 to 80 per cent. of ferric oxide is charged, in small quantities at a time, into the furnace.

In the third stage, "during boiling," nearly all the carbon is oxidised; the escape of CO gas through the metal gives the appearance of boiling. If the hematite ore is added too quickly, the ebullition may cause some metal to run out of the furnace doors. The ferric oxide in the ore is decomposed, and its oxygen quickens the burning out of the carbon; the iron which separates from it adds to the molten metal in the charge.

The chemical equation is:—

$3C \quad + \quad Fe_2O_3 \quad = \quad 2Fe \quad +$
Carbon and ferric oxide yield iron and
$3CO.$
carbon monoxide.

The gas CO burns at the surface of the metal, and, taking up more oxygen from the air, it escapes as CO_2.

Before finishing, it is beneficial to place a few halfpigs of hematite iron, containing much carbon and silicon, just inside the doors of the furnace. When they are red-hot, push them into the melted metal and rabble quickly; this will deoxidise the charge and make it quiet for tapping.

If medium or hard steel is required, a certain weighed quantity of spiegeleisen is now thrown into the furnace and the charge is almost immediately tapped.

If a mild steel is required, the iron is tapped from the furnace, and ferro-manganese is thrown into the ladle at the same time as the metal flows in, or it may be added to the charge in the furnace before tapping.

The approximate compositions of spiegeleisen and ferro-manganese are as follows:—

Components.	Spiegeleisen.	Ferro-manganese.
Carbon	5·00	6·30
Manganese . . .	15·00	77·00
Silicon	0·80	0·80
Sulphur	0·02	0·01
Phosphorus . . .	0·10	0·10
Iron	79·08	15·79
	100·00	100·00

Before tapping, samples should be taken out in an iron spoon, cooled, hammered flat, and broken. The appearance of the fracture will indicate the qualities of the steel; the percentage of carbon may be judged approximately.

To ascertain the percentage of carbon exactly, the sample is submitted to a chemical colour test. The test is made as follows:—

Fine drillings are taken from the sample—we will call these drillings "sample A"—of exactly equal weight to another sample which we know to contain the percentage of carbon which we require in our charge in the furnace. The latter sample we will call "sample B."

Samples A and B are placed separately into two similar test tubes, and into each tube is poured an equal quantity—by measurement in a glass tube—of colourless nitric acid. The nitric acid dissolves the samples of steel. The steel will be dissolved more quickly if the test tubes are heated by lowering them into a vessel containing boiling water.

When it is seen that the steel is all dissolved, the colours of the solutions in the test tubes are compared. The colours vary from a light straw to a dark brown. If the solution in which sample A is dissolved is darker in colour than the solution of sample B, it contains a higher percentage of carbon; in which case it will be necessary to reduce the amount of carbon in the charge by charging more hematite into the furnace.

If, on the other hand, solution A is lighter in colour than solution B, it contains a lower percentage of carbon. The percentage of carbon in the charge must then be increased by adding spiegel or ferro.

The following table is for the purpose of showing approximately the chemical changes that take place during the process:—

Components.	Composition.				
	Pig Iron and Scrap Steel.	When Melted.	At the Commencement of Boiling.	Before Ferro-Manganese is Charged.	Finished Mild Steel.
Phosphorus .	0·05	0·05	0·051	0·051	0·052
Carbon .	2·90	2·70	2·500	0·100	0·190
Silicon .	1·60	0·90	0·400	0·020	0·020
Manganese .	0·70	0·50	0·100	None	0·550
Iron . .	94·70	95·80	96·896	99·776	99·134
	99·95	99·95	99·947	99·947	99·946

The addition of spiegeleisen or ferro-manganese has three effects :—

1. It deoxidises the molten metal. This is shown by the equation :—

$$\mathrm{Fe} \quad + \quad \mathrm{O} \quad = \quad \mathrm{FeO}.$$

Iron and oxygen yield ferrous oxide.

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

Ferrous oxide and manganese yield manganous oxide

$$+ \ \mathrm{Fe}.$$

and iron.

The manganous oxide goes into the slag.

2. It adds carbon to convert the iron into steel of the required quality.

3. It adds manganese to the steel; this to some extent destroys the ill effects caused by the presence of phosphorus and sulphur.

The reason why spiegeleisen is added for medium and hard steels, and ferro-manganese for mild, is made clear by referring to the table (p. 46) of the compositions of spiegel and ferro.

500 lbs. of spiegel contains 75 lbs. of manganese and 25 lbs. of carbon.

100 lbs. of ferro contains 77 lbs. of manganese and 6·3 lbs. of carbon.

To get the same quantity (75 to 77 lbs.) of manganese in each case, 500 lbs. of spiegel to 100 lbs. of ferro would have to be charged. But 500 lbs. of spiegel contains 25 lbs. of carbon; therefore, it will make a harder steel than 100 lbs. of ferro, which contains 6·3 lbs. only of carbon.

Slag.—The following gives an idea of what may be the composition of the slag which results from the process:—

Components.	Percentage.
Ferrous oxide . . .	26
Manganous oxide . .	8
Silica	57
Lime	6
Alumina, etc. . . .	3

The weight of the slag will be about 13 per cent. of the total weight of the pig iron, scrap and hematite ore charged into the furnace.

Although the slag contains about 20 per cent. of iron and 6 per cent. of manganese, it does not pay to extract these metals, so the slag is useful only for such purposes as road-making and ballast for railways.

CHAPTER VII

THE BASIC OPEN-HEARTH PROCESS

Many kinds of pig iron contain a medium quantity of phosphorus, too much for it to be used for steel-making by the Siemens acid process, and not enough to enable the necessary high temperature to be maintained in the Bessemer basic process. Such iron can be converted into steel by the open-hearth basic process only.

Basic lining.—The lining of the furnace is the only matter in which the plant for the basic process differs from that of the acid process. The furnace requires a basic lining, so that the base (usually lime) which is added to the charge of pig iron shall not enter into chemical union with it, but shall remain free to combine with the phosphorus as it is oxidised from the pig iron, and to retain the phosphorus in the slag until the process is finished.

Basic materials.—The following table gives the chief components of some basic materials after they have undergone the process of calcination to remove CO_2 and other volatile matters contained in the quarried lumps:—

Components.	Formulæ.	Percentages.		
		Dolomite.	Magnesite.	Limestone.
Lime	CaO	60	2	93
Magnesia	MgO	32	93	3
Silica	SiO	3·5	1	2
Alumina	AlO	3	3	1

The basic material to be selected depends on which material is the most economical to use in the district in which steel is to be made.

Dolomite is considered the best; it is ground into powder and mixed with about 8 per cent. of anhydrous tar. "Anhydrous" means "without water."

Magnesite is a good material, but expensive in most places.

Limestone mixed with tar is fairly good.

Basic bricks are made from basic materials in a special hydraulic press with moulding boxes; they are then dried in a kiln.

LINING THE FURNACE

The basic material may be spread in thin layers and heated so that it frits together, in the same manner as the silica lining is spread in the open-hearth furnace for the acid process; or the furnace may be lined with basic bricks cemented together with basic material, and covered with the same material.

The former method is the better, as it makes a more solid lining.

Basic material is very friable, and therefore it cannot be used for building the walls and roof of the furnace; these are built of silica bricks.

Chemical action is liable to take place between the silica bricks and the basic material; the action is considerably less if the acid and basic materials are not subject to *pressure* in contact with each other.

A method of partly relieving the basic material from the weight of the walls and roof is shown in fig. 11. An angle iron is riveted on to the inside of the steel plates which form the furnace casing. Chemical action is further prevented by making a joint, which is called a *neutral course*, between the acid and basic materials. The neutral course is generally a mixture of crushed chrome iron ore and a little tar.

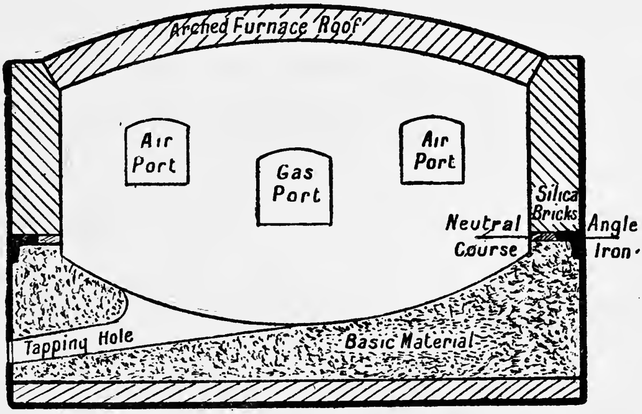

FIG. 11. FURNACE LINING. BASIC MATERIAL.

The iron plates at the bottom of the furnace are covered with silica bricks, and the basic material is fritted on to the bricks. When the furnace is in operation, there will be no chemical action between the bottom silica bricks and the basic lining, as sufficient heat will not penetrate the upper lining.

Charging the furnace.—The pig iron for use in the process should not vary much from the following composition:—Phosphorus, 1·75 per cent.; silicon, not more than 1 per cent.; sulphur, not more than 0·06 per cent.; manganese, 1·75 per cent.; and carbon, 3·5 per cent. 25 to 30 per cent. of scrap, wrought iron or steel, may be charged with the pig iron. When the charge is melted, lime and an oxide of iron is thrown into the furnace. The oxide of iron may be any form of ferrous or ferric oxide, which contains little or no silica. Best tap, the composition of which is given on page 25, is used, or "pottery mine," which is an iron ore mined in Staffordshire, England.

THE CHEMISTRY OF THE PROCESS

The oxide of iron is the oxidising agent.

Oxidation of silicon:—

$$Si \quad + \quad O_2 \quad = \quad SiO_2.$$

Silicon and oxygen yield silica.

Silica, which is an acid, is prevented from entering into combination with the basic lining of the furnace by the highly heated lime, which is a base. The silica at once combines with the lime and forms silicate of lime in the slag.

$$2CaO \quad + \quad SiO_2 \quad = \quad 2CaO,SiO_2.$$

Lime and silica yield silicate of lime.

Oxidation of carbon:—

$$2C \quad + \quad O \quad = \quad 2CO.$$

Carbon and oxygen yield carbon monoxide.

The CO gas escapes through the molten metal and gives it a motion with the appearance of boiling. When the CO reaches the surface of the metal, it takes up more oxygen from the air and escapes as CO_2.

Oxidation of manganese :—

$$\mathrm{Mn} \quad + \quad \mathrm{O} \quad = \quad \mathrm{MnO}.$$

Manganese and oxygen yield manganous oxide.

The manganous oxide, which is a base, enters into the slag; it is useful in the process, as it helps to keep the slag more basic than acid.

Oxidation of phosphorus :—

$$2\mathrm{P} \quad + \quad 5\mathrm{O} \quad = \quad \mathrm{P_2O_5}.$$

Phosphorus and oxygen yield phosphoric acid.

The phosphoric acid combines with the lime and remains in the slag as tetra-calcic-phosphate (phosphate of lime).

$$\mathrm{P_2O_5} \quad + \; 4\mathrm{CaO} \quad = \quad 4\mathrm{CaO,P_2O_5}.$$

Phosphoric acid and lime yield phosphate of lime.

Silicon and manganese are the first to be completely removed from the pig iron; carbon and phosphorus oxidise more slowly.

Small quantities of lime are added from time to time; too much lime will cause a pasty slag which will be difficult to tap from the furnace. The carbon should not be removed before the phosphorus, as the CO gas on escaping causes a commotion in the metal. This commotion is necessary in order to bring the phosphorus in the metal into intimate contact with the oxide and with the lime. Insufficient lime will cause a charge to go " off the boil," CO ceasing to escape, before enough phosphorus has been eliminated. In this case more lime is added, and some hot pig iron is charged in order to again get the metal "on the boil."

Samples are taken from the furnace at intervals, and when they are cooled and broken it can be seen by the appearance of the fracture to what extent the phosphorus has been eliminated.

At the end of the process the slag should be as non-oxidising as possible, as, if too much oxygen is present, the metal cannot be quietly teemed.

The elimination of much sulphur cannot be relied upon, and for this reason a pig iron with a small percentage of sulphur should be selected.

Manganese, during the process, has some slight effect in eliminating sulphur, and when the spiegeleisen or ferro-manganese is added, there is a further small reduction of sulphur.

To convert the iron into steel, spiegel or ferro is added as in the Siemens acid process.

It is not intended that the basic material with which the furnace is lined shall be used as a base to absorb the acids, silica and phosphoric acid—lime is added to prevent that; but the lining becomes gradually worn and damaged, and new layers of basic material are occasionally required.

Slag.—The slag resulting from the process will be approximately of the following composition :—

Components.	Percentages.
Phosphoric acid P_2O_5	13
Manganous oxide MnO	10
Magnesia MgO	6
Lime CaO	41
Oxide of iron Fe_2O_3	17
Silica SiO_2	13

The slag is broken and ground into a fine powder for manure.

If it contains much less lime, or much more silica or oxide of iron than shown in the above composition, it is dense and hard and difficult to break up into small enough pieces for grinding.

The phosphoric acid and lime, especially the phosphoric acid, makes the slag valuable in some soils as a fertiliser.

THE ACID AND BASIC OPEN-HEARTH PROCESSES COMPARED

The chief points of difference between the acid and basic open-hearth processes may now be summarised :—

Acid.	Basic.
Furnace lined with acid material, chiefly silica.	Chrome Furnace lined with basic material.
Hematite pig iron used.	Phosphoric pig iron used.
Scrap used must contain a small percentage only of phosphorus.	Phosphoric scrap may be used.
Hematite ore used as the oxidising agent.	Ore containing phosphorus may be used, but it must contain very little silica.
No elimination of phosphorus.	Phosphorus is eliminated.
Slag useless as a fertiliser.	Slag valuable as a fertiliser.

As a greater quantity of slag is produced in the basic than in the acid process, a smaller quantity of basic than acid steel is produced in furnaces of equal dimensions.

A great disadvantage of the basic process is that *good* high carbon steel cannot be made by it. The reason for this is that a small percentage of phosphorus always passes back from the slag into the metal when ferro or spiegel is added, owing to the reducing action of the carbon and of the manganese.

High carbon steel may be made by recarburising the iron after it is tapped by adding *molten* spiegel in the ladle; or by the "Darby recarburising process," which consists of passing the metal, as it flows from the furnace, through a perforated vessel into which falls a stream of fine carbon. In these methods the difficulty is to keep the slag from passing into the ladle.

The differences between mild or medium steels produced by the acid or basic open-hearth processes are not generally shown by chemical analysis or by mechanical tests, but under microscopical examination basic steel shows a more defective grain.

Steel produced by the basic open-hearth process is cheaper than that from the acid open-hearth, and it is largely used in America, Germany and Belgium. But English manufacturers consider that while basic steel is suitable for many requirements, it fails entirely, as compared with acid steel, in endurance tests, when used for tyres, angles, forgings, or for spring steel. Even for rails, acid steel is preferred.

Experience has shown that acid steel resists "fatigue" (see Vanadium, page 90) better than basic steel.

CHAPTER VIII

THE ACID BESSEMER PROCESS

The acid Bessemer process is carried out in a vessel which is called a *converter*. The pig iron to be converted into steel must be low in phosphorus and sulphur, and be similar to the composition, given on page 44, of the pig iron used in the acid Siemens process.

Melted pig iron is poured into the converter, and it is purified by blowing a large quantity of air through it; the oxygen contained in the air is the oxidising agent.

Fig. 12 is a section of a Bessemer converter built of steel plates and lined with firebricks and *ganister*. It is charged and emptied through the one open end; at the other end are the tuyere holes through which the air blast is forced.

The converter is encircled at its widest part by a steel ring, to which two trunnions are secured. The trunnions rest on bearings and act as axles. One axle is a tube through which the air blast passes to the bottom of the converter.

A toothed wheel, in gear with a pinion, is secured to the axle; as the toothed wheel is revolved, it rotates the converter to any required position. The converter is made up of three parts which are bolted together. The three parts are called the hood or nose, the body, and the bottom or plug.

LINING THE BESSEMER CONVERTER

Ganister is the material used for lining the converter; it consists chiefly of silica, but has other more easily fusible materials contained in it which enables the whole to bind it firmly together.

The three parts of the converter are lined separately. The hood is inverted and a wooden core is placed within it; the space between the core and the hood is filled and rammed with ganister. The bottom is also rammed with ganister, openings being left for the insertion of the tuyeres. The body is lined with silica bricks cemented with ganister.

The tuyeres are tapered plugs which have been moulded out of fireclay; they are cemented into the openings in the bottom of the converter with fireclay or ganister, and are held in position by means of a steel plate. Each tuyere has from 12 to 20 holes about $\frac{5}{16}$-inch in diameter.

Owing to the violence of the air blast, the bottom lining has to be frequently repaired—generally after about 20 "blows." The hood and body may not need relining more often than once a year.

CHARGING AND WORKING THE CONVERTER

A fire is lighted in the converter to heat it before charging with metal. The metal may be pig iron melted in an ordinary foundry cupola.

In this way the pig iron may be selected of a uniform quality, and the steel manufactured from it will also be uniform in quality.

It is, however, much more economical in fuel and labour to charge the converter with molten metal direct from the blast furnace.

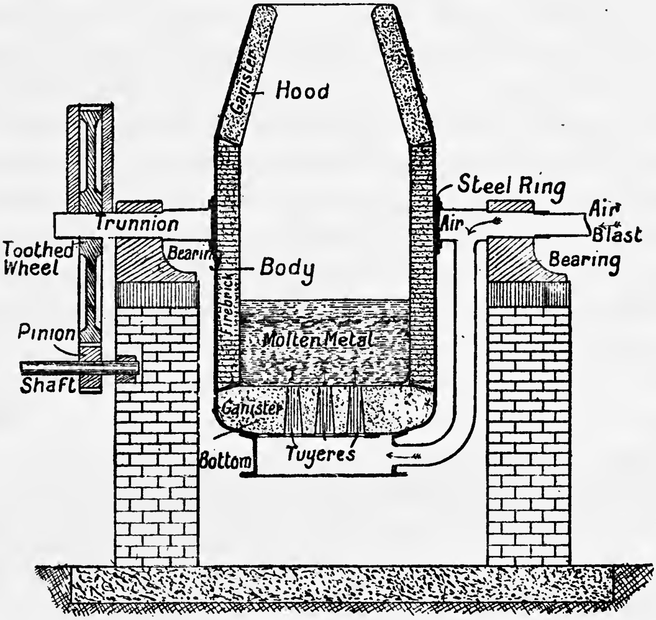

FIG. 12. BESSEMER CONVERTER

If the metal is taken from a single-blast furnace, it may vary in quality, as blast furnaces often produce irregular qualities of iron.

It is, therefore, usual to tap iron from several blast furnaces into a large vessel which is called a *mixer*.

One or two furnaces may produce iron high in silicon or sulphur, and this may be compensated for by iron from other furnaces being low in silicon or sulphur. The iron obtained by mixing the tappings of four or more blast furnaces is of a fairly uniform composition.

The mixer is a large tipping ladle—that is, a ladle which is emptied by rotating it on its trunnions.

Metal is poured from the mixer into another tipping ladle, which is carried on rails to the converter. As this ladle is being filled it stands on a weighing machine, so that the actual quantity of molten metal which it contains is known; the quantity is sufficient for one "blow" in the converter.

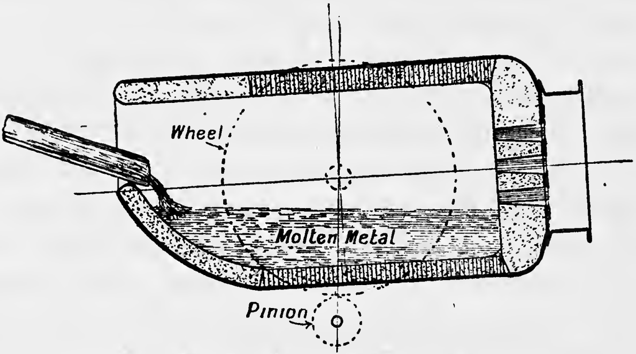

FIG 13 CHARGING THE BESSEMER CONVERTER

Before charging the converter with metal, it is rotated to a horizontal position as shown in fig. 13. In this position the metal cannot flow into the tuyere holes. When the converter is charged, the air blast is started and the converter rotated to a vertical position.

The pressure of air, 20 to 25 lbs. per square inch, prevents the metal from flowing into the tuyere holes, and the metal is kept in motion by the force of the air. The air passes up through the hot fluid metal, and, in so doing, the oxygen of the air enters into chemical combination with the silicon, carbon and manganese.

In some converters the tuyeres are placed on one side and slightly inclined downwards, just above the level of the molten metal when the converter is upright; air is then blown on to the surface of the metal. Such converters are called *side-blown* or *surface-blown converters.* The air blast causes a roaring sound, and a long flame issues from the opening at the top of the converter. The flame changes in colour during the continuation of the air blast; first it is violet, then orange, and then a dazzling white. After this the colour becomes of a faint blue and the flame almost disappears—the flame is then said to "drop"; at the same time there is a change in the *sound* of the blow. This indicates that all the carbon has been oxidised. The oxidation of the silicon and the manganese is completed before the oxidation of the carbon.

The converter is then immediately rotated to a horizontal position and the air blast stopped.

The slag, on account of its being of lower density, separates from the iron and rises to the surface.

The metal is now highly oxidised; it is supposed that at this stage free oxygen or an oxide of iron exists, dissolved with and clinging to the metal. Hot ferro-manganese or spiegeleisen is now thrown into the converter, and, as it melts, the iron is deoxidised, receives the required percentage of carbon, and is converted into mild or medium steel.

The steel is now teemed into moulds by further rotating the converter.

Chemical Actions in the Acid Bessemer Process

The following table is an example of the chemical changes that take place during the process:—

Components.	Hematite Pig Iron before Blowing.	Hematite Pig Iron after Blowing.	Mild Steel produced after addition of Ferro-manganese.
Carbon . .	3·5	None	0·2
Silicon . .	2·0	None	0·02
Phosphorus .	0·05	0·053	0·055
Sulphur. .	0·05	0·053	0·055
Manganese .	0·75	Slight trace	0·55

There is no elimination of phosphorus or of sulphur, but as the quantity originally present is now concentrated in a smaller *weight* of metal, the *percentage* of each becomes slightly greater.

The chemical reactions in the process are shown by the following equations:—

$$C + O = CO.$$

Carbon and oxygen yield carbon monoxide.

$$C + O_2 = CO_2.$$

Carbon and oxygen yield carbon dioxide.

The gases CO and CO_2 escape into the air.

$$Si + O = SiO_2.$$

Silicon and oxygen yield silica.

Silica forms the chief component of the slag.

$$Mn + O = MnO.$$

Manganese and oxygen yield manganous oxide.

The manganous oxide goes into the slag.

A small quantity of iron is oxidised.

$$\mathrm{Fe} \quad + \quad \mathrm{O} \quad = \quad \mathrm{FeO}.$$

Iron and oxygen yield ferrous oxide.

$$2\mathrm{Fe} \quad + \quad 3\mathrm{O} \quad = \quad \mathrm{Fe_2O_3}.$$

Iron and oxygen yield ferric oxide.

These oxides of iron go into the slag.

When the ferro-manganese or spiegeleisen is added, deoxidisation may be supposed to take place, thus:—

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

Ferrous oxide and manganese yield manganous oxide

$$+ \quad \mathrm{Fe}.$$

and iron.

Heat Maintained during a Bessemer Blow

The fluid metal is poured into the converter at a high temperature, and a large quantity of cold air is forced through it. The metal, however, is not reduced in temperature, but it is actually hotter at the end of the blow than at the beginning. The increase in temperature is chiefly due to the burning of the carbon and the silicon. Most of the heat evolved by the oxidation of the carbon is carried away in the gases which escape, but the silica resulting from the oxidation of the silicon remains at a very high temperature in the slag. This slag protects the metal and keeps it in a fluid condition. It is necessary to have a certain percentage of silicon in the pig iron to maintain the heat required for the acid Bessemer process.

If the metal is too hot at the finish of the process, owing to the iron containing too great a percentage of silicon, it will be in a disturbed condition resembling boiling when poured into the moulds, and the ingots will be unsound.

A remedy for this is to throw some scrap iron or steel into the converter before pouring in the melted pig iron; the heat of the whole mass of fluid metal is thus lessened by heat being absorbed in melting the scrap. With an overhead shute arrangement, scrap may be thrown into the converter during the blow.

If the metal is too cold at the finish of the process, the ferro-manganese or spiegeleisen does not become properly mixed with the fluid iron; the metal is not sufficiently fluid to pour evenly into the moulds, and some of the steel may solidify in the ladle. In this case, iron containing more silicon should be used; or, if this cannot be obtained, a greater volume of air blast, causing more rapid oxidation, may produce sufficient heat.

Acid Bessemer slag contains about 9 per cent. of iron and 12 per cent. of manganese, but, like acid Siemens slag, the composition of which is given on page 49, it does not pay to extract these metals.

CHAPTER IX

THE BASIC BESSEMER PROCESS

By the basic Bessemer process good mild steel may be made from steel containing much ($2\frac{1}{4}$ to $3\frac{1}{2}$ per cent.) phosphorus.

The plant required is the same as in the acid Bessemer process, the only difference being that the converter is lined with basic material instead of acid material.

The converter for the same amount of steel produced must be of larger dimensions for the basic process than for the acid process, as more slag results from the basic process.

Machinery for grinding the slag into powder is also required.

LINING THE BASIC BESSEMER CONVERTER

Dolomite, the composition of which is given on page 51, mixed with anhydrous tar, is the most generally used basic material.

The hood, which is the least liable to be damaged, is often lined with a mixture of new dolomite and old dolomite ground fine, tar being added to the mixture. The hood is inverted and a wooden core placed within it; the space between the core and the hood is filled and rammed with basic material. The body is lined with bricks which are made of compressed dolomite and tar, and these are cemented together with dolomite and tar. The bottom or plug is also made of the same materials well rammed. Holes, $\frac{3}{4}$-inch diameter, are left in the plug to serve as the tuyere holes for the air blast. About 90 holes would be required for a 20-ton converter.

After the bottom is bolted on, the space between it and the body is filled with basic material.

The mixed dolomite and tar is always rammed with very hot rammers, which are iron bars enlarged at one end, and as the basic material is put on in thin layers the heat of the rammers causes the layers to become cemented together into a strong solid block.

The plug quickly becomes worn out and the basic material has to be renewed. The plug may perhaps be used for 20 blows, the lining of the body for 100 blows, and the lining of the hood for 200 blows.

CHARGING AND WORKING THE CONVERTER

A quantity of calcined lime, 3 to 4 cwts. per ton of iron, is first thrown into the converter. The converter is then rotated until it is in the position shown in fig. 13, page 61, in which position it receives the charge of molten pig iron from a mixer or cupola.

The air blast is then started and the converter brought back to a vertical position.

The air blast is continued until the flame "drops," and for a short time after.

There is the period 13 to 15 minutes of the blow until the flame drops, and another period 3 to 4 minutes, which is called the "after-blow."

Nearly all the phosphorus is oxidised during the after-blow.

When the after-blow is considered to be sufficient, the converter is rotated to a horizontal position and the air blast stopped.

After allowing a short time for the slag to separate from the iron, a sample of the metal is taken from the converter by means of a long-handled spoon; this is solidified in an open mould, hammered flat, cooled with water, and broken. By the appearance of the fracture it may be judged whether or not the metal is sufficiently free of phosphorus; if high in phosphorus, long bright crystals will be shown in the fracture.

If the metal contains too much phosphorus, the blow will have to be restarted for a short time and then another sample taken and examined.

If the examination of the sample is satisfactory, as much as possible of the *slag is quickly poured off*, and the process is finished by the addition of ferro-manganese or spiegeleisen to the iron to convert it into steel.

CHEMICAL ACTIONS IN THE BASIC BESSEMER PROCESS

The following table is an example of the chemical changes that take place during the process :—

Components.	Composition of			
	Pig Iron charged.	Metal at end of Blow.	Metal at end of After-blow.	Mild Steel after addition of Ferro.
Carbon . .	3·6	0·06	Trace	0·18
Silicon . .	1·0	0·02	None	0·02
Phosphorus .	2·6	2·3	0·04	0·05
Sulphur .	0·07	0·066	0·055	0·055
Manganese .	1·2	0·16	0·13	0·6

Lime, which is a base, is used in the process, as it combines with the phosphorus and holds it in the slag. When a sample of molten iron is taken from the converter for examination, it is often considered necessary to add more lime before continuing the after-blow.

The presence of silicon, which is necessary to maintain the heat in the acid Bessemer process, is of disadvantage in the basic Bessemer process, as by combining with the lime it renders the slag less basic, and this retards the elimination of the phosphorus. To get the best results the silicon should not exceed 1 per cent., but basic Bessemer steel may be made from pig iron containing 1·5 to 2 per cent. of silicon. If the percentage of silicon is high, a large quantity of lime will be required, and the melting of the lime takes up much of the heat given by the oxidation of the silicon. It is important that the lime to be used should be as free as possible from silica.

With 1 per cent. of silicon the iron should contain about 3 per cent. of phosphorus to obtain the heat necessary in the blow. Great heat is produced by the oxidation of the phosphorus, and, as little is oxidised until the beginning of the after-blow, the greatest heat is obtained during the after-blow. Great heat is necessary for the elimination of the phosphorus and the sulphur. It is desirable to have a larger percentage of manganese in the pig iron for the basic process than for the acid process. It is oxidised from the commencement of the blow, and the heat of oxidation makes up to some extent for the percentage of silicon being low.

As manganous oxide, which is formed by the oxidation of manganese, is a base, less lime is required if there is a large percentage of manganese.

Sulphur is nearly all oxidised during the after-blow, when there is an excess of ferric oxide, a high temperature of metal, and a fluid slag.

If the percentage of sulphur in the pig iron is high, say 0·3 per cent., about 70 per cent. of it may be removed; if the percentage is 0·09, about 30 per cent. may be removed; if the percentage is only 0·05, there is usually none of it removed. If exceptionally pure lime, containing not more than 0·5 per cent. of silica and only traces of sulphur, is used, the sulphur in the finished steel may be reduced as low as 0·03 per cent.

A small percentage of phosphorus passes back from the slag into the metal when ferro-manganese or spiegeleisen is added, the phosphorus in the slag being reduced by the carbon and the manganese. The agitation caused by the production of CO gas, when ferro or spiegel is added, throws the metal into intimate contact with the slag, and assists the reduction of the phosphorus. This reduction is called the "rephosphorisation" of the metal, and, in order to lessen the reaction, as much as possible of the slag is poured off before adding ferro or spiegel.

If mild steel is required, ferro-manganese is charged into the converter; for medium or hard steel, molten spiegeleisen is added in the ladle. At the end of the after-blow the metal is highly oxidised, and before adding the ferro or spiegel it is often partly deoxidised by charging red-hot, grey, hematite pig iron, rich in carbon and silicon, into the converter.

The *chemical reactions* are shown by the following equations:—

As in the acid Bessemer process, the elements which are required to be removed from the pig iron are oxidised by the oxygen contained in the air forced through the molten metal.

$$\mathrm{C} + \mathrm{O} = \mathrm{CO}.$$

Carbon and oxygen yield carbon monoxide.

$$\mathrm{C} + \mathrm{O_2} = \mathrm{CO_2}.$$

Carbon and oxygen yield carbon dioxide.

The gases CO and CO_2 escape into the air.

$$\mathrm{Si} + \mathrm{O_2} = \mathrm{SiO_2}.$$

Silicon and oxygen yield silica.

Silica and lime form silicate of lime, which remains in the converter as slag.

$$\mathrm{2CaO} + \mathrm{SiO_2} = \mathrm{2CaO,SiO_2}.$$

Lime and silica yield silicate of lime.

$$\mathrm{Mn} + \mathrm{O} = \mathrm{MnO}.$$

Manganese and oxygen yield manganous oxide.

The manganous oxide enters into the slag and helps to keep the slag basic.

$$S + O_2 = SO_2.$$

Sulphur and oxygen yield sulphur dioxide.

The sulphur dioxide is a gas, and it escapes to the air.

Oxides of iron are formed, and they also enter into the slag.

$$Fe + O = FeO.$$

Iron and oxygen yield ferrous oxide.

$$2Fe + 3O = Fe_2O_3.$$

Iron and oxygen yield ferric oxide.

Sulphur trioxide is formed by the action of ferric oxide.

$$9Fe_2O_3 + S = 6Fe_3O_4 + SO_3.$$

Ferric oxide and sulphur yield magnetic oxide and sulphur trioxide.

The sulphur trioxide combines with lime in the slag.

$$SO_3 + CaO = CaSO_4.$$

Sulphur trioxide and lime yield calcic sulphate.

Nearly all the sulphur eliminated from the pig iron goes into the slag.

$$2P + 5O = P_2O_5.$$

Phosphorus and oxygen yield phosphoric acid.

The phosphoric acid combines with the lime and remains in the slag as phosphate of lime.

$$P_2O_5 + 4CaO = 4CaO,P_2O_5.$$

Phosphoric acid and lime yield tetra-calcic-phosphate or phosphate of lime.

Basic Bessemer Slag

The slag resulting from the basic Bessemer process is of much value as a fertiliser, because it contains a high percentage of phosphorus.

The following is an example of the composition of the slag :—

Components.	Percentages.
Phosphoric acid	19
Manganous oxide . . .	4
Magnesia	6
Lime	49
Oxide of iron	14
Silica, alumina, sulphur, etc. .	8
	100

Compare this composition with that of basic open-hearth slag given on page 55.

The slag is broken up and ground to a fine powder.

Compositions of Pig Irons used for Steel-making.

	Acid Siemens and Bessemer.	Basic Siemens.	Basic Bessemer.
Silicon . . .	2·0	1·0	1·0
Phosphorus . .	0·05	1·75	2·6
Sulphur . . .	0·05	0·06	0·07
Manganese . .	0·75	1·75	1·2
Carbon . . .	3·5	3·5	3·6

Summary.—The compositions of the pig irons used in the different processes which have been described are here placed side by side for comparison.

The best qualities of steel for guns, machinery, etc., are made by the acid Siemens process. Good quality steel can also be made by the acid Bessemer process; but as this process is not so easily controlled, the exact quality of steel required cannot be obtained with certainty.

The Bessemer process is more rapid than the Siemens; thus it is more economical for the manufacture of large quantities of steel.

Mild steel for rails, ship and bridge material, etc., is, if the composition of the pig iron is suitable, generally manufactured by the Bessemer process, acid or basic according to the composition of the pig iron obtainable.

The composition of the pig irons for the acid processes and for the basic Siemens must approximate closely to what is given in the tables.

The pig iron for the basic Bessemer may contain more phosphorus and sulphur, but the percentage of sulphur cannot be increased without a more than corresponding increase of phosphorus. For example, if the percentage of sulphur is 0·1, the iron must contain about 3·3 per cent. of phosphorus to provide sufficient heat for its elimination.

Additional heat may be obtained in the Bessemer process by adding the required amount of lime in a highly heated or even molten state, and by passing the air, used for blowing, through a chamber filled with coke, on to which petroleum is allowed to drip. Combustible gases are thus obtained, which, on being mixed with air, burn in the converter and raise the temperature of the metal. This adds to the cost of manufacture of the steel, but the additional heat sometimes makes it possible to make use of pig iron with a high percentage of sulphur which would otherwise be useless for steel-making.

To guard against a premature explosion by a shell breaking up in the gun, shell steel is required to be of a very uniform quality, and it was originally made by the open-hearth process only. In order, however, to keep up the enormous output required during the war, Bessemer acid steel was used to a limited extent. Bessemer basic was inadmissible, as its quality is even less uniform than that of Bessemer acid.

CHAPTER X

OIL COMBUSTION AND ELECTRIC FURNACES

Oil Combustion Converter

This is the "Stock" converter process, named after the inventor, used for making steel castings.

A small converter, somewhat similar to a Bessemer converter, of from 1 to 5 tons capacity is employed. Cold metal is placed into the converter and melted by heat produced by oil combustion, the flame being directed on to the upper surface of the metal in conjunction with a blast of air. When the melting is completed the oil jet is shut off, but air continues to be blown over the surface of the molten metal until the excess carbon, silicon and manganese have been eliminated.

The Electric Furnace

There is considerable controversy concerning the super-power stations which are in contemplation for the purpose of cheapening the production of electricity. The real solution of our fuel difficulties would appear to depend on the success of further research and experiments in order to establish simple processes for the extraction of oils and combustible gases from inferior grades of coal which are now quite useless. Until this is accomplished, the high cost of electricity will prevent the electric furnace from superseding existing types of furnaces for the smelting of iron ores and for the manufacture of steel. In Sweden, where water power is abundant, electric furnaces have been and are now being rapidly installed, but in England they are at present used only for the manufacture of high-grade steels.

The metal is heated by means of either an electric arc which passes from an electrode, usually made of carbon, suspended above the surface of the bath, and returns to another electrode after the current has passed through the molten metal, or by means of an electric current being passed through the metal so that sufficient resistance is offered to cause the necessary heat to be generated. A more intense heat can be produced in a furnace by electricity than by the direct use of fuel in other melting processes.

The electric furnace differs from the blast furnace by the absence of a blast of air, and in the possibility of attaining a higher temperature. Both of these differences cause the former to be a more powerful reducing and melting furnace than the latter. The strong reduction causes a very considerable percentage of the sulphur in the metal to pass into the slag, and the high temperature allows a very limey slag to be used for the removal of the sulphur.

Electric furnaces for the manufacture of steel are almost always made with a basic lining so as to allow of the removal of phosphorus and sulphur from the steel by means of a limey slag.

One of the most important of the uses of the electric furnace is the refining of steel which has been made in a Bessemer or open-hearth furnace. Other special advantages in favour of the electric furnace may be stated as follows :—

(*a*) Tool and other high-grade steels can be made at less cost than by the ordinary crucible process. Also, as less nitrogen gas is occluded, the steel is sounder and tougher.

(*b*) The production of high-grade steel from less pure grades of iron by keeping them in a molten condition beneath oxidising slags which may frequently be changed until all the impurities are removed. The high temperature of the furnace enables very basic slags to be used, and these are heated to a state of fluidity and at a much higher temperature than the metal in the bath, so that they act freely on the metal.

The pig iron which forms a part of the charge should be passed direct from the blast furnace (or electric ore-smelting furnace) in a molten state.

CHAPTER XI

TREATMENT OF STEEL INGOTS

IF the steel has not been sufficiently deoxidised by the addition of ferro-manganese or spiegeleisen, it will be " wild " or " boiling," and throw off sparks from the ingot mould after it is teemed.

The steel may be quieted by throwing small pieces of aluminium into the moulds. But even when quiet, the fluid steel contains a very large quantity of gases, in volume (at atmospheric pressure) 50 to 75 times that of the metal.

The gases are called *occluded gases* or *gases in occlusion*, and they consist chiefly of CO and H. Occluded gases have been mentioned in connection with crucible steel (page 32).

As the ingot cools, it solidifies first on the outside, and also gradually contracts. The fluid centre to some extent settles down to fill up the void caused by contraction and the void caused by the escape of some of the gases. As the fluid centre flows downwards, it forms a hollow at the top of the ingot which is called a " pipe " or " piping " ; this is shown in fig. 14.

When the top is solidified, the ascending gases given off from the fluid steel are unable to escape.

The gases collect under great pressure and form "blowholes" or "cavities" at the top of the ingot, as shown in fig. 14.

Thus the top of an ingot is unsound, and it is cut off and remelted as scrap.

A method of improving the soundness of an ingot is by "stoppering the ingot." That is, the mould is not quite filled with steel, and sand is thrown on top of the steel. A steel plate is laid on top of the sand, a bar is passed through the two lugs of the mould, and a wedge is driven in between the plate and the bar. The top of the ingot does not then solidify as quickly as when exposed to the air, and the gases have more time in which to escape. The impurities in the steel are *segregated* in the portion of the ingot which remains the longest in a fluid condition—that is, in the centre. If a chemical analysis is made of drillings taken from the centre of an ingot, higher percentages of carbon, phosphorus and sulphur are found than from drillings near the outside. Consequently, the outside is more malleable than the centre; this is an advantage when the ingot is being forged or rolled.

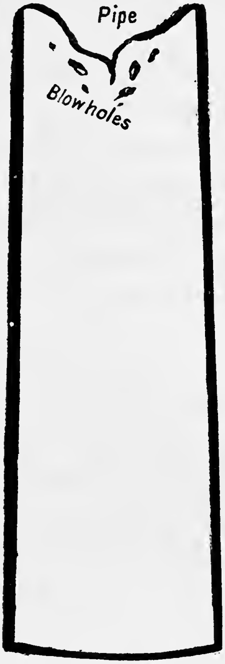

FIG. 14
STEEL INGOT

When the ingot has solidified sufficiently, so that the outside crust is strong enough to contain the fluid interior, the mould is lifted off; this is called "stripping" the ingot. In this condition the ingot cannot be forged, as the crust would be broken and liquid steel would squirt out.

If the ingot is allowed to stand until it is quite solid, the outside will be too cold for forging, and it will have to be reheated.

Ingots are reheated in *reheating furnaces*, which are either coal fired or heated by the combustion of producer gases.

SOAKING PITS

In order that ingots may be cooled more evenly and be ready for forging without the trouble and the expenditure of fuel necessary to reheat them, they are lowered into holes in the ground called "soaking pits."

The pits are arranged in sets, which are a few inches wider and deeper than the ingot.

Fig. 15 is a sketch showing two soaking pits.

In the beginning the heat from the ingots is absorbed in giving heat to the brickwork lining of the pits, so that when these ingots are taken out, they have to be reheated before they can be forged.

When the pits are well heated, heat is reflected from the brickwork on to the ingot, and during the time of solidification of the interior of the ingot the exterior is maintained at a white heat. Just as the interior becomes solid, the ingot is in the best condition for forging—slightly hotter in the centre than on the outside. Ingots reheated in a reheating furnace are in the reverse condition—hotter on the outside than in the centre.

The disadvantages of soaking pits are :—

That it is necessary to take heat from the ingots to first heat the pits, so that the first lot of ingots have to be reheated.

The difficulty of keeping up a regular supply of ingots so that they shall not remain for too long or too short a time in the pits.

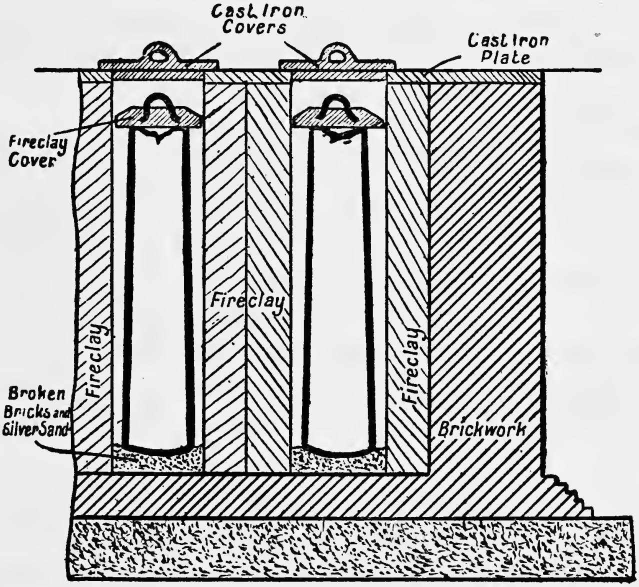

FIG. 15. SOAKING PITS

For these reasons it is now usual to lower the ingots into furnaces which are called *soaking furnaces*; these are heated by producer gases and worked on the regenerative system. They are practically reheating furnaces sunk into the ground, and, owing to there being little heat lost by radiation, they require only a small quantity of fuel.

Fluid Compression

The soundness of an ingot may be improved by subjecting the fluid steel in the mould to a very high pressure. The pressure squeezes some of the occluded gases from the fluid as water is squeezed from a sponge, and the remaining gases being compressed occupy smaller spaces within the mass of the metal. Thus the particles of steel are forced into more intimate contact with each other, and the grain is made finer and more homogeneous. The numbers of the blowholes may not be much reduced by compression, but it is evident that their sizes must be reduced. For example, a pressure of 5 tons per square inch is equivalent to a pressure of 761 atmospheres; this pressure would compress a bubble of gas into $\frac{1}{761}$ of its natural volume, or $\frac{1}{9}$ of its diameter. It has been found that pressures up to 2 tons per square inch have no beneficial effect on the steel, so pressures of 5 to 10 tons per square inch are applied. Such high pressures cannot be applied to steel cast in ordinary cast-iron ingot moulds, so special and expensive moulds have to be made.

The moulds are made of forged steel hoops, rough turned and bored, lined all round the inside circumference with cast-iron bars placed vertically and close together. The edges of the bars next to the hoops are chamfered off; the radial grooves, cut in the sides of the bars, connect with the spaces formed by the chamfering so as to permit the escape of gases from top to bottom of the mould. An inner lining of ganister is plastered on to the inner faces of the bars.

Fig. 16 shows a sectional plan of a portion of the mould. The bottom is closed by a cast-iron plate covered with fireclay, and the top of the mould consists of a cast-iron ring, into which is fitted with a slight clearance a cast-iron plug faced on its lower side with firebricks.

When hydraulic pressure is applied to the plug, a large quantity of gases escapes from the mould with a roaring sound, and the ingot shortens until its length is about 10 per cent. less than an ingot cast in the ordinary manner. It is not necessary to cut off the top of a pressed ingot, so there is no waste of metal.

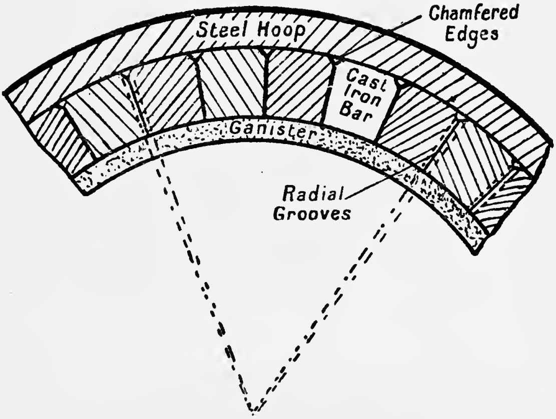

FIG 16
INGOT MOULD FOR FLUID COMPRESSION

A pressed ingot shows slightly better results in testing for elastic limit, tensile strength and elongation; and, as the grain of the steel is more homogeneous than that of an unpressed ingot, there is less risk of formation of cracks in cooling and reheating.

The process of fluid compression is too slow and too costly to be applied for ordinary commercial rolled steel, and it is used only in the manufacture of such special steel as is required for guns, crank and propellor shafts, etc.

Effects of Hammering, Rolling, and Pressing Steel

When steel is poured into a cold mould, the portion next to the mould is immediately solidified and forms a thin outer shell. As heat from the interior escapes through this shell, steel is continually being solidified and, so to speak, "frozen" on to the outer shell.

As the whole mass of metal contracts, approximately in proportion to the decrease of temperature, the fluid steel in the centre performs two functions. It continues to freeze on to the outer shell, and it also endeavours to fill the void in the centre caused by contraction.

The effect is that the steel in the interior of an ingot has a loose texture and it is defective.

To explain this in another way:—The outer shell of an ingot is immediately formed, and its dimensions are not materially altered when the metal is cold. But as there has been a considerable decrease of volume, the ingot must have either a hollow centre or be of loose texture.

The volume of steel when cold is about 6 per cent. less than when fluid; so the amount of contraction of an ingot of rectangular section, 15 inches × 14 inches, is equivalent to a cavity of about 3½ inches diameter in its centre.

The greater the size of an ingot the coarser will be the grain in the centre; therefore the centre requires the most forging in order to force the particles of steel into intimate contact with each other.

But, as force has to be applied from the outside, it is difficult to properly forge the interior of an ingot. A pressure is more effective than a blow in transmitting force from the outside to the centre.

If an ingot of mild steel could be removed from a soaking pit or a soaking furnace at the exact time that its centre is at a " welding heat "—that is, a temperature most suitable for welding—the particles of steel in the centre might be welded together by a forging press, and a steel with a fine grain would be produced.

It is, however, always uncertain that the centre is at a welding heat during the process of forging.

Ingots which have to be reheated before forging, cannot be brought to a welding heat in their centres.

An ingot of high carbon steel which does not weld is generally more defective in the centre than an ingot of low carbon steel.

The blow of a steam hammer is too rapid to permit of the pressure being transmitted from the surface to the centre, where it is the most needed. The difference in the effect of a blow and a squeeze in forging an ingot is easily seen. When an ingot is hammered, the energy is absorbed in spreading the surface, and the interior may remain quite unaffected. The effect of the surface being extended more than the interior is to make the end of a bar or an ingot of the shape as shown by A, and of section shown by B, fig. 17.

When an ingot is squeezed, as by a hydraulic forging press, the outside, on account of long contact with cold masses of metal, loses its heat more rapidly than the centre, and flows less easily than the hotter centre portion; the centre is thus squeezed out and the end is of the shape shown at C and section D.

When an ingot is rolled in a rolling mill, it is not squeezed out in the same way as by a forging press, because the surfaces of the rolls are moving in the same direction in which the bar lengthens, and the rolls drag forward the outer surfaces in contact with them, so the end of a rolled bar will be shaped as E. If the ingot is rolled between plain rolls and not in grooves, which prevent it from spreading laterally, the centre will be squeezed so that the section will be of the same shape as D.

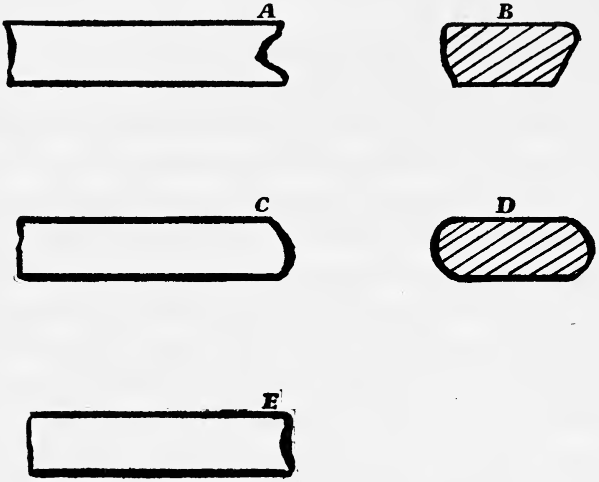

FIG. 17.
EFFECTS OF HAMMERING ROLLING AND PRESSING

CHAPTER XII

EFFECTS OF ADDING OTHER METALS TO STEEL

STEEL readily forms an alloy with most metals, and a small quantity of added metal makes a great difference in its properties.

Manganese.—Some manganese is necessary in steel to counteract a tendency to red shortness. It acts as a deoxidiser. Mild steel ingots containing 0·2 per cent. only of manganese are usually unsound. As the proportion increases, the ingots become sounder; but if the proportion of manganese is over 1 per cent. it becomes detrimental, as the power of elongation of the steel then commences to be reduced. Steel with 2½ per cent. to 7 per cent. of manganese is extremely brittle, but with over 7 per cent. up to 18 per cent. the alloy becomes practically a new metal which is called "manganese steel"; this possesses great strength and elasticity combined with hardness.

Aluminium is often added to steel, not with the object of forming an alloy, but because of the action which the metal has been found to have on molten steel. Molten steel contains dissolved oxide of iron which diminishes its fluidity and its strength. As the steel cools, the oxide of iron, by the action of carbon, is to some extent reduced, and CO gas is evolved. This gas causes an ebullition of the molten metal, and it is a cause of blowholes. A small addition of aluminium increases the fluidity of the metal and stops the evolution of gas. The reason for this is, that aluminium has a greater chemical affinity for oxygen than iron has; that is to say, it more readily combines with oxygen than iron does.

The oxide of iron is reduced, and alumina, which separates from the metal as slag, is formed. If too much aluminium is added, it will not be all separated and there will be weak spots in the steel.

Aluminium has the effect of preventing blowholes; but as it stops the evolution of not only CO gas, but of other occluded gases—that is, hydrogen and nitrogen—it increases the coarseness of the grain of the cast ingot. This coarseness, however, nearly disappears as the ingot is being forged.

Nickel increases the tensile strength and ductility of steel.

An alloy of nickel and steel is now largely used, and it is a splendid material for forgings for the moving parts of machinery.

Nickel steel containing 30 per cent. of nickel can easily be drawn out into wire, and as this large percentage of nickel renders the steel almost non-corrosive, nickel steel is well adapted for ship's hawsers and marine electric cables, which are subject to the corrosive action of salt water.

Chromium.—In small quantities, chromium slightly raises the tensile strength of steel, but it also slightly diminishes its ductility. When added in large quantities, the steel becomes brittle.

Chromium is added to steel in conjunction with nickel, for the inner "A" tubes of high-velocity guns; the proportions being:—

Carbon, 0·4 per cent.; chromium, 1 per cent.; nickel, 2 per cent.

Chromium makes steel hard, and nickel increases its elasticity.

Vanadium.—As an alloy, vanadium has, for quantity used, the most powerful influence of all alloys on the properties of steel. 0·2 per cent. of vanadium raises the elastic limit and tensile strength of mild steel by about 50 per cent. It is used in the manufacture of the highest classes of tool steel, so-called "self-hardening steel."

Steel under continual vibration or under variable strains, such as the piston and connecting rods of an engine, which are alternately under tension and compression, becomes brittle or "fatigued"; the addition of a small percentage of vanadium enables steel to resist this deterioration.

Titanium.—By adding to a bath of steel or cast iron a ferro-carbon titanium containing about 15 per cent. of titanium, the bath of metal can be almost cleansed from dissolved or occluded gases, such as oxygen and nitrogen, and from oxides of iron generally present in steel. In the Bessemer process, when air is blown through the molten iron, the titanium of the alloy combines with oxygen as titanic dioxide (TiO_2) and with nitrogen as titanium nitride (TiN_2). The oxide of iron is reduced to iron by the titanium and the carbon of the alloy, the titanium combining with its oxygen to form TiO_2. The slag, always present in a metallic bath, rises and carries with it the TiO_2 and the TiN_2 to the top of the bath. It has been proved by experiments that TiO_2 on entering the slag renders it more fluid and fusible.

One per cent. of titanium in steel renders it practically rust-proof and so hard that it can be drilled with difficulty.

Tungsten or *wolfram* alloyed with high carbon steel renders it hard, and tools made of this alloy have improved wearing properties. It also renders steel retentive of magnetism, and is therefore used in the manufacture of permanent magnets.

Tungsten was used in Germany in the composition of the "A" tubes—the inner tubes—of guns.

CHAPTER XIII

MECHANICAL TESTING OF STEEL

THERE are two classes of tests to be applied :—

1. *Hot tests.*—The steel is heated to a welding heat to find out if it is free from "red shortness," and if it has good welding qualities.

2. *Cold tests.*—To find out if it is free from "cold shortness," and to ascertain the tensile strength, elasticity, etc.

DEFINITIONS

Tensile strength (or *tenacity*) is the maximum stress which a bar of a material can sustain, without breaking, when a pulling force is applied gradually in the direction of its length.

It is usually expressed in tons per square inch of cross section.

Elasticity is the quality which enables a material to return to its original form or length on being released from a force tending to alter its form or length. For example, a metal bar may be stretched up to a certain limit in a testing machine, and on being released it will return to its original length; a steel spring may be bent by a force, but its elasticity will cause it to spring back and straighten itself when the force is released. The act of springing back is called the *resilience* of the spring.

Elastic limit (or *limit of elasticity*) is the maximum stress which a material can bear without being stretched so much that it cannot return to its original length.

Permanent set.—If a material is stretched beyond its elastic limit, it receives a permanent extension of length which is called "permanent set." A material in this condition is injured and is more liable to "fatigue," which is brittleness caused by vibration or variable stresses, than a material which has not been stretched beyond its elastic limit.

Elongation is the amount of increase in length which a metal can undergo when subjected to a stress sufficient to break it up.

Contraction of area is the amount of reduction of area which takes place at the point of fracture when a metal bar is broken by a tensile stress.

Yield point is the point at which, when testing a metal bar under a tensile stress just exceeding the elastic limit, the bar suddenly and permanently elongates by a considerable amount without any added increase of stress.

Ductility is the quality which enables a metal to hold together without being injured when subjected to squeezing and stretching, as when rolled in a rolling mill or being drawn out into wire.

Malleability is the quality which enables a metal to endure hammering when being forged without being cracked or broken.

Stress Diagram

An automatic diagram can be taken from a testing machine of the tensile stress and the elongation of a bar, up to the point of fracture.

In fig. 18 the percentage elongations are set out on the horizontal line, and the stresses in tons per square inch on the vertical line.

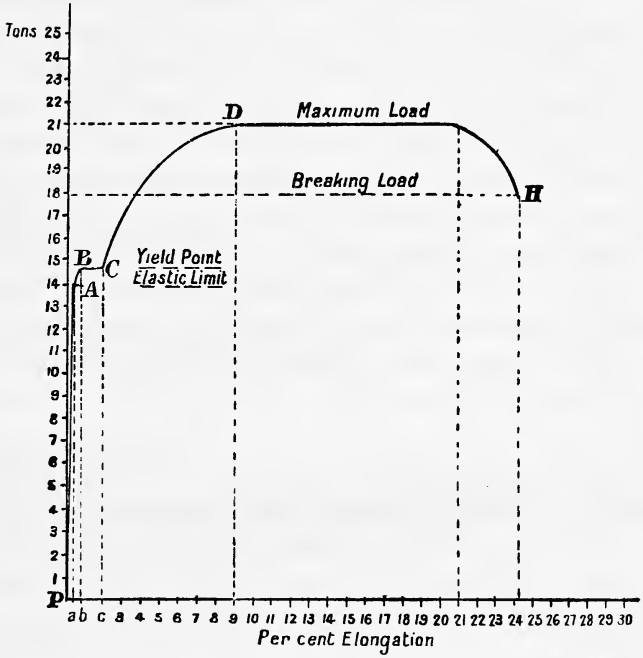

FIG 18. TESTING STEEL STRESS DIAGRAM.

As the stress is gradually applied, the bar slightly elongates until, as shown by the diagram, the load is 14 tons. The point A marks the elastic limit, and the distance Pa is the percentage elongated at that point. Up to this point there has been little elongation, and it has been uniform with the increase of load. Beyond the point A the elongation is not uniform. Between 14 and 14½ tons, from A to B, there is a sudden increase in the elongation, and at B the percentage elongation is represented by Pb.

Pb is more than twice Pa, so the increase of elongation due to the extra load of ½-ton, from 14 to 14½ tons, is more than double the total elongation due to the load of 14 tons.

At the point B, suddenly, without any addition to the load, there is a great increase in the elongation, from B to C. B marks the "yield point." Pc = about 5 × Pa.

At the point C, the elongation ceases, but when a further load, which should be applied gradually, is added, the elongation increases up to the point D, which marks the maximum load (in this case, 21 tons) which the bar will bear. From the point D, the bar goes on elongating, the elongation up to the point D having reduced its sectional area (see fig. 20, page 93), until it finally breaks at H.

The maximum breaking load at H is less than the maximum tensile stress (18 against 21 tons), as, owing to the contraction of area at the point of fracture, a less load is then required to break the bar.

In ordinary commercial testing the yield point is generally taken as the elastic limit, as it is more easily ascertained by the "drop of the beam" of the testing machine. The yield point is not the true elastic limit, but it is very near it.

To find the elastic limit accurately, the points of a pair of dividers should be held in the elongation marks on the bar (elongation marks, see figs. 19 and 20, page 97). When it is seen that a slight elongation takes place, take the load off and see if the marks return to their original distance apart. If they do, slightly increase the load and again release it; and so on, until the load required to cause a very slight permanent set is determined.

TEST-PIECES

The pieces of steel to be tested are of circular or rectangular section; the circular section is preferable, as the contraction in area after fracture can be more exactly measured. For plates and angle bars, however, it is necessary to cut strips of rectangular section.

Fig. 19 shows sketches of a piece cut from a plate, before and after testing.

If the thickness is $\frac{1}{2}$-inch, the width of the parallel portion should be 1 inch; this gives a cross sectional area of $\frac{1}{2}$ square inch.

Before the piece is tested, marks are punched on it 8 inches apart; after fracture the pieces are pressed close together and the distance between the marks measured. The distance in excess of 8 inches is the amount of the elongation; the percentage of elongation can then be calculated. The bar has been elongated from 8 inches to 9·6 inches—that is, an elongation of 20 per cent.

Fig. 20 is a sketch of a test-piece of circular section, before and after testing.

The centre punch marks are to be made within the length which is of the smallest diameter. In this case, the distance between the marks has been extended from 2 inches to 2½ inches—an elongation of 25 per cent.

The length of the parallel portion under test must be

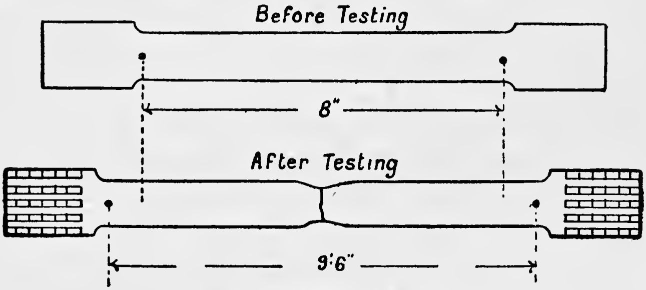

FIG. 19. FLAT TEST PIECE

longer with mild steel than with hard steel. If the length is too short, the natural flow of the metal before rupture will be retarded, and the maximum breaking load will be greater than the true breaking load of a longer test-piece. The parallel portion in pieces of

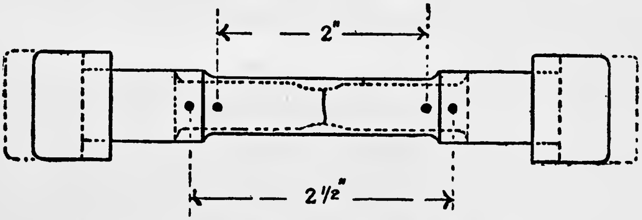

FIG. 20. TEST PIECE. CIRCULAR SECTION.

circular section may be shorter than in those of rectangular section, as the contraction is more regular with a circular section. For hard steel containing not less than 0·6 per cent. of carbon, the length of the parallel portion of the test-piece need not be more than 2 inches.

To Calculate the Tensile Strength of a Test-piece

Divide the load at which it breaks by its original sectional area.

Example.—A test-piece, 0·75-in. diameter, is broken under a load of 15·5 tons, what is its tensile strength?

$$\cdot75 \times \cdot75 \times \cdot7854 = \cdot4417\,;$$

$$\therefore\ \frac{15\cdot5}{\cdot4417} = 35\cdot1 = \text{tensile strength in tons per sq. in.}$$

To simplify the calculations for tensile strength, a test-piece of circular section may be turned of such a diameter that it will be necessary only to multiply the load, which is read off from the beam of the testing machine in lbs., by 2 and divide by 1000 to obtain the result in tons per square inch.

To Find this Diameter

Let x = sectional area in sq. ins.
and y = total load in lbs.;

$$\therefore\ \frac{y}{x} = \text{tensile strength in lbs. per sq. in.}$$

$$\text{and}\ \frac{y}{x \times 2240} = \text{tensile strength in tons per sq. in.}$$

It is required that

$$\frac{y}{x \times 2240} = \frac{2y}{1000}.$$

Then

$$x = \frac{1000}{4480} = \cdot2232 \text{ sq. in.} = \text{sectional area of test-piece.}$$

Let d = required diameter of test-piece,

$$\text{then } d^2 \times \cdot7854 = \cdot2232\,;$$

$$\therefore\ d = \cdot533 \text{ in.}$$

Now, with a test-piece of ·533-inch diameter, if the breaking load is 17,420 lbs., the tensile strength is 34·84 tons per square inch.

Micrometer.—For accuracy the diameter should be measured with an instrument called a "screw micrometer," by means of which the diameter can be ascertained to within $\frac{1}{1000}$ of an inch.

To Find the Percentage Elongation

Example.—Original distance between marks on test-piece = 8 ins.

Distance between marks after breaking test-piece = 9·6 ins.

Difference = 1·6 in.

$$\therefore \text{ Percentage elongation} = \frac{1{\cdot}6 \times 100}{8} = 20.$$

To Find the Percentage Contraction of Area of a Test-piece.

Example.—Diameter of piece before testing = ·533 in.

Diameter of piece when broken = ·34 in.

$$\cdot533 \times \cdot533 \times \cdot7854 = \cdot2232 \text{ sq. in.}$$

$$\cdot34 \times \cdot34 \times \cdot7854 = \cdot0908 \text{ sq. in.}$$

Difference = ·1324 sq. in.

$$\therefore \frac{\cdot1324 \times 100}{\cdot2232} = 59{\cdot}3 = \text{percentage contraction of area.}$$

TEST FOR WELDING AND HOT WORKING

Take two pieces of steel about 1 inch square and weld them together as shown at A B in fig. 21. Punch a

$\frac{5}{8}$-inch hole at C, and while still red-hot, expand the hole with tapered drifts until it is about $2\frac{1}{2}$ inches diameter.

The steel should show no sign of opening at the weld, and the edges of the expanded portion should be smooth and without cracks.

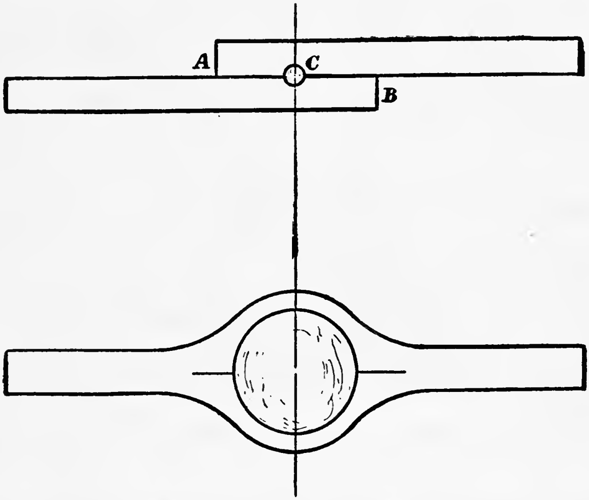

FIG 21. TEST FOR WELDING

COLD BEND TESTS FOR MILD STEEL PLATES

A strip, $1\frac{1}{2}$ inch wide, is cut lengthways or crosswise from a plate, heated to a cherry-red colour, and cooled in water at 82° F.

When cold, the strip is to be bent over a round bar, the diameter of which is three times the thickness of the strip, without showing any cracks.

CHAPTER XIII

HEAT TREATMENT OF STEEL

When steel containing 0·25 per cent. or more of carbon is heated to redness and suddenly cooled, it becomes hard.

The influence which heating to various temperatures has upon steel may be shown by the following experiment:—

Take a bar of tool steel about 1 foot long and ¾-inch diameter and cut notches with a chisel at intervals of 1 inch throughout its length. Heat one end of the bar in such a manner that it will be at a welding heat at that end, and that there shall be diminishing degrees of redness along the bar, until at the other end there is on appearance of redness.

Now quench the bar in cold water, break off pieces at each notch and compare the fractures. The piece which has been heated to a welding heat will have a coarse grain and will be very brittle. The grain becomes finer with each succeeding piece until the fracture is as that of porcelain; the fractures of the two or three pieces which have been heated to lower temperatures will show a slightly coarser grain.

The part which has the finest grain is the strongest *part of the steel bar*, so the object of heat treatment is to obtain the finest possible grain.

If a piece of steel is heated to a welding heat and allowed to cool naturally, it will have a coarse grain and will be brittle; but if the same steel is well hammered or pressed in a forging press when at a welding heat, it will have a fine grain and will be ductile.

HARDENING

There are conditions depending on the temperature of carbon in steel which are called "cement carbon" and "carbon in the hardening state." The carbon passes from the cement to the hardening state by an increase of temperature, and from the hardening state to the cement by a decrease of temperature.

Brinnel, in his experiments with steel containing 0·5 per cent. carbon, found that *on heating* there was a particular temperature at which there was a retardation in the *rate of heating*, and, at this temperature, which he denoted by the letter W, the carbon changed from the cement to the hardening state.

Also, *on cooling* steel which had been heated above W, there was a particular temperature at which there was a retardation in the *rate of cooling*, and, at this temperature, which is denoted by the letter V, the carbon changed back from the hardening state to the cement. The temperature V is about 30° C. less than the temperature W. The temperature W is known as the *critical* temperature.

At the temperature W, the steel, in passing from the cement to the hardening state, becomes of the finest possible grain that can be obtained with that particular steel. It is then in the best condition for hardening, and is hardened by quenching in cold water. If heated above W the grain again becomes coarse, and if quenched at this higher temperature the steel will be brittle.

When hardened at the temperature W, the steel has its maximum hardness combined with its maximum tensile strength. The approximate critical temperatures of steels with various percentages of carbon are :—

Carbon ·1 per cent., 890° C.; Carbon ·45 per cent., 800° C.;
Carbon ·7 per cent., 750° C.; Carbon ·95 per cent., 700° C.

Crystalline Structure

If the fracture of a steel bar be examined under a microscope, it will be seen that the metal is built up of minute crystals. The physical properties of steel vary according to the sizes of the crystals and the relative cohesion between them. The crystals are reduced in size by forging or by rolling.

Forging Temperature

The temperature at which steel is forged and the rate of cooling which follows are considerations of the highest importance. If forged at too high a temperature, the steel will have a coarse crystalline structure causing low elongation and low ratio of yield to breaking load. Theoretically, the forging temperature should not exceed the critical temperature by more than about 50° C. This, however, can hardly be carried out in practice, and good results will be obtained by a forging temperature, for example, which does not exceed 1150° C. for steel with ·45 per cent. carbon. That is to say, the steel may be heated to a bright yellow, but not to a white heat.

NORMALISING AND ANNEALING

The main difference in the above-named heat treatments is that steel is "Normalised" by reheating and rapid cooling in order to remove internal stresses and restore it to a "Normal" unstressed condition, and steel is "Annealed" by reheating and slow cooling in order to soften the metal preparatory to machining.

In both cases, for example, ·35–·55 per cent. carbon steel is reheated to about 850° C., which is slightly above its critical temperature.

Normalising.—This term was originally applied to methods of regulating and equalising the cooling of steel articles of irregular section; tyres, for example, the flanges or thin parts of which would ordinarily cool more rapidly than the thick parts and thus cause severe internal stresses to be set up. The cooling of the massive part is hastened and the cooling of the thin part is retarded, so that the whole article is cooled at a uniform rate.

Normalising is now more generally understood to mean that the material is reheated and then cooled at a rate sufficiently rapid to appreciably raise the yield point, but not so quickly as to cause brittleness or excessive hardness.

Steel is slowly heated to and allowed to soak at the required temperature; it is then removed from the furnace and allowed to cool in the open air, sheltered from rain or snow. The articles under treatment should be kept separate from each other, so that they may be uniformly cooled by the air circulating freely around them.

Steel which is not heated to just above its critical temperature is not normalised. If this temperature is not reached, its state remains unchanged; and if the temperature is greatly exceeded, it will become coarse in grain, brittle and low in yield.

If steel bars have been overheated and rolled at too high a temperature, the tensile test will show low yield and elongation. They may usually be rectified by normalising. If rolled at too low a temperature, an excessively high breaking load and low elongation should be rectified by annealing. If only slightly in excess of the requirements for these tests, rectification is better effected by normalising.

Annealing.—When the steel has been reheated it should be allowed to cool slowly, either in the furnace or by keeping a number of pieces of the material close together during cooling. If the steel is heated for too long a period or if the rate of cooling is too slow, it is liable to be weakened. Prolonged heating induces the growth of large crystals; and the effect of very slow cooling is a segregation of ferrite and pearlite, which causes the steel to be less homogeneous. The best mode of treatment can only be ascertained by experience.

Generally speaking, the process of annealing slightly raises the yield point and considerably increases the elongation.

TEMPERING

The hardening given to steel by quenching in water, at temperature W, is not suitable for all purposes, so the brittleness produced by hardening is reduced by "tempering"; the "temper" being made to suit the particular purpose for which the steel is required. This is effected by heating the steel to a temperature very much below that required for hardening; the steel is then either quenched or allowed to cool naturally.

Tempering reduces the brittleness and hardness, and increases the ductility and elastic limit; the tensile strength is not materially altered.

PRACTICAL TEMPERING OF STEEL

When a steel is stated to be of high, low, or medium "temper," it does not mean that it has been tempered to a high, low, or medium degree of hardness; it means that it is a high, low, or medium carbon steel capable of taking a high, low, or medium degree of hardness.

Thus, 1·5 per cent. carbon steel would be called "high temper" steel, and 0·3 per cent. carbon would be called "low temper."

In tempering, the steel should be first hardened by heating to a dull red heat and quenching in water. The surface is then filed bright and gradually heated by laying it on a piece of red-hot iron, or in any other convenient way. The surface then becomes oxidised and changes in colour as the temperature is raised: the colours in succession are:—

Colour.	Indicating a temperature suitable for tempering :—
Dark blue.	
Light blue	Springs, saws.
Purple	Axes, chisels for cutting iron or steel.
Light brown to dark brown	Taps, drills.
Light straw to straw	Lathe tools, files.

When the colour indicates that the right temperature has been reached, the steel is either quenched or allowed to cool in the air. If the whole of the metal is required to be of the same degree of hardness, it is air cooled; but in the case of cutting tools, only the cutting edge requires tempering. A tool is heated to a dull red at the cutting end; this extreme end only is quenched and filed bright. The end then becomes reheated by heat conducted from the rest of the tool, and when the cutting edge shows the required colour, the whole tool must be quenched.

The degree of hardness given to the steel will depend not only on the temperature to which it is heated, but on the rapidity with which it is cooled by quenching.

Quenching in mercury, cold brine, or cold water, has a greater hardening effect than quenching in hot water, oil, or molten lead.

Quenching in oil.—The effect of quenching in oil is generally to increase the elasticity of steel. Springs and saws, which should be elastic, but which are not required to be very hard, are quenched in oil.

Quenching in lead.—This has practically no effect on mild steel, but it slightly improves the tensile strength, elastic limit, elongation, and contraction of area of very hard steel.

PYROMETERS

For exact determination of the temperatures of reheating furnaces and of steel when reheated for forging or heat treatment, one or other of the following instruments are used :—

Electrical Resistance Pyrometer.—This consists of a coil of platinum or other metal wire inserted in and protected by a tube of porcelain or fused quartz, the closed end of which is exposed to the full heat of the furnace.

The electrical resistivity of pure metals increases regularly with increases of temperature and by connecting the ends of the coil with a suitable instrument accurate temperature measurements up to 1000° C. can be made.

Thermo-Electric Pyrometer.—Two wires of different metals are fused or twisted together at one end, which, protected by a fused quartz tube, is placed in the furnace. The other ends of the wires are connected to a galvanometer which measures the small electric current produced by the heating of the wires.

This instrument gives less accurate temperature measurements than the resistance pyrometer, but it can be used for temperatures up to 1700° C.

Radiation Pyrometer.—This instrument is placed outside the furnace and radiations of heat from the interior or from a billet in the furnace are concentrated by means of a concave mirror on to a "Thermo-Couple" contained in a tube. The current of electricity generated by the heating of the thermo-couple is then measured.

Optical or Photometric Pyrometer.—This instrument, also, is used outside the furnace and its action is based on a comparison of the colour of the light emitted by a heated substance within the furnace with that of a standard incandescent lamp.

A diaphragm in the instrument is rotated until the light received from the hot metal is adjusted to equal intensity with that of a beam of similar light from the lamp.

This form of pyrometer is the most convenient for ascertaining the temperature of a billet as it leaves the furnace and again after forging. It can be manipulated in a few seconds and the temperature is read from a scale on the instrument.

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