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**SIMPLY EXPLAINED**



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# STEEL MANUFACTURE

SIMPLY EXPLAINED /

BY

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WITH A FOREWORD BY

C. K. EVERITT

CHAIRMAN, MESSRS. EDGAR ALLEN & CO. LTD.

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## FOREWORD

THE manufacture of steel is an extremely old industry, so old that you will find a reference to it in Chaucer. My own favourite period in its history is that of Benjamin Huntsman, a clockmaker of Doncaster, who, dissatisfied with the steel with which he was supplied, was the first to produce cast steel by the crucible process. This he perfected in the year 1740. Much steel is still produced at the present time by practically the same method as that used by Huntsman, and for 116 years this process was the only one in use. In 1856 Henry Bessemer brought out his wonderful invention of blowing air through molten pig iron, burning out the carbon, silicon, and manganese, and producing masses of cast steel in minutes instead of hours. Then followed the open-hearth furnaces, introduced by Siemens and Martin in the nineteenth century. We now have the various electric furnace methods of producing cast steel and alloy steels of numberless compositions, and I feel some pleasure in having assisted in the birth of the high frequency electric crucible process as applied to the making of fine steels.

I have been employed in the manufacture of steel for the last fifty-eight years, and still am. During these many years I have frequently come across situations in steel manufacture of which I should have welcomed a simple explanation. Now my young friends, Dr. Edwin Gregory and Eric N. Simons, are explaining in a simple manner the whole manufacture of steel. I hope readers will have

their appetites whetted by this book, and that they will delve deeper still into the study of steel manufacture and seek the explanation of many matters still puzzling steel manufacturers to-day.

C. K. EVERITT

(*Chairman, EDGAR ALLEN & Co., LTD.*)

SHEFFIELD,  
*January, 1940.*

## PREFACE TO THE THIRD EDITION

WAR does not, as is commonly supposed, necessarily intensify metallurgical research. Rather it retards the work that, but for it, might have been done in this direction. Brilliant young men of science or steel are swept into combatant services. Trained, experienced men spend in civilian duties time that would otherwise be devoted to private investigation or to concentration upon absorbing problems of manufacture. Meanwhile, the great new discoveries await their discoverers.

War does, however, intensify the application of discoveries already made, and the third edition of this book, called for by the swift sale of its predecessors, embodies new developments of some importance.

In the first place, the increasing and extending employment of the high frequency electric crucible process has made it necessary to amplify considerably the chapter devoted to it. Many new facts have been given, and a detected inadequacy in the previous account has been remedied, with the result that much greater justice is done to, and much more information given about, this furnace and its economic advantages than in either of the previous editions. The authors have had much help here from Mr. L. F. Keeley, A.Met., of Messrs. Edgar Allen & Co., Ltd., himself responsible for the efficient running of a battery of high frequency furnaces.

The introduction of a method of accurately measuring the temperature of molten steel at various stages in the melting process is bound to exercise great influence on

steel manufacture in the near future, and the authors have felt compelled to introduce a chapter on this invaluable instrument, with illustrations. In its compilation they have been greatly assisted by Mr. T. Land, M.A., to whom their thanks are due.

A few gaps in the chapter "From Ingot to Finished Bar" have been filled, and for the reader's convenience a glossary of the principal terms used in steel making is given in the form of an appendix, so that memory may be refreshed whenever it fails without its being necessary to search through many pages. Many other slight improvements and additions have been made, and some needless repetitions eliminated.

Last, but not least, the English has been still further deflated and improved. The search for better ways of stating a fact never ends, and never should end, for the bridge between the minds of authors and their readers is built of written words. If a word is missing, the reader cannot cross. If there are too many words, he wearies and never arrives. The authors believe that in this respect the book is better than before, and its success, which even their conventional humility is forced to admit, may have partly resulted from this unremitting care for precision, concision, and grace in the writing.

E. GREGORY  
ERIC N. SIMONS

## PREFACE TO THE FIRST EDITION

THE success of *The Structure of Steel—Simply Explained* confirmed the view, expressed in its preface, that in all countries there exists a desire to have the fundamentals of metallurgy explained with as little sacrifice of precision as possible. The demand for that book was world-wide, and soon called for a reprint. At the moment of writing it continues to sell steadily and win favourable comment.

Emboldened by this happy outcome to a dangerous adventure, I propounded to my earnest and eminent collaborator the scheme for a similar book in which the tangled verbiage so often and so widely used to describe the processes of steel manufacture should be carefully disentangled and made both readable and comprehensible. This volume is the result.

I think it can, in all seriousness, be said that our collaboration has been a successful one in that each of us has brought to this book something it would not have had if it had been written by either singly. Though my part has been merely that of midwife to Dr. Gregory's encyclopædic metallurgical knowledge, it has not, I hope, been a needless or obstructive one. Here, we believe, is steel manufacture described in detail and intelligibly. We have tried to make every stage of every process as clear to the layman as to the student and the engineer; to foresee questions and answer them; to explain in simple language the why and wherefore of the most complex and difficult operations. We have not repeated the data comprised in *The Structure of Steel*, but wherever



a reference to that book would facilitate comprehension of a process, we have suggested it. While both works together make a compendium of simplified information on steel, they stand on their own feet, and can be taken separately without fear.

Our thanks are due to Messrs. Edgar Allen & Co., Ltd., Imperial Steel Works, Sheffield, for permission to reprint those portions of this work that first appeared serially in their technical journal, *The Edgar Allen News*, and for the loan of photographs and blocks; to the late Mr. R. G. Woodward, a director of the same firm, for much help and advice; to Messrs. A. Wheeler and G. Blackburn, of Edgar Allen & Co., Ltd., for considerable information on sands and refractories respectively; and to the Park Gate Iron and Steel Co., Ltd., of Rotherham, for valuable data and the loan of blocks and illustrations.

ERIC N. SIMONS

SHEFFIELD, 1940.

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# STEEL MANUFACTURE

## SIMPLY EXPLAINED

### CHAPTER I

#### From Mine to Blast-furnace

ALL steel originates in iron ore. It is true, as will be shown, that certain steels are made by remelting steel scrap and adding alloys; but in essence they derive as truly from the iron ore mines or deposits as do those steels made from pig iron, for the simple reason that the steel scrap itself would not exist if there were at the outset no iron ore.

The ores employed in steel manufacture in the Sheffield district are obtained from mines in Cumberland, the Carnforth district of Lancashire, from Northamptonshire, and other parts of the country. In addition, iron ores are normally imported from foreign parts such as the Bilbao and Santander districts in Spain, North Africa, etc. Practically all these ores are of the "hematite" variety, i.e. when pure they contain two parts of iron combined with three parts of oxygen, and are used chiefly for the production of pig iron in English blast-furnaces and, to a smaller extent, in refining molten steel in the Siemens open-hearth and electric arc furnace processes.

In Sweden, "magnetite" iron ores, as they are called, are smelted in small blast-furnaces for the production of pig iron which, in turn, is converted into Swedish wrought iron. Some of these ores are exceptionally pure, i.e. rich in iron but low in sulphur and phosphorus, and in the past the pig irons and wrought irons produced from them have formed the base materials for the manufacture of the highest quality Sheffield tool steels. It is proposed, therefore, to deal first with the manufacture of pig iron from

these magnetite or magnetic oxide ores. These ores, black in colour, are magnetic, i.e. are attracted by a magnet, and some samples will attract pins and needles towards them: hence arises the name *magnetite*. Very pure specimens of the ore contain three parts of iron combined with four parts of oxygen, but commercial samples are always contaminated by impurities. After being calcined and weathered, which will be explained shortly, the ore has a typical analysis as follows—

Ferric oxide ( $\text{Fe}_2\text{O}_3$ ) . . .	68.04	per cent
Ferrous oxide ( $\text{FeO}$ ) . . .	21.37	„ „
Manganic oxide ( $\text{MnO}$ ) . . .	1.40	„ „
Alumina ( $\text{Al}_2\text{O}_3$ ) . . .	3.42	„ „
Lime ( $\text{CaO}$ ) . . .	0.20	„ „
Magnesia ( $\text{MgO}$ ) . . .	1.18	„ „
Silica ( $\text{SiO}_2$ ) . . .	2.60	„ „
Phosphoric acid ( $\text{P}_2\text{O}_5$ ) . . .	0.01	„ „
Sulphur trioxide ( $\text{SO}_3$ ) . . .	0.01	„ „
Water (combined) . . .	1.77	„ „
<hr/> Metallic iron ( $\text{Fe}$ ) . . .	64.25	„ „

The ore has first to be mined. This is done in the usual manner by shot-firing, i.e. holes are drilled in the rock, high explosive charges inserted in these holes, the explosive fired, and masses of the ore thus detached and broken up. These are transported to the surface and picked over by hand at the mine mouth.

The masses of material dislodged by the shot-firing are not all pure ore. The magnetite is always contaminated by certain foreign substances technically known as *gangue* or *vein stuff*. The larger lumps of ore can be sorted by hand, but the smaller pieces cannot be separated in this way from the worthless material. In consequence, a mechanical process of separation is employed, which is really based on the magnetic property of the magnetite ore. A magnetic separator, consisting of a large electro-magnet excited by an electric current, is used to attract all the ore and so separate it from the useless vein stuff. At the Dannemora mines in Sweden a revolving drum, about 12 ft. 6 in. long by 2 ft. 6 in. diameter and provided with

long, powerful electro-magnets, is constantly revolved. On to it the ore is fed through small *hoppers* (receptacles) set along its length. By force of gravity the mixed ore and vein stuff are then thrown into *bogies* or wagons along the underside of the drum. As the drum rotates, the magnetite is mechanically knocked off into the small bogies on this side. By this means the raw ore is concentrated, i.e. separated from most of the vein stuff.

Magnetite occurs not only in Sweden, but in Norway, Russia, North America, Devonshire, North Wales, Spain, and India. In all these districts it exists in massive veins, but in New Zealand, Java, Iceland, and the Canary Islands it takes the form of iron sands. The problem of using these millions of tons of iron sand has yet to be solved. It seems inevitable that, sooner or later, exhaustion of the world's iron ore supplies at present regarded as suitable for the production of pig iron must take place, in which circumstance these vast natural reserves of iron must then assume extreme economic importance. At the present time, however, they are almost valueless commercially, although they may contain as much as 50 per cent of iron, because they are full of impurities that cannot be eliminated by the ordinary blast-furnace process. The sulphur and phosphorus they contain might be dealt with, but the greatest difficulty is the titanium oxide content, which renders most arduous their smelting in the blast-furnace. In contradistinction to this, the Swedish commercial ores are ideal, being rich in iron, low in sulphur and phosphorus, and easily smelted.

The steel-maker judges an ore, as will be seen, partly by its impurities, notably sulphur and phosphorus, and the history of steel manufacture can be regarded as largely a struggle to reduce the sulphur and phosphorus in the ore or in the finished product. High sulphur is almost always detrimental, and, in fact, fatal, to the properties of most steels of normal manganese contents. High phosphorus in the pig iron can be removed in the basic-



lined furnace, as will be seen when the basic steel-making processes are discussed. The pig-iron manufacturer has also to take into account the richness of the ore in effective metallic iron content.

To return to the magnetite ore: after this has been magnetically separated, it is next *calcined*. It is packed into stoves lined with *firebrick* (brick specially resistant to heat). These bricks are made from *fireclay*, which consists essentially of silica and alumina in various proportions. In the stoves the ore is heated to a yellow heat. In Sweden these stoves are heated by the burning of the waste gases from the blast-furnaces, an economy of considerable importance.

Calcination of the ore is accompanied by a change in the ore texture from its previous hard and dense condition to one less dense and more porous. In addition, calcination lessens the sulphur content of the ore: sulphur existing as iron sulphide is burnt and passes away as sulphur dioxide gas. The reader may ask why it is necessary to render the ore more porous. The answer is that when the time comes to reduce it to metallic iron in the blast-furnace, the carbon monoxide gas (CO), which is the reducing agent employed in the process, is able to penetrate the ore more easily, and reduction is therefore carried out at a greater speed. Calcination does not remove all the sulphur from the ore; some of the sulphur remains in the form of sulphates, and in amounts that may be greater than desired. To reduce the sulphur content of the ore still further, the calcined ore is *weathered*, i.e. stacked in the open in large heaps and thus exposed for some months to the action of rain and melting snow. This washes out certain soluble sulphates.

After calcination and weathering, the ore is ready for smelting into iron in the blast-furnace.

To complete this brief summary it may be mentioned that with certain ores of the non-magnetic variety, e.g. with hematite ores, separation of the ore from the vein

stuff is accomplished by water. This method of separation is based on the difference in specific gravity between the ore and the vein stuff. In some instances, as with certain *calcareous* (chalky) ores containing *carbonaceous* (carbon-containing) matter and with the iron in the form of a carbonate, roasting or calcination is carried out with the object of concentrating them.

## CHAPTER II

### From Iron Ore to Pig Iron

WHEN the magnetite has been calcined and weathered, it must be smelted in the blast-furnace, to reduce it to metallic iron.

To obtain metallic iron from the ore, a suitable flux is necessary. This washes out, as it were, many of the undesirable impurities and produces a scum or *slag* which separates from, and floats on the surface of, the main body of the molten material, i.e. on top of the molten iron. The addition of this flux increases the fusibility of these impurities, and the flux, by combining with them, prevents them from passing into the molten metal below.

In Sweden the flux used is limestone ( $\text{CaCO}_3$ ), which is basic in character. (See Chapter X.)

The fuel used in the Swedish blast-furnace for heating up the furnace charge is charcoal, perhaps the purest of all commercial fuels, being rich in carbon and containing little or no sulphur. In England coke, which contains appreciable quantities of sulphur, is generally used.

Fig. 1 (see page 8) is a diagrammatic sketch of the blast-furnace, which consists essentially of a cylindrical furnace casing lined with refractory firebricks (refractory bricks and materials are those that will withstand the action of great heat).

The blast-furnace operates continuously and is generally run for a period of several years, or until the lining of the furnace "burns out." The solid raw materials, consisting of iron ore, charcoal, and limestone, are fed into the top of the furnace. Swedish blast-furnaces are small,

but the larger furnaces in this country and others may be as high as 100 ft. and capable of producing as much as 500 tons a day.

A blast must be supplied because, so far as the generation of heat is concerned, it is really like blowing a fire with a huge pair of bellows. To generate this air blast, blowing engines, contained in a separate "house," are used, and the air is blown in at points near the bottom of the furnace through a set of *tuyères* or pipes, protected from burning by encasement in metal castings cooled by the passage through them of water, i.e. the *tuyères* are made hollow.

The air blast is first heated in stoves. It was discovered by James Neilson in 1828 that great economy in the fuel required to generate the necessary temperatures resulted if hot, i.e. preheated, air was used for its combustion. In up-to-date blast-furnaces, the air of the blast is also dried to free it from moisture, a procedure that has been found to improve the efficiency of the process. In some modern plants the air is dried by passing it over *silica-gel* spread over trays. Silica-gel is a form of silica with a particularly great affinity for moisture. As it absorbs moisture it gradually loses its efficiency, but its moisture-absorbing properties are completely recovered by heating it to a temperature of about 300° C., so that in practice it is "regenerated" in this way. As the air is denser after being dried, the blowing engine needs to make fewer revolutions, and the power-saving thus effected more than compensates for the additional cost of drying the air. A further economy is effected by using *dust-catchers*, especially when the ore being smelted contains a high proportion of *fines* (very fine particles), since this renders the flues freer from dust accumulation, and less resistance is then offered to the passage of the air and waste gases. An increase in the oxygen percentage of the air of the blast has also been suggested as a means of increasing the heat value of the gas and diminishing

the dimensions of the furnace and stoves by reason of the lessened volume of the air and the lower first temperature.

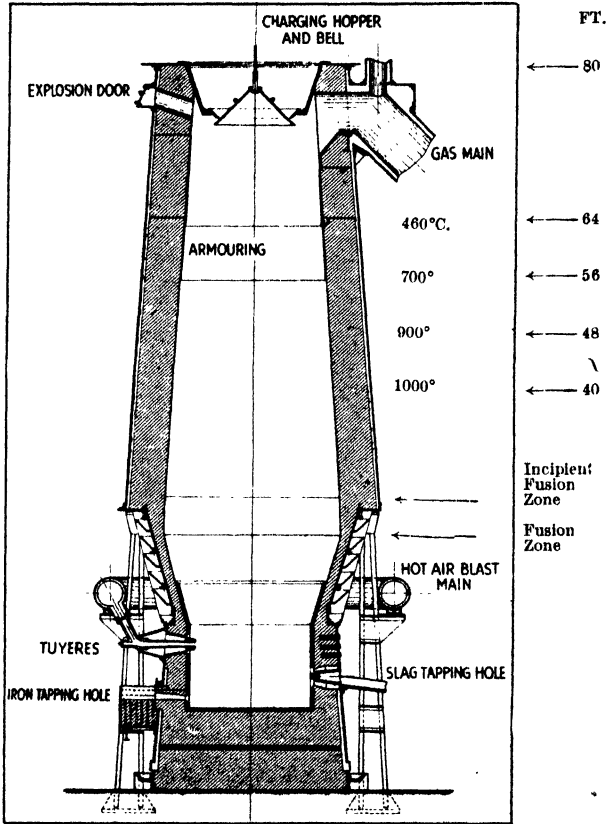


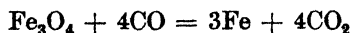
FIG. 1. A DIAGRAM SHOWING THE PARTS OF A MODERN BLAST-FURNACE

By courtesy of The Park Gate Iron & Steel Co., Ltd., and "The Meccano Magazine"

The top of the furnace casing is sealed by a conical bell (see Fig. 1). This bell fits into the lower part of a hopper, an arrangement that permits of the entrance

of the charge, but precludes the escape of gas. The blast of air acts on the fuel of the charge and generates intense heat. The hot gases given off, which are rich in carbon monoxide (CO), pass through the charge and reduce the iron oxide to the metallic state. The reduced iron then melts and falls to the bottom of the furnace, but on its way absorbs carbon and silicon. The vein stuff or earthy matter in the ore combines with the flux (limestone), which has been converted into lime (CaO) by the action of the hot gases, and forms the fusible slag. (A fusible slag is one that easily melts.) This slag also descends to the lower part of the furnace, but floats on the surface of the heavier liquid metallic iron, and can therefore be drawn off or tapped now and again before the metal itself is tapped at a somewhat lower level.

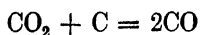
Before the purely mechanical features of the process are further described it is important to know the chemical reactions taking place. What has exactly occurred within the furnace? In rough outline it is this; in the blast-furnace there are (i) iron ore, consisting essentially of iron oxide ( $\text{Fe}_3\text{O}_4$ ), silica ( $\text{SiO}_2$ ), and alumina ( $\text{Al}_2\text{O}_3$ ), (ii) limestone, which generates lime (CaO) and carbon dioxide ( $\text{CO}_2$ ), (iii) charcoal (or coke), consisting essentially of carbon and small proportions of ash, (iv) air, consisting chiefly of oxygen ( $\text{O}_2$ ), and nitrogen ( $\text{N}_2$ ). The oxygen of the air combines with carbon to form carbon monoxide (CO). This substance is a gas which rises in the furnace and acts upon the iron ore, reducing the iron oxide to metal. This operation is represented by the equation—



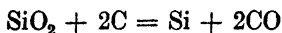
In other words, iron oxide plus carbon monoxide produce metallic iron and carbon dioxide (carbonic acid gas).

In the neighbourhood of the tuyères, carbon dioxide ( $\text{CO}_2$ ) is acted upon by the incandescent fuel and is

converted into carbon monoxide according to the reaction—



A portion of the silica ( $\text{SiO}_2$ ) in the ore is reduced to silicon and passes into the molten iron—



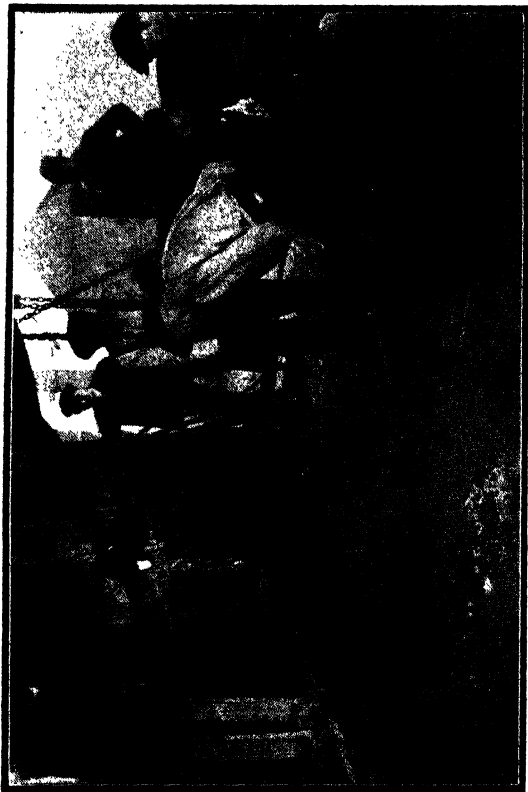
The aluminium oxide or alumina ( $\text{Al}_2\text{O}_3$ ) in the ore fluxes or combines with the lime ( $\text{CaO}$ ) to form part of the slag, as also does the ash of the coke. The limestone itself is first converted into lime ( $\text{CaO}$ ) and carbon dioxide ( $\text{CO}_2$ ). The lime thus formed, as stated, then combines with the silica and alumina of the ore and the ash of the coke to form the fluid slag, which floats on top of the molten iron and is run off through a slag-hole situated near the bottom of the furnace, but at a level above the surface of the molten iron.

The waste gases, consisting of carbon dioxide, nitrogen, carbon monoxide, etc., pass up to the top of the furnace and then along a downtake, whence they go to heat both the ore calciners and the air blast for the furnace itself. An average analysis of the waste gas is 27·5 per cent of carbon monoxide and 11 per cent of carbon dioxide, the rest consisting mainly of nitrogen. It is thus evident that the waste gas still contains a considerable proportion of combustible matter in the form of carbon monoxide ( $\text{CO}$ ), and the combustion of this for the generation of heat is often utilized in the raising of steam and the generation of electricity.

The approximate temperatures at different heights in the blast-furnace are indicated in Fig. 1 (p. 8).

The molten iron is run out through the metal tap-hole. This is situated at the bottom of the furnace, at a lower level than the slag-hole or slag *notch* (see Fig. 2, p. 11).

The iron is allowed to run along a sand channel from which lateral channels branch off. The main channels are



**FIG. 2. PREPARING FOR TAPPING A BLAST-FURNACE**

The molten iron is run into ladles, or cast in the form of pigs  
*By courtesy of The Park Gate Iron & Steel Co., Ltd., and  
"The Meccano Magazine."*

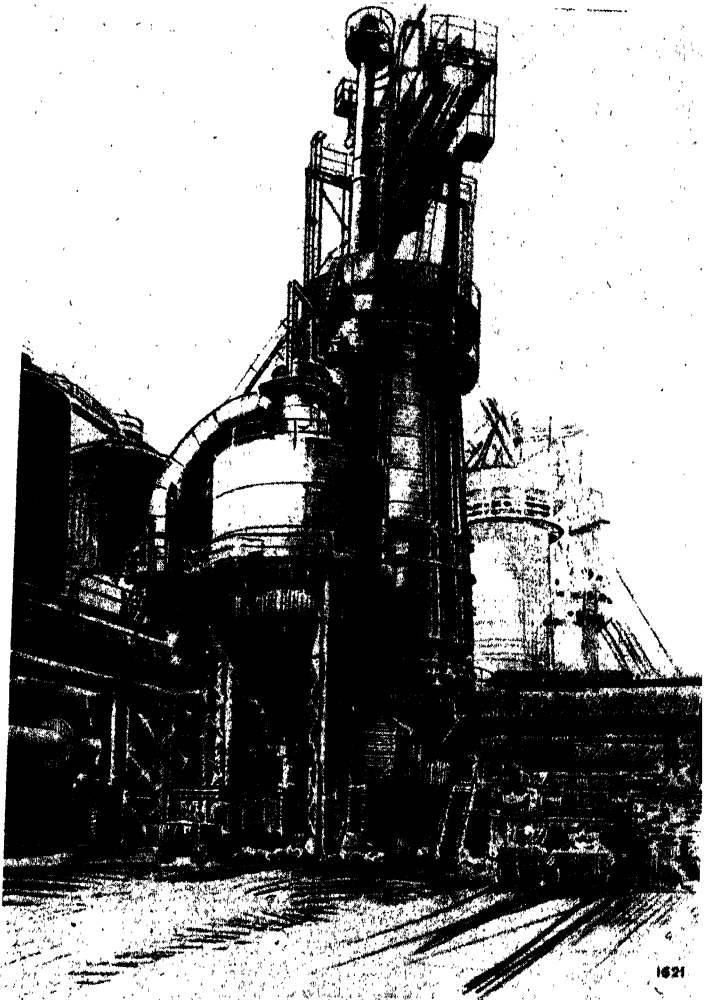




**FIG. 3. SLAGGING AT A BLAST-FURNACE**

The slag is tapped off into ladles that carry it to the plant in which it is made into road-making material

*By courtesy of The Park Gate Iron & Steel Co., Ltd., and "The Meccano Magazine"*



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**FIG. 4. THE BLAST-FURNACE**

*By courtesy of The Park Gate Iron & Steel Co., Ltd., and  
"The Meccano Magazine"*

known as *sows* and the smaller channels fed by them as *pigs*. Hence arises the expression *pig iron*. The metal is broken up when solid but still hot, and transferred to trucks to be used as required.

The iron may sometimes be used directly in the molten condition, in which case it is poured into what is really a large bucket known as a *ladle*, instead of being allowed to solidify in the sand moulds or *pig-beds*. Again, it is sometimes cast into pigs by means of a pig-casting machine, which is an appliance for the continuous casting of pig iron in *iron* moulds, as distinct from sand moulds. In this instance it is first poured into a ladle. The machine itself consists essentially of one endless band, or more than one, rotated by drums, on which the metal moulds are mounted. The iron is run into the moulds from a ladle at one extremity and quickly chilled by water-cooling as the moulds move forward, so that the pigs are sufficiently cold to be loaded into a truck or similar vehicle on reaching the other end. One great disadvantage of pig-casting by machines of this description is that the pigs, owing to chilling, cannot be graded by fracture so easily as when cast in sand beds in the usual way.

What has been achieved at the conclusion of the Swedish blast-furnace process? Magnetite has been converted into crude iron known as pig iron; but this is not pure enough for commercial purposes since it still contains about 5·5 per cent of impurities. The next operation, therefore, brings it to the commercially pure stage, containing about 0·2 to 0·3 per cent of impurities only.

## CHAPTER III

### British Blast-furnace Practice

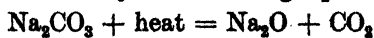
In the first chapter it was mentioned that the ores employed in steel manufacture in the Sheffield district are obtained from mines in Westmorland and Cumberland, the Carnforth district of Lancashire, Northamptonshire, and other parts of the country. So far as the smelting of ores for the production of pig iron is concerned, the Cleveland, Lincolnshire, Leicestershire, Oxfordshire, and South Wales ores might also be mentioned.

In general, the ores used in the manufacture of pig iron in this country may be divided into two classes, according to their phosphorus contents. Practically the whole of the phosphorus in the ore goes into the pig irons produced from them. Generally, low phosphorus ores are of the hematite type, i.e. when pure they contain two atoms of iron and three of oxygen per molecule ( $\text{Fe}_2\text{O}_3$ ). The Cumberland ores are of this type but, unfortunately, supplies of these are not so plentiful as previously. In consequence, hematite ores from Spain and other countries are in normal times imported into Great Britain. In this country, as in most other countries in the world, excepting Sweden, and Mysore in India, coke is used as the fuel in the blast-furnace.

The sulphur content of coke is generally between 1 and 2 per cent, values considerably higher than that of charcoal. Precautions must therefore be taken against the production of pig iron high in sulphur, and this necessitates the addition of a considerable proportion of limestone to the blast-furnace "burden," to eliminate as much sulphur as possible. The amount of limestone required is, of course, to a large extent dependent on the silica ( $\text{SiO}_2$ ) content of the ore. Incidentally, the burden of the blast-furnace is the proportion of the ore to the fuel. A "heavy"

burden means a high proportion of ore to fuel and, conversely, a "light" burden implies a relatively small proportion of ore to fuel. The ratio or proportion of fuel to ore determines the kind and quality of the iron. Strong reducing conditions prevail with a light burden, i.e. a condition is set up that leads to the removal of sulphur by its combination with other elements, and when these are combined with a slag decidedly basic in character, i.e. when the slag is relatively rich in lime, the tendency is to yield irons low in sulphur. In this respect, however, temperature also plays an important part. Thus, a high working temperature inside the blast-furnace, combined with basic slag conditions, produces low sulphur irons: with less limestone and lower temperatures, higher sulphur irons are obtained and these are lower in silicon. Generally, for a given series, the higher the silicon content, the lower the sulphur, although, as indicated, the furnace conditions exert a profound influence on the composition of the iron produced.

At this point, it may, perhaps, be as well to refer to the newly-developed "Brassert" *acid-burdening* process for the production of pig iron. As the name of the process indicates, there is an excess of silica ( $\text{SiO}_2$ ) over and above that required to combine with the lime ( $\text{CaO}$ ) in the charge, so that the slags produced are *siliceous* (silica containing) in character. In consequence, the sulphur content of the iron is relatively high. To reduce it to the desired extent, so that the iron may be suitable for the manufacture of steel, the molten iron is *tapped* (poured) into ladles containing soda-ash (or sodium carbonate— $\text{Na}_2\text{CO}_3$ ). The sodium carbonate is decomposed by the heat, and the liberated oxide of sodium ( $\text{Na}_2\text{O}$ ) removes sulphur from the iron by converting it into sodium sulphide ( $\text{Na}_2\text{S}$ ), as indicated by the following equations—



(in the iron)

Both the sodium sulphide and the oxide of iron thus produced float on the surface of the molten pig iron in the ladle, and are removed by skimming the surface before pouring the iron into the converter or furnace. Preferably, the desulphurized iron is poured into a molten metal mixer, from which the necessary amount is withdrawn at intervals. Treatment with soda-ash or sodium carbonate in this way not only lowers the sulphur content, but also lessens the silicon percentage of the iron.

The Brassert process has been developed largely for the smelting of *lean* (low-iron high-silica) ores of relatively high phosphorus contents. If these were smelted in the ordinary way, large amounts of limestone would be required and an abnormally large volume of slag produced. This process is, in principle, that adopted by Messrs. Stewarts & Lloyds, Ltd., at Corby, for the manufacture of basic Bessemer steel.

Reverting to the hematite irons, it may be remarked that in view of their relatively low phosphorus contents, they are primarily intended for the production of steel in acid-lined open-hearth furnaces, or in Tropenas converters (see Chapter XII), and for the manufacture of ingot moulds. In the smelting of hematite ores, however, as indeed in all other instances, the kind of iron produced depends on the nature of the burden and the slag. Usually, the higher the silicon content, the lower the sulphur. The higher silicon pig irons, when broken, exhibit grey

SEATON CAREW Co.'s IRONS (EAST COAST)

	C.C.	Gr.	Si	S	P	Mn
No. 1 . . .	0.30	3.73	2.50	0.02	0.05	1.00
No. 2 . . .	0.45	3.53	2.25	0.03	0.05	1.00
No. 3 . . .	0.56	3.18	2.00	0.04	0.05	1.00
No. 4 . . .	1.00	2.75	1.50	0.10	0.05	1.00
No. 5 . . .	1.55	2.45	1.00	0.20	0.05	0.75
Mottled . . .	2.05	1.50	0.75	0.25	0.05	0.50
White . . .	3.15	trace	0.65	0.30	0.05	0.50

fractures, whereas the fractures of the low silicon irons are more metallic or whiter in appearance. As far as the English pig irons are concerned, therefore, the grey irons can generally be associated with lower sulphur contents than the white irons. It is on this account that only the grey irons are suitable for the manufacture of steel in acid-lined furnaces. These grey irons are, in turn, graded according to their sulphur contents, as indicated in the table shown on page 17.

The uses to which these irons are put are indicated in the table on page 19, and it should be noted that ingot moulds are manufactured from high-quality hematite pig irons.

The carbonated and hydrated ores found in Lincolnshire, Leicestershire and elsewhere in England, are usually of the phosphoric type, i.e. their phosphorus contents are high, and the pig irons produced from them are only suitable for the manufacture of basic open-hearth or Bessemer steel. The iron contents of most of these ores are low and, in some instances, concentration is brought about by a preliminary roasting or calcination before smelting. This calcination treatment naturally influences production costs, so that in many instances the raw ironstones are charged directly into the blast-furnace. This method is adopted by the Park Gate Iron & Steel Co., Ltd., and other works.

Certain of these ironstones are *self-fluxing*, i.e. they contain almost enough lime to yield a slag of proper composition; others are siliceous in nature so that limestone must be added to the charge.

Typical analyses of ironstones and pig irons are given in the tables on pages 20 and 21.

In addition to the above ores or ironstones, "scale" from the forge, cinder from the puddling and reheating furnaces, sintered pyrites ores, basic slag, and sheet steel scrap, may form part of the blast-furnace charge.

A typical Park Gate charge consists of a mixture of

**HEMATITE PIG IRONS. CUMBERLAND IRONS (WEST COAST)**

	Comb. Carbon	Graphite	Silicon	Sulph.	Phosph.	Mang.	Uses
No. 1 Bessemer	0.5	3.5	2.0-3.0	0.01	0.02-0.05	0.1-0.3	Acid steel manufacture, ingot moulds, annealing boxes, etc.
No. 2 "	0.6	3.3	2.0-2.5	0.02	0.02-0.05	0.1-0.3	
No. 3 "	0.8	3.1	1.5-2.0	0.04	0.02-0.05	0.1-0.3	
Foundry No. 3	0.9	2.8	2.0-2.5	0.05	0.02-0.05	0.1-0.3	Strong castings or for diluting inferior irons, ingot moulds.
Forge No. 4	1.1	2.5	1.5	0.08	0.02-0.05	0.1-0.3	In puddling for the production of superior wrought iron.
Forge No. 5	1.3	2.1	1.2	0.11	0.02-0.05	0.1-0.3	Ornamental castings where little strength is required.
Mottled iron	1.8	1.4	0.7	0.15	0.02-0.05	0.1-0.3	Basic open-hearth steel-making in limited amounts only.
White iron	3.0	trace	0.3	0.20	0.02-0.05	0.1-0.3	



	Good Magnetite (Swedish)	Good Red Hematite (Cumberland)	Calcareous Brown Hematite (Lincolnshire)	Eston Block Ironstone (Cleveland)
Fe <sub>2</sub> O <sub>3</sub> . . .	68.04	74.23	47.14	2.13
FeO . . .	21.37	—	—	37.96
MnO . . .	1.40	0.28	1.72	0.69
Al <sub>2</sub> O <sub>3</sub> . . .	3.42	6.61	4.08	8.82
CaO . . .	0.20	1.02	11.45	5.51
MgO . . .	1.18	0.01	2.97	3.73
SiO <sub>2</sub> . . .	2.60	8.62	11.95	9.11
P <sub>2</sub> O <sub>5</sub> . . .	0.01	0.02	0.87	1.32
SO <sub>2</sub> . . .	0.01	0.02	0.10	(S) 0.056
H <sub>2</sub> O . . .	1.77	8.43	12.40	30.75
CO <sub>2</sub> . . .	—	0.79	6.87	
Metallic iron	64.25	51.96	32.99	30.92
			Fe (calcined)	42.14
			Fe (dry)	33.10

	Sproxton	Glebe
Fe . . .	30	23
SiO <sub>2</sub> . . .	12	10
CaO . . .	1	17
H <sub>2</sub> O . . .	21	14

siliceous ironstone of the Sproxton type, calcareous (lime-bearing) ore such as Glebe, sintered ore, sheet steel scrap, magnesian limestone and coke. In view of the very mixed nature of the burden, it will be appreciated that the blending of the various materials calls for no little skill in order to produce pig iron of the requisite composition. The irons produced from these low-grade ores are essentially phosphoric in character and the following composition may be regarded as typical—

Total Carbon . . . . .	3.00 per cent
Silicon . . . . .	1.25 " "
Phosphorus . . . . .	1.50 " "
Sulphur . . . . .	0.05 " "
Manganese . . . . .	1.20 " "

Analyses of irons produced by Messrs. Bolckow, Vaughan & Co., Ltd., are as follows—

CLEVELAND PIG IRON (BOLCKOW, VAUGHAN & Co.)

	C.C.	Gr.	Si	S	P	Mn
No. 1 . . . . .	0.10	3.50	3.42	0.034	1.50	0.67
4-5 per cent Si . . . . .	0.03	3.10	4.0-5.0	0.040	1.50	0.72
No. 3 . . . . .	0.15	3.45	2.5-3.0	0.050	1.50	0.62
No. 4 Foundry . . . . .	0.25	3.41	2.38	0.080	1.50	0.55
No. 4 Forge . . . . .	0.32	3.25	1.84	0.120	1.50	0.61
Mottled . . . . .	1.60	1.60	1.32	0.230	1.50	0.59
White . . . . .	3.20	trace	0.46	0.520	1.50	0.54

Irons of the above types are described as *basic* pig irons, since they can only be converted into steel in basic-lined Bessemer or Siemens open-hearth processes. The manufacture of steel by these processes will be fully described later.

## CHAPTER IV

### From Pig to Iron Bar

As this outline progresses it will become clear that a simple continuous account of steel manufacture is impossible. Steel is produced by several different processes, used for making different kinds and forms of the alloys called *steel*. Each of these processes will, therefore, have to be described. For example, the steel castings manufacturer often depends entirely on the blast-furnace product, pig iron, as his raw material, whereas the tool steel industry requires raw materials considerably more refined than ordinary pig iron.

Since the processes comprised in tool steel manufacture are probably more numerous than in the production of any other type of steel, it may be as well to continue the story from the pig to the tool steel bar. This ground having once been covered, it will then be possible to return and consider divergent or parallel processes such as are used in the manufacture of constructional steels, stainless steels, steel castings, steel ingots, etc.

In an earlier chapter it was pointed out that pig iron contains between 5 and 6 per cent of impurities. The first step towards the manufacture of fine-quality tool steels is to bring down the impurity percentage in the iron to something less than 0.3 per cent. There are several ways by which this may be achieved. Perhaps the oldest is the Walloon process, still largely practised in Sweden, into which country it was introduced some 250 years ago by a Dutchman (to-day he would be called a Belgian or Fleming, since he came from Flanders), who took along with him a number of Walloon iron-makers. These men became permanently established in Sweden, and it is said that even to-day their descendants are recognizable by

their dark hair and complexions in contrast to the natural blonde complexions of those of pure Swedish descent.

The Walloon process is, at first sight, extremely crude. It must, however, be judged by results, and it cannot be denied that it has produced wrought iron of quality inferior to none.

The basis of the method is a furnace having a rectangular hearth, constructed of unlined cast-iron plates cooled by water, furnished with a single open pipe or tuyère through which a blast of air enters. The furnace is heated by the combustion of charcoal, and the pig iron is introduced at its rear end. On the ground level, outside the furnace, is a series of wooden rollers, and on these rollers is placed a long D-shaped cake of pig iron. These pigs are specially cast to shape and weigh about a ton. They are run forward by levers until the ends protrude above the hot region of the furnace where the blast of air meets the charcoal. Their ends then melt drop by drop above the fire, being moved forward as they liquefy until a sufficient quantity has melted and reached the bottom of the hearth to produce a lump weighing between 70 and 90 lb., consisting mainly of "spongy" iron. This mass is continually worked up into the region of the blast by means of an iron bar. This is hot and trying work, and the only garments worn are a long gown and wooden "sabots" or sandals, with thick woollen stockings to protect the legs. When the worker's "touch," acquired only after long experience, tells him that the iron has been purified to the required degree, the mass is seized with tongs, broken up, and then raised above the tuyère so as to bring it up to a welding heat. It is next removed from the furnace by means of the tongs, and fashioned into a bloom under a water-driven hammer or *helve*. Throughout the whole sequence of operations in the Walloon process, the temperature is so low that the iron is never completely fluid, but is at the most in a pasty condition.

When ready, the bloom is reheated to about half its length and shaped again under the hammer into a bar about  $\frac{1}{2}$  in. thick by 3 in. broad. The other half is similarly treated, and the result is Swedish bar iron containing 99.7 to 99.8 per cent of pure iron. This is the material exported to Sheffield for conversion into steel for tools. It has, indeed, for many years constituted the raw or basis material for the manufacture of tool steels of the highest grade. This material is *wrought* (worked) iron, sometimes described as *malleable iron*. It is low in carbon, and because of its pastiness during the process of manufacture, is liable to contain varying percentages of slag or dross. The carbon content is usually below 0.15 per cent, and that of the other constituents, not reckoning the slag, below 0.25 per cent.

Another process, known as the Swedish Lancashire process, is also worked in Sweden for the manufacture of wrought iron. The essential difference between this and the Walloon method is in the working temperatures. In the Walloon process the operations are carried on throughout at the lowest possible temperatures, while in the Swedish Lancashire process higher temperatures prevail. For instance, in the latter the blast is preheated and there are two or more tuyères in each furnace. So far as the ordinary constituents are concerned, i.e. carbon, silicon, manganese, sulphur, and phosphorus, there may be very little difference between the wrought irons made by the two processes, but Walloon irons have always been regarded as of superior quality. This is generally considered to be the result of their lower oxygen contents, a consequence of the relatively low temperatures involved during working. The irons produced by both processes have been, and still are, used as the basis for the manufacture of high-grade tool steels. In the past (but to-day to a limited extent only), the next stage was the conversion of the wrought iron into what is known as *blister steel*.

In some respects the above processes bear some resemblance to the English *puddling* process, i.e. the impurities are oxidized from melted pig iron in order to produce wrought iron. In the puddling process, however, the furnace is of the *reverberatory* type and the oxidation is effected mainly by oxides of iron present in the furnace hearth, and oxides added to the molten pig iron. A reverberatory furnace is one whose charge is not directly heated by fuel, but by gaseous combustion products—i.e. the flame—no blast being used. As the pig iron becomes purified, its melting-point rises and the purified iron is pasty at the end of the process, so that when it is afterwards hammered into bars, these bars contain streaks of involved slag. It is these slag streaks that distinguish genuine *wrought iron* from *mild* or *low carbon steel*. English puddled iron cannot be used for the production of tool steels, mainly because the phosphorus content is generally above 0.1 per cent. Large quantities of puddled iron are, however, used for links and pins in colliery haulage work.

## CHAPTER V

### From Bar Iron to Blister Steel

THE bar iron made by the processes described in the preceding chapter arrives in the steel works, and, as a preliminary in its long and complicated journey from iron bar to steel tool, is first transformed into what is technically known as *blister steel*. This is achieved by a process called *cementation*.

The purpose of cementation is to introduce a pre-determined amount of carbon into the bar iron. The general consensus of opinion is that the maximum percentage of carbon that can be introduced by this method is 2 per cent. (The process could almost be termed dry carburizing, since the steel never goes beyond a yellow heat—1100° C.—at which it is in a plastic condition. But as carburization is not being dealt with, the authors will not pause here to amplify this comment.) Those who have read *The Structure of Steel*\* will realize that the introduction of this amount of carbon into iron produces those mechanical and physical properties that differentiate steel from iron. Others are referred to that work for the detailed explanation. Here the authors are concerned only with how the introduction is brought about, but a brief explanatory note on what occurs will be appended.

The process is carried out in firestone or earthenware chests or chambers, sometimes called *converting pots*. There are two of these chests to each cementation furnace, and the conical tops of these furnaces, shown in Fig. 5, were once a familiar sight in Sheffield, the home of the process.

In the chests the bars, measuring 2½ in. to 3 in. wide,

\* *The Structure of Steel—Simply Explained*, by Eric N. Simons and Edwin Gregory. Blackie & Son, Ltd., Second Edition, 1943. 5s. net.

$\frac{1}{4}$  in. to  $\frac{3}{4}$  in. thick, and about 12 ft. long, are packed in layers, each layer being separated from the next by a layer of charcoal. The size of the chests is governed, of course, by the size of the furnace. Some furnaces are large enough to deal with as much as 50 tons at a time, i.e. 25 tons in each chest.

To ensure the success of the process, air must be carefully excluded from the chests, and for this purpose



FIG. 5. CEMENTATION FURNACES

*wheel-swarfe* is smeared over the top of the arches of each chest. These arches are about 6 in. thick.

Wheel-swarfe is a mixture of siliceous (containing silica) particles and partly steel dust, obtained as a rule from the residue in a grinder's shop after the grinding of cutlery, being a mixture of the grindstone dust and the steel dust. It is argued that when the furnace is heated, the silica of the wheel-swarfe contracts and cracks as a result. The steel particles, however, rapidly oxidize and expand. The two phenomena thus compensate each other, and produce a completely airtight and non-contractible cover.

As against this purely conjectural explanation, it is sometimes held that the two substances form a fusible silicate



of iron, which partly melts and becomes pasty, thus providing a semi-plastic airtight covering.

The furnace does not reach its maximum temperature until from three to four days have passed. It is then kept at this temperature from seven to eight days for mild carbon heats, about nine and a half days for medium carbon heats, and about eleven days for high carbon heats. These comparisons relate to the amount of carbon it is sought to introduce, the longest period corresponding to the highest carbon percentage, within the limit of 2 per cent already mentioned. The cooling down requires from four to six days.

Naturally, the steel-maker needs to know from time to time how things are going on inside the furnace. He cannot afford to waste weeks of work. For this reason he provides special little openings in the chests through which trial bars may be drawn for examination.

When the furnace has cooled down, the bars are withdrawn. A man, known as the *bar sorter*, *ends* the bars (knocks off the ends with a hand hammer), so that by examination of the fractured surface he can ascertain the percentage of carbon they contain. (This "ending" process will be met with again when the manufacture of the tool steels is described.)

How does the bar sorter, by merely looking at a fractured surface, know the carbon percentage? The answer is—by experience. However unscientific the method may appear, it has actually been tested and proved to be of amazing accuracy, and is analogous to the experience that enables skilled steel hardeners to determine furnace temperatures by the eye alone, again with extraordinary, if not perfect, accuracy.

When it was first stacked in the cementation furnace, the wrought iron was so soft that it could be bent double without breaking, but on its emergence a single tap with an ordinary hand hammer is enough to break it. As a result of cementation it has become quite brittle.

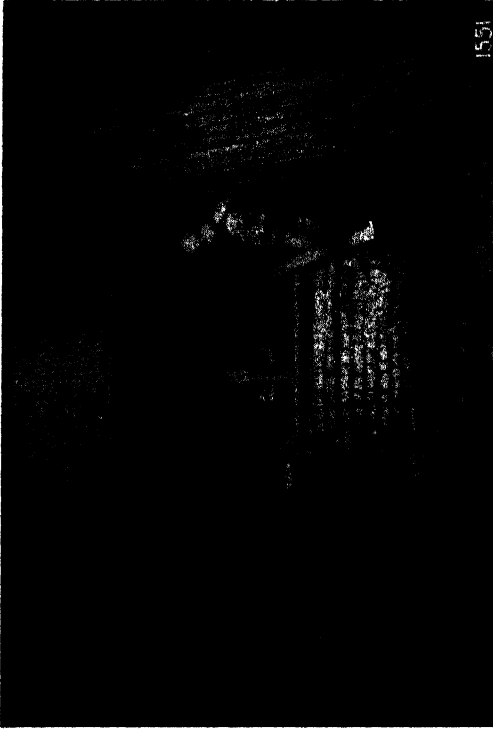


FIG. 6. INTERIOR OF CEMENTATION FURNACE

There is another striking difference. Whereas the iron bars originally had smooth surfaces, they are now covered with small blisters, whence arises the term *blister steel*.

These blisters are due to a reaction between the included slag and the carbon. The bar iron inevitably contains small particles of slag. These consist mainly of iron oxide. When the carbon comes in contact with these particles—which only happens when the iron is hot enough and therefore soft—it reduces the oxide to metallic iron. The oxygen is given off as a gas, carbon monoxide (CO), and this, pushing its way to the surface of the soft iron, causes it to expand, raising blisters on the bars, just as they form on the white of an egg that is being fried.

These blisters are generally accepted as an indication of quality, showing that the blister steel bar has been made from Swedish wrought iron. Imitations have often been attempted by unscrupulous persons anxious to profit by the high price this steel commanded in the market, and in one instance an American manufacturer designed rolls to *roll* the blisters on inferior material. He “got away with it” for a brief period, but the fraud was quickly detected.

What has actually taken place in the iron bars during the cementation process? Briefly this: the bars are packed in charcoal, and when they are at a yellow heat the carbon in some manner actually penetrates into the iron bars. In all probability, carbon is absorbed by the outer layers, then diffuses or flows into the interior of the bars, more carbon is then absorbed by the surface layers, and this process may be indefinitely repeated.

The depth of penetration, as previously explained, depends upon the length of time during which the process is continued. It may be of interest to describe as nearly as possible in the absence of actual specimens the exact appearance presented by the fractured surfaces examined for carbon content by the bar sorter. The carbon penetrates from the exterior towards the interior of the bar,

so that if the steel is *mild*, i.e. cemented for the minimum period, it will have a core of uncarburized material. This core presents a dull appearance, and its fractured surface does not reflect the light in the same way as the fully carburized material. The hardened or cemented portion round it has, on the contrary, a bright or "staring" appearance. It is by the relative extent of these two surfaces that the bar sorter is able to determine the average carbon content. Good quality blister steel never shows too sharp a division between the hardened case and softer core, as this is liable to cause trouble. This, however, can be discussed at a later stage.

The next stage is the conversion of this comparatively crude blister bar steel into a higher grade of material known as *shear steel*.

## CHAPTER VI

### From Blister Bar to Shear Steel

THE steel bars produced by the cementation process are, as has been said,  $2\frac{1}{2}$  in. to 3 in. wide,  $\frac{5}{8}$  in. to  $\frac{3}{4}$  in. thick, and about 12 ft. long. They are brittle, easily broken by a blow from a hammer, and covered with blisters. They have now to be converted into shear steel.

Many years ago—about A.D. 1750, and probably even earlier—the Yorkshire cloth industry gave this new term to the steel trade. The cloth cutters, particularly those in the Leeds district, were in the habit of using one special type of steel for the shears with which they cut the cloth. No other steel was tolerated, and therefore the material came to be generally known as shear steel. There were two distinct qualities of this material, *single shear* and *double shear*.

To-day, nearly two hundred years later, the same names are still in current use, and describe the steel whose manufacture is dealt with in this chapter. How the terms “double” and “single” originated will be seen as this account proceeds.

The first stage in the process of making these steels is to break up the blister bar into lengths or pieces about 18 in. to 20 in. long. These are heated up to an orange heat ( $900^{\circ}$  C.), and subjected to a preliminary hammering under a power-driven hammer. The object of this is to flatten out the blisters and make the brittle blister steel tough enough to withstand the severe operations that follow.

These hammered lengths are known as *plated bar*, and the steel of which they are composed is comparatively tough and smooth. The reason why forging causes brittle steel to become tougher will be given later, but for the

moment this description will be confined to the actual processes.

A number of these plated bars, ranging from five to seven, are placed in a steel clip with a handle, and a wedge is driven in to keep them tightly packed, as shown in Fig. 7. This operation is called *piling together*. The *piled* bars are then heated to a welding heat ( $1200/1300^{\circ}\text{C}.$ ), i.e. a heat at which two pieces of steel can be welded

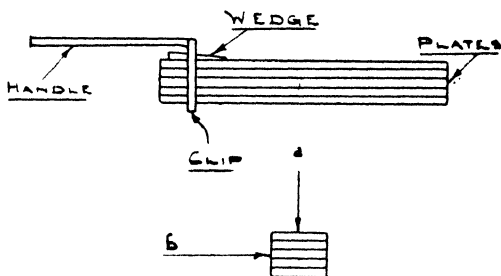


FIG. 7

firmly together by the application of pressure, and are covered with a flux, in order to prevent the heat from causing any loss of carbon. There are many of these fluxes, but possibly the best are sand and fluorspar.

The bars are next hammered at a white heat ( $1200^{\circ}\text{C}.$ ) and welded together. The result is a *faggot* or *bloom*, not quite square in section, as shown in Fig. 7. The reason these blooms are rectangular rather than square is that by this means the smith is readily able to discover the line of the weld. Why this is important will be seen. If the forging hammer strikes in the direction of the arrow *a*, the welded pieces will be pressed more tightly together, and the welds will therefore be stronger. On the other hand, if the hammer were to strike in the direction of arrow *b*, as it might if there were no quick guide to the welding line, there would be a grave risk of opening the welds.

This bloom is now one of single shear steel, and is ready for cutting down to any required size. Only a single welding and forging operation has been carried out on the piled bars, whence arises the term *single shear*.

To make *double shear*, a second operation is necessary. The bloom is first nicked in the middle, and bent or folded back upon itself by mechanical means. It is then hammered down to its original size, so that although the bloom is exactly the same as it was before in shape, size, and weight, it has had double the work put into it, and is consequently more uniform in structure and of better quality. Hence the name *double shear*.

This bloom is then rolled into the desired shape, exactly as with single shear steel. It is then the purest steel known to the commercial world, and has unique properties. Its makers rightly claim that steel made by no other process equals it in quality.

For cutlery it is probably the finest steel in the world, having never been surpassed so far as cutting properties are concerned. This does not imply that the modern stainless cutlery steels do not possess excellent cutting properties; they do, and for most purposes the slightly better cutting properties of double shear steel are countered by the labour-saving properties of knives, etc., made from stainless steel. Even so, however, for a really keen cutting edge readily sharpened there is nothing better than shear steel. Messrs. Edgar Allen & Co., Ltd., are one of the few original shear steel-makers left who carry on this old-time process.

The reason for the old and oft-repeated contention that stainless steel knives will not cut is that, because the knife is stainless, users often never trouble to sharpen it. Actually, stainless knives are sharper than most ordinary steel knives *if* given a keen edge and if that edge is carefully maintained by sharpening. The steel knife is cleaned and sharpened by passing it through the knife-grinder. The

stainless knife is washed and nothing more. In the earliest days some stainless knives were soft because wrongly treated by cutlers with no experience of the new material. That is all over, and to-day the Sheffield-made stainless steel knife is as sharp, sharpenable, and sound a domestic tool as there is in the world, with the one exception already mentioned. The moral is: *sharpen the stainless knife as often as the ordinary knife, and it will last longer and prove as sharp.*

Shear steel was the first steel to be made from blister bar, and the process by which it was manufactured was known and used in Sheffield hundreds of years before molten steel was thought of.

It would need a separate monograph to explain exactly how hammering transforms a brittle steel into one of tougher character. A brief explanation only will be attempted here, and should be read in conjunction with *The Structure of Steel*. The effect of hammering on a sufficiently heated metal is quite different from that of rolling or pressing, because the blow is sudden. The force is applied to the steel for a very brief period, and before the structure of the material has completely broken down under it the pressure is removed. As the metal, is to some degree, elastic, it partly, but not wholly, recovers. In large masses the effect is therefore confined, as a rule, to the surface of the steel, leaving the centre relatively unaffected. Thus, the more the steel is forged, the greater is the effect on the structure and the improvement in the quality of the steel. This is why double shear is superior to single shear steel.

It has still to be shown what causes the improvement. For this it is necessary to understand what is meant by *flow lines*. The mechanical hot working of steel (and, of course, of other metals) causes certain of the grains or crystals of which it is composed to elongate in the direction of the working. These crystals are, as it were, rearranged by force, and the steel flows along the desired paths. If



the structure of the steel is macroscopically examined, a section will reveal lines running in the direction along which the metal flowed as a result of the pressure. As a result of this flow the steel acquires a *grain* or direction of fibres such as is found in wood. In rolled steel the similarity between its macrostructure and the grain of wood is at once evident. Like wood, steel is stronger when tested across the grain than with it. When a steel is forged under the hammer its grain is more confused and less laminated, so that its properties are more uniform in all directions.

If one imagines a sudden cavalry charge on a fairly tightly packed crowd in a square, it will be seen that the crowd will give way before the onrush, and flow in the directions in which flow is possible. If, among the crowd, are certain individuals dressed in vivid scarlet or some other distinctive and readily visible colour, it will be possible for an aerial observer to ascertain by watching these in what directions the crowd is flowing or has flowed. They will represent the flow lines.

The physical characteristics of a steel are governed to a large extent by its structure. Forging breaks down by force the coarser, i.e. larger, crystals, and so produces a more uniform structure. It reduces the section or size of the piece, and brings about a refinement carrying with it improved mechanical properties. This improvement is mainly a greater toughness.

There has to be borne in mind the singular phenomenon that the ductility and resistance to shock of a hot-worked steel will vary according to whether the shock and other stresses are applied in the direction of the flow lines, i.e. parallel to them, or perpendicular to them. The resistance to shock and ductility will be greater in the one instance than in the other.

Thus, steel of relatively coarse type, such as blister bar, is not only improved and toughened by forging, but the amount of forging is also important, while any part made

from a forged steel should be so designed that the stresses fall principally at right angles or perpendicular to the lines of flow.

The reader desirous of pursuing the matter further will find much of interest and value in the sections on forging, etc., in *The Mechanical Working of Steel* by the same authors. (Pitman.)

## CHAPTER VII

### The Manufacture of Steel by the Huntsman Crucible Process

THE process of making double and single shear steel described in the previous chapter was employed for centuries by steel manufacturers, and it was not until 1740 or thereabouts that a revolutionary process was introduced, and *cast tool steel* became known. The process was invented by a Doncaster clockmaker named Benjamin Huntsman. He used shear steel for making clock and watch springs, and owing partly to the trouble caused him by the inevitable weld marks, and partly to the fluctuating quality of the steel itself, he set to work to produce a steel more uniform and suitable for his needs. (The reader should note the distinction between *cast steel* and steel castings (see Chapter XX). It is often not realized that crucible and high frequency furnace products are known as cast steel, although they are forged and rolled into sections for tools, etc.)

There is no need to repeat the familiar romantic legends that have sprung up concerning his discovery. Here we are concerned with the process itself. Huntsman's method was to take the ordinary blister bar, break it up into small pieces, and melt it in a closed clay crucible by means of a coke fire, which was built around the pot. When this had been done, the molten steel was poured into an ingot mould of internal section about 3 in. square, the resulting ingot having a weight of about 56 lb. He next broke this ingot into pieces and melted it up again, producing in this way the celebrated Huntsman steel.

Although the remelting part of the process is now seldom employed, Huntsman had quite good reasons for using it. If 50 lb. or 60 lb. of blister bar are simply melted in a crucible, skimmed, and poured into an iron

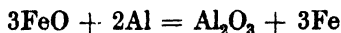
mould, the steel, being *fiery* (over-oxidized)—so that it spits and sparks as a result of the violent escape of gases while the metal is in a pasty condition—will boil up in the mould and form on the top of the ingot what is technically known as a *bonnet* (an overflow “solidified” of worthless, because spongy, material). But an ingot so made would have no commercial value, as it would, on examination, be found riddled with *blowholes* (gas-containing cavities). It is not enough, then, merely to melt and *teem* or pour the steel into the ingot mould. Its fieriness must be removed, which is called *killing* it. Killing steel means preventing the release of gases when the molten metal actually solidifies. These gases are chiefly carbon monoxide together with a little nitrogen and hydrogen. If present they are liberated during solidification and form blowholes or gas bubbles in the ingot.

Blowholes may be of two kinds: (a) *subcutaneous* and (b) *internal*. Subcutaneous blowholes, as the name implies, are found just beneath the skin and are often coloured blue or violet, like the temper colours found on the surfaces of hardened steel that has been reheated, i.e. tempered. The colours are due to very thin films of iron oxide. Internal blowholes are found in the interiors of unkilld ingots and are silvery-white in colour. They may *weld up* (close up and disappear) when the ingot is reheated and forged or rolled, but the oxidized subcutaneous or *skin* blowholes are almost invariably drawn out into long *seams* or *rokes*, which are the equivalent of surface cracks. In high quality steels, such as those used for tools, the steel should be fully killed, i.e. free from blowholes of either description.

There are several ways of killing steel. One of the methods, perhaps the most remarkable of all, is the addition in the ingot mould before teeming of about 0.02 per cent of metallic aluminium (Al) to the melt. When the finished ingot is analysed, barely a trace of this metal is found in the analysis, but the ingot itself is free from

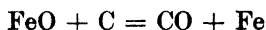
blowholes. There are few phenomena in steel manufacture more remarkable than this. There must also be a fair percentage of manganese, itself a strong deoxidizer in the steel, for this method to be fully effective.

The chemical reaction that occurs as a result of the introduction of aluminium can be represented by the following formula—



In other words, the oxide of iron in the steel is converted into alumina ( $\text{Al}_2\text{O}_3$ ) and iron.

If oxide of iron ( $\text{FeO}$ ) is present in the steel during its solidification, then the following chemical reaction occurs—



This means that putting carbon and iron oxide together produces a gas, carbon monoxide, and pure iron, separately.

This liberated carbon monoxide ( $\text{CO}$ ) gas is the main cause of the blowholes. Alumina ( $\text{Al}_2\text{O}_3$ ), on the other hand, does not react with the carbon in the steel, and so the addition of the aluminium prevents in a simple and effective way the formation of blowholes.

Other killing agents or deoxidizers are ferro-manganese, ferro-silicon, and ferro-titanium.

It must not be assumed that a killed steel will produce a sound ingot without more ado. There is a defect, almost as serious in the ingot as blowholes, known as *pipe*, beginning at the top and sometimes running right through the centre of the ingot almost from top to bottom.

Pipe is an internal cavity of longitudinal direction. It is a natural consequence of the contraction of molten steel as it solidifies. The exterior of the ingot, which is in contact with the much cooler walls of the mould, is necessarily lower in temperature than the interior, and in consequence solidification begins from the outside and proceeds inwards. The outside layers thus contract first, so that the level of the molten steel in the

interior drops as the metal flows outwards to take up the space freed by the contraction. The next layers then solidify, the level of the molten steel drops again, and this process continues until the level of the liquid steel in the centre on final freezing, or solidification, is considerably below the original level. A contraction cavity or pipe is thus formed down the middle of the ingot.

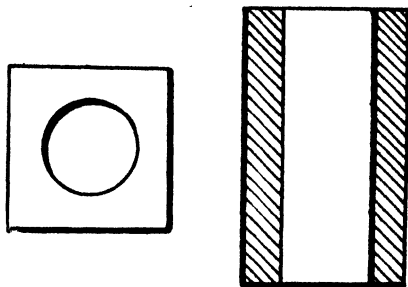


FIG. 8

Piped ingots are almost useless. They could only be used at all by scrapping the upper portion through which the pipe runs and using only the lower. This would be commercially unprofitable. The steel manufacturer's problem is, therefore, to fill up this gap. Fortunately, a simple method of doing this has been invented.

Some little time before the molten steel in the crucible is teemed into the ingot mould, a square fireclay *dozzle*\* with a cylindrical hole running vertically through it is placed in the flue of the *melting hole* (the hole in which the crucible or *pot* is placed for heating). The dozzle is shown in Fig. 8 in vertical section and in plan. In the flue it is heated to a white heat just before teeming. Then, when all but a few pounds of the molten steel has been poured into the mould, a worker extracts the white-hot dozzle from the flue with tongs, and sets it on the top of the mould, above the steel. The teemer fills the dozzle's cylindrical interior up to the top

\* Sometimes described as a *core*.

with the last remains of the steel in the crucible, so that on the top of the actual ingot is a little cap or cylinder of molten steel enclosed in glowing fireclay, which is a bad conductor of heat, and so prevents premature solidification of the steel in the dozzle.

Because of this low heat conductivity, the steel in the dozzle remains fluid for a considerable time, and as fast as contraction of the steel in the ingot mould below causes a cavity to form at the centre of the ingot, liquid steel from within the dozzle slips down to fill it up. At the finish of the operation, there is merely a hollow shell of steel

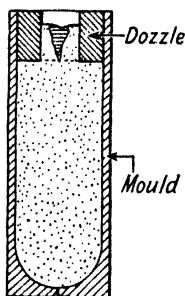


FIG. 8A

in the narrow neck formed by the dozzle, and the pipe, if present at all, goes only a negligible way into the ingot top.

For further notes on the manufacture of steel ingots, the reader is referred to Chapter XIX.

It should be pointed out that the process as originated by Huntsman has undergone important modifications. The Americans employ wrought iron (and sometimes even basic open-hearth steel)

in contact with charcoal, in preference to the blister bar used in Europe, and claim a quality as high, though this is disputed. The English steel-maker relies mainly, although not entirely, on clay crucibles, whereas on the Continent graphite crucibles are favoured, as in the United States.

The steel produced by this method was a definite improvement from Huntsman's point of view, though it has always been an open question whether crucible cast steel is in actual fact better in quality than genuine double shear steel. But the crucible process made it possible not only to produce in larger quantities, and at less cost, fine quality carbon tool steels; but also enabled the steel-maker nearly two hundred years later to produce high-speed and other alloy tool steels, the ingredients of

which are all carefully weighed before being melted in the crucible. The crucible itself was teemed by manual labour, and the teemer remained for many decades, and still remains, a characteristic and in a measure poetical and symbolic figure in the steel industry. The exhausting physical effort and the trying conditions of heat and strain were overlooked, as is so often the case with these romantic human symbols of manufacture.

Not until late 1927, when Messrs. Edgar Allen & Co., Ltd., introduced the first high frequency electric crucible steel furnace in the world to be used for the commercial manufacture of fine tool steels, was the supremacy of the Huntsman process for the manufacture of high-grade tool steels seriously challenged. Now it is steadily declining in importance, although still employed in the smaller works, and sometimes in the larger where a very small quantity of steel to a special analysis is required.

No description of the crucible process would be complete without a detailed account of how the charge for the crucibles and the crucibles themselves are prepared.

In this process it is of the first importance to have good crucibles. They are made of several kinds of special fireclay from Burton, Stourbridge, etc., usually mixed with about 5 per cent of good ground coke dust. These materials are mixed with water and worked up, then kneaded on the floor for five or six hours by the naked feet of men who keep incessantly trampling them (see Fig. 9). The object of this is to press out the air *bells* or bubbles, thus preventing dangerous air cavities in the finished crucible, and also to eliminate extraneous hard particles or lumps, which again might impair the finished pot. These hard particles are readily detected by the bare feet and ejected. This work is monotonous, laborious, and, in cold weather, highly unpleasant. Men's legs and feet often swell up painfully, and few workers in any industry, apart from mining, earn their bread with more effort. It is not the least advantage of the high



frequency process that it has largely eliminated so severe and trying an operation from steel manufacture.

The trodden clay is weighed out into suitable quantities and roughly moulded to shape on the bench by hand. This lump is then placed in a mould of crucible shape, well oiled with creosote, forming part of a mechanical press (see Fig. 10). An oiled plunger or plug having the form of the interior of the crucible is pressed down, being

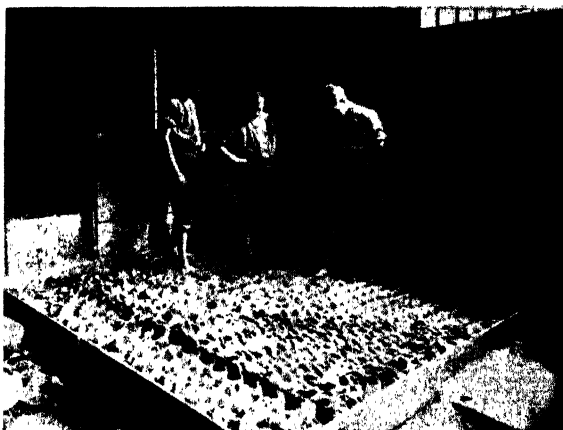


FIG. 9. TREADING CLAY FOR CRUCIBLES

centred by a pin which passes through a hole in the bottom of the mould or *flask*. The mould is then removed from the plug and after it the flask. The crucible top is pressed by hand, slightly inwards, a metal *former* being used, which gives it almost a barrel-top form.

The next stage is drying, which is done naturally on shelves in the *crucible-house*, where the crucibles or pots remain from about ten to fourteen days. They are afterwards transferred to an annealing furnace or *grate* (see Fig. 11). The grate bars of this are close to each other, so that combustion of coke, the fuel used, is slow. The crucibles are gradually raised to a good red heat. At

the end of the annealing period they are transferred directly to the melting holes and rest on fireclay stands, which have been similarly treated. With a hand-made crucible it is necessary to make good the hole in the bottom before it can be charged. This is done by throwing white sand, mixed with a small amount of red sand, into the pot. Under the action of heat the sand *frits* (becomes semi-plastic), and, in addition to filling up the hole,

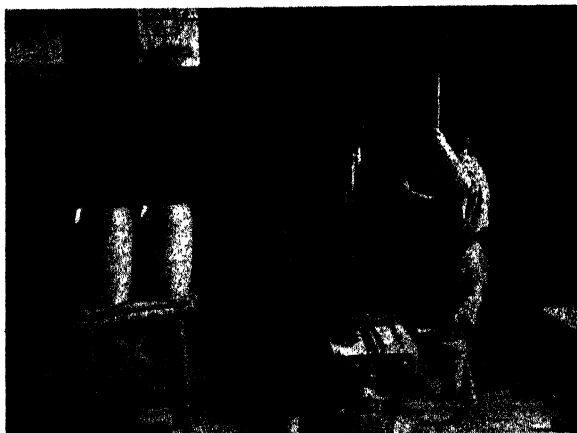


FIG. 10. MACHINE FOR MOULDING CRUCIBLES

firmly cements the pot and stand together. If the pots are machine-made there is no hole in the bottom of each pot, so that the *sanding* operation becomes unnecessary.

Slow drying and annealing are essential, otherwise the pots are liable to crack or flake-off, or develop small pinholes through which molten metal might percolate, with the consequent loss of all or part of the charge.

Each pot can be used for only two or three charges or *rounds* before it is scrapped, and after each melt it is immediately returned to the melting hole while still red-hot; otherwise it is liable to crack. *Plumbago* crucibles, which consist of a mixture of graphite and fireclay, are

sometimes used, particularly for the manufacture of castings. They have the advantage of a much longer life than the ordinary *white* pots, and may be cooled down to ordinary temperatures and used again without much risk of cracking. Their disadvantage, however, is that they contaminate the molten charge with carbon, although this contamination gradually decreases, until after about the seventh heat the extent of the additional carburization



FIG. 11. ANNEALING THE POTS

becomes almost negligible. Even with the earlier melts the crucible steel-maker can allow for the extra amount of carbon brought in by contact of the molten steel with the walls of plumbago pots.

The charge for the crucible is prepared by breaking up the highly brittle blister bars into smaller pieces. According to the carbon content required in the finished steel, certain proportions of good quality scrap, Swedish wrought iron, Swedish white pig iron, or charcoal, are added to the blister steel, the quantities of each being carefully weighed before mixing. (See Fig. 12.) The crucible, already in position in the furnace, is charged

with these materials by directing them into a tapering mild steel tube or funnel placed on top of the crucible. (See Fig. 13.)

In the old-fashioned crucible furnace, still used and likely to be, despite modern developments, for years to come, coke is the fuel. In large-scale production, producer gas is sometimes used as the fuel and the furnaces are of the *regenerative* type, i.e. the air and gas required for



FIG. 12. WEIGHING THE CHARGE

combustion are preheated in special chambers which, in turn, have been heated up by the waste products or gases of combustion. These chambers, or *checkers*, as they are called, are situated at each end of the furnace and it is so arranged that the gas and air pass through separate chambers at one end while the waste gases are heating up the chambers at the other end. At intervals, the directions of the gas, air and waste gases are reversed. By this means the gas and air are heated to a high temperature before they mix and before combustion actually takes place. There is then no difficulty in gaining the necessary high temperatures for the melting of the charge.

Each melting chamber holds six or more crucibles, as against two only in the older coke-fired furnaces.

Oil is also used as the fuel in some crucible melting furnaces. The oil is forced through fine jets by means of compressed air so as to secure effective combustion, and each furnace chamber will hold two or more crucibles. These oil-fired furnaces are mainly employed for the manufacture of steel castings. It is a curious fact that gas- and



FIG. 13. CHARGING THE CRUCIBLE

oil-fired crucible furnaces do not yield tool steels of such high quality as those produced by coke-fired furnaces.

In gas- and oil-fired furnaces the crucibles are generally machine-made, so that the stands previously mentioned in connexion with hand-made pots are unnecessary. The crucibles thus made have no hole in the bottom made by the centring pin.

In the ordinary coke-fired furnace the stand rests on the grate-bars and raises the crucible into the hot zone, since it is then surrounded by the incandescent coke. Each melting chamber, which, as already indicated, is capable of holding two pots, is known as a *melting hole* and

has a separate flue. Each hole has a separate cover consisting of a steel framework enclosing firebricks.

To revert to the actual process, it may be mentioned that some special elements, such as tungsten, chromium



FIG. 14. ADDING THE ALLOYS

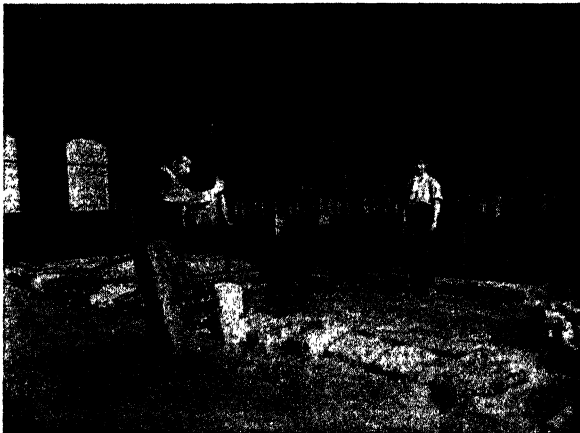


FIG. 15. PULLING OUT THE CRUCIBLE

and nickel, are added with the charge. Others, such as manganese and vanadium, etc., are added in the form of small packets during the melting period. (See Fig. 14.) High-speed steel containing tungsten, chromium, etc., takes longer to melt than ordinary tool steel.

Meantime, the ingot moulds have been prepared to receive the charge. They are coated with soot to prevent



FIG. 16. TEEMING

the steel from sticking to their sides. The soot is formed by burning tar or *pot-oil* (creosote) under the moulds.

About four hours of the intense heat of the furnace suffices to melt and make the steel suitable for teeming. Each crucible is *pulled out* of the furnace by a worker standing astride the melting hole, or close up to it, and by sheer physical strength lifting it with a strong pair of tongs. (See Fig. 15.) As the heat, when the furnace cover is removed, is intense, the worker's legs are strongly protected, and he inserts a *gag* into his mouth to exclude the hot air and fumes he would otherwise breathe. This exacting operation is steadily being eliminated by the increasing use of the high frequency process.

When the crucible has been pulled out, its fireclay cover or lid is removed, and the slag or dross floating on the molten steel skimmed off with a suitable implement. The teemer then balances the crucible in the tongs preparatory to teeming, and afterwards pours the fluid metal into the moulds. The moulds are slightly inclined, so that the steel can be poured to the bottom without touching the sides. (See Fig. 16.)

After the steel has solidified and cooled to about a red heat, the wedges and rings holding the mould together are knocked off, and the ingots removed from the moulds. This may be called the final stage of the crucible melting process.

The great advantages the crucible steel process possesses over later processes, such as the open-hearth or Bessemer, which made its use imperative for high-grade tool steel manufacture until the high frequency furnace was developed, were the more careful choice of materials and temperatures, the closer control possible when only small units were handled, and the much lower degree of contact with the atmosphere.

It would be logical to follow up this chapter with a description of the processes by which the ingot cast in the crucible furnace is turned into the finished tool steel bar, but as the high frequency furnace has been referred to so extensively and is so important in the modern manufacture of tool steels, it is more expedient to deal with it at once, even if chronological sequence has to be broken for the purpose.



## CHAPTER VIII

### The High Frequency or "Coreless" Induction Process

IN order to obtain the best possible results from tool steels, it is essential to control most carefully the composition of the steel itself. Care must also be taken to prevent undue contamination by impurities such as sulphur, phosphorus, etc. This is by no means easy. Even in the crucible process, where contact with the atmosphere is noticeably less than in other processes, there is inevitably contact with the gases within the furnace, since the pot or crucible is not hermetically sealed, and through its permeable walls the gases can enter. Even in the electric arc furnace, which will later be described, contamination by the carbon electrodes cannot altogether be avoided.

It was always the dream of the steel manufacturer to discover some new process in which contact with the atmosphere or with fuel could be eliminated, but it was not until 1927 that this dream was partly realized.

It had been known long before 1927 that melting of metals by means of induced eddy currents was feasible, and that this method enabled very accurate control of the alloy composition to be obtained without the complication of external impurities entering the steel, but at that time melting by means of high frequency or *coreless* induction furnaces was a matter of laboratory practice only, and large-scale production was impracticable. The problem was primarily a technical one (see p. 53), but also it indirectly involved the development of sufficient high frequency current at a commercially profitable or at least economical price. Without the high frequency the eddy currents could not be developed in the steel. The larger the furnace, the lower the frequency need be. Thus,

1000–2000 is usual for small plants, and as much as 1,000,000 for experimental furnaces of 1 lb. capacity.

Eventually, however, non-ferrous alloys were commercially produced in this way. At Bilston, Staffs., in 1925, a high nickel alloy of special quality for electric cable wire was made in a group of forty small high frequency furnaces, each of which produced 17 lb. or 18 lb. of metal in fifteen or twenty minutes. The temperatures and outputs required for steel were, however, far beyond the capacity of these furnaces.

In November, 1927, Messrs. Edgar Allen & Co., Ltd., of Sheffield, installed, and in December successfully operated before a large company of representatives of the technical and daily press, the first high frequency electric crucible furnace in the world to be commercially used for the manufacture of tool steels. The success of this furnace in actual daily production was soon demonstrated, and before many years had passed, installations of similar furnaces for tool steel and stainless steel manufacture in other large Sheffield works proved that the enterprise of this firm had been fully justified.

It would be impossible, within the limits of this book, to outline in simple language the electrical principles on which the high frequency steel-melting furnace is based, nor is such an outline necessary. The electrically trained reader will gather from the following notes as much as is immediately helpful.

The earliest high frequency induction furnaces had excessive magnetic leakage and low power factors, the *power factor* being the proportion of available electrical energy converted into useful work (or heat). The principle of induction is best explained by analogy with a simple transformer, the coil being the secondary winding and the steel bath making a single-turn primary winding.

The coil is an *inductor* and causes the current to lag behind the voltage, thus giving rise to *wattless current*, owing to the fact that the voltage and amperage are *out of*

*phase*. This wattless current does no work, and is the main cause of a low power factor. It also means that a generator is required many times larger than that actually needed to supply the useful current. This condition can be remedied by placing condensers in parallel with the coil, so that by varying the number of condensers, i.e. capacity, the coil and condenser circuits may be tuned, and the power factor greatly improved. It was the need for strong and trustworthy condensers of large capacity that held up the application of high frequency currents to steel melting, although the principle had been demonstrated by Professor Northrup at Princeton University in 1916, and by others before him.

Great care was also necessary to obtain sufficient electrical resistance by restricting the cross-section of the ring of metal.

The problem of high frequency steel melting was solved by specially designing an alternating current generator consisting of a 260 h.p., 3 phase, 5 cycles induction motor (350 V., 380 A.) at 3000 r.p.m. run from the town electricity supply, coupled to a 150 k.V.A. alternating current generator with 60 volts excitation. This gave the current, which was applied to the furnace coil at 1200 volts and 2200 frequency.

The whole assembly of heat-resisting pot and lining is contained within a cylindrical copper coil of approximately 20 turns, according to the size of the furnace, and cold water is continually circulated through the coil. This water-cooling is essential, as otherwise the copper coil would melt. The coil carries the current, and must be protected in case the crucible cracks and molten metal flows through the crack.

Since Messrs. Edgar Allen & Co., Ltd., installed the first furnace in 1927, larger units have been built, and furnaces up to 10 tons capacity are now employed for the manufacture of high-grade alloy steels. In the larger furnaces it is usual to build up the furnace lining by

the Rohn method. The copper coil is first protected by being plastered with refractory clay. A hollow steel former is then placed inside this cylinder, and the refractory material for the lining gently tamped or rammed between the coil and the former. By this means the lining of the furnace may be *acid* or *basic* in nature as circumstances demand. (For an explanation of these terms, see Chapter X.) If an acid lining is required, ganister may be used, and magnesite or magnesite-alumina mixtures if a more refractory and basic lining is needed. After the tamping or ramming of the lining in this way, the current is passed through the water-cooled copper coil and is gradually increased. This slowly heats up the steel former and eventually melts it, but long before this occurs the surface of the lining in contact with it has become sintered into a mass capable of holding, without any leakage whatsoever, any molten metal within it.

Later, when the crucible or Rohn lining is charged with metallic materials, such as steel scrap, the high frequency current, passed through the copper coil, generates eddy currents in the charge, which eventually melts. The current does not flow evenly throughout the metal, but only on the surface. This is known as the *skin effect* and gives the necessary resistance.

The walls of the crucible or lining serve merely as a container, and no heat is passed from the outside of the crucible to the metal within.

As the eddy currents, which are induced and generate heat in the steel, vary as the square of the frequency (electrical terms it is not needful to explain here), a high frequency is necessary in this method of induction heating.

The high voltages with a high frequency are not dangerous.

The first furnace was contained in a wooden case or box, and this gave rise to the "stunt" headline "Steel-making in a wooden box," with which this process was first announced to the world in the British non-technical press.

(It is amusing to note that some journals described the process as "steel-making by wireless," while a Japanese journal went so far as to aver that the steel was melted by wireless waves brought into action by pressing a button two miles away!) The box had to be non-metallic or it, too, would have heated up, and although it was within two or three inches of molten metal, it remained quite cool. In large furnaces to-day the box or case is metallic, but non-magnetic and properly insulated. The top, bottom, and supports are of *syndanyo*, a non-conducting material of asbestos-base. The pot stands in sand and on *silocal* (heat-resisting) bricks. The furnace is tilted for pouring with the spout as the axis, so as to maintain the pouring lip in a constant vertical position. This is a great help towards expeditious and safe handling. Tilting is done by an electric motor with a reserve hand tilt. The steel is not teemed directly into the ingot moulds, but through a clay *tundish* (see pp. 132-3), which produces a vertical pencil of metal. A head of metal is kept in the tundish so that any flux will float.

Since no heat is transmitted from the outside of the crucible and no gases are evolved, as in processes where solid, liquid, or gaseous fuels are used for melting, the metal is kept uncontaminated and there is no wear on the outside of the crucible or lining, although the circulation of the molten metal wears its interior.

The mass of metal in the charge is first subjected to a small amount of current. For the first heat the *former* is held at a red heat for about two hours to ensure *fritting* of the lining, so that it is essential to have a strongly-welded former. Fritting is the fusing or sintering of one grain to another to give a coherent mass. Some impurity or *bond* may have to be introduced to secure this, especially with very pure lining material. A lining that would be considered satisfactory is one lasting for fifty or more heats. The charge rapidly rises in temperature, and, when melted, circulates quickly, as shown in Fig. 16A, so that

heavy alloying metals, which in the less dynamic crucible process might sink to the bottom of the pot, are kept in continuous motion and are evenly disseminated throughout the mass of the metal—an obvious advantage. This circulation is caused by electromagnetic forces. It results in the steel's being higher in the centre than at the sides. Another important effect is the thrusting outwards of the slag and the building up of a slag line instead of wearing it away. This slag must be knocked off from time to time or the charge will *scaffold* or hang up. When all the lumps

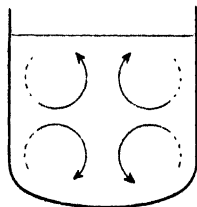


FIG. 16A

are melted, the slag flows evenly over the surface. A third effect of the continuous motion is that it gives full effect to the deoxidizing agents in the metal: e.g. ferro-silicon, etc.

The advantages of the high frequency electric crucible process can be subdivided into (a) technical and (b) economic. Taking the technical first, there are (1) the purity of the steel, which is remarkably low in sulphur if low sulphur materials are charged; (2) ingots of steel required to conform to a special analysis can be made very quickly, though it should be mentioned here that the furnace is almost essentially a melting and not a refining unit, because in this type of melting only the purest base materials may be used, and these do not need desulphurization or dephosphorization. It is only fair to state, however, that there are possibilities of *reduction* by this process, and before the war the Germans were reducing high-carbon ferro-chromium by the induction method; (3) the violent electrical stirring of the metal, so strong that the surface of the metal in the centre of the pot may be as much as an inch higher than at the sides. This ensures very thorough mixing, and in consequence greater uniformity in alloy steels, as explained above; (4) great homogeneity of the steel when making large ingots, since such ingots cast by the old crucible process are made from the contents



FIG. 17. TEEMING MOLTEN TOOL STEEL INTO INGOT MOULDS

of several crucibles, whereas in the high frequency furnace the ingot is cast from one pot; (5) the final temperature of the molten metal can be more closely controlled and is easily adjusted; (6) this furnace can be operated intermittently, with very little loss of efficiency; (7) the absence of furnace gases containing sulphur is important as preventing contamination. There are no electrodes to break and yield undesired carbon; (8) there is a steadier load on the central station than with the violent fluctuations of an arc operating on cold metal. The maximum input of current is not possible until the magnetic change point is passed—about 700° C. The temperature increase is very sharp—about 40° C. a minute, until near the end, when the radiation losses are considerably greater, in all probability, than the electrical losses; (9) the linings may be allowed to stand and grow cold without fear of deterioration or cracking. In one instance power was cut off just as teeming was about to begin. The steel solidified in the crucible, but was remelted next day, leaving the lining unharmed. As many as 77 heats have been obtained between 9 a.m. Monday and 9 a.m. Saturday, work being continuous with a power consumption little more than that of an arc furnace.

The economic advantages are (1) much smaller space is required to produce tool steel by this process as compared with that required to produce an equal amount by the crucible process, whether using coke or gas as fuel; (2) a lower cost per ton of steel produced; (3) the capacity of the furnace is a much more convenient quantity than the 60 lb. or so per crucible of the crucible method; (4) the facility with which the crucible can be completely emptied at each heat; (5) the heat-retaining quality of the insulation used, which renders it possible to pour many small quantities before the temperature falls too low; (6) the readiness with which reheating can be accomplished by the simple manipulation of a switch; (7) if several crucibles are available, these may be supplied



in parallel by a single generator or switched on one after another if the generator capacity suffices for only one at a time; (8) uniformity of product is also helped by the size of the melt. Using the gas or coke crucible process it is difficult to get 10 pots with identical analyses with the modern complex steels embodying 6-12 ingredients. The weighing of larger quantities reduces the error of weighing the alloying elements, although the rapidity in melting makes this weighing a full-time job for one man. In one works the steel is first melted in an electric furnace and afterwards finished in crucibles, but to the authors this seems a roundabout method; (9) the small oxidation losses of vanadium, chromium, etc., owing to the shorter melting period; (10) the design of the furnace lends itself to melting under different conditions, such as in a neutral or reducing atmosphere; (11) the process is extremely flexible, carbon, stainless, heat-resisting, and non-magnetic nickel steels all having been made consecutively from the same pot. If austenitic (11-13 per cent) manganese steel is required, however, a *magnesite* lining is advisable, owing to the heavy losses of manganese and erosion of the pot with a siliceous refractory.

Finally, there is the tremendous social advantage that the steel is made under cleaner and less arduous conditions with vastly less severe manual effort. 550 lb. of steel can be melted in the high frequency furnace in fifty to seventy-five minutes according to the composition and size of the charge. To this must be added the time required for charging and teeming. In the larger furnaces the rate of melting is even quicker than this. Whereas, in the old crucible process, the workers were bathed in sweat even in the depth of winter, they are more likely with the new process to need overcoats or at least warm clothing, while breweries must have experienced a considerable local decline in demand for their wares.

In addition to ingots, castings may be made varying from a few ounces to the entire charge. The larger





castings are cast direct, but the smaller are *shanked*, i.e. the steel is first poured into a smaller receptacle, whence a number of moulds obtain their requisite quantity of steel. The receptacles are heated in advance of use so that they shall not chill the steel poured into them from the furnace.

## CHAPTER IX

### From Ingot to Finished Bar

THE ingot of steel produced by either the crucible or the high frequency process has to undergo various finishing processes before it is ready to leave the works. These processes can be roughly classified as forging, cogging and rolling.

*Cogging* is a hammering operation that precedes finishing and prepares the steel for the final processes. It consists of forging down the ingot or billet to the required size by the aid of heavy and powerful mechanical hammers. In some instances, however, this reducing operation is carried out by a *cogging mill* or set of large rolls that bring the ingot down to size. In general, if tool steel is required in blooms 6 in. square or above, or in large flat bars or pieces, it is clogged down to the required size.

Hammering, where tool steel is concerned, is usually taken to mean *finish forging*, or reducing the clogged steel to the required size and shape by hammering mechanically with special hammer tools. Rounds of 2 in. diameter or above, flats over  $\frac{1}{2}$  in. thick, and squares over  $\frac{1}{2}$  in. are generally forged.

Rolling for tool steels is carried out when the steel is required in bars or rods up to 1 in. round,  $\frac{1}{2}$  in. square, and in flat bars up to  $\frac{1}{2}$  in. thick. For rounds between 1 in. and 2 in. diameter, it is optional whether forging or rolling is adopted, although the structure of the steel is more uniform if forged only.

Rolling these smaller sizes has one advantage over hammering. A more uniform measurement over the bar can be obtained, especially in bars of 10 ft. or 11 ft. in length. To finish-hammer a bar of this length dead to

size would be difficult, and could, in fact, only be done by the most highly skilled workers.

In addition to these three finishing processes of cogging, hammering and rolling, two other mechanical operations are carried out on tool steel bars. These are known as "reeling" and "straightening."

*Reeling* is the latitudinal rolling (rolling from side to side as distinct from end to end) of a tool steel bar

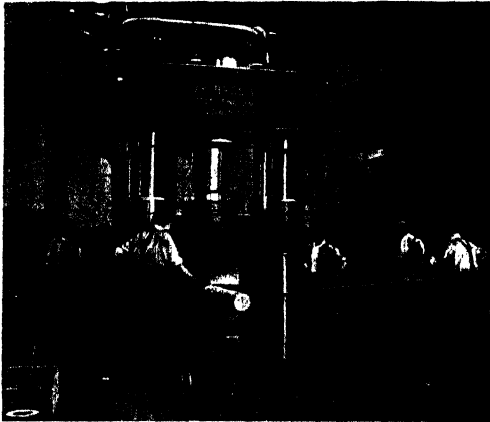


FIG. 18. PRESS-FORGING STEEL

that has already been rolled. It is adopted as a means of giving a better finish to the steel. The bar, when cold, is taken and passed between rolls revolving at right angles to its length. By this means the oxidized surface is removed from the bar, a smoother finish is given, and to a certain extent the bar is also straightened. The reeling process can, of course, only be used on round steel.

*Straightening* is, as its name implies, the insertion of the cold bar in a machine which grips and straightens it.

For ampler descriptions of these and other mechanical working processes, the reader is referred to *The Mechanical Working of Steel*.

From the forge or rolling mill the steel passes to the

steel warehouse, unless, as with high-speed steel and certain other tool steels, it first requires to be annealed. The object of annealing is to soften it and render it machinable, so that it can be made up into tools, e.g. twist drills, milling cutters, dies, etc. The annealing process also relieves strains set up in the forging and rolling operations.\*

In the steel warehouse the bars are ended, i.e. the ends are nicked and then knocked off, and the fractured



FIG. 19. ENDING INGOTS

surfaces examined carefully in order to detect flaws, such as seams and pipe, and to check the quality. If sound, the bars are then branded, varnished, painted with distinguishing colours so that they may be readily recognized by the user without the necessity for analysis, and labelled. If being sent inland by rail, they are *bundled* (bound together into bundles for transit purposes by twisting red-hot bundling-iron strips around them). If

\* For an explanation of the structural effect of annealing, see *The Structure of Steel*.



FIG. 20. ENDING BARS



FIG. 21. HAND GRINDING HIGH-SPEED STEEL



being sent overseas, they are generally packed in stout wooden cases fastened with hoop iron.

An essential part of the tool steel manufacturer's plant is the hack-saw, a machine for mechanically sawing bars into short lengths suitable for *tool holder bits* (short ready-hardened pieces of high-speed steel of small diameter or

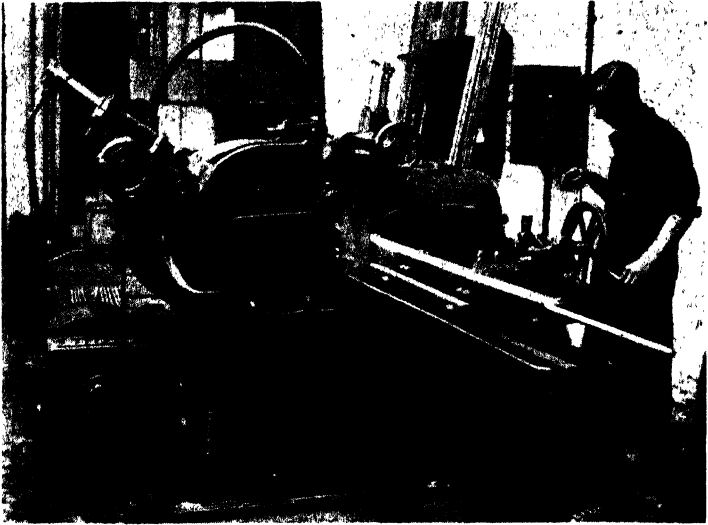


FIG. 22. CENTRELESS GRINDING MACHINE

cross-section used in a lathe for machine-cutting of metals, etc.), twist drills, etc.

The pneumatic *chipping* of steel billets must also be mentioned. Certain defects in steel billets are not visible to the eye, but if the surface skin is removed, they may be detected by an experienced worker. Accordingly, with certain alloy steels the practice is adopted of chiselling suspected areas of the billet with a *pneumatic* (driven by compressed air) chisel, which cuts away a shaving of the superficial, and often oxidized or rusted, metal to reveal the bright surface below.

High-speed and other tool steel bars are usually ground by an abrasive wheel to reveal surface defects (see Fig. 21)

There is one other finishing process of recent development which has not yet been discussed. This is *centreless grinding*. Modern production demands tools so accurate to size and lays so much emphasis on cost that a demand has steadily increased for bars made to finer dimensions than the previous processes can provide. This accuracy reduces the amount of work the user himself has to do in order to produce an accurate tool from a bar of steel. To achieve it, precision grinding of the bars before they leave the steel-maker's works is essential.

This involves the installation of costly centreless grinding plant, and additional reeling machines. A typical plant of this type will take bars from  $\frac{1}{8}$  in. thick up to  $1\frac{1}{4}$  in. thick, and up to 15 ft. long, and according to the amount to be removed, the grinding will be completed in three passes, which remove about ten thousandths of an inch at a time, except at the final pass, where the cut is lighter. The speed of pass is about 15 ft. per minute. The size of the finished bar can be guaranteed between plus or minus 0.0005 in., and a limit of 0.00025 in. can be worked to if necessary. Some steel-makers claim even higher speeds and accuracies.

For centreless grinding of tool steel bars, carborundum wheels are used, of special grit and grade. The grinding wheels are always trimmed for wear before the last pass to ensure that they are perfectly cylindrical.

In certain instances, usually at the customer's request, tool steel bars are heat-treated before dispatch, i.e. normalized or hardened and tempered. There is no need to outline these processes here as they are not fundamental processes of steel manufacture, and have been fully and carefully dealt with in *The Structure of Steel* and in *The Heat-treatment of Steel*. Similarly, testing and metallurgical inspection have been discussed in the first-named work and will not be treated here.

The manufacture of tool steel from its production by crucible or high frequency process down to its dispatch as finished bars having been described, the following chapters will deal with other steel-making processes designed for making different types of steels.

## CHAPTER X

### Acid and Basic Steel—The Difference

*Acid* and *basic* are terms applied to steel, often, it must be confessed, erroneously, because their meaning is not thoroughly understood. The purpose of this chapter is to explain what an acid steel is, and in what respects it differs from a basic steel. It will then be easier to describe in detail the processes by which these respective steels are made. The reader must bear in mind that the words acid and basic really apply to the *lining* of the *furnaces* in which the steels are made, and are only by derivation employed in the nomenclature of steel. *Acid steel is thus steel made in an acid-lined furnace, and basic steel that made in a basic-lined furnace.*

An acid furnace is one lined with either silica bricks, white sand, or ganister. These materials result, as will be later described, in the formation on the surface of the molten metal of a *siliceous* (silica-containing) slag. *Ganister* is a hard, close-grained siliceous rock which often forms the stratum underlying a coal seam, and silica bricks are manufactured from this mineral. Both ganister and white sand consist essentially of *silica* (silicon dioxide— $\text{SiO}_2$ ) which is *anhydrous* (free from water of crystallization) silicic acid. Consequently, steel manufactured on such a furnace lining is known as acid steel.

A basic furnace, on the other hand, is lined with burnt *dolomite*, which is a *magnesian limestone* (a limestone containing magnesia). Dolomite derives its name from the French geologist D. Guy de Dolomieu (1750–1801). This type of furnace lining is worked in conjunction with a lime (calcium oxide— $\text{CaO}$ ) slag on the surface of the molten metal. Dolomite is composed of roughly equal

parts of lime and magnesia (magnesium oxide— $MgO$ ). Both substances are oxides, and strong chemical bases, a base in this sense being a substance entirely opposite to an acid. In chemical language it is a compound body that combines with an acid to form a salt. It will now be seen why a vessel or furnace lining in which these bases figure is called a basic lining, and the steel made upon it a basic steel.

Acid steel is chiefly manufactured in the Sheffield district, Scotland Barrow, and South Wales. Basic steel, on the other hand, is produced chiefly in the Scunthorpe, Rotherham and Middlesbrough districts, in Manchester, and in Scotland.

Considerable controversy has raged among steel manufacturers in the past as to the comparative merits of the two qualities, and the question is still unsettled. In general, acid steel is used where the highest characteristics are required. Basic steel is for less exacting work. It is a moot point, however, how far this rough distinction is an arbitrary one founded on engineering prejudices.

Thirty years ago, basic steel was considered untrustworthy, and was believed to give poor results wherever consistent efficiency was required. In consequence, before 1914 all specifications for steel usually insisted on the acid process in preference to the basic if reliability was the essential requirement.

It must not be overlooked, however, that Germany built up her steel industry largely on basic Bessemer steel (the Bessemer process is dealt with later). In 1913-14, for instance, nine-tenths of the total German steel output consisted of basic steel. This predominance resulted from the character of the ores used by the Germans and a *British* discovery—the *Thomas-Gilchrist* process—which enabled them to utilize these ores. Those mined in the Rhine valley and Briey districts contain a high percentage of phosphorus, and are thus particularly suitable for the manufacture of basic steel.

The United States also produce a much larger amount of basic than of acid steel. Most of their steel was made by the Bessemer process, the converters being acid-lined, but of recent years steel production by the open-hearth furnace with basic linings has exceeded production by the Bessemer process. Only a small percentage of their total production of open-hearth steel is made by the acid open-hearth process. In 1918, for example, 32,476,571 tons were produced by the basic open-hearth process as against 1,982,820 by the acid open-hearth, and 9,376,236 by the Bessemer process.

The war of 1914-18, with its increasing demands upon the steel resources of all countries, largely defeated the prejudice against basic steel among engineers in the United Kingdom. The shortage of *hematite*, that form of iron ore chiefly used in the production of acid steel, and the interruption, owing to shipping difficulties, of its imported supply, led British steel manufacturers to seek other means of maintaining the enormous steel output required. They could no longer depend entirely upon those qualities of steel whose production was governed by the quantity of hematite ore imported into or mined in this country. Basic steel was accordingly demanded in larger tonnages to fill the gap caused by the shortage of ores for acid steel production.

British furnaces in most of the steel manufacturing areas were, however, adapted to acid steel production only. In consequence, before they could be switched over to basic steel manufacture, they had to be converted to basic linings. Under the auspices of the Ministry of Munitions, these conversions were eventually made, and the number of purposes for which basic steel was used measurably increased. A great deal of the extra bulk produced was required for shells.

As a result, the attitude towards basic steel changed, and it is now used for work for which it would formerly not have been tolerated. For instance, it was at one

time almost impossible to get British engineers to use basic steel plates in ship-building. To-day they are even being used in boiler-making and have given complete satisfaction.

To summarize, properly made basic steel is in every way as good as acid open-hearth steel. Indeed, if a good residual manganese content, say not less than 0·20 per cent, is maintained throughout the whole melting process, the product may even be better than acid open-hearth steel, since this residual manganese is an insurance against excessive over-oxidation. On the other hand, badly made basic steel is likely to be inferior to badly made acid steel, because the reactions in the basic furnace are more complex.

## CHAPTER XI

### The Bessemer Process

THE Bessemer process of manufacturing steel may be either acid or basic, according, as has been seen, to the type of *refractory* (heat-resisting) material with which the vessel is lined. It is often known as the *converter process*, and was invented by Sir Henry Bessemer in 1856. (The original process was carried out in acid-lined vessels.) The method consists of blowing, by mechanical means, a blast of air through liquid pig iron contained in a pear-shaped vessel. The oxygen in the air burns out some of the impurities in the iron, thereby generating intense heat, which serves to maintain the iron in the molten condition. The oxides thus formed combine together chemically to form a fluid scum or slag on top of the molten iron. During the blowing, particles of this slag and metal sparks are ejected white-hot from the conical mouth, thus giving the characteristic and beautiful pyrotechnic display associated with the Bessemer process.

The vessel itself is known as a *converter*, and comprises a mild steel casing lined with refractory material which may be either acid or basic in character. (Some notes on refractories will be found in Chapter XXI.) The choice of process depends on the chemical composition of the pig iron employed.

In the acid Bessemer process, the impurities reduced to small proportions by the blast are silicon, manganese and carbon. In the basic process, most of the phosphorus is removed, in addition to some of the sulphur.

Molten pig iron may be charged directly into the converter. Otherwise, it is first melted, together with steel scrap, coke, limestone, and a little fluorspar, in a furnace known as a *cupola*. This is a relatively short



cylindrical furnace of uniform diameter, heated by the combustion of coke.

The limestone is used as a *flux*, i.e. it combines with any silica formed by the oxidation of silicon in the pig iron, and at the same time combines with sulphur in the coke, thus preventing it from going into the iron. The *limey* slag is rendered more fluid by the addition of the fluorspar, and can then retain more of the sulphur.

In the larger Bessemer plants, a receiver or *mixer* is frequently employed as an intermediate stage between cupola and converter. This receiver is a large receptacle or furnace into which the molten pig iron from the cupola is periodically run, and from which the converter is fed. Oxidation of manganese and silicon takes place in the mixer, and in the basic Bessemer process a good deal of sulphur is also eliminated. (The need of removing all these impurities is carefully explained in the companion book *The Structure of Steel*.)

The converter itself has a flattish underside pierced by a large number of holes formed in bricks of special design, through which the blast enters. Accessory to the vessel is a blowing engine. This compresses in cylinders the air for the blast used in the conversion of the iron into steel, and forces it through the pipes or tuyères into the molten metal.

There have been numerous variations of the Bessemer process, such as the Robert and Tropenas processes. These have mostly concerned themselves with the method of blowing, and as the Tropenas process is of considerable importance in the modern manufacture of steel castings, it will be dealt with extensively in a later chapter.

The principles common to both acid and basic Bessemer processes having been outlined, the two methods may now be considered separately.

In the acid process, the refractory material used for lining the furnace is rammed ganister, which was described in the preceding chapter. A lining of this type will not

eliminate or aid in the elimination of phosphorus or sulphur. In both acid and basic processes, once the metal has been run into the converter (by way of a metal ladle or chute) no further heat of external character is applied. The metal has, however, to remain liquid, which means that it must not fall so sharply in temperature as to become viscous or even solid. The metal, in practice, does remain quite fluid during the blowing, and this is achieved not by a separate fuel heating the vessel externally, but *internally* by chemical action. Students of chemistry know that many strong chemical reactions generate heat. (The slaking of lime provides an excellent example. The combination of oxygen with various impurities also generates heat, and does so sufficiently to keep the metal liquid during its conversion into steel. In this instance it is the oxygen in the blast and the elements carbon, silicon, manganese, and, in the basic process, phosphorus, that constitute what may be termed internal fuels.

In the acid process, with which this chapter is now dealing, silicon is vitally necessary as an internal fuel of this type, and if there is not enough (about 2 per cent) in the iron more has to be added in the form of ferro-silicon before or during the *blow*, i.e. during the time that the blast is passing through the molten metal. A typical analysis of ferro-silicon is as follows --

Silicon	.	.	.	.	12.74	per cent
Phosphorus	.	.	.	.	0.095	" "
Manganese	.	.	.	.	0.087	" "
Sulphur	.	.	.	.	0.02	" "

The refractory lining is important and must be kept in a thoroughly efficient state. To ensure this, it is patched with fresh refractory material between heats, i.e. after each blow, and over the week-end is even more carefully repaired.

The temperature of the cupola, receiver, or metal mixer, is also of great moment, because if the metal is too hot, the carbon may, under the influence of this heat

combine with the oxygen before the silicon, and instead of the type of steel desired, the manufacturer may find himself left with an unwanted high silicon steel. It is necessary to get rid of the silicon during the earlier stages of the blow. Too high a starting temperature of the molten iron is usually remedied by the addition of cold steel scrap, which chills it to some extent.

The converter when cold is never charged with molten iron. If not hot from a previous blow, it is heated by lighting a fire inside. As soon as the metal has been run into it from the cupola or mixer, the blast is turned on and the conversion process begins. (This vessel can be rotated mechanically about its axis to the extent necessary at various stages.)

The metallurgists who control the process are enabled to ascertain the progress of conversion by closely observing the flame issuing from the mouth of the vessel. This flame is caused by the burning of the various impurities, and its character reveals to the trained eye exactly what is happening inside the converter. At the outset it is short and not conspicuously brilliant. Only the manganese and silicon are then being oxidized, and these do not cause intensive pyrotechnics. After the silicon has been almost completely eliminated, however, the carbon is next attacked by the oxygen and forms carbon monoxide, a gas, which is freed as a result and forces its way upwards through the heavy crust of slag (consisting essentially of *silica*, the oxidized form of silicon). This gas then ignites and burns at the vessel mouth, the pressure of the blast producing a long and brilliant flame, which steadily lengthens and is accompanied by an impressive shooting forth and cascading of multitudinous white-hot slag particles or sparks. This phase is known as *the boil*.

As soon as the carbon has been almost completely oxidized the flame drops, which marks the conclusion of the process. It is at this juncture that the metallurgist's skill is all-important, since if the blow were too greatly

prolonged (as little as fifteen seconds would be enough) through inexperience in judging from the flame the stage reached, the whole contents of the converter (from  $3\frac{1}{2}$  tons to 30 tons, according to size) would be spoiled. The reason is that, having oxidized all the carbon, the oxygen would then unduly attack the iron itself, forming abnormal amounts of iron oxide, an ingredient fatal to the quality of the steel. A certain amount of oxide of iron is inevitably produced, and this is one of the main reasons why additions of ferro-manganese and ferro-silicon are necessary. Any alloys introduced for various purposes would be largely wasted by losses due to oxidation, and low-quality steels with an inadequate manganese percentage would result.

Similarly, to bring the blow to a close too soon would produce wrong results, since the steels obtained would be too high in carbon, silicon and manganese, and such steels are undesirable, for reasons carefully explained in *The Structure of Steel*. While an individual blow may vary in duration between fairly close limits, governed by the percentages of silicon, carbon and manganese in the molten iron, the average time taken from beginning to end of the blow is twenty minutes.

To show the effect of the process, here is a typical analysis of the iron as run into the converter—

Carbon	.	.	.	.	3.0 per cent
Silicon	.	.	.	.	1.5-2 per cent
Manganese	.	.	.	.	0.5-1 " "
Sulphur	.	.	.	.	below 0.04 per cent
Phosphorus	.	.	.	.	below 0.04 " "

and contrasted with it a typical analysis of the metal found in the converter after blowing—

Carbon	.	.	.	.	0.04-0.08 per cent
Silicon	.	.	.	.	0.02-0.07 " "
Manganese	.	.	.	.	traces to 0.08 " "
Sulphur	.	.	.	.	0.04 per cent
Phosphorus	.	.	.	.	0.04 " "

As it stands, the metal is not in its final condition. It contains an excess of oxygen in the form of oxide of iron ( $\text{FeO}$ ), which, if retained, would cause blowholes, i.e. gas cavities, or produce impurities in the form of non-metallic inclusions in the solid steel. It also contains insufficient carbon, and is, in consequence, too soft for most purposes for which the steel is required. To decrease the amount of oxygen, or oxide of iron, and at the same time increase the carbon content, alloying substances containing manganese are added, these being thrown into the vessel so forcibly that they break through the heavy slag crust to the molten metal beneath. Broken glass is also thrown into the converter to yield a more fluid slag, which absorbs a certain amount of oxide of iron from the blown metal and thus reduces the amount of ferro-manganese required.

The manganese may be added in two forms, either as *spiegel*, which is an alloy of iron and manganese containing 12–20 per cent of manganese, or as ferro-manganese, which contains approximately 80 per cent of the element.

What is the effect of these additions? First, a portion of the manganese combines with the oxide of iron to form a chemical compound known as *manganous oxide*. This compound, unlike oxide of iron, does not dissolve in the liquid metal, and, coming to the top, enters the slag, which can be skimmed off.

The rest of the manganese—about 0.70 to 1 per cent—remains as an essential alloying element in the steel. But in both *spiegel* and ferro-manganese are important percentages of carbon, so that the addition of either of these substances raises the carbon content (and therefore the hardness and strength) of the steel. In *spiegel* the carbon percentage is between 2 and 4 per cent, and in ferro-manganese, between 6 and 7 per cent. If the metal is excessively low in carbon, a practice sometimes adopted is to run into the vessel a little molten pig iron from the

cupola or receiver, care being taken to ensure that the silicon content shall not be unreasonably increased by this means.

Every *charge* (the total quantity of metal dealt with at one time) loses about 12 to 16 per cent of its weight during the blow and therefore one not hitherto mentioned result of the process is to raise the sulphur and phosphorus percentages slightly because of the greater concentration brought about.

The acid Bessemer process is mainly used for the production of steel castings, although steels made by it have also been used successfully for other purposes. It is generally assumed, however, that acid Siemens steels are superior to them in quality.

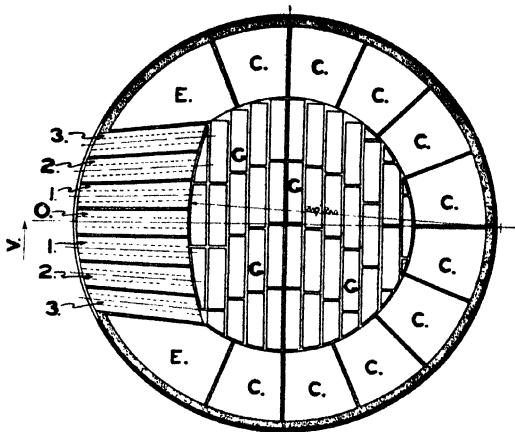
## CHAPTER XII

### The Tropenas Acid Process

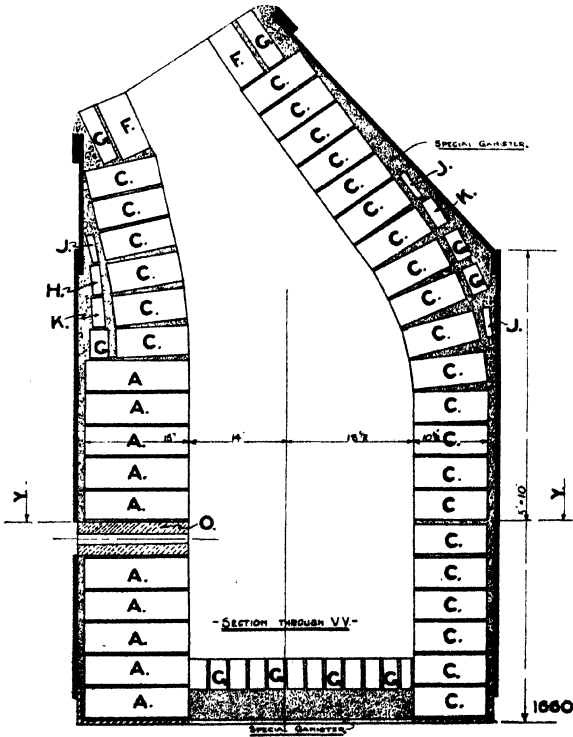
ALEXANDRE TROPENAS, who invented the improved acid Bessemer type of converter suitable for making relatively small quantities of steel at a time, is less widely known than many other pioneers of metallurgical processes. Nevertheless, his side-blown converter had an important economic effect on the electrical industry, because it made possible the production of sound steel castings suitable for dynamos. Until his process was invented, the manufacture of small steel *castings* (parts made by pouring molten metal into a previously formed mould) for electrical purposes on a commercial basis was practically impossible. Afterwards, steel castings replaced the wrought iron previously used for this purpose.

Tropenas was General Manager of the Société Industrielle de Fonderie de Bronze, and in this capacity became interested in a variant of the Bessemer vessel known as the Robert converter. In this, the tuyères or blowing pipes were set at a tangent to the surface of the metal in the converter. The air blast entered *below the surface* of the metal, and this imparted a rotary motion to the *bath* (the molten metal in the converter) the advantage of which was, so Robert held, the more rapid and complete purification and conversion of the pig iron into steel.

Tropenas persuaded his firm to make steel castings, and a Robert converter was at first installed, but the results were unsatisfactory. Several good hot blows (i.e. the operations from start to finish of the process) would be followed by several others that were cold, i.e. where the steel was not hot enough to flow freely, as it should when poured or cast into the sand moulds. The steel also rose in the moulds, i.e. it would contain an excessive



- SECTION THROUGH V-V -



- SECTION THROUGH V-V -





FIG. 24. TROPENAS CONVERTERS TURNING PIG IRON INTO STEEL

amount of oxygen, overflow the mould, and produce a spongy casting, which had to be scrapped.

Tropenas, after failing to obtain help from Robert, decided that the theory of tangential tuyères with the bath sloped to give a gyratory motion was unnecessary, and began experiments of his own. After about a year, he became convinced that success with the small converter for the manufacture of steel castings could only be achieved by blowing *across the surface* of the metal. He communicated in 1890 with Messrs. Edgar Allen & Co., Ltd., who had experienced similar trouble with the Robert converter, and eventually, in 1891, a converter on Tropenas's lines was installed at the Imperial Steel Works, Sheffield, under his own supervision, and the firm's resources were placed at his disposal so that he could perfect his method. After some disappointments and difficulties, success was finally achieved. In 1896 and 1897 converters of the Tropenas type were installed at the Royal Arsenal, Woolwich. Two years later the Midland Railway followed suit at Horwich, and in 1900 Vickers Limited adopted the system at their Barrow-in-Furness works. Since then the process has made its way into most parts of the world where steel castings are produced.

Tropenas used a deep bath. His two rows of tuyères were in a straight line, and blowing took place across the surface of the metal, the conversion of the iron into steel being effected solely by oxidation at the surface. Tropenas never claimed to have made any remarkable discovery, but only to have adopted a simple method that made the handling of a small converter easy for a man familiar with the steel foundry, and allowed small steel castings of good quality to be manufactured at a comparatively low price.

Fundamentally, the method of producing steel is identical with the acid Bessemer process, and consists in oxidizing the impurities in the charge by means of the

oxygen of the air blast, thus producing commercially pure iron, which is then *recarburized* to the required degree, i.e. the carbon percentage is increased to the desired amount by suitable additions. The lower set of tuyères directed the air blast on to the surface of the metal, and the upper set, usually termed *tuyères of combustion*, furnished the air for burning the carbon monoxide to carbon dioxide, thereby giving greater heat efficiency. *The upper set of tuyères was gradually dispensed with, however, and now it is usual to employ only one set.* The upper row was invariably stopped up by slag. Refractories have also improved considerably, and a much longer life is now obtainable than the forty heats referred to by Tropenas in a paper read at the Cincinnati Convention of the American Foundrymen's Association in June, 1898. Tuyères will last from eighty to a hundred heats. Another point is that the temperature can be increased by the addition of ferro-silicon during the blowing.

According to the paper referred to above, the first Tropenas converter had a capacity of about 800 lb. and was erected in about 1891-2 in the works of Messrs. Edgar Allen & Co., Ltd., Sheffield. The trials made with this vessel were so satisfactory that after a few weeks it was decided to build a 2-ton converter. The capacity of the latest converters in actual operation to-day is  $3\frac{1}{2}$ -4 tons.

## CHAPTER XIII

### The Basic Bessemer Process

THE basic Bessemer process for making steel is nearly sixty years old. Although invented by two Englishmen, Thomas and Gilchrist, it has been developed largely on the Continent of Europe. There, millions of tons of steel are made each year by this method. In France, Germany, and other continental countries, it is known as the *Thomas* process. It differs from the acid Bessemer process, as already explained, in that the converter is lined with rammed burnt dolomite instead of ganister. *Dolomite*, sometimes called magnesian limestone, is a compound of the carbonates of lime and magnesia; it is a refractory (heat-resisting) material known to chemists by the formula  $(Ca, Mg) CO_3$ . Dolomite has no definite chemical composition and the formula, as written, simply means that calcium (Ca) and magnesium (Mg) can replace each other in indefinite proportions in their carbonates. When properly *burnt* (heated to a very high temperature), the carbonates in dolomite are converted into oxides.

Another difference between the acid and basic Bessemer processes is that in the basic process the pig iron with which the vessel is charged has usually a high phosphorus content (up to 2.5 per cent) and only a relatively low silicon content (approx. 0.5 per cent), whereas the pig iron for the acid process contains from 1 to 2 per cent silicon and not more than 0.06 per cent of phosphorus. The phosphoric ores mined in England are usually rich in silica, so that a considerable amount of silicon inevitably finds its way into the pig irons produced from them, if precautions are taken to keep the sulphur as low as possible. High silicon pig irons are unsuitable, however,

for the basic Bessemer process, because the scum or slag produced, being rich in silica, and therefore acid in character,\* would attack and damage the lining of the converter. Furthermore, much silicon in the iron means a longer time for its oxidation and for the removal of the slag, so that it takes longer to bring the phosphorus content of the iron down to the desired low values.

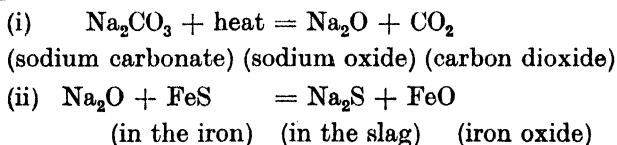
As already mentioned, the pig irons used in the basic process are usually high in phosphorus. It will be remembered that silicon is necessary in the acid Bessemer process to generate, by its chemical combination with the oxygen of the air blast, the necessary heat required, so that in the basic Bessemer process the place of silicon as a heat-provider must be filled by some other element that will not produce a destructive acid slag.

Manganese is the element used for this purpose. This metal combines with the oxygen in the blast to form manganous oxide ( $MnO$ ), a chemical reaction that generates the heat required. The manganous oxide, being basic in character,\* also neutralizes any slag acidity produced by the unavoidable presence in the charge of oxidized silicon. The best irons for the basic Bessemer process are, therefore, those rich in manganese and phosphorus, but low in silicon. Richness in phosphorus is no obstacle to the success of the process, and has the advantage that the slag produced is rich in phosphates, so that it may be crushed, ground, and sold for commercial use as an artificial manure. The native ores of Germany and France are highly phosphoric but low in silica, and the pig irons produced in these countries are particularly adapted to the basic process. It is for this reason that the basic Bessemer or Thomas process is so extensively used on the Continent. Until recently, it was hardly used at all in England, mainly because, as already explained, the phosphoric English ores are principally of the siliceous type. In order to produce pig

\* See Chapter X, "Acid and Basic Steel—The Difference."

irons low enough in sulphur from English ores, high proportions of silicon are almost inevitable; conversely, if low silicon irons are produced, the sulphur contents are generally much too high. These difficulties have been overcome by means of the *Brassert process* (see Chapter III).

This consists in smelting the ores under such conditions that an iron low in silicon is produced, irrespective of its sulphur content. The iron is then *desulphurized*, i.e. its sulphur content is lowered to the required degree, by treating the molten metal with sodium carbonate (carbonate of soda) in the ladle before it is transferred to the converter. Under the influence of the intense heat, the sodium carbonate decomposes, liberating carbon dioxide ( $\text{CO}_2$ ) as gas and oxide of sodium. The latter then combines with the iron sulphide ( $\text{FeS}$ ) in the iron to produce sodium sulphide ( $\text{Na}_2\text{S}$ ), which rises to the surface of the molten iron and forms a slag (scum) which can be skimmed off. These reactions can be represented by the following equations—



This is the principle adopted at Messrs. Stewarts & Lloyds' works at Corby in Northamptonshire, where large quantities of basic Bessemer steel are now being made.

Manganese is not the only heat-producing agent in the basic process. Towards the end of the blow or conversion period, the surplus phosphorus is eliminated by its combination with the oxygen in the blast. This reaction is *exothermic*, i.e. it gives out or generates considerable heat and provides what is required in this way to complete the purification process.

The exact details of the basic process are very similar to those of the acid process. The charge is generally taken

direct from the blast-furnace, although the pig iron may be loaded into a cupola furnace and remelted. As in the acid process, the largest plants frequently use metal mixers to advantage. Perhaps it will be useful at this juncture to describe these mixers.

They are large receptacles or reservoirs for holding molten pig iron, and, according to the needs of the user, can be made to hold from 300 to 1500 tons. In appearance they resemble open-hearth furnaces of the tilting type, and are constructed of steel or iron plates lined with either acid or basic material according to the steel-making process that follows. The molten iron is *tapped* or poured from the blast-furnace into buckets or ladles, which are emptied into the mixer by way of a trough. The mixer is tilted as required for pouring. It can be used to keep the pig iron liquid until needed: to produce a more uniform iron by mixing the products of more than one blast-furnace: or to eliminate some of the sulphur in the pig iron. This last operation takes a little over an hour, and the iron must contain a high proportion, say about 1 per cent, of manganese.

To revert to the basic Bessemer process, the molten pig iron is run into the previously heated converter or vessel, and lime is added to the charge at the same time, or beforehand with the higher silicon irons. This creates a slag rich in lime, which neutralizes the acidity caused by the unavoidable presence of silicon in the iron, and so protects the lining of the vessel from injurious attack.

The first excess impurities removed by the oxidation of the blast are silicon, carbon and manganese in the order given. When the carbon flame drops, there is no stopping of operations, as in the acid process. Instead of the vessel's being turned down, blowing is continued for from three to five minutes, during which period the phosphorus and some of the sulphur are eliminated, passing into the slag. This additional blowing period is called the *afterblow*. Its accurate estimation in order

to ensure satisfactory steel demands a high degree of metallurgical skill and experience. If the period is too greatly prolonged, the steel produced will be too highly oxidized, foamy and effervescent when cast into ingots. If the blowing period is too short, there will be an excess of phosphorus in the metal, leading to weakness in the steel.

When the blown metal is ready to be poured, the converter is turned down, as much as possible of the slag is poured off, and *recarburization* (the introduction of the requisite quantity of carbon into the metal) is carried out either in the converter before pouring or in the ladle into which it is teemed. Recarburization is effected by adding alloys of iron, carbon and manganese, known as *spiegel* and *ferro-manganese*. *Spiegel* (*spiegel-eisen*) contains about 2 per cent of carbon and 20 per cent of manganese; and *ferro-manganese* contains usually between 6 and 7 per cent carbon and 80 per cent manganese. By adjusting the proportions of these two alloys it is therefore possible to produce steels of almost any specified carbon and manganese contents. Some silicon is generally added also by means of alloys of iron and silicon known as *ferro-silicons*; alloys containing 25, 50 or 75 per cent of silicon may be used for this purpose.

In manufacturing steel by the basic process, internal heat must be generated, especially in the *foreblow* or normal blowing period, as distinct from the afterblow. If the heat is not adequate, the phosphorus oxidizes first, and continuance of the process throughout the afterblow merely badly over-oxidizes the metal, so that the resulting ingots are *badly blown* (full of gas cavities). Adequate heat gets rid of practically all the silicon as well as the carbon, leaving most of the manganese and phosphorus untouched. The afterblow proceeds at the lower temperature required, and while eliminating the phosphorus, leaves behind a desirable percentage of manganese (0.15–0.2 per cent).



Control of the temperature can be partly achieved by withholding some of the added lime until after the elimination of the carbon. The chilling effect, when the balance of the lime is added, cools the metal before the afterblow begins. A graph, based on figures quoted in Gregory's *Metallurgy*, will show clearly the variation in the analysis of the metal during the various stages of the blow. (See Fig. 25.)

Basic Bessemer steel is mainly used for rails, tyres for locomotives and carriages, axles, boiler and ship's plates, girders and sections of all types for use in the construction of bridges, etc. Wire, bolts, forgings and castings are also made from it in considerable quantities. Basic Bessemer steel is not generally regarded as being of such good quality as basic open-hearth Siemens steel, since the chemical reactions during the process are not under the same exact control. Nevertheless, for certain purposes steel made by this process appears to give satisfactory results.

In the Swedish process the converter is acid lined and the metal is taken straight from the blast-furnace, no mixer being interposed. The blow is ended as soon as the carbon has been brought down to the desired figure, which is ascertained by observation of the flame and by carrying out rapid fracture tests. Pig irons rich in manganese are used, and even at the end of the process there is always enough of the element present in the finished steel to make additions of ferro-manganese unnecessary. Swedish Bessemer steel has always been regarded, quite rightly, as material of high quality.

In the American acid process the pig irons used are comparatively low in both silicon and manganese. In consequence the heats follow each other with great rapidity, so that the process is not under quite the same rigid control as either the English acid or Swedish processes.

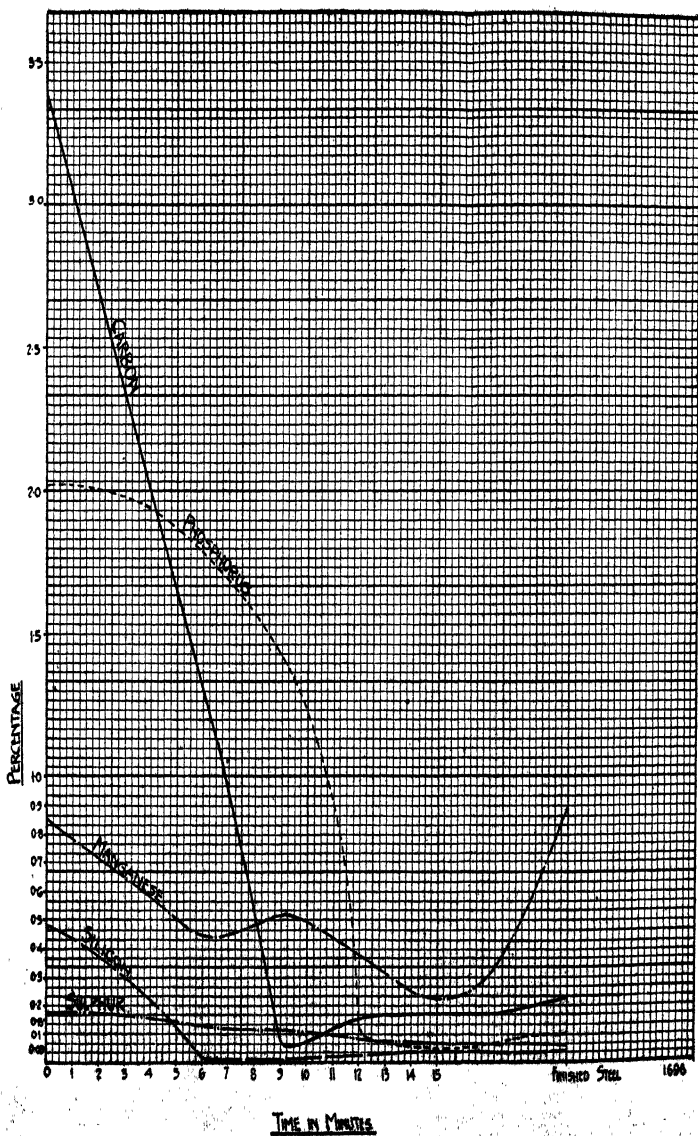


FIG. 25. COMPOSITION OF METAL DURING THE VARIOUS STAGES OF THE BLOW

(B.331)



## CHAPTER XIV

### The Open-Hearth Process

THE *open-hearth process* can be described briefly as a means of producing purified steel by oxidizing and removing the impurities contained in molten iron lying in the hearth or floor of a special type of furnace. As the name implies, the actual melting chamber is a relatively shallow hearth or furnace floor open or exposed to the action of the flame, so that the ratio of the depth of the molten metal to its surface area is small when compared with that in either crucible pots or the cylindrical Bessemer converter.

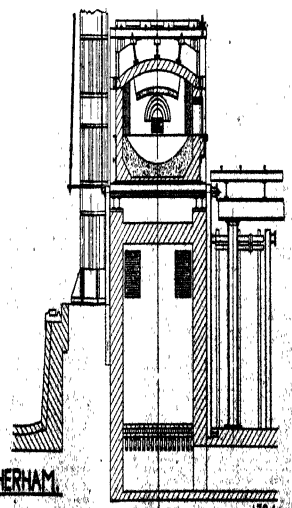
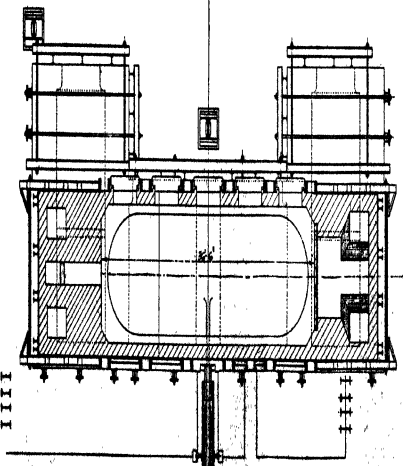
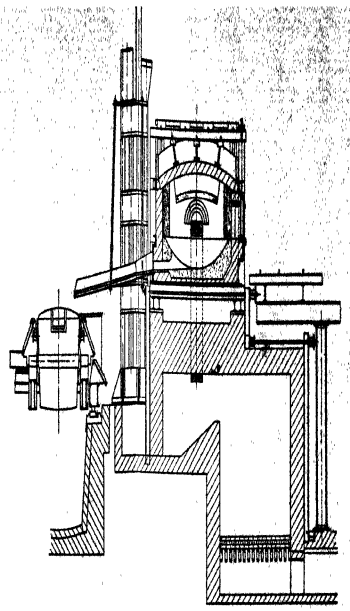
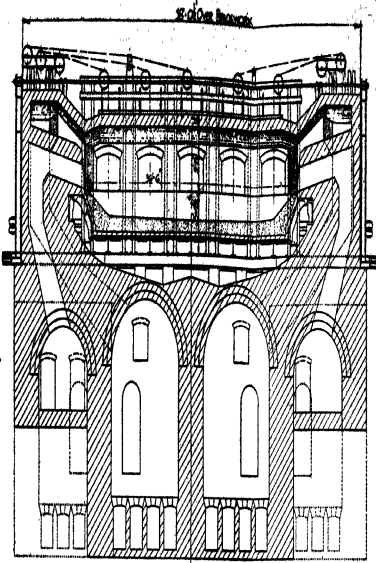
Like the Bessemer converter, the open-hearth furnace may be lined with either acid or basic refractory material.

The section of a modern basic open-hearth furnace in use at the works of the Park Gate Iron and Steel Co., Ltd., is shown in Fig. 26.

Before entering the melting chamber, the gaseous fuel (generated from coal in *gas-producers* or *gas-machines*) and the air needed for its combustion are passed, independently, through specially constructed chambers called *regenerators* or *checkers*. At the same time, the hot waste gases or combustion products are passed through another pair of regenerative chambers (sometimes referred to as *recuperators*) on their way to the chimney stack; in doing so, they give up most of their heat to the brickwork in these chambers. At regular intervals the directions of the gas, air, and waste gases are reversed, so that the ingoing gas and air are always maintained at high temperatures before they mix and burn in the actual furnace hearth. Without this preliminary heating of the gas and air before combustion it would be impossible to melt steel in the open-hearth furnace.

The hearth carries the charge, and is roofed over by an arch of refractory material, usually silica bricks, although in many basic-lined furnaces chrome-magnesite bricks are now used in constructing the roof. At each end of the melting chamber there are openings or *ports* through one set of which the preheated gas and air enter the hearth, the combustion products passing through the ports at the opposite end of the hearth on their way to the regenerators. The air is denser or heavier than the gas, so that to ensure their thorough mixing during combustion and to keep the flame from the roof, the air-port, which has the greater cross-section, is situated above the gas-port. Further, in order to deflect the flame on to the charge and so protect the roof, the ports are inclined, with the air-port having the steeper inclination. The regenerative chambers are linked with the ports by vertical flues. Below these flues are generally small chambers, known as *slag-pockets*, which collect small particles of dust and slag carried through the ports, since these particles are likely to injure or block-up the brickwork in the regenerators. The slag-pockets are readily accessible for cleaning purposes.

The hearth itself is built up, outside, of steel plates covered with refractory bricks, usually of either silica or magnesite, according to the acid or basic nature of the final lining, and the lining proper is applied over these. In the acid process, this lining consists of fine silica sand, containing a small proportion of iron oxide. Under the action of intense heat, this sand *frits*, or fuses, into a hard, solid, coherent mass which provides a safe receptacle for the molten steel. In the basic furnace, on top of the magnesite bricks are placed layers of crushed dolomite, previously mixed with a modicum of anhydrous (without water) tar. Crushed magnesite is also used as a lining material for the hearth. The furnace arch or roof and the walls are generally constructed of silica bricks, even in basic furnaces so far as the portion above the slag level



75 TONS OPEN HEARTH FURNACE THE PARKGATE IRONSTEEL W. ROTHERHAM.



heat of combustion is additional to that obtained by regeneration.

Incidentally, the gas generated from producers or gas-producing machines is a combustible material obtained by forcing steam and some air, under pressure, through glowing coal. The gas thus produced has the following approximate composition: carbon monoxide 26 per cent, hydrogen 11 per cent, methane 4 per cent, carbon dioxide 5 per cent, and nitrogen 54 per cent. The first three of these are the combustible gases which act as heat-producers, the carbon dioxide and nitrogen being inert and unavoidable gases.

The currents of the air, gas, and combustion products are reversed every twenty to thirty minutes. In modern plants this reversal period is controlled by temperature rather than by time. *Pyrometers* (temperature measuring instruments) are inserted in the air and gas checkers, and when the temperatures thus indicated fall below or rise above certain predetermined values, an automatic alarm is sounded and the directions of the gases are then reversed. By this means the heat efficiency of the furnace is improved, since reversal is placed on a more scientific basis. The gas and air are thus preheated to temperatures lying between 900° and 1200° C. before their actual combustion in the furnace occurs. The extra heat derived from this combustion serves to maintain the necessary high temperatures for making the steel.

Even after passing through the regenerator chambers, the combustion products still contain a considerable amount of available heat, as the gases have a temperature of about 500° C. In modern plants, waste-heat boilers are therefore installed, through which the waste gases are passed on their way to the chimney-stack, in order to generate steam for use in the works.

With this description of the furnace, the ground has been cleared for a detailed study of the steel-making process and, as with the Bessemer process, the acid



method, known generally as the Siemens-Martin acid open-hearth process, will be taken first. The regenerative system, already described, was invented by Sir William Siemens, but it was the Martin brothers of France who conceived the idea of melting and refining in an open hearth, as distinct from the crucible or Bessemer converter.

## CHAPTER XV

### The Acid Open-Hearth Process

IN the acid process, the pig iron used as a constituent of the furnace charge must be of low sulphur and phosphorus contents, as neither of these elements can be removed during the process. In fact, the average sulphur and phosphorus contents increase slightly, the phosphorus by concentration and the sulphur by contact of the charge, during melting, with the furnace gases. On the other hand, the pig iron must contain a reasonable percentage of silicon, otherwise, as a result of the oxidizing action of the flame, the iron oxide produced as it melts would react chemically with the silica contained in the furnace lining, so that the latter would be eroded away, with perhaps disastrous results. When the iron in the charge possesses an adequate silicon content, the oxygen in the furnace gases results in the formation of silica as well as oxide of iron, and these two oxides, which are generated together, combine chemically to form a silicate of iron or *slag*, which lies on top of the fluid charge. Abnormal erosion or eating away of the furnace lining is thus minimized. In addition, the transformation or oxidation of the silicon to silica creates heat and so assists in the melting or liquefaction of the metal.

In the actual making up of the furnace charge, a proportion of steel scrap, usually greater than the proportion of pig iron, is added, the amount used depending mainly on the type of steel to be produced, although generally an attempt is made to obtain an average silicon content of something like 1 per cent. The higher the carbon percentage required in the ultimate steel, the greater is the proportion of pig iron in the charge, so that sufficient latitude is allowed to control the oxidation of

the carbon down to the correct value. If mild, i.e. low-carbon, steels are required, less pig iron and more scrap will be needed in order that the process shall not be unduly prolonged. If the carbon content of the melted charge is too high, then obviously a longer time will be taken to reduce it to the desired figure, as it is essential to control the oxidation rate of the carbon. If the carbon drops too rapidly, there will not be quite the same control, and inferior quality steels will be produced.

High silicon charges also mean a lengthening of the time between the melting of the charge and the appearance of boiling, when carbon monoxide is being liberated from the molten bath. As already indicated, an average of about 1 per cent of silicon is generally aimed at, as this percentage has been found by experience to give satisfactory results. With a lower silicon percentage, there is a grave risk of *over-oxidation* during melting. Over-oxidation is difficult to define, but is a real factor in steel-making processes.

The materials of the charge have to contain less phosphorus and sulphur than is to appear in the finished steel. Specifications usually demand less than 0.06 per cent of either element and, in some instances, the sulphur and phosphorus contents must be less than 0.03 per cent.

Usually the pig iron is charged first, with the scrap on top. The object of this is to avoid injury to the furnace lining by the iron oxide formed in the melting process, in the way already mentioned.

During melting, a good deal of the silicon and manganese, and some carbon also, are oxidized. A slight rise in the sulphur percentage may occur owing to contact with the producer gas, which contains a fair amount of this element. The phosphorus content may also increase slightly owing to *concentration* (the oxidation and removal of carbon, silicon and manganese from the charge, as well as some iron, which enters the slag).

If low-carbon or mild steel is required, the melted charge, or *bath*, as it is technically called, should contain about 0.6 per cent of carbon. If a higher carbon steel is required, the melted or *melter sample* usually contains more than 1 per cent of carbon.

These percentages of carbon are obtained by controlling the pig-iron-to-scrap ratio, and are necessary in order that sufficient latitude shall be given in boiling-down to the required carbon content.

Metallurgists ascertain the carbon content and the general analysis of the bath by taking out a small spoonful; not, of course, the domestic spoon, but a special spoon-shaped receptacle at the end of a long mild steel rod, which is thrust into the furnace, first in the slag to give the spoon a protective coating, and then into the metal. This spoonful of molten metal is poured into a small mould or allowed to solidify in the spoon. When the test-piece thus obtained has solidified, it is sometimes quenched in water *right-out* (until quite cold) and fractured. Examination of the fractured surface reveals to the trained eye of the furnaceman or sample-passer the carbon content of the metal. (For an explanation of this, see *The Structure of Steel*, and also the notes in Chapter V.) Fracture tests for the estimation of the carbon contents are as a rule only used in the early stages of the process. Later, and particularly when the carbon content is approaching the desired value, the spoon tests are cooled and drilled and the drillings analysed by rapid means. (See Chapter XXII.) In many open-hearth laboratories, the carbon contents are determined by means of an instrument known as the *carbometer*, which is undoubtedly the most rapid method available, since accurate results may be obtained within three minutes of thrusting the sampling spoon into the molten bath. The spoon sample is poured into a cylindrical mould to which aluminium wire is added to kill the steel, so that a round test-bar of definite dimensions is obtained. This test-bar is then air-cooled or water-

quenched (depending on its approximate carbon content) and when quite cold is inserted into a cylindrical hole in the carbometer. By the turn of a handle the bar is magnetized, and when a button is pressed, the amount of residual magnetism in the bar is measured by an instrument known as a *galvanometer*. Since the amount of residual magnetism depends on the actual percentage of carbon in the steel, accurate determinations of the carbon content are possible when the instrument has been properly checked or *calibrated*.

As already indicated, the carbon content of the melt is usually much higher than that required in the finished steel. Additions of hematite iron ore (consisting essentially of ferric oxide,  $\text{Fe}_2\text{O}_3$ ) are then added to the bath. These oxidize first any silicon and manganese in the bath, and then some of the carbon, forming carbon monoxide (CO), but do not cause injury to the furnace lining, because this is now protected by both the molten metal itself and the already-created covering of slag. The added iron ore actually dissolves in the slag.

If the carbon content of the melt is too low, the bath may not be hot enough for tapping after the carbon has been virtually eliminated. A low carbon melt generally means that the average silicon content of the charge has been too low, so that not enough heat is derived from its oxidation. In such circumstances, it may become necessary to add more pig iron to the banks of the hearth in order to generate more heat and bring the carbon nearer to the desired value.

During the process, carbon elimination is stimulated by stirring the bath with mild steel rods or wood-ended rabblers.

While the various *oxidation processes* (the chemical combination of the impurities with the oxygen in the furnace atmosphere) may and do give out useful heat, most of the heat required comes from the burning of the gas. The temperature within the furnace is mainly judged

by the eye, aided by empirical "dodges" such as the insertion of a bar of mild steel of given diameter for some such specified period as ten seconds; if the end of the bar is completely melted away, the liquid bath will be hot enough, whereas if the bar is thickened, the bath will be too cold. Instruments known as *optical pyrometers* have been used to determine furnace temperatures, but too much reliance cannot be placed on the indicated values, although recently *thermo-couple pyrometers* have given most encouraging results. The notes in Chapter XXIII on the Schofield pyrometer will be found of interest in this connexion.

Shortly before the end of the process, the slag thickens up; when samples are extracted, cooled and fractured, they assume a glassy and characteristic "lime" or "marmalade" tint as distinct from the earlier opaque and dull-brown fractures. Alterations in the appearance of the slag are of great value in indicating the condition of the molten steel beneath it. In many instances, too, the slags are crushed and analysed, particularly for their iron oxide contents. By such means the process is placed under entire chemical control, which is vitally necessary if high-quality steels are to be produced.

At the end of the process, a little ferro-silicon and/or a manganese-iron alloy may be thrown in to arrest any further oxidation and elimination of the carbon and also to assist in the deoxidizing of the bath. The iron-manganese alloy commonly used is known as *silico-spiegel*, a low-grade alloy containing from 10-15 per cent of silicon and up to 20 per cent of manganese.

Two means of securing the proper carbon content are employed. The first consists in eliminating almost all the carbon, followed by *recarburization* (the addition of fresh carbon, either in the ladle or in the furnace itself). Recarburization in the furnace is achieved by adding hematite pig iron: anthracite coal is used if the recarburization is carried out in the ladle.

The second and more satisfactory method consists in tapping the furnace as soon as the carbon content of the bath approximates to that required in the finished steel.

In both methods manganese (and sometimes silicon) has to be added, usually in the ladle, in order to eliminate undesirable amounts of oxide in the metal, i.e. to kill or *deoxidize* the steel.

Before the furnace is tapped, by knocking out the refractory material from the tap-hole, or, in a tilting furnace, by tilting until the molten metal pours through the orifice, a final sample for analysis is taken.

The molten metal, when tapped, flows along a channel or *lander* (sometimes *launder*) into the ladle, and from this into suitable moulds, by means of a refractory nozzle and stopper arrangement. (See pp. 131-135.)

Additions of nickel and chromium are made in the furnace, but other elements such as manganese, vanadium, titanium, etc., are usually added in the ladle, and aluminium additions in the ingot moulds.

The chemical changes that occur during the process are indicated by the table on p. 102, taken from a contribution by Dr. W. H. Hatfield, E. Dawtry and C. W. Wright to the 1938 Steel-making Symposium of the Iron and Steel Institute.

Open-hearth furnaces range in capacity from 10 to 300 tons. Furnaces of 150 tons and over are usually of the tilting type. As a rule, the entire process takes from eight to ten hours, and a furnace will produce approximately from nine to twenty melts, according to its size; the larger the furnace, the smaller the number of melts per week.

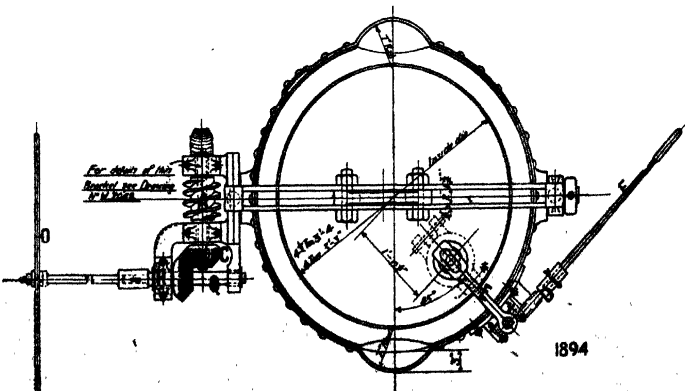
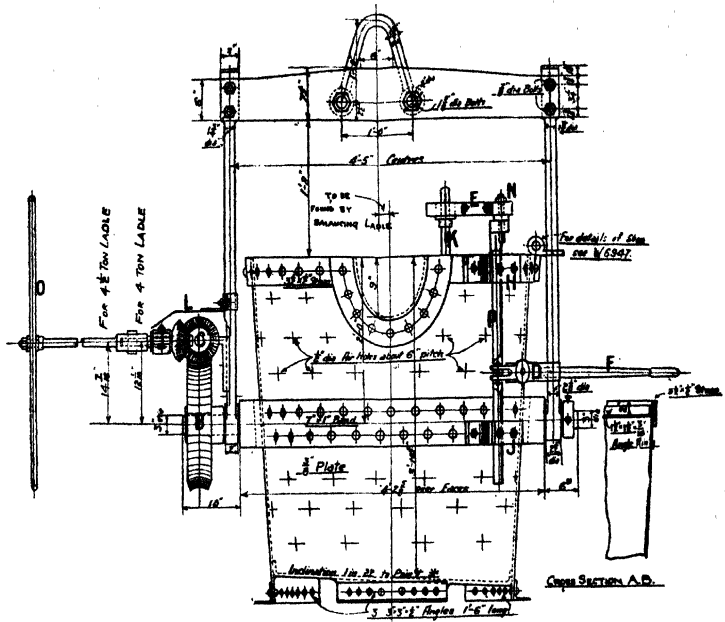
Charging of the furnaces used to be carried out by hand, but to-day is done mechanically by a *charger* or *charging machine*. The material is loaded into rectangular-shaped receptacles known as *charging boxes*. These are picked up by the charger and engaged by the end of a thickened long bar splayed out at its extremity. The

	When completely Melted	After 1 hr.	After 2 hr.	After 3 hr.	After 4 hr.	After 5 hr.	After 6 hr. and before adding Finishing Alloys
Carbon	%	%	%	%	%	%	%
Silicon	1.30	1.18	1.04	0.70	0.48	0.32	0.26
Manganese	0.55	0.48	0.08	0.06	0.07	0.07	0.07
Oxygen	0.24	0.20	0.06	0.08	0.09	0.08	0.07
	0.004	0.004	0.008	0.012	0.015	0.016	0.018
Silica (SiO <sub>2</sub> )	48.0	48.0	54.0	58.0	58.0	59.5	59.5
Iron Oxide (FeO)	27.0	27.0	18.0	12.0	11.0	11.2	11.0
Manganese Oxide (MnO)	15.0	14.5	12.0	11.5	11.0	11.0	10.5
Lime (CaO)	0.5	0.5	6.0	12.0	13.0	13.5	13.8*

\* Lime or limestone additions are made to bring the slag into proper condition and so control its oxidizing character.

(Hatfield, Dawtry & Wright)





1894

FIG. 27. SECTIONAL VIEW AND PLAN OF FOUNDRY LADLE, SHOWING NOZZLE AND STOPPER ARRANGEMENT.



operator than rotates this bar horizontally until opposite the furnace door, when the picked-up box is thrust inside and its contents deposited in the hearth.

Steel made by the Siemens acid open-hearth process is used for many different purposes, e.g. railway rails, boiler fireboxes, locomotive crank axles, springs, railway tyres, piston rods, steel castings, gun-forgings, shells, etc.

## CHAPTER XVI

### The Basic Open-Hearth Process

IN a previous chapter a section of the basic open-hearth furnace was illustrated.

In this furnace the charge consists of steel scrap and grey phosphoric, i.e. phosphorus-containing pig iron, to which are added millscale (see later) or iron ore, and lime or limestone. The grey pig iron is sometimes charged cold, but is more often withdrawn from a large metal mixer and charged into the open-hearth furnace in a molten condition. English white pig iron, which is too rich in sulphur for other steel-making processes, sometimes forms a part of the basic charge.

The materials charged into the basic open-hearth furnace do not need to be so low in phosphorus as acid open-hearth charges, and the *average* phosphorus content is about 0.5 per cent. The average sulphur content, on the other hand, must be considerably below this figure, because the furnace is not nearly so efficient in eliminating sulphur as in eliminating phosphorus. About 0.10 per cent is regarded as a maximum value, and if a lower figure is possible, as is usual, it is preferred. Low silicon in the pig iron is also desirable so as to dispense with an excess of lime to neutralize the silica formed by the oxidation of the silicon. If there is not enough lime present to satisfy the silica formed, the slag will not be sufficiently basic, and practically no phosphorus will be removed from the molten steel. In tilting furnaces, the slag first formed is run off, so that a new slag, much lower in silica, can be formed.

The manganese content of the pig iron is also important. In the first place manganese rapidly oxidizes during the melting of the charge, i.e. it combines with oxygen in the furnace atmosphere and in the slag to yield manganous

oxide, which provides a base to combine with some of the silica. (It will be remembered that a base or basic oxide is a substance that will neutralize an acid or acid oxide.)

Again, the presence of manganese in the molten metal and of much manganous oxide in the slag is an insurance against *over-oxidation* (the ingress of surplus oxygen into the molten steel). With really good basic open-hearth practice, a residual manganese content of 0.2 to 0.3 per cent is maintained throughout the whole process, and this is mainly responsible for the excellent quality of properly made basic steel.

Manganese also combines with sulphur to form manganese sulphide, which is believed to react with oxygen and thereby liberate sulphur dioxide, a gas that passes away with the waste gases from the furnace. Manganese, therefore, aids in the removal of sulphur from molten steel, so that its presence in the charge is advantageous up to about 1.5 per cent.

Another substance used in the basic process is *fluorspar* (calcium fluoride,  $\text{CaF}_2$ ), which is also added as a sulphur remover. Fluorspar has the advantage that it makes slags rich in lime liquefy at lower temperatures. In this way, the slags are rendered less viscous, and are therefore easier to work at steel-melting temperatures, can carry more lime, and can then hold more calcium sulphide in solution. The conversion of the *sulphide of iron* (ferrous sulphide) in the steel, in which it is soluble, into calcium sulphide ( $\text{CaS}$ ), which is insoluble in the molten metal but dissolves in the slag, is the means whereby desulphurization is accomplished.

A normal charge comprises approximately equal quantities of pig iron and scrap, although these proportions are varied to suit the carbon and phosphorus contents of the finished steel.

As the lining of the furnace is basic in type, the steel scrap is charged directly on to the furnace hearth or bottom. (It will be remembered that in the acid process

'it is usual to charge the pig iron, which is rich in silicon, first.) The reason is that any silica formed from the oxidation of silicon in the pig iron would, if this were charged first, attack and damage the basic lining.

As already indicated, the average carbon percentage of the charge is mainly governed by the carbon percentage desired in the finished steel, and ranges normally from 0.5 to 1.5 per cent.

The first operation is lining the hearth with the burnt dolomite, which is usually put down *under heat* (when the furnace is hot). The dolomite is first crushed, of course, and then *calcined* (burnt). After being burnt, it is again crushed and graded to such size as the steel-maker demands. Burnt dolomite disintegrates into powder or perishes when it has stood for a long time, owing to the action upon it of the moisture and *carbon dioxide* (carbonic acid gas) in the atmosphere. Such perished dolomite is useless for lining a basic open-hearth furnace. The perishing is greatest when the size of the dolomite is smallest, so that many steel-makers prefer to receive the burnt dolomite in relatively large pieces, and crush it to the required grade immediately before use.

As each layer of dolomite is put down, it is saturated with basic slag. This is to put the furnace lining into proper condition for steel-making. If this procedure were omitted, the lining would extract slag from the surface of the molten steel, leading thus to complexities and delays in the working of the heat. Even when the above procedure is adopted, several heats are required before the lining is in proper working condition.

Magnesite or chrome-magnesite hearths are sometimes employed, as indicated in Chapter XIV. One of the main objections to the use of these materials is their high first cost. *Chrome-magnesite* bricks are used in basic furnaces for the roof, walls and ports. They certainly have a high refractoriness and are *non-spalling* (do not splinter or flake off), but unfortunately readily absorb

iron oxide. This results in a swelling or growth with accompanying disintegration. Chrome-magnesite bricks are eminently suitable for the construction of roofs and the *back-walls* of modern furnaces, but are not yet so satisfactory for the port-blocks and the *down-takes* (downward running ducts) to the checkers. Future research may result in the production of material free from these objectionable faults of growth and disintegration.

When the basic open-hearth furnace has been satisfactorily lined and the hearth itself thoroughly saturated with basic slag, steel scrap is first charged, then the lime or limestone, and finally the pig iron. The reason for this order is to prevent oxidized silicon in the pig iron, i.e. silica (which is acid in nature), from attacking the basic furnace lining.

Iron ore is sometimes charged with the lime, and when molten pig iron from a mixer is being used, this is not charged until the steel scrap has been heated to a sufficiently high temperature. After the melting, burnt lime and *millscale* are added to produce a thick "limey" slag. (Millscale is the coating of oxide,  $\text{Fe}_3\text{O}_4$ , formed on the surfaces of heated ingots, blooms and billets, which cracks and breaks off during rolling or forging.) Fluorspar is next added to thin the slag and bring it to the desired consistency.\* Further improvement of the slag is brought about by periodical additions of lime and millscale. Iron ore is sometimes used instead of millscale, but millscale is favoured because it is likely to contain less silica ( $\text{SiO}_2$ ) than the ore and, therefore, requires less lime to neutralize the silica. If the amount of lime present is inadequate, there is incomplete removal of the phosphorus, since the lime will preferably attach itself to the silica present. To remove the phosphorus it must first be oxidized to its oxide,  $\text{P}_2\text{O}_5$ , which then combines with

\* Fluorspar additions are omitted when the slag is required for fertilizing purposes in agriculture, but only when there is no need to remove much sulphur from the molten metal.

the free lime to form a phosphate of lime. When the lime does not exceed that required to satisfy *both* the silica and oxidized phosphorus, the elimination of the phosphorus from the molten bath of steel is retarded.

In English and most other basic open-hearth steel-making practice, it is usual for the carbon and phosphorus to undergo simultaneous oxidation and removal, but although the ideal would be for both elements to be reduced to their correct percentages at the same moment, this is in practice seldom feasible. As a rule, the carbon content desired is achieved in advance of the necessary lowering of the phosphorus content. Thus, by the time the phosphorus is down to the right amount too much carbon has been removed, except when very low-carbon steels, say less than 0.10 per cent, are being made.

Generally, therefore, it is necessary to reintroduce carbon, i.e. to recarburize the molten steel. This is sometimes done by adding spiegel, or pig iron low in silicon, to the molten metal in the furnace. Spiegel, as earlier explained, is an iron alloy rich in carbon and manganese.

It is more usual, however, to introduce the necessary amount of carbon by the addition of anthracite coal as the molten steel is poured into the ladle. Anthracite is a hard coal, rich in carbon but extremely low in *volatile matter* (matter readily driven off by the application of heat). This method is, however, not without its disadvantages, because if the amount of added anthracite is excessive, the fluid metal in the ladle may not be completely *homogeneous*, i.e. the carbon may be unequally distributed, resulting in a lack of uniformity in the finished steel.

The experienced basic steel-maker "catches" the carbon content of the bath as it falls, i.e. he decides to tap the furnace when the molten steel has a carbon content slightly lower than that required in the finished steel. The necessary recarburization is then accomplished



by the addition of anthracite in the ladle. Heavy additions of anthracite, however, are not indicative of good basic practice.

		When Melted	2 hours after Melting	Just before Tapping	Finished Steel
		%	%	%	%
Metal	{ Carbon . . . . .	1.100	0.610	0.540	0.560
	{ Silicon . . . . .	—	—	—	0.103
	{ Sulphur . . . . .	0.042	0.038	0.031	0.034
	{ Phosphorus . . . . .	0.380	0.045	0.035	0.035
	{ Manganese . . . . .	—	0.230	0.300	0.600
Slag	{ Silica (SiO <sub>2</sub> ) . . . . .	19.40	14.00	11.80	—
	{ Ferrous oxide (FeO) . . . . .	3.33	5.76	9.42	—
	{ Ferric oxide (Fe <sub>2</sub> O <sub>3</sub> ) . . . . .	2.13	3.71	2.00	—
	{ Alumina (Al <sub>2</sub> O <sub>3</sub> ) . . . . .	1.22	1.31	1.37	—
	{ Manganous oxide (MnO) . . . . .	8.74	6.82	5.95	—
	{ Lime (CaO) . . . . .	50.50	52.20	53.90	—
	{ Magnesia (MgO) . . . . .	5.07	5.21	6.70	—
	{ Titania (TiO <sub>2</sub> ) . . . . .	0.66	0.78	0.96	—
	{ Phosphorus pentoxide (P <sub>2</sub> O <sub>5</sub> ) . . . . .	8.60	9.73	7.33	—
{ Sulphur . . . . .	0.19	0.27	0.38	—	

During the basic process, the type and composition of the slag are under rigid control as well as the molten steel beneath it.

With good working conditions, a residual manganese content of not less than 0.2 to 0.3 per cent is present in the metal throughout the whole process, and this amount of manganese is an insurance against excessive oxidation. With this proportion, the amount of work the *deoxidants*, ferro-silicon, ferro-manganese, silico-manganese, etc., have to do when added to the ladle is reduced to a minimum. In consequence, the deoxidation products that form non-metallic inclusions in the solid steel can also be reduced to a minimum. It is mainly because a good residual manganese content is always present in properly made basic steel that it resembles acid steel in quality.

Usually, the iron content (as oxide) in the slag is of

the order of 10 per cent or less, although it may rise to more than 15 per cent when dead-soft steels of low carbon contents are dealt with.

Typical metal and slag analyses are given in the table on p. 109.

Assuming that the correct carbon content is obtained uniformly with an adequate manganese percentage in the bath throughout the working period, and all the requisite conditions for satisfactory operation have been fulfilled, basic open-hearth steels are eminently suitable for a wide range of uses. For example, they are employed in enormous tonnages for such exacting purposes as girders, tin-plate, normal general constructional work, boilers, deep-drawing steels, plates of all descriptions, free-cutting steels, etc. Nickel and other alloy steels for constructional purposes are also being made in increasing quantities by this process.

## CHAPTER XVII

### The Electric Arc Furnace

It has been shown that coal, coke and gas are used as fuels in the manufacture of steel. In Chapter VIII the use of the high frequency or "coreless" electric current in the manufacture of high-quality tool and other steels was discussed.

The use of electricity in other types of furnaces for the commercial manufacture of steel must now be considered. In these, as in the high frequency furnace, electricity is used to generate the heat required, but not to bring about direct chemical reactions, as in electric furnaces employed for the production of aluminium from its ores, where direct (D.C.) current is utilized.

For the manufacture of steel, 3-phase alternating current (A.C.) is almost universally employed.

As already explained, current having a frequency higher than the normal is used in the *high frequency or "coreless" induction furnaces*, but in other types of electric furnaces, current of normal or low frequency (50 cycles) is employed. Of these other furnaces there are two main types, viz.—

- (a) the low frequency induction furnace; and
- (b) the arc furnace.

The arc furnace is the more widely employed in this country for steel production.

#### (a) THE LOW FREQUENCY INDUCTION FURNACE

In this type of furnace the charge, or metallic bath, really constitutes the secondary circuit of a transformer, the current supply constituting the main or primary circuit. By offering resistance to the electric current's passage the desired degree of heat may be

generated in the molten metallic charge. This principle was utilized in the Kjellin, Rochling-Rodenhauser and Frick furnaces, but for reasons that need not be discussed here, this method of melting and refining is not now used for the production of iron and steel, although the Ajax-Wyatt and some other furnaces, which operate on this principle, are extensively used for the melting and manufacture of non-ferrous alloys such as brass and bronze.

#### (b) THE ELECTRIC ARC FURNACE

In these furnaces, the required degree of heat is secured from the arc or arcs formed between two or more electrodes, or between the electrodes and the material to be melted. (An *electrode* is simply the pole or terminal point—in electric arc furnaces the graphite or amorphous carbon conductor—which conveys the electric current.)

When the arcs are formed between the extremities of the carbon or graphite electrodes situated above the metal to be melted, the furnaces are said to be of the *indirect arc* type, and it will be evident that the charge is then melted by radiation.

The Stassano and Rennerfelt furnaces are of this type, but are not much used nowadays, although the “*Detroit*” *rocking-arc furnace*, working on the same principle, is fairly extensively used for the manufacture of cast iron and certain non-ferrous metals and alloys.

If the arcs are struck between the ends of the electrodes and the molten metal, the furnaces are described as *direct arc* furnaces. Direct arc furnaces may be further subdivided. Thus, the *Hérault* furnace incorporates three electrodes, and the arcs are formed between the extremities of the electrodes and the metal, the electric current traversing the surface of the metal on its return to the transformers. In the *Greaves-Etchells* furnace the current, after arc-ing from electrode to metal, passes through the metallic bath and the furnace hearth or bottom to a copper-plate attached to its casing. Since the current goes

through the hearth or bottom, furnaces of the Greaves-Etchells type are known as *bottom electrode* furnaces. Many furnaces of this type are still in operation in England, but modern development has been mainly on the lines of the Héroult principle, as, for instance, in the *Siemens-Schuckert* furnace. The tendency has been towards increased melting voltages, resulting in a quicker rate of melting and a lower current consumption per ton of steel.

Electricity is not a cheap form of heating, so that it is necessary to bear cost in mind when considering its employment. The high operating cost is to a large extent offset, in the usual process, by the use of relatively low-priced raw materials, such as scrap containing fair proportions of both sulphur and phosphorus. For this reason the majority of electric arc furnace linings are basic in character and consist of dolomite or magnesite.

#### ADVANTAGES OF THE ARC FURNACE PROCESS

Apart from the removal of sulphur and phosphorus there are other incidental advantages gained by using the electric arc in steel melting furnaces. These are—

1. There is almost no limit to the temperature that can be obtained, and higher temperatures may be attained than by any other method.

2. The molten metal can be more completely purified, particularly of its sulphur content, mainly because the higher temperature permits of a fluid slag of higher lime content, which can hold more sulphur than slags formed at lower temperatures. Further, the second slag can be made of a strongly *reducing* (elimination-of-oxygen-producing) type, so that there is almost no limit to which the sulphur content may be decreased. In addition, the reducing character of the slag results in greater freedom from dissolved oxygen, and therefore greater freedom from oxide inclusions when the finishing alloys are added.

3. Air and other gases are more efficiently excluded than with any other steel-making process (except, perhaps, the crucible and high frequency furnace processes).

4. The steel can be completely killed in the furnace before tapping, so that ladle additions are almost unnecessary, apart from the readily oxidizable elements, such as titanium and vanadium.

5. The carbon content of the molten bath can be kept stationary at any desired value for any reasonable length of time. In consequence, it is possible to produce steel of carbon contents lying within a relatively narrow range.

#### THE PROCESS

In the actual electric arc furnace process, the furnace is lined with dolomite or magnesite, or sometimes a blend of both materials in varying proportions. The lining is rammed into position, and to ensure its remaining firmly in place during ramming an adhesive or bonding substance has to be added. Boiling *anhydrous tar* (tar free from water) is used. Crushed *basic slag* (slag produced during the first stage of the electric furnace process and then crushed) is also mixed with the dolomite. This slag contains *silicates* (combinations of silica with bases) which merge into and cement together the grains of the dolomite at operating temperatures. The tar burns away when the furnace is heated, so that it may be regarded as the bond at ordinary temperatures, and the silicates in the slag as the bond at steel-making temperatures.

It is possible to cut down the proportions of the impurities, sulphur and phosphorus, to barely perceptible percentages, but in practice such refinement offers no special advantages, and it is usually sufficient to aim at sulphur and phosphorus contents between 0.01 and 0.015 per cent. The elimination of either of these impurities down to this extent does not take an abnormal or unreasonable time, so long as the charge does not contain over 0.1 per cent. If the original percentage is greater







than this, however, the operations have to be lengthened, which means that more current is used, the electrodes are consumed to a greater degree and, in consequence, operating costs may become excessive.

The scrap with which these furnaces are charged is usually steel scrap made by the acid or basic open-hearth, the Bessemer, or even by the electric, process.

The ordinary process is divisible into three separate stages, as follows—

(a) Melting the scrap under oxidizing conditions in the presence of a highly basic slag to remove phosphorus, silicon, and carbon to the required degree.

(b) Removal of the phosphorus-containing slag, followed by the required degree of recarburization of the bath.

(c) The formation of a slag and atmosphere of reducing type within the furnace, in order to remove oxides from the slag and metal, and to bring about *desulphurization* (the removal of sulphur) from the steel.

The (a) stage is essentially oxidizing, and is carried out primarily for the removal of phosphorus and silicon, although the oxidation of these elements is accompanied by that of both carbon and manganese. Stage (b) is achieved by mechanically tilting the furnace to remove the slag and then adding anthracite coal to introduce the necessary amount of carbon. Stage (c) involves the addition of reducing agents such as ferro-silicon and carbon, in the form of finely-crushed coal, coke, or even old electrodes, to the slag.

When the furnace is charged, the electric current is switched on and the electrodes are lowered until arcs are struck between their ends and the metallic charge. Great heat is thereby generated, which melts part of the charge, and eventually a pool of molten metal forms between the electrodes. At this juncture, the metallurgist introduces materials designed to yield the desired kind of slag. These materials are lime or limestone, iron ore, fluorspar,

and sand. Melting and oxidation of the charge then proceed hand in hand, so to speak.

#### OBJECT OF OXIDATION

The object of this oxidation, as already indicated, is to eliminate phosphorus and silicon, the chemical reactions being somewhat similar to those outlined in the chapters dealing with the basic open-hearth process, i.e. silicon is oxidized to silica and the phosphorus to *phosphoric anhydride* (phosphorus pentoxide).

These acidic oxides then combine with the lime in the slag to yield stable silicates and phosphates.

The oxidation must be controlled, but it is generally necessary to reduce the carbon content down to about 0.1 per cent, in order to make certain that the phosphorus of the metal will be lowered to the required extent. On the other hand it is undesirable to lower the carbon content below about 0.05 per cent, particularly when the manganese content of the metal is very low, as this is liable to yield an over-oxidized bath, which will be difficult to reduce in the later stages of the process. So long as the carbon is kept within the limits of about 0.05 and about 0.1 per cent, however, the necessary oxidation of the phosphorus is effected without any undue trouble later.

On analysis the sample should reveal only small percentages of phosphorus and silicon. The amount of manganese in the sample does not matter so much, although less than 0.05 per cent is undesirable, as it indicates excessive oxidation of the bath.

At this stage there is a scum or slag on the surface of the molten steel which must be removed before the process is continued. If the slag were left on, there would, during the later stage, designed essentially to reduce oxides, be a break-up of the *phosphates* (combinations of phosphorus, oxygen and bases) in the slag and a re-entry of phosphorus into the metal, thus undoing the

work previously accomplished. The result would be not only to produce a steel too high in phosphorus, but also great difficulty in reducing oxides in the slag and in the deoxidation of the molten steel beneath it.

### SLAGGING

The removal of this first slag, or *slagging* as it is called, is one of the most important operations of the whole process, and calls for much judgment and skill. If not enough slag is removed, bad steel and troublesome working will follow, as explained. On the other hand, if slagging is not carefully carried out, much steel may be removed with the slag, so that not only will there be serious waste, but also the weight of metal remaining will be uncertain and the final analysis of the steel may be seriously affected.

After the slag has been removed (by tilting the furnace and skimming the surface with special tools), it is generally necessary to bring the carbon content to the required percentage, i.e. the bath is *recarburized*. Anthracite coal (crushed) or broken electrode is used for this purpose and is added to the slag-free surface, after a preliminary addition of ferro-silicon and/or ferro-manganese. Generally the coal will float on the metal's surface, so that the metal is stirred with a long wooden pole or sapling. This catches fire, resulting in a vigorous flare-up and violent agitation of the metal, which brings it into such intimate contact with the coal that the carbon in the coal is completely absorbed.

When steels of low carbon contents are being made, such as case-hardening steels, this recarburizing by anthracite coal is dispensed with.

### REMOVING OXIDES

The next operation is the removal of oxides and sulphur from the molten metal. Elements must be introduced

that, by their great affinity for oxygen, will reduce oxides of iron, manganese, chromium, etc., in the slag.

This reduction influences the oxygen content of the steel. Thus, if the slag contains oxide of iron, it has been shown, both theoretically and practically, that the metal beneath it will also contain dissolved oxide of iron. If, therefore, the amount of oxide of iron is reduced by adding to it some reducing element such as carbon in the form of crushed coal, or silicon in the form of crushed ferro-silicon, the result will be a transfer of some of the dissolved iron oxide in the metal to the slag. Theoretically, at all events, it should be possible to remove completely all oxygen in the form of oxide of iron from the metal. In practice, perfect deoxidation in the furnace is probably never obtained, but such perfection is certainly approached in the electric arc furnace process.

To make the reducing slag required, lime, fluorspar, crushed coal, coke or electrode, and crushed *high-grade ferro-silicon* (containing more than 50 per cent silicon) are added. The carbon in the coal and the silicon in the ferro-silicon combine with the reducible metallic oxides in the slag, and are also active agents in removing sulphur from the metallic bath.

Before considerable sulphur can be eliminated, it is essential that the manganese and iron oxides in the slag should be reduced, i.e. the oxygen removed from them by combination with elements forming stable oxides such as silica, etc., or, alternatively, gaseous oxides passing into the furnace atmosphere, such as carbon monoxide. The experienced furnaceman is able to tell when this stage is reached by the colour of the slag. At first, the slag is dark brown, or even black, and of close texture, which gradually becomes almost a true white, while its texture changes from close to spongy or open.

If the operating conditions are ideal, the cooling of this slag, after its extraction from the furnace, causes a remarkable transformation. The slag, greyish in colour,

breaks up of its own accord, disrupting itself into an extremely fine white powder. It appears to be almost alive, and the transformation must be seen to be fully appreciated. Practically, the condition when a *white falling slag* is obtained is a satisfactory assurance to the metallurgist that (i) the reducible oxides in the slag, such as iron oxide and manganous oxide, are present in very small proportions, which necessarily means that the oxygen (or iron oxide) content of the molten steel beneath it, attains a very low value, and that (ii) removal of sulphur from the molten steel is in progress.

### WHY SLAG DISRUPTS

What causes the spontaneous disruption of white falling slag? It is believed to be caused by the formation of Äkermanite solid solutions or solid solutions of lime silicates. (The significance of solid solutions is explained in *The Structure of Steel*.) Äkermanite itself has the chemical formula  $2(\text{CaO} \cdot \text{MgO} \cdot \text{SiO}_2)$ . During their cooling, i.e. after they have become solid, these solid solutions undergo a tremendous alteration in density as soon as they reach the temperature of about a blood-red heat. This change in density involves a considerable increase in volume, which is sufficient to shatter the slag into an extremely fine white powder.

Another effect is the formation of *calcium carbide* (the substance that reacts with water to generate acetylene gas), and if the slag is quickly cooled by quenching it in water or by throwing water on to it, a pronounced smell of acetylene may be detected.

Too much ferro-silicon must not be added to the slag, otherwise the steels produced will be too high in silicon. Even when the greatest care is taken, some of the silicon from the ferro-silicon, added to the slag, finds its way into the metal, and for this reason the average silicon contents of electric arc furnace steel are generally higher than those

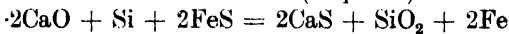
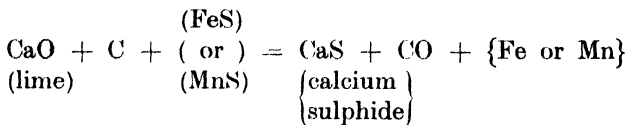
produced by the Bessemer, Siemens-Martin open-hearth, crucible and high frequency furnace processes.

Sulphur exists in the metal in the form of *ferrous* (iron) and manganese sulphides. The lime and fluorspar added to the slag remove sulphur by converting it into calcium sulphide (CaS), which dissolves in the slag but not in the metal.

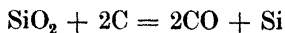
It is, however, not only sulphur that has to be reduced, but also oxygen. Indeed, the removal of oxygen from both slag and metal is a necessary preliminary before much sulphur removal will take place. Thus, the change in colour of the slag from brown or black to white not only indicates the almost complete reduction of the reducible oxides of iron and manganese it contains, but also indicates that sulphur is being removed from the metal.

#### REACTIONS

The reactions generally assumed to account for the removal of sulphur are as follows—



The condition of the slag is all-important at this stage, and additions to it must be carefully made. If too much ferro-silicon is added, or added in the form of lumps, the tendency is to produce high-silicon steels. A similar effect may result if the slags are too rich in silica and the temperature is very high, since the following reaction may then occur—



Assuming the state of the slag to be satisfactory, spoon samples of the metal are taken and quickly analysed. On receipt of the results of this analysis, the metallurgist in charge is then in a position to calculate what amounts

of the finishing alloys have to be added to the bath to give the requisite final composition to the steel. No more materials need now be introduced for reducing purposes (deoxidation). The temperature of the bath is raised to the proper degree for casting, the furnace mechanically tilted, and the molten metal discharged into a ladle.

In the Siemens open-hearth process, the steel is drawn from the bottom of the hearth or floor of the furnace, so that it enters the ladle uncontaminated with slag, but with the electric furnace, slag inevitably falls into the ladle together with the steel. In the ladle, therefore, liquid slag particles exist in an emulsified form in the liquid steel. When the ladle stands, these slag particles coalesce and rise to the surface. Time is needed for this to take place, however, and the rate at which the particles rise varies with the character and fluidity of the slag. It is obviously impossible to hold the steel in the ladle for too long a time before casting, so that it is desirable to have a slag of such constitution that coalescence will occur rapidly and the particles rise to the surface in the least possible time.

Otherwise, slag particles are entrapped in the steel when it is poured into the moulds, and may result in the presence of an abnormal amount of non-metallic matter or *inclusions* in the solid steel. To prevent this, the slag is generally *thinned*, i.e. its viscosity is decreased, just before the steel is tapped, by the addition of a certain amount of "pure" white sand.

Sometimes, as a further precaution, a small proportion of ferro-titanium is added to the ladle. It is then assumed that low melting-point compounds known as *titanates* (compounds of titanium oxide,  $TiO_2$ ) or *silico-titanates* (compounds of silica and titanium oxide) are formed, which flux out more readily than normal slag particles. Whatever its action, there seems no doubt that titanium does function as a cleanser or scavenger, not only for slag particles, but also for oxygen.



FIG. 29. WORKING AN ELECTRIC ARC FURNACE



TABLE A

Metal			Slag								Remarks					
C	Si	Mn	S	P	SiO <sub>2</sub>	MnO	S	P <sub>2</sub> O <sub>5</sub>	Fe <sub>2</sub> O <sub>3</sub>	FeO	Al <sub>2</sub> O <sub>3</sub>	MgO	CaO	CaF <sub>2</sub>	CaC <sub>2</sub>	
0-06	0-02	0-06	0-055	0-005	14-5	0-63	0-184	0-59	16-58	22-10	3-36	3-42	31-0	6-60	—	Melted sample.
1-09	0-08	0-09	0-043	0-005	16-4	0-97	0-932	0-23	—	5-85	0-20	6-41	51-5	9-50	7-85	Slag white but non-falling.
1-11	0-11	0-32	0-017	0-006	20-6	0-35	1-142	0-12	—	2-73	1-55	5-78	60-1	6-30	0-65	Tapping sample—both slag and metal in good condition.

TABLE B

Metal			Slag								Remarks					
C	Si	Mn	S	P	SiO <sub>2</sub>	MnO	S	P <sub>2</sub> O <sub>5</sub>	Fe <sub>2</sub> O <sub>3</sub>	FeO	Al <sub>2</sub> O <sub>3</sub>	MgO	CaO	CaF <sub>2</sub>	CaC <sub>2</sub>	
0-06	0-006	0-06	0-053	0-005	15-5	1-85	0-168	0-56	17-20	29-80	6-10	3-02	20-21	5-70	—	Melted samples.
0-18	0-050	0-12	0-045	0-007	19-7	0-68	0-562	0-32	—	5-57	3-15	6-32	48-24	8-95	2-85	Slag falling but not quite white.
0-34	0-210	0-38	0-021	0-015	21-4	0-23	0-840	0-25	—	3-61	0-43	6-03	58-11	6-89	0-59	Finishing samples—both slag and metal in ideal condition.

It should be noted that during the whole of the deoxidation period, precautions are taken to exclude the oxygen of the air by stopping or *luting* up the doors, roof apertures, etc., in order to facilitate the maintenance of reducing conditions.

Tables A and B show the chemical changes that take place in both slag and metal during the process.

## CHAPTER XVIII

### The Electric Arc Furnace (*continued*)

It is sometimes possible to produce steel by the electric arc furnace process without having recourse to oxidation. If this can be done, it considerably speeds up the process. The first requisite is good *clean* (pure) *electric scrap* (scrap steel that has itself been made by the electric arc furnace process). This scrap will contain many of the special elements required in the finished steel, so that at once important economies are effected in materials, and in the electrical energy required. Even more valuable, however, is the freedom of the steels from oxygen, in which respect they are superior to those made by any other process.

Where these conditions obtain, the early addition of materials for the formation of a suitable slag becomes unnecessary. A little lime and fluorspar are generally added, but nothing more until the steel is entirely liquefied. The ordinary oxidation due to the atmosphere will have sufficed to eliminate most of the silicon, but will not remove much carbon, chromium and manganese, which remain almost unchanged.

As soon as the charge is quite fluid, more lime is added, and in addition, fluorspar, ferro-silicon, and crushed coal or coke-dust. These act as reducing agents. Whatever manganese and chromium may have oxidized during melting and passed into the slag in oxide form are liberated again by these reducers, and dissolve in the metal. Removal of the slag is not necessary, because it is not desired to eliminate any further phosphorus, since this will be low enough if the scrap is of electric furnace origin.

In principle this method has great similarity with that of the ordinary crucible process, but two advantages of

importance are gained in addition—removal of sulphur and more complete elimination of oxides and oxygen. Some highly alloyed steels, such as *high-speed steel*, have been made by this process in small electric arc furnaces, though the best-known makers of these steels do not really regard the arc furnace as the ideal process for their manufacture. It must be admitted, nevertheless, that in the ordinary crucible process the resultant steel ingot is almost always higher in sulphur content than the original charge, as a result of contamination by the sulphur gases from the source of heat, which permeate the walls of the crucible. In the arc furnace, however, each successive remelting of high-speed steel scrap necessarily still further reduces the sulphur percentage. The high frequency electric crucible process, now widely used in the manufacture of fine tool steels, can be made to combine the advantages of both processes. (See Chapter VIII.)

The electric arc furnace is much used in the manner described for producing high chromium steels and irons for corrosion- and heat-resistance. Alternative methods are sometimes employed, two of which may be outlined here.

1. Low carbon ferro-chrome is diluted with virtually pure iron. The requisite amount of iron very low in carbon content, which quantity is ascertained by careful preliminary calculation, is made from ordinary scrap. Good slag and bath conditions are secured, but care is taken to avoid slags with a high percentage of calcium carbide. For this reason, *carbonaceous* (carbon-containing) matter, such as coke, is not added to the slag. The ferro-chrome is then gradually introduced into the bath, and ferro-silicon added in order to reduce any chromium oxide in the slag. As soon as the metal is completely melted, the operations are finished off in the normal way.

2. Good quality ordinary low carbon and stainless steel scrap are melted together with *chromite ore* (chrome iron ore— $\text{FeO} \cdot \text{Cr}_2\text{O}_3$ , the principal source of chromium), lime,

and fluorspar. As soon as the carbon percentage has been reduced to the desired amount, crushed ferro-silicon of good quality and aluminium are added to the slag so as to reduce the chromium oxide added as chromite. This method involves a risk of excess silicon in the steels produced, but experienced operators have been able to avoid this.

Turning now to the uses and characteristics of steels produced by the electric arc furnace process, it must be admitted that in the earlier days of this process much poor steel was made by it, largely as a result of imperfect technique. A bias against *electric steel* was thereby caused, and has even now not entirely disappeared. To-day, however, though a trained and experienced metallurgist is essential to the successful operation of the furnace, the position has changed, and large tonnages of alloy steels of first-rate quality are regularly being produced in it.

As a result, many industries have more and more adopted electric steel in place of acid Siemens steel. The aircraft and automobile industries in particular have employed it freely for engine construction, especially where alloy steels of high mechanical strength are necessary. Many steels once made exclusively by the old Huntsman crucible process are to-day made in the arc furnace. The close control of composition made possible by it results in steels of remarkable uniformity. Alloy steels are easily made because the high temperatures necessary for complete diffusion of the alloying elements are readily obtained. The process is flexible, and can be used not only for the stainless chromium steels and irons, but also for nickel, nickel-chromium, and similar highly alloyed steels for ball bearings, heat-resistance, cutting tools, etc.

#### THE ACID ELECTRIC ARC FURNACE PROCESS

Before leaving the electric arc furnace, it must be mentioned that steel manufacture by an acid-lined furnace

of the Héroult type is perfectly feasible, and is, in fact, increasing. The furnace is first lined with silica bricks, the hearth or lining proper consisting of a mixture of sand and ganister, containing a small proportion (about 5 per cent) of iron oxide ( $\text{Fe}_2\text{O}_3$ ). The hearth is generally built in layers about 2 in. thick, each layer being subjected to the intense heat of the arcs before the next layer is introduced. For this purpose, cokes or broken electrodes are placed on the hearth so that arcs can be formed between them and the ends of the electrodes.

If the steel is required in ingots, the process is mainly confined to stainless, heat-resisting, and high-speed steels. The furnace is then simply used as a crucible for melting up specially chosen materials, although the character of the slag can be so controlled that *reducing* (non-oxidizing) conditions are possible.

Steel castings are, however, often made by this process, and for these it presents advantages as compared with the basic furnace. The close control so essential in the basic is less urgent in the acid furnace. There is no need to remove the slag, and on the whole the process is speedier. It is not possible to eliminate sulphur or phosphorus in the acid arc furnace since, as previously pointed out, the removal of these elements demands basic conditions, and for this reason the scrap employed must be of high quality, low in both elements. Low silicon scrap steel can be charged straight on to the floor of the furnace, because there is no flame oxidation as with the Siemens acid process.

The scrap has first to be melted with little oxidation. Sand and broken glass are then added, if necessary, to provide a slag covering, as soon as the furnace charge is completely molten. Small quantities of iron ore or *scale* are next added to oxidize the carbon percentage to the requisite figure, while lime additions may be made to give a slag of proper consistency.

The process concludes by a prolonged heating or

*stewing* at a fairly high temperature, ferro-manganese and ferro-silicon are added, after which the molten metal is teemed into ladles.

Not quite so much oxygen is eliminated as in the basic-lined arc furnace, but steels of very high quality and of any required degree of fluidity—a factor of considerable importance in making steel castings—can be produced. Fluidity is important because many steel castings have thin sections, etc., into which the steel must readily flow.

## CHAPTER XIX

### Steel Ingots

THERE are two main methods of casting steel ingots. The first is to pour the molten metal straight into the ingot mould as one fills a cup, i.e. pouring in at the top and leaving off when the mould is full. This is the method more commonly practised and almost invariably used in casting ingots of relatively small size, such as those produced by the crucible and high frequency furnace processes.

In the second method, the moulds are filled from the bottom. This is done by pouring the molten metal down a central fireclay pipe or *trumpet* as it is called. From this trumpet the metal flows along radial fireclay channels or *runners* into the bottom ends of four, six or eight moulds, which are therefore filled simultaneously. It is as if the moulds were the rim of a wheel, the runner bricks being the spokes, and the central pipe or trumpet the hub.

This method, seemingly cumbersome as compared with the simplicity of pouring straight into the mould, has not been adopted without good reason, and there are certainly several advantages associated with *bottom* or *up-hill casting*. In the first place, splashing is minimized, if not entirely avoided. When metal is teemed straight into a mould, some of it splashes up the sides and adheres, quickly cooling and turning solid. Oxidation of the surface of these splashings then takes place. As the metal rises in the mould, it does not fully melt and re-absorb these solid blobs of metal adhering to the sides. The result is that when the ingot is withdrawn from the mould, it has a bad and irregular surface. Bottom-pouring almost completely avoids this, so that much



better surfaces are obtained, not only on the ingots but also on the blooms and billets rolled or forged from them.

Another advantage obtained from bottom-pouring is that the gradual steady rise of the metal in the moulds gives evenness and relative calm in the liquid surface, producing a smooth skin on the ingot, whereas top-pouring causes a more violent disturbance, again producing a poor ingot surface.

A bad or irregular surface in an ingot may lead to defects such as cracks and rokes (see earlier in this book) in the forged or rolled billet or bloom.

Another advantage of bottom-pouring is that the casting temperature of the whole charge is rendered much more uniform, since groups of ingots are poured simultaneously instead of in succession, with a total pouring time considerably less than when the ingot moulds are filled one at a time. This means that the molten metal remains in the ladle for a shorter period, and heat-radiation losses are lessened, so that the tapping temperature need not be so high, which is all to the good. Furthermore, with bottom-pouring, a larger diameter nozzle may be used in the ladle—a very definite advantage when the temperature of the steel is low. Again, in practical operation, bottom or uphill-pouring is advantageous because the nozzle of the ladle is less often closed. A difficulty that may arise with repeated closings of the nozzle is this. If the nozzles and stopper ends, which are made of fire-clay, are not sufficiently heat-resisting, they stick to one another when the stream of metal from the ladle is cut short. In such instances, it may no longer be possible to pour through the nozzle in the ladle bottom and the remaining metal must, where possible, be poured from the lip or spout of the ladle. This has the drawback that an unusual amount of slag may slip into the mould and so cause the steel to contain an abnormal quantity of non-metallic matter (inclusions), thereby weakening its structure and ductility.

A similar difficulty may arise when the steel is tapped "too cold" from the furnace, the nozzle then being *made-up* (stopped up) by solid steel after several ingot moulds have been filled either partly or completely. In such circumstances the *oxygen lance* has proved invaluable. This is a bent steel tube through which oxygen is rapidly passed, the extremity of the tube being inserted in the nozzle hole. This rapidly oxidizes and melts the steel in the nozzle, which is therefore cleared so as to enable the still molten metal in the ladle to flow through it. Such *burning out* of the nozzle is certainly undesirable, but a cast of steel may often be rescued by this means and the resulting ingots utilized for certain common purposes, where otherwise the steel would become scrap material, unsuitable for any purpose other than remelting.

To revert to bottom-pouring, there is one disadvantage. The fireclay channels or runner bricks along which the metal flows may, as a consequence of the intense and sometimes excessive heat, fuse to some extent and allow particles of their substance to be washed away and become entangled in the liquid steel. If this erosion is excessive, it may give rise to the presence of abnormal and harmful amounts of non-metallic impurities in the resulting solid ingot. This difficulty can, however, be largely overcome by careful control of casting temperature and careful choice of refractories.

It must not be assumed that no attempt has been made to overcome the difficulties of top-pouring. Where there is, as in large ingot moulds, a certainty of considerable splash, a contrivance known as the *tundish* is often used to reduce this. The tundish is a box lined with refractory materials and provided with nozzles of the usual ladle type in the bottom. More often than not there are two compartments, connected by a central well, with a nozzle in each. This contrivance is placed on top of the mould or moulds, or on the feeder-heads, and acts as a secondary ladle. When the double

tundish is used, the central well is kept filled with the metal from the ladle, and the liquid steel then flows over the connecting bridges into the two tundish compartments, so that two ingots are cast simultaneously. Tundish casting reduces the velocity of the flow into the mould, and therefore the *ferrostatic pressure* (the pressure resulting from the height of the metal, corresponding to the hydrostatic pressure for a head of water), so that splashing is minimized and confined to the lower surfaces of the ingots. The general surfaces of the ingots are therefore more smooth and regular. The great difficulty when splash occurs is that the globules are not re-absorbed in their entirety by the rising metal, and when the ingots are rolled, become flattened and elongated, giving rise to the surface defect known as *spelliness* or *shelliness*. During later operations such as cold-rolling and cold-drawing, spells give a bad surface to the sheet or bar, and may open out and split away.

With a top-poured ingot a *splash-can* may be used to minimize this trouble. This is made of thin sheet steel, bent roughly into the form of an open-topped cube, and is placed on the bottom of the mould before the ingot is poured. The stream of metal thus strikes the bottom of the splash-can first, so that the splashed globules are formed on the sides of the can instead of on the mould walls. The thin sheet steel of the can is dissolved by the liquid steel. By a combination of tundish teeming and splash-cans, the ill-effects of splash due to top-pouring are reduced to a minimum.

Earlier reference has been made to slag inclusions in ingots. These are non-metallic in character, and their presence may be troublesome. In the crucible and high frequency processes there is not a large mass of slag, and most of what there is can readily be removed either before or during the casting operation. In the open-heartl, Bessemer, and electric arc furnace processes, on the other

hand, the slag volume is much greater. In the ladle the slag layer floats on the surface of the molten steel, and is prevented from slipping into the mould by pouring the steel from the bottom of the ladle through the nozzle hole. Slag particles mixed up with the liquid steel rise, or tend to rise, to the surface. No mass of molten metal, however, is completely free from particles of slag that have not

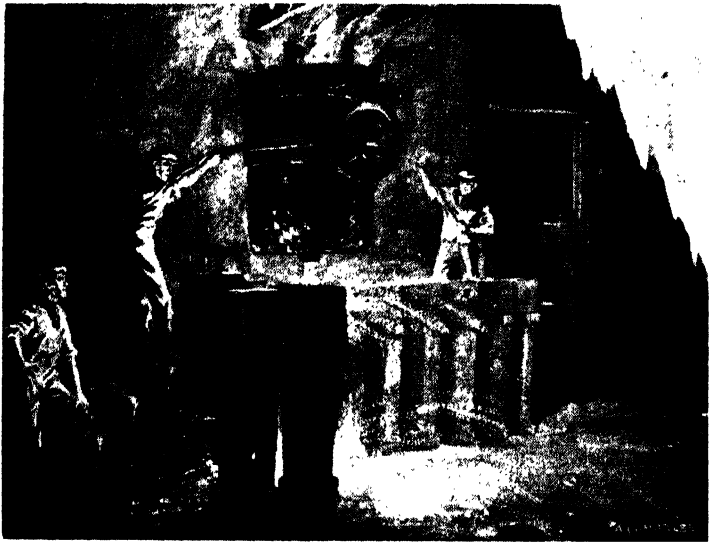


FIG. 30. TOP-POURING OF STEEL INGOTS

yet risen to the top, and these may enter the mould and become caught and held in the solid ingot.

Furnaces that teem or pour by being tilted forward, such as the Bessemer, Tropenas, high frequency and electric arc, are more likely than the fixed open-hearth furnace to produce steel with excessive *occluded* (trapped) particles of slag, since the metal and slag enter the ladle together and there is therefore a far greater likelihood that slag will be mixed up with the metal in the mould.

In smaller furnaces, to keep back as much slag as possible from entering the ladle, a kind of stationary iron scraper or barrier called a *rabble* (resembling a hoe) is placed athwart the emergent stream, whose slag-encumbered surface it scrapes clean, allowing only metal almost slag-free to issue forth.

Slag is by no means the major source of non-metallic inclusions. When liquid steel is killed, or deoxidized, in the ladle by the addition of ferro-manganese, ferro-silicon, etc., oxides of manganese and silicon are produced in it. Silicate of manganese particles are thus dispersed throughout the molten metal. If these are sufficiently fluid when formed, possessing both low density and low viscosity, they will coalesce and rise to the surface on standing in the ladle. In order to reduce the non-metallic matter from this source to a minimum, special care has to be taken in regard to the kinds of alloys used. For the best results the different oxides should be produced at one and the same time, and for this reason alloys containing two or more deoxidants, e.g. silico-manganese and silicon-manganese-aluminium alloys, are now commonly employed. By adding, for example, ferro-manganese and ferro-silicon simultaneously, a similar result may be achieved, but not so effectively. When steels are killed with aluminium (generally added to the moulds), the oxide, alumina, is produced as a consequence of the deoxidation. The alumina particles are solid even at steel-melting temperatures, and do not exhibit nearly the same tendency to rise as the more fusible silicate particles. Aluminium-killed steels are therefore always liable to contain particles of alumina.

When the slag inclusions are of minute size and present, in no considerable amount, they do very little harm. If however, the quantity present is excessive, the steel is said to be *dirty* and may be unreliable in service, particularly when the inclusions consist mainly of elongated silicates or oxide-silicates. The non-uniform distribution

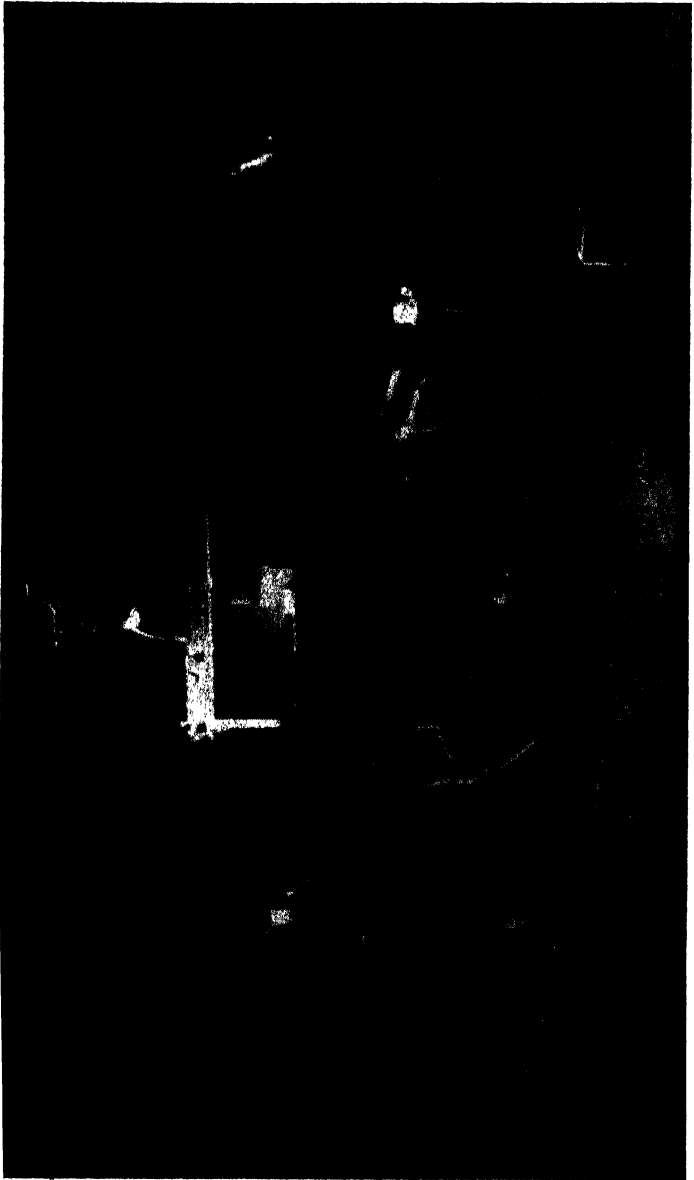


FIG. 31. CASTING AN INGOT

of inclusions may also give rise to erratic Izod impact or notched-bar values.\*

Slag particles and non-metallic inclusions become centres of corrosion, and even in the stainless steels may initiate corrosive attack of the entire surface if present in abnormal proportions, even though in all other respects, e.g. analysis, microstructure and mechanical properties, the material may be fully satisfactory. In stainless and other highly polished steels, non-metallic particles, particularly when aluminous, may be responsible for a poor surface finish.

To minimize slag—and other—inclusions a method sometimes adopted is to leave the steel in the ladle for a time before pouring. This gives the fusible particles, such as silicates, a better chance of rising to the surface. Unfortunately, for obvious reasons, the time the molten metal can be held in the ladle is strictly limited.

As indicated on p. 41, precautions must always be taken to minimize the harmful effects of *pipe* (the contraction cavity formed when properly killed steel finally solidifies in the ingot moulds). With ingots weighing more than a few hundredweights the *dozzle* method described on p. 41 becomes impracticable and *feeder-heads* are then employed for a similar purpose. These are cast iron boxes lined with firebricks, or some other heat-insulating refractory material, and placed on top of the ingot moulds. When filled with molten metal they serve the same purpose as the *dozzles* or *cores* in small ingot moulds. These *feeder-heads* cannot be satisfactorily used when ingot moulds are used *narrow-end up* (where the cross-sectional area is greater at the bottom than at the top), and are therefore almost exclusively employed for the casting of ingots wider at the top than at the bottom. Incidentally, when ingots are cast with the narrow end at the top, the top pipe or *primary pipe* is more elon-

\* For an explanation of these testing methods, see *The Structure of Steel*.

gated and may extend a considerable distance down the ingot, but a further disadvantage associated with this method of casting is the possible formation of a *secondary pipe* towards the lower end of the ingot. This is exceedingly difficult to detect, and may not be found until the final fabricated part has failed. Ingots cast in this way are generally of the low carbon *rimming* or semi-killed types, where the solid steel contains blowholes but is practically free from pipe. These blowholes weld up during hot-rolling.

To revert to killed steels, it is essential, if the primary pipe is to be confined to the feeder-head, that the metal in the head should remain fluid until practically the whole of the ingot below it has solidified. To help matters in this respect, the so-called *anti-piping compounds* have been developed. These are fine powders having heat-generating and heat-insulating properties, and added to the surface of the liquid steel in the head immediately after casting. It has also been shown by Gregory (*Journ. Iron and Steel Institute*, No. 1, 1940) that such treatment raises the position of the major segregate in the ingot.

This subject of steel ingots cannot be left without reference to *ingot cracks*. These often occur while the ingot is cooling, and are more frequent when the casting temperature is excessively high. Sometimes they run from top to bottom of the ingot; sometimes transversely, i.e. across it. Transverse cracks are often due to badly fitting feeder-heads, and the cracks are then confined to the upper parts of the ingots. The explanation is that as the fit is not perfect, there is a space through which the metal can force its way between mould and feeder-head. This creates a solid flange or rib of metal which resists the normal contraction on cooling, and so causes a fissure. It is not uncommon for these cracks to be unnoticed in advance of forging or rolling, and they then elongate and open-out, producing *roky billets* and blooms.



When the cracks are from top to bottom (longitudinal) it is usually because cooling, after the ingot has been taken out of the mould, has been uneven. Bad (irregularly surfaced) moulds may give rise to both types of cracking.

With large ingots allowed to go cold and then reheated there is a greater danger of crack development. For this reason, they are more often transferred directly from the moulds into soaking-pits, in which they are gradually *soaked* (heated until completely penetrated by the heat), and reheated to the necessary forging or rolling temperatures.

When the molten steel is poured into the mould too swiftly, cracks may be caused during cooling, partly as a consequence of excessive splash and violent agitation of the liquid surface. This may also cause excessive pipe. Too slow a rate of teeming leads to *laps* or *folds* in the ingot and, in turn, to bad surfaces on the rolled blooms and billets.

Another serious defect in steel ingots is *segregation*, the concentration of impurities in certain zones in the ingots and the blooms, etc., made from them. It cannot be entirely avoided and is due to the entanglement of the insoluble impurities in the branches of the *dendrites* (tree-like aggregations of crystals formed as the steel solidifies). If the steel is cast at a very high temperature, these crystals may extend a considerable distance into the interior, because the metal still liquid does not offer great resistance to their growth. In this instance, the middle parts of the ingot are considerably richer in impurities than the remainder.

Generally, the elements that segregate most are sulphur and phosphorus, and for this reason the *sulphur-printing* method is commonly employed in the detection of segregated zones. This consists in soaking a sheet of bromide photographic paper in dilute sulphuric acid solution (usually of about 5 per cent strength), then laying it on



FIG. 32. PHOTOGRAPH OF SULPHUR PRINT OF 2-TON INGOT. V-SEGREGATES CLEARLY SHOWN

*By courtesy of Blackie & Son, Ltd.*

the prepared polished surface of the steel to be examined, a rubbered roller or squeezer being rolled backwards and forwards to get rid of air-bubbles. Sulphide particles in the surface of the steel decompose under the action of the acid and produce dark brown stains of silver sulphide in the paper. After a time, the paper is stripped off, thoroughly washed with water, and then *fixed* in a solution of ordinary photographic *hypo*. When dried, the picture thus obtained indicates not only the segregation of the sulphur, but also that of the other elements with which it may be associated. With ingots, the picture generally shows segregated zones in the middle having a pronounced V-form, with inverted V or A segregated zones occupying positions roughly between the outside and central positions in the ingot. These zones are clearly indicated in Fig. 32.

It should be clearly understood that segregation in the ingot persists throughout its later rolling or forging, and in this respect the temperature at which the steel actually enters the ingot moulds is of considerable importance and to a large extent governs the amount of material that must be cut off and discarded from the top portion of the rolled ingot.

Blowholes, other ingot defects, have been dealt with in Chapter VII.

## CHAPTER XX

### Steel Castings

WHILE many fabricated parts can be machined from forged or rolled blooms, billets and bars, others are so intricate in shape and section that they have to be cast in moulds of sand, the voids or spaces of which are of the form required for the casting. Certain steels, e.g. the nickel-aluminium and the nickel-aluminium-cobalt magnet steels, cannot be forged or rolled, and must be cast to shape. This book would, therefore, be incomplete without a description of the processes and principles of steel founding.

The types of furnaces in which the steel is melted for casting have already been described. The Tropenas acid process, the Bessemer converter, the Siemens open-hearth, the high frequency electric crucible, and even the electric arc and the ordinary Huntsman crucible furnaces, have all been used for making steel castings. To-day, either the Siemens or a cupola furnace in conjunction with a Bessemer, Tropenas, or other converter, is used for the larger castings, although the *Stock converter*, where melting and blowing are conducted in the same vessel, is still commonly used here. Within recent years oil-fired crucible furnaces have been developed and successfully employed for the production of small castings.

#### PATTERNS

Given the steel, of which more later, the first requisite is a wooden pattern, which must be correctly made. Foundry methods have been so perfected that a pattern made in an unsuitable manner may easily increase the cost of the casting by several pounds a ton. The most accurate and uniform castings are made from those patterns which can be made to "leave their own cores,"

i.e. have no internal cavities that must be formed by inserted cores. Nevertheless, cores are often rendered essential by intricacy of design, speedy production methods, or lightness of section.

The wood used for patterns is usually Quebec best yellow pine, though in war conditions western white pine is also being used in some foundries. For small patterns and those from which large quantities of repetition castings are required, baywood or mahogany is employed in normal times, and even to a limited extent to-day, because its hardness ensures the necessary durability. With the smaller castings, especially in machine moulding, where extra accuracy is desired, steel and brass patterns were commonly used before the war.

Patterns are made from *blue-prints* (photographic prints made from designers' drawings, traced and coloured blue, the lines showing up white) supplied by the customer. Allowances have to be made for contraction due to the cooling of the steel. Sometimes, as with manganese steel, chromium- and other alloy steels, the amount of contraction varies, and only the steel-maker's practical experience can decide the allowance to be made. Even the normal standard figure may need modification in practice, because the number of cores, the intricate shape, or other obstructions to the flow of the liquid metal, affect the contraction of a casting on cooling.

When made, the pattern is carefully checked as regards its dimensions. As an additional safeguard in good steel foundries, whenever a large number of castings have to be made from one pattern, sample castings are made before the rest are proceeded with, to ensure that everything is satisfactory. Most modern pattern-making shops are provided with the requisite wood-working machinery, as well as dust-extractors to remove from the atmosphere the particles of wood-dust caused by band-saws, planing, sand-papering, and other machine tools.

Badly-made patterns produce bad castings, and as the

conditions a pattern has to meet in a steel foundry are much heavier than in any other branch of the foundry industry, it is essential to have them solid, well-designed, and well-constructed.

From the pattern shop the pattern goes to the foundry to be imprinted in the sand of the moulds. Sand is important to the steel founder, because however perfect the analysis of the steel, however successfully it may be poured, if the sands of which mould and core are made are not of the right quality, the casting will probably be defective.

### FOUNDRY SANDS

Sand for steel foundry use is of two kinds—*bonded sand* and *silica sand*. The bonded sand contains clay, and forms the shape of the casting as given by the wooden pattern, while retaining this shape without collapse when the molten steel is poured into the mould. Silica sand is a straight sharp sand containing approximately 98 per cent of silica. It contains no clay or other *bonding* (binding) material, and is used to dilute the more expensive bonded sand. It is also used in a special oil sand core-making process employed at some works in the manufacture of steel castings of extreme accuracy.

If this dilution were not carried out, the bonded sand would be too tough and resistant to the *rammers* that press the sand tightly about the pattern to form the shape for the moulds. Cores made from undiluted bonded sand would be too strong or tough, and, when the molten steel cooled, would resist its contraction so strongly as to cause a *pull* or distortion. In short, foundry sand must have collapsibility. As distinct from the sand used in casting iron and non-ferrous alloys, the sand used in steel founding must also be highly refractory.

The moist sand bought by the steel founder is carefully analysed, and tested for *permeability* (ability to be permeated by gases), compression, tensile strength, and

transverse strength. When passed as fit for use, a proportion is stored and the balance passed straight into chutes to be *milled*, i.e. the silica sand and bonded sand are mixed in the required proportions to ensure that the clay bond is distributed evenly around the grains. Milling breaks up the nodules of clay to smaller sizes so that each sand grain shall, as far as possible, be embedded in a thin clay matrix or bond. Sand after milling is very much finer, and therefore better for the steel founder's purpose.

After leaving the milling machine the sand cakes together, and is therefore passed by means of conveyers and elevators to a *spinner*, or series of blades rotating at speed. These break up the cakes of sand and aerate the mass, giving the powdery form required.

#### SAND DRYING

From the spinner, the sand is conveyed to the moulders at the various points. Moisture has been added to it in milling, but care has to be taken to keep the moisture percentage below the maximum permissible figure, or a rapid fall in the strength of the mould will result. Where the moisture content is excessive or a low moisture content is required, the sand is first dried in a *rotary dryer* (a revolving cylindrical shell through which heated air or hot gases pass to dry out and carry away the moisture). A large number of the smaller castings are cast in *green sand moulds* (moulds that have not been dried in drying stoves). These must not have above 4 per cent of moisture or defective castings may result, the steam generated by the hot metal causing gas blowholes, etc. Green sand moulding is being used more and more in mechanized foundries. Ingenious machinery for using the sand and *stripping* (removing) the patterns has been developed, eliminating the human element. Foundry sand after use is sometimes *reclaimed* and used again, special plant being installed for this purpose. In green sand practice, the sand is invariably reclaimed, and



FIG. 33. MAKING A MOULD IN THE STEEL FOUNDRY



special plants have been installed for reclaiming some dry sand. Moulds for large castings are made from sand with a higher moisture content, and then dried in stoves at 350° C. Different firms employ different moulding techniques and methods of casting. It is common practice to use a special sand for *facing*, i.e. for the faces of the mould that come into contact with the molten steel, and reclaimed sand for backing the body of the mould. Extensive use is also made of *moulder's compo*, a mixture of ganister and other substances. Furthermore, as the mould must be highly refractory, to withstand the heat and wash of the liquid steel, special paints with which the faces of the mould are painted have been developed. The backing sand must, of course, be well provided with vents so that the steam and gases formed on casting can rapidly escape.

Reference has been made to the *oil sand core process*. This is a special process for making cores. By using a special binder for the sand and mixing in a vegetable oil, a type of core adequately collapsible, yet strong and accurate enough to provide light steel castings remarkably well finished and of extreme accuracy, is produced. Sea-sand is commonly used for making cores. In recent years a large number of synthetic sands have been made, and a variety of products are on the market, such as synthetic clays, that may be added to the sand to yield desired features, e.g. quick air drying and workability. This specially applies to the U.S.A., where an abundant supply of naturally bonded sand, such as is found in England, is not possessed. The work of moulding is of great importance and involves considerable skill. Foundry manager and head foreman-moulder first examine the pattern to decide if it has been made in the best form to suit the moulding methods in vogue. If necessary, it is sent back to the pattern shop for alteration or modification. Usually this is only essential when the pattern has been made or supplied by the customer.

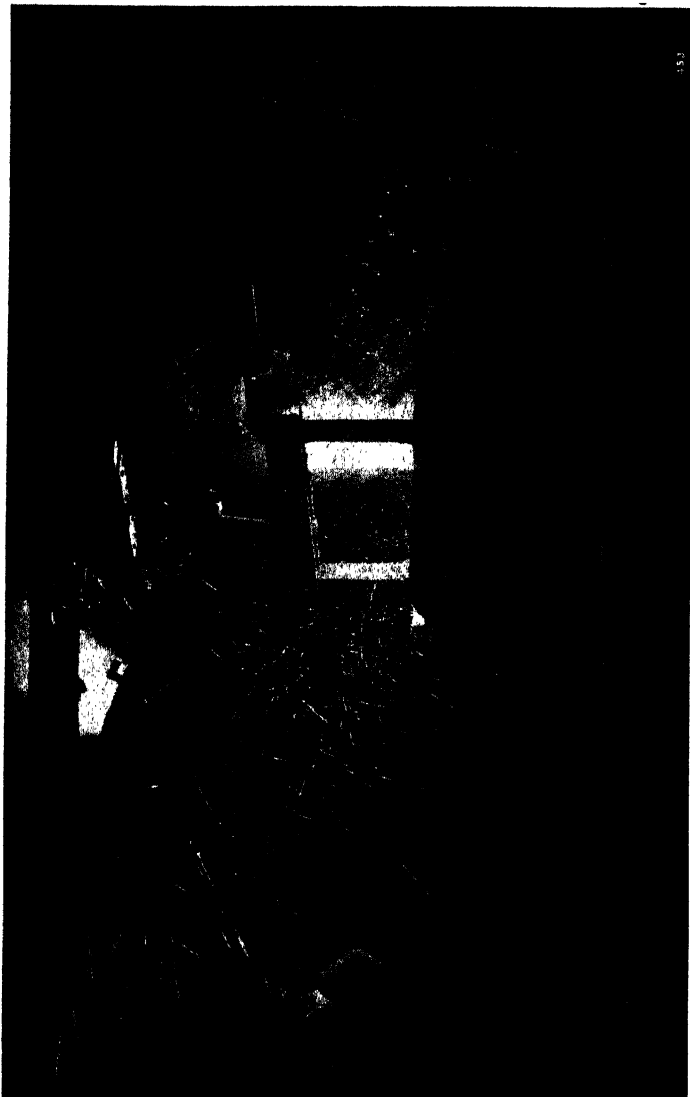


FIG. 34. POURING STEEL FROM THE TROPENAS CONVERTER

## RUNNERS AND FEEDING-HEADS

The size and position of the runner and of the feeding-heads are then discussed, the *runner* being the channel along which the molten steel passes to the interior of the mould. If care is not given to these points, the casting will suffer. Steel contracts on cooling by about  $\frac{1}{10}$  in. to the foot. That portion which has the greatest section is the last to solidify, and will have a cavity left in it if adequate feeding-heads are not provided. These heads or risers are lumps of metal often larger in section than the casting itself. In these the shrinkage takes place instead of in the casting, on the same principle as the dozzle described in a previous chapter. The heads are afterwards cut off and remelted. Heads and runners may account for about a third of the tonnage of steel produced in a foundry.

The quality of sand to be used, the size of moulding box or container for the sand mould, and other technical details, are decided before the moulders begin their work, which consists of ramming sand by hand or mechanically round the pattern, withdrawing the pattern, trimming and finishing the surfaces of the mould so as to leave clean, sharp edges and surfaces, inserting the cores, where cores are required, providing heads and runners, and closing the mould for casting.

The actual casting, after the mould has been dried in stoves, is supervised by trained foremen whose duty is to acquaint the steel plant manager with the quality of steel required. After the casting has been *poured*, i.e. the mould filled with steel, they have to see that the mould is taken to pieces and the sand and *core irons* (the pieces of iron that hold the core in place) eased away from the casting where necessary, in order to allow for free contraction and the prevention of the stresses set up by rapid and unequal cooling. These core irons are usually employed for the heavier cores, being set inside



FIG. 35. CASTING IN THE STEEL FOUNDRY

them, and run through the core print to the outside of the mould, to which they are fastened. The *core prints* are small projections on the pattern, forming holes in the mould into which the cores are set. The normal cores are prevented from shifting their position by metallic pieces called *chaplets* or *studs*, which are fastened against them in the sand. For small cores special nails with flat heads are used, and these are sometimes supported by a block of wood previously driven into the sand.

#### IMPORTANCE OF CASTING TEMPERATURE

With extremely intricate castings, success or failure depends largely on the skill with which this work is carried out. The casting temperature is particularly important in its bearing on the structure and properties, and the relevant notes in the chapter on steel ingots should be studied in this connexion.

Great precautions have to be taken to avoid cracking due to sudden changes of section, and pipe cavities due to inadequate risers or feeding-heads. In extreme instances it is often necessary to place a still hot casting in a preheated annealing stove. This applies only to castings of intricate design, which, because of varying sections, will cool unevenly after the steel has come into contact with the mould. The internal portions of the mould prevent the natural contraction of the steel, and consequently stresses that may cause the casting to break when cold are rapidly set up. These can be obviated by removing the sand while the casting is still hot, then plunging the casting into a hot stove where the temperature is raised until every part is uniformly heated. If it is then allowed to cool slowly, heat will be dissipated at a uniform rate.

Few castings are in a suitable condition for use until subjected to some form of heat-treatment, but before discussing this aspect of their manufacture it will be as well to follow the casting through its later processes.

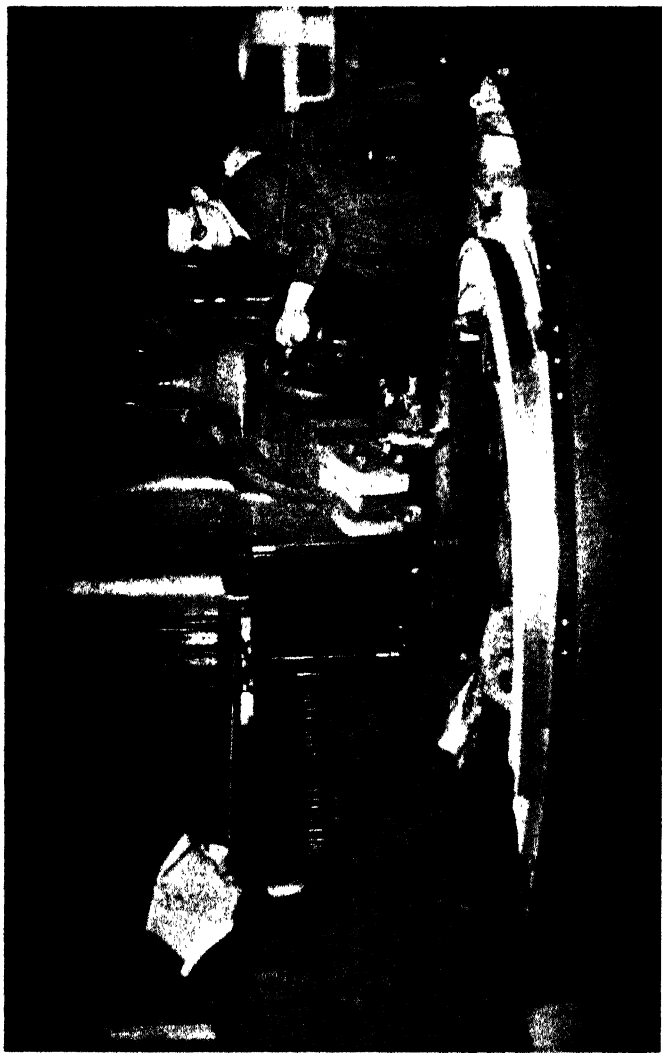


FIG. 36. MACHINING A STEEL CASTING

### FETTLING

When the mould has cooled sufficiently, it is broken open and the casting with its adherent sand removed. This sand has to be cleared away by rough dressing or fettling. First, in shot-blast rooms or chambers, a jet of chilled iron shot propelled by a blast of air at a pressure of 25 lb. per square inch is projected against the surface of the casting, and in this way the whole of the adherent sand and scale is removed. Castings up to 200 lb. in weight are now being cleaned in airless shot-blasting plants. (See p. 154.) The casting then passes to the fettlers, who remove all fins, *fashes* (rough irregular accretions of metal), and projections, by the aid of pneumatic chipping chisels or hand tools.

The feeder-heads are next removed by the oxy-acetylene torch, which burns through the metal, by circular saw, band-saw, or plane, lathe, slotter or shaper, as may be required. In good foundries this work is done in a separate machine shop so as to keep all the dust and dirt of fettling away from the costly machine tools. In the machine shop, rough machining and finished machining, as required, are carried out on the castings. Some purchasers of steel castings are unable to deal with them on their own machines or may not have machines of the proper type. In other instances, castings present such difficulties in manufacture that particular places of vital importance are apt to contain defects that will make the castings useless.

As these defects cannot be seen in the rough state, a machine cut is commonly taken across the doubtful portion, and in this way the dispatch to the customer of sound castings only is ensured.

The next operation is the final *fettling* or finishing of the casting, which is carried out by hand grinding machines specially designed for this work. Here the casting assumes its finished form, all negligible defects being welded by

electric welding, and the surfaces of the casting smoothed up where necessary with the help of a hammer and chisel and the grinding wheel. Finally, the casting passes to the forwarding shop, where it is weighed, marked, loaded up into trucks, and dispatched.

If a casting has *pulled* (warped as a result of uneven cooling, or distorted) not too severely for rectification, it can be straightened by heating it up to remove the internal stresses and reforming it by hammering or pressing.

### CLEANING

Another cleaning method is *tumbling* or *rumbling*, which consists of loading small castings into a rotating metal receptacle, so that they continually toss and tumble over one another, and against the barrel of the container, thus dislodging their adherent sand and scale by shock and friction. A recent and valuable development of the shot-blasting plant is the *Wheelabrator*, described below, in which the operator is *external* to the process, and is therefore not brought into contact with the dust and dirt. In the ordinary shot-blast chambers the operator is *inside*, though protected by a suitable head-dress.

Shot-blast cleaning of steel castings removes every trace of sand. Many castings would be useless if this were not done. For example, one small grain of sand would do great harm to a casting carrying an oil well to hold lubricant for a bearing. Many castings of intricate shape and design could not be manufactured satisfactorily but for the shot-blast apparatus, and even if hand-cleaning would do what was required, the blast would improve the appearance of the castings. Furthermore, the treatment reveals many small defects that might otherwise pass unnoticed, and enables the founder to judge whether these are important or negligible.

The *Wheelabrator* is an airless shot-blasting plant in which chilled iron shot, instead of being sprayed on the casting by compressed air (as in the static shot-blast



chambers earlier mentioned), is thrown on by centrifugal force at high speed—2400 r.p.m. Work is done at four times the speed of a pressure plant with only one-tenth of the power, and the finish is vastly improved. The apparatus is far more hygienic than the pressure chamber, since the castings are cleaned in a dust-tight chamber, no operator being required inside the chamber, as with the pressure plant. All risk of silicosis is thereby eliminated.

Castings up to 200 lb. in weight may be cleaned in a plant of 36 in. by 42 in. size, and such a plant will give an output of from 1 ton to 30 cwt. an hour. Larger-sized plants measuring 48 in. × 48 in. are also being made, and one of these will do the work of three static pressure chambers.

#### HEAT-TREATMENT

During the last few years the heat-treatment of steel castings has been intensively studied, and in few high-class steel foundries to-day are steel castings allowed to leave the works without some form of treatment.

The first essential is a furnace in which temperature can be easily controlled and kept uniform throughout. Producer gas (see page 47) is a satisfactory heating medium, as the operator can so adjust gas and air as to reduce scale to a minimum, and keep the temperature constant once the requisite heat has been attained. The latest type of furnace, however, has a special burner equipment utilizing town gas, and gives working temperatures between 500 and 1000° C. when the bogie is loaded with charges up to 9 tons in weight, with a temperature variation of not more than 25° C. in any part of the furnace. A recording pyrometer is necessary to ensure proper temperature regulation.

The heat-treatment proper comes under the headings of annealing, normalizing, or quenching, followed by tempering.

## ANNEALING

For carbon steels this comprises heating up the castings to not more than  $50^{\circ}\text{C}$ . above the  $\text{Ac}_3$  point in the iron carbon diagram shown (Fig. 37). The heat-treatment temperatures are shown by the dotted line. (For a full explanation of this diagram see *The Structure of Steel*.) The

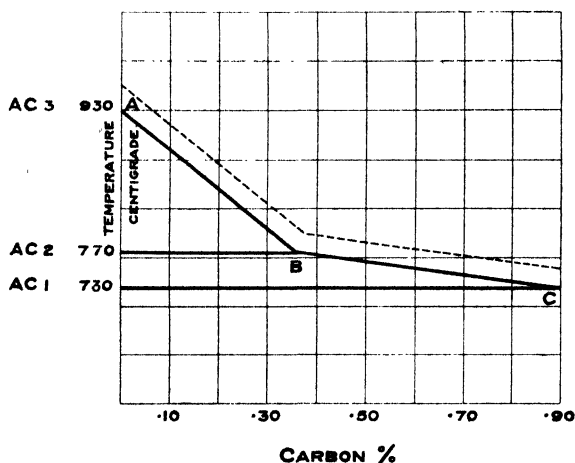


FIG. 37. IRON CARBON DIAGRAM

castings are *soaked* (heated right through) at these temperatures for several hours, the exact period depending on the mass of the castings. They are then cooled in the furnace. Annealing, as earlier indicated, removes the stresses set up in the casting during cooling from liquid to solid state and brought about by uneven contraction of the metal due to varying thickness. These stresses, as already stated, are sometimes so great as to necessitate placing the castings in a hot furnace before they have cooled below a red heat. Otherwise they would crack and become useless. Annealing also refines the crystalline structure, which is extremely coarse and angular in the

as cast condition, and so improves the ductility and resistance to shock.

### NORMALIZING

After being removed from the mould, the casting is heated up to  $50^{\circ}\text{C}$ . above the  $\text{Ac}_3$  point and allowed to cool in the air. This produces a finer crystalline

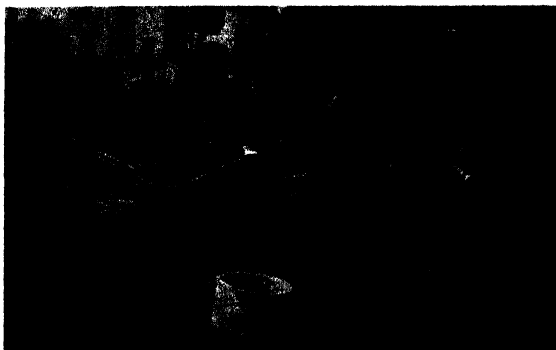


FIG. 38. QUENCHING A MANGANESE STEEL CASTING

structure than annealing and also improves the yield-point and tensile strength, the ductility remaining about the same, although the reduction of area per cent value is raised. If the castings are made of high tensile material, the ductility may, however, be reduced. Normalizing is not carried out if unusual variations of metal thickness in different parts of the casting occur, as this may cause cracks. With intricately shaped castings annealing is more satisfactory.

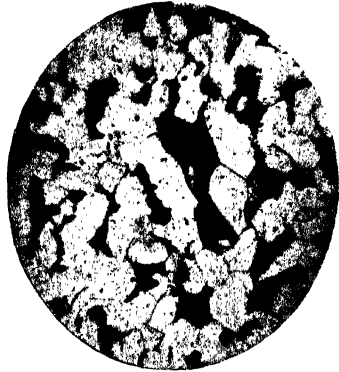
### QUENCHING AND TEMPERING

This treatment is seldom given, as it involves a risk of cracks due to rapid cooling and the unequal thickness of metal in castings. Where the metal is of almost uniform thickness, however, it can be employed with benefit. The annealed casting is heated to about  $50^{\circ}\text{C}$ . above the  $\text{Ac}_3$  point, and quenched in water, oil or air, according to the

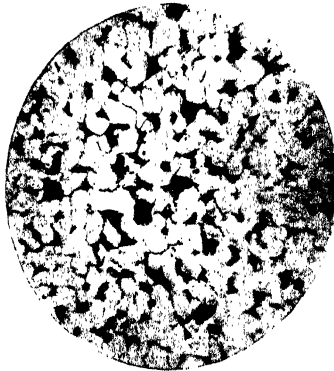
composition of the steel, then reheated to a temperature below the  $A_{c1}$  point and cooled in air. This treatment



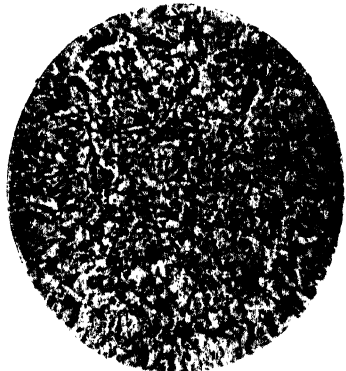
STRUCTURE AS CAST. 200 MAG.  
CARBON .22



ANNEALED AT 920° C.  
200 MAG.



NORMALIZED AT 920° C. 200 MAG.



QUENCHED IN WATER AT 920° C.,  
REHEATED TO 600° C. AND COOLED IN AIR  
200 MAG.

FIG. 39

raises the ultimate strength, yield-point and reduction of area, as well as the resistance to shock as shown by the Izod impact test.

Mild Steel Casting (C. 0.20, Si 0.25, Mn. 0.96, S. 0.050, P. 0.048.)	Annealed	Normalized	Quenched in Water at 920° C. Tempered at 600° C.
Yield-point. Tons per sq. in..	14.5	16.5	22.2
Ultimate Stress. Tons per sq. in. . . . .	29.2	31.4	33.8
Elongation % . . . . .	29.0	27.0	26.0
Reduction of Area % . . . . .	45.4	44.0	46.4
Alloy Steel Casting (C. 0.42, Si 0.28, S. 0.045, P. 0.051, Mn. 0.92, Cr. 0.56)	Annealed	Normalized	Quenched in Water at 920° C. Tempered at 600° C.
Yield-point. Tons per sq. in..	27.0	29.6	55.0
Ultimate Stress. Tons per sq. in. . . . .	52.6	57.0	64.8
Elongation % . . . . .	13.0	10.0	9.0
Reduction of Area % . . . . .	18.4	17.6	15.2

The microstructures of a piece of steel casting in the *as cast*, annealed, normalized, and quenched and tempered conditions, are shown in Fig. 39, while the tables reproduced above show actual typical tests from a hard alloy steel casting and a mild steel casting.

From these tests it will be seen that by quenching and tempering the maximum stress is considerably improved, together with the yield-point. It would, however, be fatal to subject the majority of steel castings to such treatment.

### INSPECTION

The more efficient steel foundries often maintain their own inspection departments, independent of the production staff. Usually the inspectors report straight to a director or manager of the firm. In this way a close and immediate check is kept on careless production methods. A record

of every casting made from each cast of steel supplied to the foundry is kept, and as each heat is analysed day by day, it is easy to trace, and, if necessary, scrap during the early stages of manufacture, any castings not conforming to specification. A highly skilled inspector also examines all castings before dispatch to ensure their correctness. As explained in *The Structure of Steel*, magnetic tests and X-rays are now being used to detect internal flaws and defects in steel castings and in welded parts, although the application of these methods is strictly limited to castings of relatively thin section.

## CHAPTER XXI

### Refractories in the Steel Foundry

SAND is not the only material of vital importance to the manufacture of steel castings. One of the principal items of steel foundry consumption during the year is bricks, not the ordinary red bricks for house building, or the blue bricks for walls and pavements found in the Midlands, but special refractory bricks resistant to abrasion, heat, and other exacting steel foundry conditions. The importance of refractories to the steel foundry is often overlooked, but they are indispensable at many stages in the progress of the casting from molten pig iron to finished product.

The refractories themselves have to withstand wear and tear in service, since no one type of refractory will satisfactorily meet all the specific conditions encountered. It is necessary, therefore, to decide which is the most important factor in the particular conditions of use. The refractory bricks mostly used in the steel foundry are bought from specialized British manufacturers with experience in supplying refractory bricks for specific applications. After careful testing at their makers' works, these bricks come from various parts by rail, or, in emergency, by road, and are deposited in a central brick store. From this store they are drawn upon as required by the different sections of the foundry. (It should be borne in mind that refractory bricks are used in other steel making processes besides those for the manufacture of steel castings, hence the need in many works for a central store.) The bricks required exclusively for foundry use are taken from the central store to the foundry brick store, which is a subsidiary devoted solely to the refractories of the foundry.

One of these stores is devoted to the housing of what are known as *common firebricks*, a term that will shortly be explained, and the other store is for the housing of silica and magnesite bricks.

It will thus be seen that in general three main types of refractories are employed in the steel foundry. The first of these is the "common" firebrick; but the use of the word "common" in this connexion should not be misunderstood. It has no relation to quality, but only to the extensive character of use: in other words, this brick is more commonly used than the other types of refractory bricks. Actually *common firebricks* are of high quality. They are used for conditions in which temperatures up to 1000° C. will be encountered, and have the following analysis—

ANALYSIS	
Silica . . . . .	53·8 per cent
Alumina . . . . .	39·21 " "
Iron . . . . .	2·72 " "
Titanic oxide . . . . .	1·6 " "
Lime . . . . .	0·3 " "
Magnesia . . . . .	0·71 " "
Potash . . . . .	0·75 " "
Soda . . . . .	0·6 " "
Loss when calcined . . . . .	0·21 " "
	99·90 " "

In this analysis the essential elements are alumina and silica, which compounds are highly resistant to heat, and for this reason constitute the basis of firebrick.

*Silica bricks* are a quite different class of refractory, used only for certain furnaces in which the conditions are exceptionally severe. They have the analysis shown at the head of the following page.

The particular furnaces for which these bricks are used will be mentioned later in this chapter.



Silica . . . . .	95.75 per cent
Alumina . . . . .	0.76 " "
Iron oxide . . . . .	0.87 " "
Titanic oxide . . . . .	0.03 " "
Lime . . . . .	1.63 " "
Magnesia . . . . .	0.27 " "
Alkalis . . . . .	0.49 " "
Loss when calcined above 110° C. . . . .	0.17 " "
	<hr/>
	99.97 " "

Magnesite bricks are used in the electric arc and basic open-hearth furnace, and have a composition similar to that shown below—

Silica . . . . .	2.50 per cent
Alumina . . . . .	2.63 " "
Iron oxide . . . . .	4.37 " "
Titanic oxide . . . . .	Trace
Lime . . . . .	0.06 " "
Magnesia . . . . .	89.96 " "
Alkalis K <sub>2</sub> O . . . . .	0.05 " "
Na <sub>2</sub> O . . . . .	0.10 " "
Loss when calcined above 110° C. . . . .	0.10 " "
	<hr/>
	99.77 " "

The first use of refractories in steel casting manufacture is in the cupola furnace. (See p. 73.)

The best quality firebrick has to be used in this furnace because of the severe shock and abrasion encountered during the charging of the cupola. It will be realized that the loading into this furnace of lumps of pig iron and scrap must cause severe abrasion of the furnace lining owing to the impact of solid pieces of metal upon it, so that the brick used must be well able to withstand this form of wear and tear, as well as the melting heat. After the charge has been melted, the mixture is tapped into a receiver, a steel cylinder lined again with the best quality of firebrick identical with that used in the cupola. Here, however, conditions are less exacting than in the cupola, because the wear and tear of a solid charge have not to be encountered.

From the receiver the molten metal is run down a chute into the *Tropenas acid converter*. With the introduction of this mixture into the converter, a very different set of conditions from those obtaining in the cupola or the receiver is encountered. In the first place, the temperature in the converter is several hundred degrees higher than in the cupola, largely because the introduction of the air blast creates chemical reactions that generate heat. For this reason, the temperature resistance of the refractory bricks has to be considerably higher, and silica bricks of the type previously described are always used. What is more, these bricks have to be made in special shapes to suit the form of the vessel. If they were to fail, the consequences would be serious, because not only would the casing of the converter be seriously damaged, but there would be, in addition, a considerable delay in the production of the large castings for which this converter charge was intended, and in bad cases the entire melt, consisting of several tons of steel, might be lost.

Another use for fireclay refractories is for the sleeves and stoppers used on the stopper rod to regulate the flow of steel from the ladle when making an ingot or casting. Illustrations of these sleeves and stoppers are shown in Fig. 27, facing p. 102, and also in Fig. 40. The refractories used for this purpose are of special firebrick designed to withstand the action of molten steel.

Steel castings are also made by the electric arc furnace process, and here a basic lining is employed. For this reason silica bricks cannot be used, and therefore magnesite, dolomite, or other basic refractories have to be employed. There are, of course, works in which the electric furnace has an acid lining, and in these instances it is quite permissible to use silica bricks or other siliceous lining.

There are other important uses in the steel foundry for refractories. There are, first, the drying stoves in which the sand cores and moulds are dried before being

closed up to make the casting. These stoves are not subjected to a high temperature, however, so that the refractory bricks for building them need not be of so high a quality: in fact, it would be quite possible to use ordinary red builders' bricks for these stoves, but actually, although not absolutely necessary, refractory bricks are often used

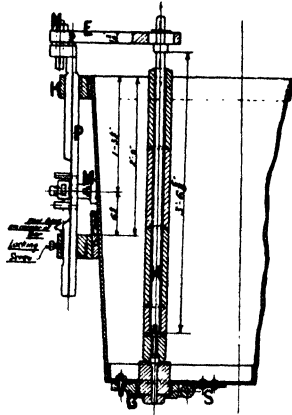


FIG. 40. LADLE NOZZLE AND STOPPER

for preference. The only difference between these bricks and the higher quality bricks used for the severer conditions is that the alumina, etc., occur in smaller percentages. The most important thing in these stoves is that suitable insulation should be provided to conserve the heat during drying. For this purpose, between each two courses of firebrick is laid a course of insulating brick. This is a different kind of refractory from any previously discussed. These bricks are porous and composed of a *diatomaceous* or fossilized earth. This course of insulating bricks keeps the heat in the stoves. As a refractory brick for other purposes, such as those enumerated for the steel foundry, it would not be sufficiently strong.

The annealing furnace is lined with the best quality firebricks, which have to withstand a temperature up to

1000° C. approximately. The top of the carriage or bogie on which the castings are placed is also of firebrick, of a special quality, possessing great mechanical strength, in order that it may withstand not only the heat of the furnace, but the weight of the casting.

## CHAPTER XXII

### The Steel Works Laboratory\*

#### Its Work and Apparatus

" WE have analysed the sample of steel sent to us, and the following is the composition of the material . . . "

Behind that simple statement, so frequent in steel works correspondence, lies a marvellous story, the story of skilled chemists and metallurgists and the intricate and delicate apparatus they daily employ. Only those with a first-hand intimate knowledge of chemical research and investigation in a steel works are fully equipped to explain and describe the amazing complexity, and even the ordinary routine work, of the metallurgical laboratory.

General routine laboratory work may be roughly classified into four categories: (1) the checking of casts of steel made; (2) the analysis and control of production materials; (3) the analysis of customers' samples; (4) the investigation of failures and defects.

Routine analyses carried out of casts of steel at one large steel works consist of—

1. Steel foundry cast analyses. From each cast obtained from the Tropenas converters in the steel foundry, spoon samples are taken and sent to the laboratory for analysis. Analyses are reported at the earliest possible moment, so that any castings not complying with the specifications may be isolated, thus preventing wastage of money in useless heat-treating and machining.

2. Electric arc furnace cast analyses. Samples are taken during the melting process and analysed, enabling the necessary alloy additions to be calculated. The alloys themselves are then added to bring the steel up to the required specification. Samples are also taken of the finished cast.

\* In the compilation of this chapter the authors have been greatly aided by the enthusiastic co-operation of Mr. F. C. Swannack, of Messrs. Edgar Allen & Co., Ltd.

3. High frequency electric crucible furnace analyses of samples taken on casting.

4. Acid and basic Siemens furnace analyses of samples taken during the melting process to control the *working* of the charge and, on casting, to check the final analysis. The large variety of steels made by the electric arc and high frequency furnaces, including tool steels, manganese steels, stainless steels, etc., demands extreme versatility on the part of the analyst. Speed and accuracy are essential to prevent financial losses due to delay in correcting and controlling later heats. Each heat is analysed for the essential constituents. The ease with which these furnaces are controlled facilitates the carrying out of these routine analyses. Not only steels come within the purview of the metallurgical chemist in a steel works. At any moment the chemist may have to carry out elaborate analyses on such materials as ferro-alloys, deoxidizers, pig iron, coal, coke, slag, refractory bricks, sands, and even flue gases, materials forming the basis of steel production. The reader will find later in this chapter a full account of the analytical procedure for pig iron.

The methods of microscopic examination have already been described in *The Structure of Steel*. It is necessary only to point out that examination of this kind, besides being invariably employed at "inquests" on defective materials, is gradually taking more part in routine control. Specifications stipulating *grain size*, for example, freedom from inclusions, and general soundness, are quite common, and the number of such specifications is to-day rapidly increasing, hence the importance of microscopic examination at every stage of investigation into modern steels.

The general laboratory is fitted with fume cupboards (see Fig. 41) of the latest and most efficient type in order to remove noxious fumes from the laboratory, and most of the chemical operations involving the production of fumes are conducted in these cupboards.

When a sample of steel is sent to the laboratory, either

by a customer or by the works production staff, as defective, the fractured surface, if any, of the material is first examined with the naked eye. The experienced metallurgist can tell from optical examination alone a number of important things. For example, he can obtain some idea whether the failure of the steel has been caused

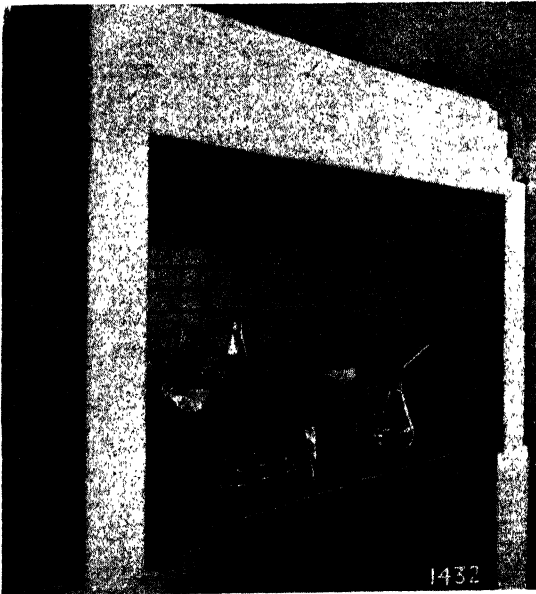


FIG. 41. TYPICAL FUME CUPBOARD

by faulty heat-treatment, fatigue, or any other recognizable defect. These facts having been noted, the more complex and systematic methods of investigation are then brought into play. In the first place, the sample or specimen is subjected to the Brinell Ball Test, described in *The Structure of Steel*. The sample, of course, has to be used with discrimination. For example, if it is extremely thin, the ordinary Brinell test ceases to be

accurate enough, and it is necessary to use a machine such as the Hardometer with a one millimetre ball, or diamond. This test gives, of course, a measure of the hardness of the material.

The next process is direct analysis. To obtain this it is necessary to drill the specimen and use the drillings as the basis of investigation. Here again, care has to be exercised in procuring these drillings. For example, if the surface of the specimen has, for some reason, suffered heavy decarburization, to take drillings from the surface, or embodying a proportion of the surface, will render the analysis inaccurate and therefore futile. For this reason, the specimen is first ground to remove any trace of decarburization. For the benefit of those not entirely familiar with technical terms, it may be explained that the presence of decarburized portions among the drillings would lead to insufficiency of the carbon percentage figure in the final analysis, a percentage that would not represent the actual carbon content of the steel. The surface having been ground, the specimen is then drilled according to its thickness, avoiding the centre of bars, for the reason that if there is any segregation of impurities at all, it is likely to be in the centre, a legacy from the ingot stage. If the sample is too hard to be drilled, it must be sufficiently softened. Wherever possible, specimens for microscopical examination are first removed. The analytical processes for steel will shortly be described in detail, but before this, it should be mentioned that other methods of investigation, such as the sulphur print, the macroscopic examination, and the microscopic examination, are also employed. These processes have, however, been fully described and illustrated in *The Structure of Steel*, and there is no point in repeating these descriptions here.

With case-hardening steels, it is usually the core that has to be analysed, which generally means that the hard case must be machined off after softening.

In the actual analysis of the steel the first and most



important thing the chemist has to do is to ascertain whether the specimen is an alloy steel or a carbon steel. If he knows in advance which it is, his problem is simplified, but if not, he has to find out. Not only is it often difficult to decide whether a material is an alloy steel or a carbon steel, but it is difficult sometimes even to decide whether a material is steel or iron. The reason it is so important to decide in advance on the type of steel is that the result governs later analytical procedure. The presence of certain alloys would render particular methods of analytical determination useless.

Carbon has been likened to the blood of steel, and is certainly a most important constituent. Chromium is one of the commonest alloying elements. As the procedure in the estimation of carbon content by analysis is not interfered with by the presence of chromium, one of the first operations of the chemist is to test for chromium by dissolving the drillings, for preference in dilute sulphuric acid. In some instances hydrochloric acid is necessary. The chromium is later converted to potassium dichromate. The chromium content of the potassium dichromate is obtained by a process known as *titration*. In volumetric analysis, titration is a process of ascertaining the quantity of any given constituent present in a compound by observation under the application of standard solution. The actual procedure is to add one liquid to another from a burette. This addition is carried out very slowly and carefully, drop by drop if necessary, until the desired chemical reaction is complete. When one chemical is added to another, the one acts upon the other in such a way that a third product is formed with properties different from those of the two original chemicals, forming a new substance. This is termed a *chemical reaction*. Thus, in the analytical procedure described for chromium, the quantity of ferrous sulphate required to complete the reaction, which consists of removing oxygen from the potassium dichromate and reducing it to chromium sul-

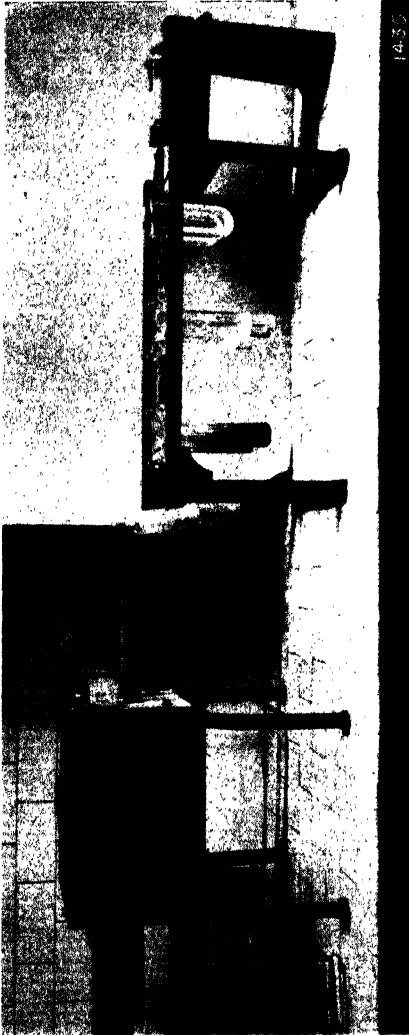


FIG. 42. APPARATUS FOR CARBON DETERMINATIONS

phate, is a measure of the chromium content. This seems obscure until it is realized that one millilitre (1000th part of a litre) of ferrous sulphate of a certain strength equals a known percentage of chromium. Thus, with a known weight of drillings, it is possible to calculate the amount of chromium present. If, on the other hand, no chromium is present, the next procedure is to analyse for silicon, sulphur, phosphorus, and manganese, which, after carbon, are the principal elements of ordinary steel.

Carbon exists in the form of carbides of iron, manganese, etc. It is determined by heating a known weight of drillings at approximately  $1000^{\circ}$  C. in a stream of oxygen. Carbon dioxide ( $\text{CO}_2$ ) results and this gas is absorbed in a suitable medium, e.g. soda asbestos. As it is known that carbon dioxide contains 27.27 per cent of carbon by weight, the weight of the carbon dioxide thus gives a measure of the carbon content in the steel, this weight of the carbon dioxide being obtained by weighing the soda asbestos before, and again after, it has absorbed the carbon dioxide gas. In this analytical process, elaborate precautions are necessary to ensure that no accidental contamination takes place. Fig. 42 shows a typical apparatus employed in carbon determinations.

*Silicon*: In steel this exists in the form of silicides, and a determination of the silicon percentage in the steel is obtained by dissolving a known weight of drillings in hydrochloric acid. The solution is *taken to dryness* (boiled dry), and the residue is then baked ( $150$ – $200^{\circ}$  C.). Silicon, in steel, it may be explained, forms *silicic acid* ( $\text{SiO}_2$  plus water), which, on being baked, loses its water content and, on the addition of dilute hydrochloric acid, remains insoluble, whereas the iron (as chloride) is dissolved. Thus the  $\text{SiO}_2$  can be filtered out through a filter paper, washed clear of impurities and, when the filter paper has been burned away in a muffle furnace, pure white silica remains, which is weighed. This contains 47 per cent silicon, hence the silicon can be calculated from a known weight.

*Sulphur:* In plain carbon steel the sulphur generally exists as a sulphide of manganese, sometimes both. The combustion method of determination is mostly used; 1 gramme of steel drillings is weighed into a small boat of special refractory material, which should be sulphur free, and this is placed in a tube contained in a specially designed electric furnace maintained at a temperature of 1250–1300° C. A stream of pure oxygen is passed through the tube for about four minutes, and the gases bubbled through water contained in a suitable vessel. The sulphur evolved from the steel as sulphur dioxide gas is collected by the water, where it forms a solution of sulphurous acid. Hydrochloric acid is added to this solution, and is followed by a few millilitres of starch solution. From a burette, a standard solution of potassium iodide and iodate is added till a faint blue coloration persists. The number of millilitres of standard solution required, multiplied by a known factor, represents the percentage of sulphur, as a steel of known sulphur content is used to determine the sulphur equivalent of each millilitre.

The sulphur contents of the standard steel used in the standardization of either the potassium iodide–iodate solution or the caustic soda solution should be determined by the *gravimetric* process devised by the Standard Methods of Analysis Sub-committee of the Iron and Steel Institute, particulars of which are issued by the British Standards Institution.

In some laboratories the evolved sulphur dioxide gas is passed into a solution of silver nitrate and then the nitric acid formed is titrated with a standard solution of caustic soda whose sulphur equivalent is known.

*Phosphorus:* Phosphorus exists in steel as phosphide of iron in solid solution. To obtain the phosphorus content, the steel is generally dissolved in dilute nitric acid and the phosphorus converted into ortho-phosphoric acid by adding potassium permanganate. Phosphorus is then precipitated by a solution of ammonium molybdate

forming a complex compound. This precipitate is caused to react with a standard solution (whose equivalent per millilitre in phosphorus is known) of caustic soda, and thus the number of millilitres required is the measure of the phosphorus content.

*Manganese:* In ordinary steels manganese is alloyed with iron and exists also as manganese sulphide. For this determination, a known weight of drillings is dissolved in dilute nitric acid, and the manganese oxidized to permanganic acid by ammonium persulphate. For this reaction, it is necessary to add a solution of ammonium persulphate in the presence of silver nitrate. The solution is boiled briskly and cooled. The purple colour of the permanganic acid is destroyed by the addition from a burette of a standard solution of sodium arsenite whose equivalent in manganese content per millilitre is known. The amount required to destroy the colour gives the manganese content.

Briefly, these are the methods of analysis adopted when no chromium is present in the steel, and with the exception of the carbon analysis, which remains virtually the same in both instances, these analytical procedures have to be modified for a steel containing chromium. In the presence of appreciable amounts of chromium, therefore, different methods of analysis have to be adopted, as follows:

*Silicon:* To some extent the same procedure is followed, except that the resulting silica has to be purified by treatment with hydrofluoric acid, which evolves silicon fluoride as gas. Determination by loss of weight indicates the silicon content. The impurities are left behind after the evolution of this gas.

*Sulphur:* Where chromium is present, this element's percentage is generally determined by the combustion method, otherwise the steel is first dissolved in *aqua regia* (royal water, so called because it dissolves the royal metal—gold), which is a mixture of hydrochloric and nitric acids

to which a small quantity of potassium chlorate is added. After the steel is dissolved, the solution is taken to dryness, baked, and redissolved in hydrochloric acid. Then the silica is filtered out. The acidity of the filtrate is then adjusted (this means that there is an optimum percentage of free acid desirable for the precipitation of the sulphur which takes place on the addition of barium chloride. If there is too much acid, errors may ensue, so that the acidity of the filtrate is adjusted by regulating this bulk. In other words, if there is too little, more is added).

Sulphur is precipitated as barium sulphate, filtered out through filter paper and washed clear, the paper being destroyed in the muffle. The resulting pure white barium sulphate is weighed, and as barium sulphate contains 13.74 per cent of its weight of sulphur, calculation of the sulphur becomes easy.

*Phosphorus*: In general, the only difference in the method of analysis adopted is that the solution is generally obtained in aqua regia when chrome is present instead of nitric acid, and taken to dryness. The residue is then dissolved in hydrochloric acid and silica filtered off. The solution is made alkaline with ammonium hydroxide, and then acidified with nitric acid, the phosphorus being precipitated with ammonium molybdate as before.

*Manganese*: A known weight of drillings is dissolved in dilute sulphuric acid and oxidized with nitric acid. The solution is made nearly neutral with a solution of sodium carbonate to which an emulsion of zinc oxide is then added. This precipitates the iron and chromium as hydroxides which may be filtered off, leaving manganese in solution. Nitric acid is added together with silver nitrate solution and ammonium persulphate and the manganese titrated as previously explained.

Readers may wonder why in some instances volumetric methods are used, and in others gravimetric methods, which involve actual weighing. Briefly, the explanation

is that the volumetric methods are used in routine work wherever possible, because generally speedier than the gravimetric, while the accuracy obtained is usually adequate for the job. The gravimetric methods are, on the whole, more accurate but slower.

Another alloying element whose estimation in the steel works laboratory is frequent and of great importance is nickel, generally analysed by one or other of two methods, one gravimetric, the other volumetric. In the gravimetric method the nickel is precipitated from a slightly alkaline solution, in the presence of citric or tartaric acids, by dimethyl-glyoxime solution. The bright red precipitate is filtered off, well washed with hot water, dried and weighed, or ignited in the muffle furnace to nickel oxide. This method is particularly useful because it separates nickel from cobalt, copper, and iron. In the volumetric method, which is largely used for nickel steels free from copper or cobalt, the drillings obtained are dissolved in hydrochloric acid: oxidized with nitric acid: and a solution of tartaric acid is added, followed by ammonium hydroxide to slight alkalinity. The reason for the introduction of tartaric acid is to prevent precipitation of the iron, chromium, etc., which the addition of ammonium hydroxide would cause. A standard solution of potassium cyanide is then added in excess, after which the excess is caused to react with a standard solution of silver nitrate in the presence of potassium iodide. A slight excess of silver nitrate causes a turbidity resulting from the formation of silver iodide. This is the so-called *end point* of the titration (the point at which the reaction is considered complete). The quantity of potassium cyanide, less that of the silver nitrate, constitutes a measure of the nickel content of the solution, since the equivalent percentage of nickel per millilitre of the standard potassium cyanide is known.

In gravimetric methods, careful and accurate weighing is indispensable, which leads to a consideration of the

weighing apparatus employed in modern steel works laboratories. In recent years, vast improvements in the sensitivity, accuracy, and general convenience of balances have been made. The tendency is to eliminate drudgery in weighing, e.g. a *vernier*, which is a carefully calibrated measuring instrument, operates a delicate chain attached to the beam, obviating the use of small fractions in weights i.e. usually those below 1 gramme. The latest type of balance, illustrated in Fig. 43, embodies an optical device of high sensitivity for the purpose of providing greater accuracy and speed of weighing. Known as the *aperiodic, prismatic, reflecting balance*, it is manufactured by L. Oertling, Ltd., of London. By its aid, the handling of the smaller weights and riders is eliminated, and the saving in time and fatigue where many weighings have to be made is enormous. At the same time, the risk of error is greatly reduced. The sensitivity is 0.1 milligramme and the capacity 100 grammes. The graduations are 500 divisions from "0" on the left, to 500 on the right, shown on an illuminated index mounted at the top of the balance case. When the balance is not loaded, the beam is so adjusted that the pointer moves to zero. This is adequately illuminated by a 12-volt electric projector lamp. An aperiodic device is furnished by means of air damping cylinders attached to each end of the beam. The knife edges and the planes are of agate, and the pans are circular concave aluminium plates measuring 4 in. between wires, the pan supports being adjustable. The reading index consists of a finely divided *graticule* (a transparent scale, such as is frequently used in microscopic measurements). This is attached to the end of the pointer and its magnified reflection is shown on an illuminated ground glass screen at the top of the balance case.

As already indicated, the analysis of specimens of customers' materials is only one portion of steel works laboratory work. Routine analyses are daily carried out, and to these increasing importance is



being attached because of the general tightening up of specifications.

In the analysis and control of production materials, a characteristic example is pig iron, extensively used as

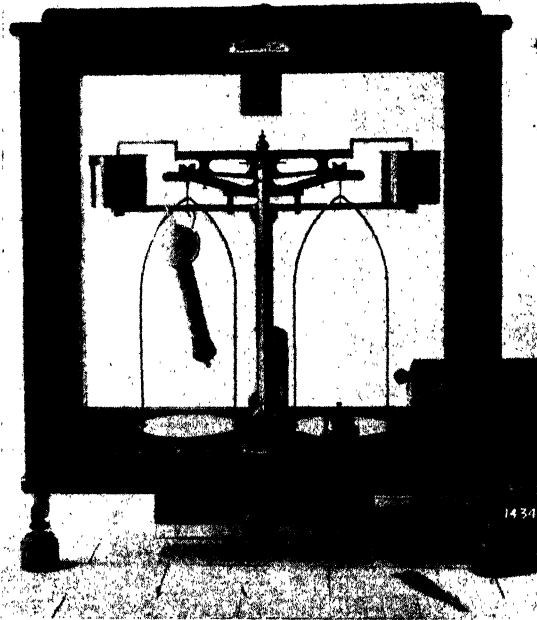


FIG. 43. OERTLING APERIODIC BALANCE

a raw material for the production of steel castings. When a truck load of pig iron arrives at the works, the laboratory is notified, and from each truck two pigs are taken as representative samples. These are first shot-blasted in order to remove as much loosely adhering sand as possible, then fractured and the fractured surface drilled to prevent contamination of the drillings by sand from the external

surface of the pig, which would falsify the silicon percentage.

Before the drillings are weighed, they are subjected to a further operation to ensure their complete freedom from sand. This is *magnetic separation*, a magnet being employed to remove all the drillings, the residue of impurities being left behind.

The first determination is for carbon, which exists in pig iron in two forms: (1) Chemically combined with the iron as iron carbide, and (2) as graphite or free carbon. The total carbon content is estimated by the combustion process used in the analysis of steels, as earlier described, and obviously does not discriminate between these two types. To obtain a correct figure for each type of carbon, therefore, one of the types must be estimated separately and the corresponding figure subtracted from the total carbon percentage obtained by combustion methods. The quickest method suitable for daily use in the steel works laboratory is to estimate the combined carbon by means of the Eggertz colour method, described below.

In steel foundry pig iron the combined carbon is usually about 0.3 per cent. As a general rule 0.1 gramme of the pig iron drillings is weighed into a clean, dry test-tube. Three millilitres of dilute nitric acid are added, and the solution is boiled for about twenty minutes in a water bath, then cooled. The small residue of graphite is filtered off.

Simultaneously with the weighing of the pig iron, the same weight of a steel of carbon content as near as possible to that of the combined carbon (excluding graphite) of the pig iron, is similarly treated. The two solutions are transferred to a couple of graduated *comparing tubes* (narrow tubes carefully graduated in millilitres and matched as far as possible). The known standard solution is diluted to a mark representing its carbon percentage. The other solution is matched with it in colour by dilution with water, the two being compared by holding them against the light. The carbon content of

the second solution is then read off on its own graduated tube. This gives the combined carbon percentage and this figure subtracted from the total content, as estimated by the combustion method, gives the percentage of graphite.

It might be supposed that this method of optical colour matching is a very rough and ready means of estimating the carbon content, but in actual practice it is amazing how closely the experienced chemist can determine the carbon percentage by this means. For example, he can detect a difference of 0.01 per cent of carbon by the eye alone in typical solutions, and in the days before steel works laboratories were scientifically organized, many thousands of tons of steel were manufactured and their carbon content controlled by this colour method alone. It is, of course, essential that both types of solution should come from materials manufactured by identical processes.

The determination of the silicon percentage in pig iron is of very great importance, because oxidation of the silicon content in molten pig iron by a blast of air is the basis of the heat generation necessary in the Tropenas acid converter process. Hence, to verify the silicon content of pig iron by daily determination is, as indicated, a necessary precaution.

The method of determination adopted is as follows—

One gramme of the pig iron drillings is dissolved in a mixture of 30 millilitres of hydrochloric acid, 10 millilitres of nitric acid, 20 millilitres of sulphuric acid and 30 millilitres of water. The iron dissolves very rapidly, and the solution is boiled down steadily until white fumes of sulphur trioxide appear. This ensures that all the silica is *dehydrated* (freed from water). When about 50 millilitres of 50 per cent hydrochloric acid are added and the solution boiled, the sulphate of iron goes into solution and the silica may be filtered off, well washed, transferred to the muffle, and ignited to form pure white silica containing 46.9 per cent of silicon.

It is important that the sulphur and phosphorus in the pig iron should be as low as possible, preferably about 0.02 per cent. Sulphur is determined by the combustion process.

In determining the phosphorus percentage, the volumetric process as applied to carbon steels is used, interference arising only from the graphite, and the large amounts of silica that remain out of solution. These have both to be filtered off, after which potassium permanganate is added and the process carried on as for steels.

Where an absolutely accurate figure is required for phosphorus, the drillings are dissolved in aqua regia; the solution is baked; every trace of silica is filtered off, as otherwise these traces, if left in the solution, would react with the standard solution of caustic soda, and thereby give a higher phosphorus figure.

In the determination of manganese in pig iron, the ammonium persulphate process as applied to carbon steel holds good, the graphite being filtered off and the usual procedure then ensuing.

Enough has been written to show that steel works metallurgists need wide experience both in analytical practice and in the theory of steel metallurgy. It is commonly stated that it takes a minimum of five years to make a good steel works chemist, and the statement is no exaggeration.

If this chapter has made steel works laboratory practice and methods a little clearer to those not themselves technical men, it will have achieved its object.

Readers who wish to pursue the subject more closely should study *Chemical Analysis of Metals and Alloys*, by E. Gregory and W. W. Stevenson (Blackie & Son, Ltd.).

## CHAPTER XXIII

### The Quick Immersion Thermo-couple

IN the "Eighth Report on the Heterogeneity of Steel Ingots" of the Iron and Steel Institute, Dr. F. H. Schofield and Mr. A. Grace gave full details of a new type of pyrometer known as the *quick immersion thermo-couple*, and this present account is based on the information therein given. It is a 13 per cent rhodium-platinum, platinum

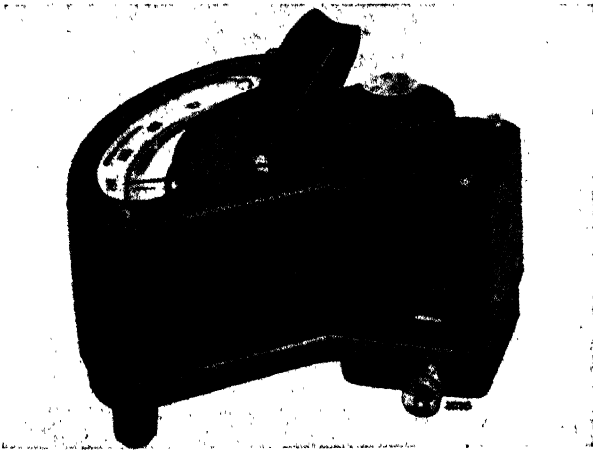


FIG. 44. MILLIVOLTMETER TEMPERATURE INDICATOR  
*Cambridge Instrument Co.*

thermo-couple, 0.5 mm. diameter lightly sheathed in *vitreous* (glassy) silica. It is not, like ordinary pyrometers, maintained in constant contact with a furnace atmosphere, but is designed to be plunged into liquid steel in furnace, ladle, or other receptacle, and quickly withdrawn, the temperature being read just before withdrawal. It will be obvious that the conditions such an instrument encounters will be extremely severe. Not only is the temperature of molten steel higher than that of the ordinary

heat-treating furnace, but the risk of damaging the instrument itself is incomparably greater, owing to the heat and turbulence of, and its direct contact with, the hot metal. The equipment will give an accurate reading in 10-20 seconds.

Developed at first experimentally, it was next adapted

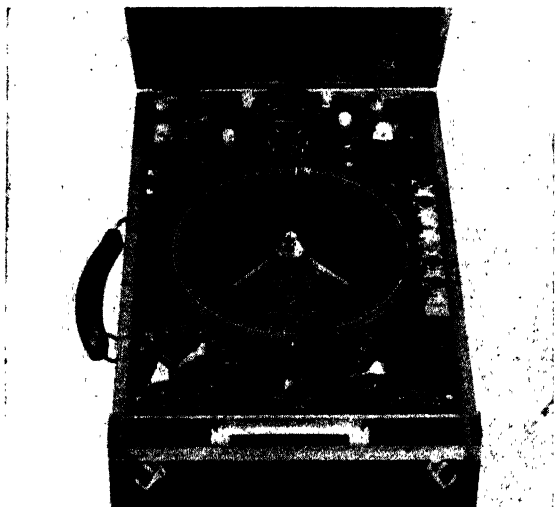


FIG. 45. POTENTIOMETER FOR "QUICK-IMMERSION" TEMPERATURES  
(Negretti and Zambra)

to actual works' use. The form of the pyrometer has been varied to meet different furnace conditions. Sometimes a light instrument that can be manually inserted in the furnace is used. Under other conditions it seems preferable to mount the pyrometer on wheels so that a heavier instrument can be used and manœuvred into position through the furnace door.

The body of the pyrometer is made up of gas pipe or steam pipe of suitable section, bent over at the end so that the thermo-couple can be dipped into the steel. It is usually about 12 to 16 ft. long, so that the pyrometer

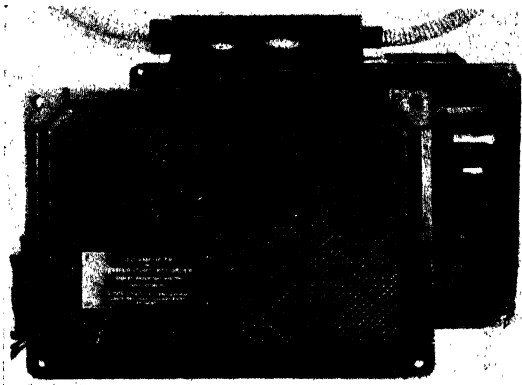


FIG. 46. THERMO-COUPLE TEMPERATURE AMPLIFIER  
*Tinsley & Co.*

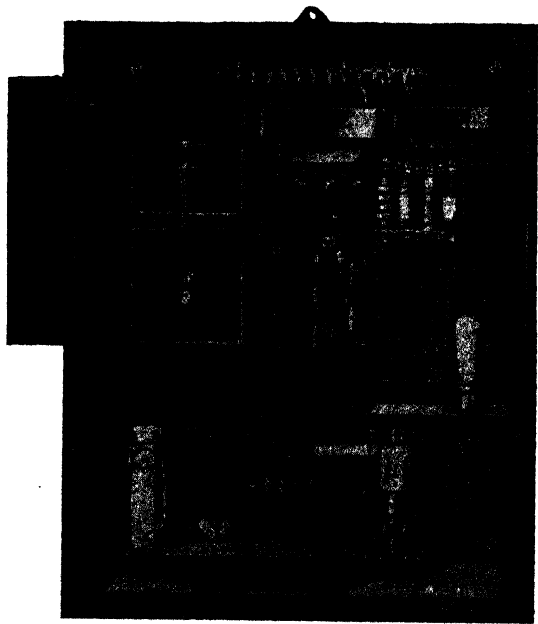


FIG. 47. AMPLIFIER

can be well inserted into the furnace. The part of the tube in the furnace must be insulated to prevent its getting overheated and bent. One type of insulating material frequently used is diatomite, which is highly porous and

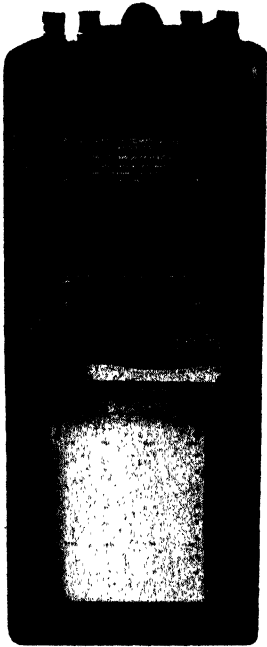


FIG. 48. THERMO-COUPLE  
TEMPERATURE RECORDER  
*Tinsley & Co.*

therefore an extremely effective insulator of heat. Alternatively, a suitable refractory cement may be applied to the tube, and reinforced with a spiral of iron wire. The thermo-couple wires usually extend into that part of the pyrometer outside the furnace, where they are connected to compensating extension leads. The platinum-rhodium-platinum wires are insulated by twin, finely bored tubes of heat-resisting materials, vitreous silica being used for the hottest part. That part of the pyrometer immersed in the steel may be either of diatomite brick, or of *electrode graphite* (the graphite usually employed for electrodes in electric arc furnaces). From this, the thermo-couple wires protrude 2 in. or 3 in. Before each reading, a new silica sheath is placed over the

wires and secured to the diatomite or graphite block with refractory cement or asbestos string.

The pyrometer is very simple to use, although care must be taken that the thin silica sheath enclosing the hot end of the thermo-couple is not broken while putting the pyrometer into the furnace. The furnace door is opened, the pyrometer pushed through to the required distance and immersed in the liquid steel to a suitable



depth. When a steady temperature reading has been obtained, the pyrometer is taken out of the liquid steel and removed from the furnace. Figs. 50 to 52 show types of this pyrometer ready for taking temperature readings. This method of temperature measurement depends essentially on speed, the time of response being governed by the thickness of the thermo-couple wires and the way in which they are mounted and sheathed. Various temperature indicating arrangements are available, e.g. millivoltmeters of the pivoted or suspended types and various potentiometric devices. If speed and accuracy are not of prime importance, the pointer millivoltmeter is probably the most satisfactory. It is cheap and useful, but only exact for a certain external (thermo-couple) resistance. Wherever the resistance varies by more than about 1 ohm, the millivoltmeter method is not advisable. The potentiometer, on the other hand, is not governed in its accuracy by the thermo-couple resistance and is, for this reason, suitable for pyrometers with long thermo-couple wires

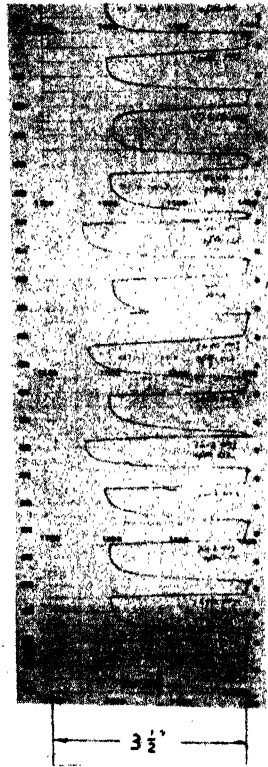


FIG. 49. RECORD OBTAINED OF A SERIES OF MEASUREMENTS ON A HIGH FREQUENCY FURNACE

subject to considerable temperature variations. A high-speed pen recorder of the potentiometric type is now

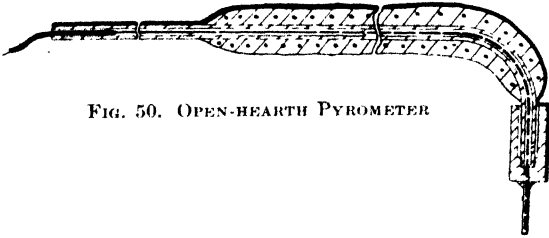


FIG. 50. OPEN-HEARTH PYROMETER

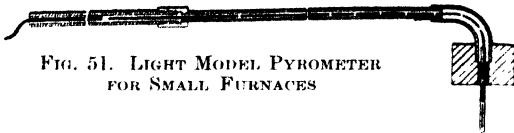


FIG. 51. LIGHT MODEL PYROMETER  
FOR SMALL FURNACES

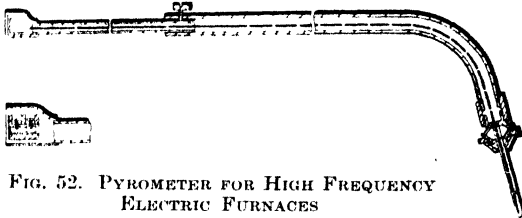


FIG. 52. PYROMETER FOR HIGH FREQUENCY  
ELECTRIC FURNACES

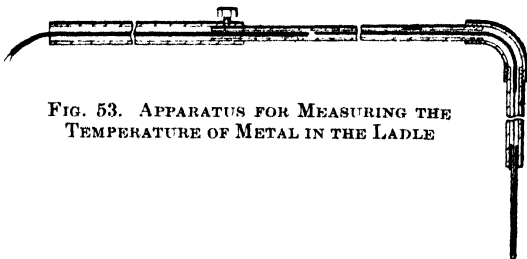


FIG. 53. APPARATUS FOR MEASURING THE  
TEMPERATURE OF METAL IN THE LADLE

available. It has an adequately rapid response for liquid steel temperature measurement and gives a written record of the temperature measured. (Fig. 49.)

Certain theoretical possibilities of error in readings may arise as a result of (a) local cooling of the steel following sudden contact with the cold instrument; (b) contamination of the thermo-couple; (c) not sufficient length of couple immersed, with the result that the temperature recorded is lower than the true temperature. In practice, however, there is no appreciable error due to these causes, but as there must inevitably be some deterioration of the couple after a number of immersions, it becomes important not to exceed the number regarded as safe, which appears to be about six. The couple can be made good again by letting down about 1 in. of wire, removing an inch from the hot end, and making a new junction.

F. Holtby also has developed a tungsten-graphite thermo-couple for the determination of molten steel temperatures. A major objection to the employment of tungsten as a thermo-electric element is the need to heat it in an atmosphere of controlled type to avoid oxidation, since if the least oxidation of the tungsten occurs, the e.m.f. temperature relation will at once be seriously affected.

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# GLOSSARY OF TECHNICAL TERMS

- Acid Steel.** Steel made in a furnace with a lining of silica bricks, white sand, or ganister.
- Akermanite.** ( $2 \text{CaO} \cdot \text{MgO} \cdot \text{SiO}_2$ ) a compound of lime and magnesium silicates formed when electric arc furnace slag cools after extraction from the furnace after reduction.
- Anhydrous.** Free from water of crystallization.
- Anti-piping Compounds.** Fine powders, having heat-generating and heat-insulating properties, added to the surface of liquid steel in the head of the ingot mould immediately after casting, to prevent pipe.
- Badly Blown.** A steel full of gas cavities or blowholes.
- Bar Sorter.** The man who knocks the ends off bars for visual examination.
- Base.** A substance entirely different from an acid.
- Basic Steel.** Steel made in a furnace with a lining of burnt dolomite.
- Bath.** The molten metal in a converter, ladle, or receptacle.
- Bell.** The conical portion at the top of a blast furnace allowing the charge to enter, but precluding the escape of gas.
- Blister Steel.** Steel made from wrought iron by the cementation process. It is covered with small blisters.
- Bloom.** See "Faggot."
- Blow.** The period of blowing a converter.
- Blowholes.** Gas-containing cavities in steel.
- Blue-prints.** Photographic prints made from designers' traced drawings and coloured blue, the lines showing up white.
- Bogies.** Wagons.
- Boil.** The period in the converter process when a long, brilliant flame with many sparks appears.
- Bonded Sand.** Sand containing clay.
- Bonnet.** A solidified overflow from the mould forming a mass of spongy steel on the top of the mould.
- Bottom Electrode Furnace.** See "Greaves-Etchells Furnace."
- Bottom or Up-hill Casting.** Filling moulds with steel from the bottom instead of from the top.
- Bundling.** Binding steel bars into bundles for transit, using twisted iron strips.
- Burning Out.** Clearing a stopped-up ladle nozzle by means of the oxygen lance.
- Burnt.** Of dolomite, heated to a very high temperature for lining basic Bessemer converters.
- Calcination.** The process of roasting iron ore to remove sulphur and give it a more porous structure.
- Calcium Carbide.** The substance that reacts with water to generate acetylene gas.
- Calibration.** The checking of an instrument, e.g. a pyrometer, by comparison with a standard.

- Carbonaceous.** Containing carbon.
- Carbon Dioxide.** Carbonic acid gas ( $\text{CO}_2$ ).
- Castings.** Parts made by pouring molten metal into a previously formed mould.
- Cast Steel.** See "Cast Tool Steel."
- Cast Tool Steel.** Tool steel made by the high frequency or crucible process.
- Cementation.** A process by which carbon is introduced into bar iron to produce blister steel.
- Centreless Grinding.** A finish-grinding process designed to produce steel bars of very great accuracy to size.
- Chaplets or Studs.** Metallic pieces fastened against the cores in the sand mould to prevent their shifting position.
- Charge.** The total quantity of metal dealt with at one time in a furnace or converter.
- Charger.** A machine for charging a furnace.
- Charging Box.** A rectangular receptacle into which the charge for a furnace is placed.
- Checkers.** The chambers of a regenerative furnace.
- Chemical Reaction.** The action of one chemical upon another so that a third product is formed with properties different from those of the two original chemicals, forming a new substance.
- Chipping.** The cutting out of surface defects in steel billets by means of a pneumatic chisel.
- Chrome-magnesite Bricks.** Similar to chromite bricks, but containing magnesite.
- Chromite Bricks.** Bricks of heat-resisting type that are neither acid nor basic.
- Chromite Ore.** Chrome iron ore ( $\text{FeO} \cdot \text{Cr}_2\text{O}_3$ ), the principal source of chromium.
- Cogging.** A hammering operation on tool steel that precedes the finishing processes.
- Cogging Mill.** A rolling mill designed to reduce a steel ingot to smaller size.
- Comparing Tubes.** Narrow tubes carefully graduated in millilitres and matched as far as possible.
- Concentration.** The oxidation and removal of carbon, silicon and manganese from a furnace charge, as well as some iron, which enters the slag.
- Converter.** The pear-shaped vessel in which the converter process is carried out.
- Converter Process.** A process of making steel by blowing air through liquid pig iron in a specially constructed vessel.
- Converting Pots.** Firestone or earthenware chests or chambers in which bar iron is converted into blister steel.
- Core Irons.** Pieces of iron that hold the core in place in a mould.
- Coreless Induction Furnace.** The high frequency electric crucible furnace.

- Core Prints.** Small projections on a foundry pattern, forming holes in the mould into which the cores are set.
- Crucible House.** The store in which crucibles or pots are kept for drying.
- Cupola.** The furnace in which the pig iron for the converter process is melted.
- Dehydrated.** Freed from water.
- Dendrites.** Tree-like aggregations of crystals formed as steel solidifies.
- Deoxidant.** A material, e.g. ferro-silicon, added to molten steel in the ladle to remove surplus oxygen.
- Diatomaceous Earth.** An earth composed of fossilized diatoms used in making refractory bricks of a porous, insulating type for foundry drying stoves.
- Direct Arc Furnace.** One in which the arcs are struck between the ends of the electrodes and the molten metal.
- Dolomite.** A limestone containing magnesia.
- Double Shear Steel.** Steel made from piled bars by a double welding and forging operation.
- Down-takes.** Downward running ducts in a furnace.
- Dozzle.** A square, fireclay cylinder with a central vertical hole through it placed on an ingot mould to prevent the formation of "pipe."
- Electric Scrap.** Scrap steel made by the electric furnace process.
- Electric Steel.** Steel made by an electric furnace process.
- Electrode.** The pole or terminal point, conveying the electric current in an arc furnace.
- Electrode Graphite.** The graphite usually employed for the electrodes in electric arc furnaces.
- Ending.** Knocking off the ends of bars so that the fractured surfaces may be examined.
- Facing Sand.** A special sand for the faces of a mould that come into contact with the molten steel.
- Faggot.** A rectangular solid piece of steel produced by welding together a number of piled bars.
- Fash.** A rough, irregular accretion of metal on a casting or forging.
- Feeder-heads.** See "Dozzle." They are used for the same purpose with ingots and castings weighing more than a few hundred-weights.
- Ferro-silicon.** A ferro-alloy usually containing more than 50 per cent silicon.
- Ferrostatic Pressure.** The pressure resulting from the height of the metal.
- Ferrous.** Containing iron.
- Fettling.** Finishing a casting by chipping away sand and fash.
- Fiery.** Over-oxidized steel that spits and sparks and boils up in the mould.
- Fines.** Very fine particles of a crushed or ground substance.
- Finish Forging.** Reducing clogged steel to the required size and shape by mechanical hammering with special tools.

- Firebrick.** Brick specially resistant to heat, composed essentially of silica and alumina.
- Flask.** A mould in which crucibles are formed.
- Flow Lines.** The lines along which metal has flowed under pressure, as revealed under the microscope or by visual examination.
- Fluorspar.** Calcium fluoride ( $\text{CaF}_2$ ) added to steel in the basic process to remove sulphur.
- Flux.** A material added to molten metal to combine with impurities and cause them to pass into the slag.
- Foreblow.** The normal blowing period in a basic Bessemer converter.
- Former.** A formed metal plate designed to round off the tops of crucibles while they are still plastic.
- Fritting.** The effect of heat on sand, when a semi-plastic condition is obtained.
- Galvanometer.** An electrical instrument for measuring residual magnetism in a bar, or other fine amounts.
- Gangue.** The foreign matter in magnetite or other iron ores.
- Ganister.** A hard, close-grained, siliceous rock from which silica bricks are made.
- Gas Producers.** Gas-making machines.
- Grate.** An annealing furnace.
- Graticule.** A transparent scale, frequently used in microscopic measurements.
- Greaves-Etchells Furnace.** An electric direct arc furnace in which the current after arc-ing passes through the bath and the hearth to a copper-plate attached to its casing.
- Green Sand Moulds.** Moulds that have not been dried in drying stoves.
- Helve.** A water-driven hammer.
- Héroult Furnace.** An electric direct arc furnace incorporating three electrodes, in which arcs are formed between the ends of the electrodes and the metal.
- High-speed Steel.** A highly alloyed tool steel for cutting metals at high speed in a machine tool.
- Homogeneous.** Uniform in character or in some particular property.
- Hoppers.** Receptacles for material to be fed into a machine.
- Inclusions.** Non-metallic matter trapped in steel as it solidifies.
- Indirect Arc Furnace.** One in which the arc is formed *above* the metal to be melted.
- Ingot Cracks.** Cracks occurring while an ingot is cooling.
- Killing.** Preventing the release of gases when molten steel solidifies.
- Ladle.** A large bucket for holding molten metal.
- Lander or Launder.** The channel along which molten metal flows when tapped.
- Lean Ores.** Iron ores low in iron and high in silica.
- Luting.** Sealing up furnace openings.
- Made-up.** Stopped up.



- Magnetite.** Magnetic iron ore.
- Malleable Iron.** Wrought iron.
- Melting Hole.** The hole in which a crucible or pot is placed for heating.
- Mild Steel.** Steel of low carbon content.
- Milling.** Mixing of silica sand and bonded sand in the right proportions to ensure even distribution of the clay bond around the grains.
- Millscale.** The coating of oxide ( $\text{Fe}_2\text{O}_3$ ), formed on the surfaces of heated ingots, etc., which cracks and breaks off during rolling or forging.
- Moulder's Compo.** A mixture of ganister and other substances used in making steel foundry moulds.
- Non-spalling.** Not splintering or flaking off.
- Occlusions.** Particles of slag trapped in steel when poured into moulds.
- Oil Sand Core Process.** A special process for making cores in moulds for small steel castings.
- Open-hearth Process.** A means of producing purified steel by oxidizing and removing the impurities contained in molten iron lying in the hearth of a special furnace.
- Optical Pyrometer.** An instrument for determining furnace temperatures by visual means.
- Over-oxidation.** The ingress of surplus oxygen into molten steel.
- Oxidation Processes.** The chemical combination of the impurities in molten steel with the oxygen in the furnace atmosphere.
- Oxygen Lance.** A bent steel tube through which oxygen is rapidly passed. Its end is inserted in the nozzle of a ladle bottom, to clear a stoppage.
- Permeability.** Ability of a sand to be permeated by gases.
- Phosphates.** Combinations of phosphorus, oxygen and bases.
- Phosphoric Anhydride.** Phosphorus pentoxide.
- Pig Beds.** Sand moulds for casting pig iron.
- Pig Iron.** Iron made in *pigs* (q.v.) by the blast furnace.
- Pigs.** The smaller channels fed by the *sows* (q.v.).
- Piled Bars.** Plated bars placed in a clip for manufacture into shear steel.
- Piling Together.** Placing a number of plated bars in a steel clip in readiness.
- Pipe.** The contraction cavity formed when properly killed steel finally solidifies in the ingot mould.
- Plated Bar.** Hammered lengths of blister steel.
- Plumbago Crucibles.** Those made of a mixture of graphite and fireclay.
- Pot Oil.** Creosote.
- Puddling.** A process for producing a very pure wrought iron from melted pig iron by removing the oxides in a reverberatory furnace.
- Pull.** A warp in a casting caused by uneven cooling.

**Pyrometers.** Temperature-measuring instruments.

**Rabble.** A furnace tool resembling a hoe, placed athwart the emergent stream of steel to scrape its surface clean, so that only slag-free metal emerges, and for stirring a bath of molten metal.

**Rammers.** Tools that press the sand tightly about a pattern to form the shape for a casting mould.

**Recarburization.** Increasing the carbon content of a steel.

**Recuperators.** Chambers in a regenerative furnace through which hot waste gases pass on their way to the chimney stack.

**Reduction.** Elimination of oxygen from molten steel.

**Reeling.** The latitudinal rolling of a tool steel bar that has already been rolled longitudinally. It is designed to give the steel a better finish.

**Refractory.** A heat-resisting lining or brick.

**Regenerative Furnace.** One in which the air and gas required for combustion are preheated in special chambers, themselves heated by waste gases.

**Reverberatory Furnace.** One in which the charge is not directly heated by fuel, but by gaseous combustion products, no blast being used.

**Rimming Steel.** Low carbon steel of the semi-killed type containing blowholes but virtually no pipe. These blowholes weld up during hot rolling.

**Rokes.** See "Seams."

**Rotary Dryer.** A revolving cylindrical shell through which heated air or hot gases pass to dry out and carry away the moisture in a foundry moulding sand or other material.

**Round.** A single charge of a crucible.

**Runner.** A fireclay channel along which metal flows into ingot moulds; also the opening through which steel flows into the mould in making steel castings.

**Seams.** Internal discontinuities caused by blowholes.

**Segregation.** The concentration of impurities in certain zones in steel ingots, and the blooms made from them.

**Shanking.** Pouring steel from a large into a smaller receptacle and thence into a mould.

**Siemens-Schuckert Furnace.** See "Héroult Furnace," which it resembles.

**Silica-gel.** A form of silica with a great affinity for moisture.

**Silica Sand.** A sand containing about 98 per cent silica.

**Silicates.** Combinations of silica with bases.

**Silico-titanates.** Compounds of silica and titanium oxide formed when ferro-titanium is added to steel in the ladle.

**Silocal Brick.** A heat-resisting brick.

**Single Shear Steel.** Steel made from piled bars, by a single welding and forging operation.

**Skin-effect.** In a high frequency furnace, the flowing of the electric current on the surface alone, and not evenly through the metal.

- Slag.** The scum that forms on the surface of a molten metal.
- Soaking** Complete penetration by heat.
- Sow.** The main channel into which iron flows when tapped from the blast furnace.
- Spinner.** A series of blades rotating at high speed, designed to break up cakes of foundry sand and aerate the mass, giving the powdery form required for moulding.
- Splash Can.** In top-pouring ingots, a thin, sheet-steel, open-topped cube placed on the mould bottom before the ingot is poured, to reduce splash.
- Stewing.** Prolonged heating of steel at a fairly high temperature.
- Sulphur Printing.** A method of detecting segregated zones in steel ingots.
- Syndanyo.** A non-conducting material of asbestos base.
- Tap-hole.** The orifice in a furnace through which the metal is tapped.
- Tapping.** The pouring of molten metal from a furnace.
- Teeming.** Pouring molten steel into a mould or receptacle.
- Thermo-couple Pyrometer.** An electrical type of pyrometer for temperature measurement.
- Thinning.** Adding materials to slag to decrease its viscosity just before the steel is tapped.
- Thomas Process.** The basic Bessemer process.
- Titanates.** Compounds of titanium oxide ( $\text{TiO}_2$ ) formed when ferro-titanium is added to steel in the ladle.
- Titration.** A process of ascertaining the quantity of any given constituent present in a solution by observation under the application of a standard solution.
- Toolholder Bits.** Short, ready-hardened pieces of high-speed steel of small diameter.
- Trumpet.** A central fireclay pipe for pouring steel into ingot moulds.
- Tumbling or Rumbling.** Cleaning small steel castings by loading them into a rotating metal receptacle so that they continually toss and tumble over one another and against the barrel of the container, thus dislodging their adherent sand and scale.
- Tundish.** A box lined with refractory materials and provided with nozzles in the bottom, used to reduce splash in pouring steel into ingot moulds.
- Tuyères.** Pipes introducing air into the Bessemer or Trowbas converter.
- Under Heat.** The state of a furnace when hot.
- Vein Stuff.** See "Gangue."
- Vernier.** A carefully calibrated measuring instrument.
- Volatile Matter.** Matter readily driven off from coal, etc., by the application of heat.
- Weathering.** Stacking calcined ore in the open for some months to wash out soluble sulphates.

**Welding Up.** Causing internal blowholes in an ingot to close up and disappear by forging and rolling.

**Wheelabrator.** A type of shot-blasting plant for cleaning steel castings.

**Wheel-swarte.** A mixture of silica-containing particles and steel dust, being the residues from grinding steel.

**Wrought Iron.** Iron produced from molten pig iron by a working or puddling process. It is malleable.

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