A.L.MENZIES

ELEMENTARY
PRACTICAL METALLURGY

LIST OF BOOKS ON

MINERALOGY, MINING, METALLURGY, ETC.

SYSTEMATIC MINERALOGY. By Hilary Bauerman, F.G.S. With 373 Illustrations. Crown 8vo, 6*s.*

DESCRIPTIVE MINERALOGY. By Hilary Bauerman, F.G.S. With 236 Illustrations. Crown 8vo, 6*s.*

MINING. An Elementary Treatise on the Getting of Minerals. By Arnold Lupton, M.I.C.E., F.G.S., etc. With a Geological Map of the British Isles, and 596 Diagrams and Illustrations. Crown 8vo, 9*s.* net.

A PRACTICAL TREATISE ON MINE SURVEYING. By Arnold Lupton, M.I.C.E., F.G.S., etc. With 209 Illustrations. 8vo, 12*s.* net.

ENGINEER'S VALUING ASSISTANT: being a Practical Treatise on the Valuation of Collieries and Other Mines, etc. By H. D. Hoskold. With an Introductory Note by the late Peter Gray. 8vo, 7*s.* 6*d.* net.

ASSAYING AND METALLURGICAL ANALYSIS for the use of Students, Chemists, and Assayers. By E. L. Rhead, Lecturer on Metallurgy, Municipal School of Technology, Manchester; and A. Humboldt Sexton, F.I.C., F.C.S., Professor of Metallurgy, Glasgow and West of Scotland Technical College. 8vo, 10*s.* 6*d.* net.

THE STUDY OF ROCKS: an Elementary Text-book of Petrology. By F. Rutley, F.G.S. With 6 Plates and 88 other Illustrations. Crown 8vo, 4*s.* 6*d.*

THE ANALYSIS OF STEELWORKS MATERIALS. By Harry Brearley and Fred Ibbotson, B.Sc. (Lond.), Demonstrator of Micrographic Analysis, University College, Sheffield. With 85 Illustrations. 8vo, 14*s.* net.

THE CRYSTALLISATION OF IRON AND STEEL: an Introduction to the Study of Metallography. By J. W. Mellor, D.Sc. With 65 Illustrations. Crown 8vo, 5*s.* net.

THE ART OF ELECTRO-METALLURGY. By G. Gore, LL.D., F.R.S. With 56 Illustrations. Crown 8vo, 6*s.*

METALS: their Properties and Treatment. By A. K. Huntington, Professor of Metallurgy in King's College, London, and W. G. M'Millan, late Lecturer on Metallurgy in Mason's College, Birmingham. With 122 Illustrations. Crown 8vo, 7*s.* 6*d.*

LABORATORY NOTES ON PRACTICAL METALLURGY: being a Graduated Series of Exercises. Arranged by Walter Macfarlane, F.I.C. Crown 8vo, 2*s.* 6*d.*

METALLURGY. By E. L. Rhead, Lecturer on Metallurgy at the Municipal Technical School, Manchester. With 94 Illustrations. Fcap. 8vo, 3*s.* 6*d.*

LONGMANS, GREEN, AND CO.

LONDON, NEW YORK, AND BOMBAY.

ELEMENTARY
PRACTICAL METALLURGY
IRON AND STEEL

BY

PERCY LONGMUIR
CARNEGIE RESEARCH SCHOLAR AND MEDALLIST
IRON AND STEEL INSTITUTE

WITH ILLUSTRATIONS

LONGMANS, GREEN, AND CO.
39 PATERNOSTER ROW, LONDON
NEW YORK AND BOMBAY
1905

To

PROFESSOR J. O. ARNOLD AND A. McWILLIAM

THIS VOLUME IS RESPECTFULLY DEDICATED

BY THE AUTHOR

AS A SLIGHT EXPRESSION OF GRATITUDE

FOR THE YEARS

1891 TO 1897 AND 1902 TO 1904

PREFACE

So many works on Metallurgy have been written that an explanation seems required from an author who adds to their number. Experience in both the practical and scientific aspects of metallurgy leads to the conclusion that what the beginner—whether he be old or young—really needs is a book which will primarily awaken interest. Such a work should not be overloaded with detail, but the facts presented should be accurate and the matter reliable.

Naturally it is easier to indicate an ideal than to achieve it, but so far as is possible the author has endeavoured to present his matter in a form acceptable to the student, and which, when assimilated, will lead him in the right direction.

Much that has been written on Metallurgy has served only to discourage the practical man, an opinion supported by fifteen years' intimate contact with Scotch and English workmen. The complaint is, that the matter presented never fits in with practice. The author's experience leads to the conclusion that this complaint has in it a large measure of truth.

Therefore the following work is designed to serve as an introduction to the metallurgy of iron and steel, and as such has been written from a practical standpoint. The only theoretical considerations included are those having a direct bearing on practice. This accounts for the treatment accorded to the constitution of steel, and the theory given is one which harmonizes with practice.

The author has endeavoured to keep within his own experience, and yet take full advantage of the work of others. In such cases he trusts that due acknowledgment has been made, and sincerely hopes that no omission has occurred.

PERCY LONGMUIR.

NORFOLK ROAD,
SHEFFIELD,
September, 1905.

CONTENTS

LIST OF ILLUSTRATIONS

ELEMENTARY
PRACTICAL METALLURGY

IRON AND STEEL

INTRODUCTION

Metallurgy may be conveniently considered under two heads—as a science and as an art. The current definition of metallurgy describes it as the art of extracting metals from their ores and adapting these metals to meet the manifold wants of industrial humanity. The art, therefore, consists in the actual methods of obtaining the metals and working them up into industrial forms. The science of metallurgy is to be found in a study of the properties of the metals, and the extent of their application and effect in association with either other metals or metalloids. In actual practice metals are never procured in a state of perfect chemical purity, and in studying their properties due consideration must be paid to the effect of this association with foreign matter. The enormous change in the physical properties of a metal brought about by the presence of a trace of a foreign element is a problem that has received much elucidation of late. Not a few theories have been advanced, some of which have been merely hypothetical, whilst others have proved of a very practical character. At a later stage these theories will be collated and their bearing on shop problems considered. In everyday work we are continually meeting with new and ofttimes inexplicable phenomena. A mixture of metal satisfactory one day may utterly fail to yield the desired result another, and this, as far as can be detected, under similar conditions. Trouble may be experienced in the production of a sound metal, especially if that metal be the complex substance known as steel. Difficulties may be encountered in hardening, tempering, or annealing, fractures may develop later, and test bars of what is known to be good material may fail to meet specified requirements. All the difficulties of everyday practice can hardly be enumerated, but so far as is consistent with the scope of this work due consideration will be paid to them.

The marvellous progress of the last twenty-five years in methods of chemical analysis and the microscopical examination of metals, together with the advance in pyrometric measurements of temperature, has resulted in very exact and delicate methods of observation. These in turn have yielded a mass of information and facts of great practical utility. In the practical adoption of the results yielded by scientific research may be found the keynote of all industrial progress, and progress in the metallurgical industries is by no means an unimportant factor of national development.

The art of metallurgy has been practised from time immemorial, and the literature of its history is a singularly rich one. The metallurgical industry has been practised during all historical time, and to an undetermined extent in prehistoric ages; but speculations on this head, though possessing a powerful fascination, are beyond our immediate purpose. Roughly, the later periods of the world's history may be grouped into three ages—those of stone, bronze, and iron. The later part of the iron period—that in which we are now living—may be described as the steel age. On looking backwards there are no distinct lines of demarcation visible between the separate ages; neither were these ages exactly simultaneous in all countries. Those countries most highly developed or most civilized, then, as now, adopted the most advanced methods; consequently the stone, bronze, and iron periods overlap one another in various countries. On turning to the more immediate development of metallurgical industry, we have in the recently completed Victorian period an epoch standing unrivalled in all the recorded history of metal-working. In the year 1856 Bessemer gave a description of his new process of steelmaking before the Cheltenham meeting of the British Association. The revolution inaugurated by this memorable process can hardly as yet be adequately realized—it is too recent; but it is well to bear in mind that in the year that witnessed the publication of Bessemer's ideas the total make of steel for Great Britain was something under 50,000 tons, and the cost of this steel anything between £50 and £75 per ton—certainly never lower than £50. Thirty years later the production of Bessemer steel alone was 1,570,000 tons, and ship plates were put on the market at £6 10*s.* per ton. Before the close of the Victorian era the production of steel by Bessemer's process exceeded 2,000,000 tons.

In connection with the development of this process, the work of Mushet must not be overlooked. Following Bessemer were many who, stimulated by his success, introduced other processes of steelmaking. Of these processes, the foremost, and one that is gaining ground yearly, is that of the regenerative furnace associated with the name of Siemens. This furnace gave rise to the now well-known Siemens-Martin process of steelmaking. The product of this process is a very uniform steel, and one that offers wide adaptability for structural purposes, ship and boiler plates, castings, etc. The latest development of the Siemens-Martin process is that of the Talbot open-hearth continuous method of steelmaking, which attracted so much attention at the Spring meeting of the Iron and Steel Institute, 1900. At this meeting the probable substitution in the near future of Bessemer steel by that of the open-hearth (Siemens-Martin) make was discussed. The ever-increasing stringency of the specifications now applied to steel lends much probability to the eventual suppression of Bessemer steel by that of open-hearth make. In connection with these two methods of steelmaking, the dephosphorization process of Thomas and Gilchrist must be mentioned, resulting in the production of basic steel. Germany and Britain annually produce large quantities of steel from basic Bessemer converters or basic lined open-hearth plants, thus utilizing irons for the production of good-quality metal, which, under other conditions, would be useless from a steelmaking point of view.

The blast furnace for the production of pig iron has undergone a development quite in keeping with that for the making of steel, and the daily output of modern types—particularly American ones—is a noteworthy feature of this period. But not only have advances been made in the direction of increased output: attention has also been devoted to fuel consumption and to the development of what were once termed "waste products." The blast furnace of to-day constitutes a typical example of the economic application of scientific research and effort.

The escaping gases from the furnace top, at one time wasted in the atmosphere, were in the first stage of development applied to the heating of stoves; in the second stage to firing under boilers for the production of steam; and now the latest phase is in the direct-driving of gas-engines. In addition to the power so obtained, a certain quantity of valuable by-products are obtained from the gas itself by preliminary treatment before combustion under the boilers, or use in the gas-engine.

These remarks are sufficient to indicate the wealth of opportunity to be found in a successful application of the otherwise waste products of the metallurgical industry.

So far we have spoken simply of the development of iron, but the period just closed is no less rich in valuable discoveries in general metallurgy. Electrolytic processes are exemplified in the production of copper of high purity on a large commercial scale. The development of nickel and its alloys, and the growth of the aluminium industry, constitute in themselves distinct phases of the evolution of metallurgy. With regard to the latter metal, it has not yet reached the full extent of the perhaps too sanguine expectations of a few years ago; nevertheless, it is finding application in fields unthought of then, and in one respect alone—that of the Goldschmidt method for producing high temperatures—offers extensive scope. Our knowledge of the alloys has during the "steel age" been considerably augmented, and the various high-tension bronzes now produced find wide application in engineering practice.

The development of iron alloys has resulted in the production of the now familiar chromium, tungsten, nickel, and manganese steels—alloys which in their respective spheres find extensive adoption for specific purposes.

Such, in brief, constitute a few phases of metallurgical development in an era noteworthy for its advance in all directions. Many discoveries have been made, but the field for original work is in no wise lessened. New discoveries result in the unfolding of new problems for attack and elucidation, and it therefore follows that the science of metallurgy is an ever-expanding one, and of which a complete knowledge will never be attained.

Skill in metallurgical science is necessarily founded on a knowledge of the sister ones of chemistry and physics, chemical and physical methods being essential for the solution of many metallurgical problems. Metallurgy has been defined as a branch of applied chemistry, but, as will be seen later, such a definition is far too narrow. Speaking generally, the methods of examination applied to metals and alloys include—

1. Chemical analysis.
2. Microscopical examination of polished and etched sections.
3. Mechanical tests.

4. Pyrometric observation of the metal during heating or cooling.

By means of chemical analysis the exact composition of a metal is determined—or, in other words, the proportion of the various constituents present that go to build up the alloy or metal is estimated. Microscopical examination reveals the internal structure, showing the relative grouping or crystalline arrangement of the various constituents. By means of an instrument termed a pyrometer, exact temperatures at which certain changes occur in the metal are estimated. The varieties of pyrometers do not concern us at present. The most popular, however, is that of Le Chatelier, which meets with fairly extensive adoption in scientific work, and in actual practice is used for the estimation of furnace temperatures, controlling the heating of particular forgings—as, for instance, varieties of gun steel,—for the control of annealing or tempering operations, or for any purpose in which exact temperatures are required. By means of mechanical tests, conducted in suitable testing machines, the compressibility and resistance to torsional strains are estimated. However, the most important mechanical test is that known as the tensile one, which yields the elastic limit, breaking load, ductility, and extensibility of a metal. Elasticity in a metal is the length to which a rod may be extended without permanently lengthening it—on removing the stretching force the rod returning to its original length. Elastic limit is therefore the load required to produce the first appreciable permanent set or permanent extension. Tenacity or breaking load is represented by the weight in tons or portion of a ton required to effect fracture by means of a stretching force.

No matter what the size of the test pieces may be, elastic limit and tenacity are always in British practice expressed in tons per square inch. If, as is generally the case, the area of the test piece is less than an inch, then—

Load in tons producing the first permanent set $\div$ original area $=$ elastic limit or yield point in tons per square inch,

and—

$$\frac{\text{Breaking load}}{\text{Original area}} = \text{tenacity in tons per square inch.}$$

Ductility is measured by the reduction in area of the test piece at the point of fracture, and is expressed in terms per cent. of the original area. Extensibility is measured by the stretch a test piece undergoes during rupture by a tensile force, the difference between the original length and that of the broken pieces held together constituting the elongation, which difference is also reported in terms per cent. The transverse strength of cast iron is estimated by placing a bar of standard length and section on knife-edge supports a specified distance apart, and by mechanical pressure applying a load in the centre. The load required to break the bar represents the transverse strength, and is usually expressed in hundredweights on section.

It has just been stated that ductility is represented by the reduction in area at the point of fracture in a test piece; ductile metals are therefore those which possess the property of being drawn out into wire, and malleable ones are those which permit of rolling out into sheets without fracture. Hardness is the property of resisting abrasion, and may be measured by the time taken to produce a cut of definite depth. Brittleness is the sudden interruption of crystalline cohesion, which interruption may be caused by a blow or change of temperature.

CHAPTER I

REFRACTORY MATERIALS

ANY material capable of successfully resisting an intense temperature may be defined as a refractory substance. But materials employed for the interior construction of furnaces have in many cases to possess other properties than that of withstanding heat. In addition to high temperature, then, a furnace may have to resist one or more of the following conditions:—

1. The expansion or contraction due to heating or cooling, and resulting from intermittent working.

2. The cutting action of flames, the abrading effect of molten metal, and the searching action of metallic oxides or scouring slags.

3. Variations in the furnace atmosphere, such as a reducing or an oxidizing one.

4. Mechanical properties must be such as to withstand the rough wear and tear of charging solid metal, often in heavy weights and other more or less rough treatment.

The conditions a refractory material has to meet are by no means easy ones, but Nature provides many substances which alone or in admixture with others lend themselves readily to furnace construction. These substances are for general purposes divided into the three following classes:—

I. Acid.
II. Neutral.
III. Basic.

Class I.—Materials embraced under the general term "acid" consist essentially of silica, the oxide of silicon. Silica acting as an acid will combine with various bases forming fusible silicates, a fact of importance, and one to be guarded against in furnace construction. Pure silica is extremely refractory, and is found in Nature chiefly in the form of quartz. Other less-pure varieties of silica are flint chalcedony, agate, etc. Sands are usually quartz or flint in a minute state of division, and in this form silica enters all sandstones. There are several forms of silica known to the mineralogist. Those of immediate interest to the metallurgist are varieties of sandstones, which when used in a native state are technically known as "firestones," together with various sands, ganisters, and similar siliceous materials, which may be used in practice as found in Nature, or after suitable treatment in the form of brick, etc.

Ganister is a local name for an argillaceous sandstone found chiefly in the carboniferous formations of South Yorkshire and other localities of Britain. It is a close-grained, dark-coloured rock, or, in other words, it may be described as a fine-grained sandstone containing no mica, and therefore possessing no cleavage. The clayey matter is present in just sufficient quantity to permit of the rock, when ground, being moulded into suitable forms.

The composition of ganister varies within the following limits :—

Silica	from	87·00	to 95·00	per cent.
Alumina	,,	4·00	,, 5·00	,,
Ferric oxide	,,	0·00	,, 1·50	,,
Lime and magnesia	,,	0·25	,, 0·75	,,
Alkalies	,,	0·00	,, 1·00	,,

The following is an actual analysis of a Yorkshire ganister :—

Silica	95·00	per cent.
Alumina	3·00	,,
Ferric oxide	1·50	,,
Lime and magnesia	0·50	,,

Ganister, after mining, is ground under edge runners into a coarse powder. In certain cases—that is, when the powder does not bind well—lime cream is added during the grinding process, and which, when burned, forms silicate of lime, giving to the ganister a more or less glazed surface. This addition of lime is in all cases kept low, and only added when the material is deficient in binding qualities. If added in excess the essential property of the ganister—that of resisting high temperatures—is destroyed. Ganister as ground is used for lining the acid Bessemer converter, iron-melting cupolas, crucible-melting furnaces, and any other form of furnace which will permit of the material being rammed around a wooden model. Ground ganister is also moulded into bricks and other sections for furnace building. These bricks are commercially known as silica bricks, and permit of an extensive use in the construction of any form of acid furnace. In composition, silica bricks are found to vary within the following limits :—

Silica	from 90·0 to 96·0	per cent.
Alumina	„ 3·0 „ 5·0	„
Ferric oxide	„ 0·8 „ 2·0	„
Lime	„ 0·2 „ 1·0	„
Magnesia	„ 0·1 „ 0·5	„
Alkalies	„ 0·5 „ 1·0	„

Of the various sands which form members of the acid group of refractory materials, it is only necessary to notice one. Silica sand, or, as it is otherwise termed, Belgium white sand, is extensively used in open-hearth steel-making practice. The hearth portion of an acid furnace is usually formed of a boiler-plate shell, lined first with firebrick, then with silica brick, and the bath or basin formed with silica sand.

Various siliceous or quartzose rocks, such as sandstones, varieties of granite, millstone grit, etc., are very refractory, and may be used to a certain extent in furnace construction. Examples of such use are found in the firestones or "hearthstones" of blast furnaces, in the formation of cementation boxes, in the construction of reverberatory furnaces, and the like. With sandstones special care must be taken to bed them in the plane of their stratification in order to prevent exfoliation, and herein lies the chief difficulty in adapting rocks as found in Nature for direct furnace construction.

Flints, when calcined and ground, offer a refractory material capable of resisting high temperatures, and wherever available this material may be successfully used.

Class II.—Neutral materials are so termed owing to the fact that they form no compounds with either basic or acid substances. Acid and basic materials, which individually may be highly refractory when in contact, at furnace temperatures soften and liquefy, forming a more or less fluid slag. Therefore one very important phase of neutral materials is that of acting as isolating layers between the acid and basic portions of furnaces. For instance, the roof and sides of a basic furnace may be formed of acid silica bricks isolated from the basic hearth or lower portion by a dividing layer of neutral material, such as chromite, the purpose of this dividing layer being to prevent the acid portion coming into actual contact with the basic portion.

Neutral refractory materials vary, but three typical representatives of this group are to be found in varieties of clays, carbon, and chromite.

Carbon in the form of graphite, otherwise termed plumbago, is very refractory, and will successfully resist high temperatures. In a reducing atmosphere it is practically infusible, but in a fine state of division and with free access of oxygen graphite will slowly burn, forming carbon dioxide. The best qualities of graphite contain from 94 to 96 per cent. of carbon; in inferior qualities the carbon may only reach 36 per cent., the remainder consisting of variable amounts of ash, which in turn is composed of iron, silica, and earthy matters. Two analyses of graphite are shown below:—

	Normal Graphite.	Ceylon Picked Graphite.
Carbon	80·0	99·8
Ash	16·0	0·1
Volatile products	4·0	0·1

Ferric oxide constitutes the larger portion of the ash of graphite, and in commercial samples this is removed by digesting with sulphuric acid. The graphite is then ground, sifted, kneaded, and left for some time to "temper."

Graphite is capable of wide industrial application. Its chief metallurgical use lies in the manufacture of plumbago crucibles which contain from 25 to 50 per cent. of this material, the remainder consisting of mixtures of various fireclays. These crucibles or "pots," as they are technically termed, are, in contrast with clay ones, very durable. After careful annealing they will stand repeated reheating and cooling. Used to a limited extent in steel-melting practice, these crucibles find their chief field in the production of bronzes, brasses, and other industrial alloys.

Chromite, as mentioned a little earlier, is a member of the neutral series of refractory materials, and one that will very successfully meet intense temperatures. It remains unaltered in either reducing or oxidizing atmospheres, and being neutral is unaffected by the presence of either basic or acid substances. Its chief mechanical drawback is its lack of cohesion. Chromite varies greatly in composition, as the following figures show:—

Chromic oxide	from 40 to 60 per cent.
Magnesia	" 6 " 18 "
Ferrous oxide	" 15 " 36 "
Alumina	" 5 " 30 "
Ferric oxide	" 0 " 21 "

The most familiar members of the neutral group of refractory materials are those known under the general head of fireclays. Clays are formed by the decomposition of rocks such as granites, and consist essentially of silica, alumina, and water in combination, together with varying impurities such as lime, magnesia, soda, or potash. Clay is therefore a hydrated silicate of alumina, and is represented by the formula—

$$Al_2O_3, 2SiO_2, 3H_2O,$$

this formula giving a theoretical composition of—

Silica, 46·5 per cent.
Alumina, 39·5 per cent.
Combined water, 14·0 per cent.

The plasticity of a clay is dependent on the presence of chemically combined water. Heated to any temperature below 100° C. the hygroscopic water only is expelled, but when heated to temperatures higher than 100° C. the water of combination is driven off, and the clay loses all plasticity. This property cannot be recovered again, the clay being technically known as "burnt." The varieties of clay used as fireclays are those which at furnace temperatures do not soften or fuse. They form an important class of refractory materials, and meet with an extensive application in industrial metallurgy. Clays are mined in the usual course, and on reaching the surface are hand-picked and weathered by exposure to atmospheric influences for some time. They are then ground to an impalpable powder, and in this condition are ready for the furnace builder, crucible manufacturer, or brickmaker. In actual use mixtures of clays give better results than are to be obtained by using a single brand only. Especially is this the case with the manufacture of crucibles and bricks.

The theoretical composition of clay previously given is seldom met with in Nature, the nearest approach being that of china-clay, or kaolin. The impurities to be chiefly guarded against are those of lime and magnesia, with the alkalies soda and potash. The two latter should in no case exceed 1 per cent., for if higher the heat-resisting property of the clay is seriously impaired. When examining a new batch of fireclay the four impurities already quoted are estimated together with the quantity of oxide of iron present. A physical test of the clay is also made. This may be readily done by moulding cubes of the clay in question, keeping the corners very square, and submitting them to a temperature just a little higher than that which in actual practice the clay will have to meet. The appearance of the corners after this treatment is a very fair index of the heat-resisting qualities of the clay. The actual analyses of four typical fireclays are given below:—

	I.	II.	III.	IV.
Silica	46·30	63·30	52·00	47·60
Alumina	40·00	23·30	36·00	35·40
Magnesia	0·40	Trace	0·50	1·10
Lime	0·40	0·70	0·80	1·00
Ferric oxide ...	0·27	1·80	2·00	3·50
Combined water ...	12·67	10·30	9·00	10·60

Class III.—Infusible bodies, which are strongly basic in character, come under the heading of the third group, that of basic refractory materials. The chief members of this group are bauxite, lime, dolomite, and magnesia. The basic property of these materials is taken advantage of in certain steel-making processes to abstract the phosphoric acid from the iron-forming slags of stable phosphates.

Lime, in the absence of an acid such as silica, is one of the most refractory substances known, being practically infusible. Crucibles of lime are used for the fusion of platinum. However, owing to the tendency of lime to become hydrated, and consequently to disintegrate, it cannot be extensively used in furnace construction, and when used at all the operations must be continuous.

Magnesia is extremely refractory, and crucibles or bricks of this material resist high temperatures very successfully, but the initial cost of magnesia is high, and constitutes a drawback to its further adoption.

Magnesite is used as a source of magnesia, and when pure has a composition of—

Magnesia	48·73 per cent.
Carbonic acid	51·27 ,,

Lime, the silicates of iron, and free silica are often found associated with magnesite.

Dolomite is a double carbonate of lime and magnesia, and when pure contains—

Carbonate of lime	54·35 per cent.
Carbonate of magnesia	45·65 ,,

It is otherwise known as magnesian limestone. Dolomite, after mining, is calcined at a high temperature, and then ground to a powder and mixed with anhydrous tar. The tar is added in order to bind the powdered dolomite together whilst being pressed into shape and until the bricks are fired. A further coating of tar is given to the completed bricks, in order to protect them from atmospheric influences—that is, to prevent them absorbing moisture, and so disintegrating. Ground dolomite is also used for lining the beds of furnaces. For this purpose it is again mixed with tar, to give the requisite consistency, and rammed to the desired shape, gradually heated to drive off the tar, and then fired as in the case of brick.

Bauxite, an hydrated ferric aluminate, represents a very refractory aluminate of iron. It will resist high temperatures and meet severe furnace conditions, and is used for lining the beds of basic open-hearth furnaces. It may be applied in a similar manner to dolomite. In composition, bauxite varies within the following limits:—

Alumina	from 50 to 60 per cent.
Ferric oxide	„ 10 „ 25 „
Silica	„ 3 „ 5 „
Water	„ 10 „ 15 „

CHAPTER II

METALLURGICAL FUELS

A GENERAL definition of fuel is that of an element, or combination of elements, capable of combining vigorously with the oxygen of the atmosphere, and of giving rise during such combination to the phenomena of light and heat. Commercially, the term fuel is used to denote substances which may be burnt by means of atmospheric air with sufficient rapidity to evolve sufficient heat capable of economical application.

Metallurgical fuels are in nearly all cases found in one of the following forms:—

1. Solid carbon, which may contain small percentages of inert gases and more or less mineral matter—*e.g.* coal, coke, and charcoal.

2. Gaseous carbon half saturated with oxygen in the form of carbon monoxide, examples of which may be found in varieties of "producer gas."

3. Hydrogen, either in the free state or combined with carbon in the form of solid, liquid, or gaseous hydrocarbons.

4. Mixtures of the gaseous bodies, hydrogen, carbon-monoxide, and various hydrocarbons.

For the convenience of this section, fuels will be divided into two groups, natural and artificial, each group having various subdivisions. In a tabulated form they are shown below:—

NATURAL FUELS.

SOLID.	LIQUID.	GASEOUS.
1. Wood. 2. Peat. 3. Lignite. 4. Coal. Non-caking, rich in oxygen. Caking. Non-caking, rich in carbon. 5. Anthracite.	Petroleum.	Natural gas.

ARTIFICIAL FUELS.

SOLID.	LIQUID.	GASEOUS.
1. Charcoal. 2. Coke. 3. Prepared briquettes.	Mineral oils obtained by the distillation of oil-yielding minerals.	Water gas. Siemens gas. Wilson gas. Mond gas.

NATURAL FUELS.

Wood, from a metallurgical point of view, possesses little interest as a fuel, but when converted into charcoal becomes of more importance. Dried wood consists of 96 per cent. woody tissue and 4 per cent. sap. It is readily combustible, and whilst burning produces a large amount of flame, but owing to the quantity of water contained by wood it is incapable of producing high temperatures. The density of wood varies greatly.

Varieties containing 20 per cent. moisture and of a higher specific gravity than 0·55 are termed "hard." Woods of a lower specific gravity than 0·55 are termed "soft." The density may be brought up to 1·4 by completely expelling the air from the pores of the wood.

The composition of well-dried wood is approximately—

Carbon	50 per cent.
Hydrogen	6 ,,
Oxygen	42 ,,
Nitrogen	2 ,,

Peat is the accumulation of decayed vegetable matter in the form of rushes, reeds, and mosses. The decomposition of this vegetable matter is effected by water and a limited supply of air; consequently, deposits of peat are always found in marshy districts. In Ireland, one-seventh of the total area consists of peat bogs, and in Great Britain peat deposits cover an area of six million acres, with an average depth of 12 feet. Large deposits are found in Russia, where peat is to some extent used as fuel in metallurgical operations. An average composition of air-dried peat is given below:—

Hygroscopic water	25 per cent.
Combined water	28 ,,
Hydrogen	2 ,,
Carbon	45 ,,

All varieties of peat contain a large percentage of ash, which may be anything between 1 and 30 per cent., but generally averages 10 per cent. This ash is not wholly derived from the plant life from which the peat has been formed, but much of it is deposited by percolating water and afterwards held in suspension by the peat. It is this ash, together with the large amount of water carried by peat, that constitute the chief objections to its use as an industrial fuel. In order to obtain the same evaporative power as that of average coal, from six to twenty times the bulk is required.

Coal may be regarded as having been produced by the combined action of chemical change and mechanical pressure on the accumulated remains resulting from decayed trees and other vegetable matter during past geological ages. Coal is therefore a fossil of vegetable origin, and occurs chiefly as black or pit coal in the carboniferous system of the geologist.

Newer coals—that is, coal of more recent deposit—are found in the strata above the chalk, and are known as brown coal or "lignite," and represent a stage between peat and true coal. The formation of coal may be regarded as a series of geological changes acting successively on vegetable matter, and, according to the length of time during which those changes have been operative, resulting in either brown coal, black coal, or anthracite.

Anthracite is the oldest coal of the series—that is to say, has been deposited the longest, and subjected to the most geological changes. The successive gradations from wood to coal and anthracite are shown in the following table :—

	Carbon.	Hydrogen.	Oxygen.	Nitrogen.
Wood	50	6	43	1
Peat	60	6	33	1
Lignite	70	5	24	1
Coal	82	5	12	1
Anthracite	95	2·5	2·5	trace

Each stage on the foregoing table shows the elimination of oxygen, and, to a less extent, that of hydrogen, resulting in a corresponding concentration of carbon. Coals, as found, are always associated with more or less earthy matter, which may vary from 1 to 70 per cent., but any appreciable amount of this earthy matter renders the coal useless as a fuel, and it then passes into what is termed bituminous shale.

Lignite, or brown coals, represent an intermediate stage between peat and black coal, being of more recent formation than the coals of the carboniferous period, and older than the peat deposits. The compositions vary widely, as the following table shows :—

Carbon	from 52	to 80	per cent.
Hydrogen	,, 3	,, 6·5	,,
Oxygen	,, 7·5	,, 37	,,
Nitrogen	,, 0·5	,, 1·5	,,
Ash	,, 1	,, 40	,,

A wide range is shown in the ash, but when this becomes too excessive the material is not used as a fuel. In average lignites used commercially, the ash is found to vary between 5 and 15 per cent. Recently mined samples of lignite contain large quantities of moisture, often up to 20 or 30 per cent., but on air drying fully half of this amount is lost. Four varieties of structure are found. These are known respectively as fibrous, earthy, conchoidal, and bituminous. In colour they vary from brown to brownish-black; but the streak—that is, a mark obtained by scratching with a knife—is always brown, and on burning they emit a long smoky flame.

True coals are distinguished from lignites by the greater density and deep black streak given on scratching with a knife point. The density of a coal is in direct proportion to the amount of carbon present, and in samples low in ash varies from 1 to 1·5. A cubic yard of coal weighs approximately 2016 lb. When subjected to dry distillation—that is, heating in a closed vessel free from atmospheric contact—they yield a large amount of carbonaceous residue, and the condensed products contain less water than is the case with fuels of a more recent formation.

The quantity of a coke left after this distillation varies between 45 and 90 per cent. The compositions vary within the following limits:—

Carbon	from 75	to	90	per cent.
Hydrogen	„ 3	„	6	„
Oxygen and nitrogen	„ 2	„	20	„

Owing to the many varieties of coal, various classifications have been adopted or proposed. The most convenient for our purpose is that of Gruner, which gives the six following varieties:—

1. Non-caking coals with long flames, the compositions of which vary within the following limits:—

Carbon	from 75	to	80	per cent.
Hydrogen	„ 4	„	6	„
Oxygen and nitrogen	„ 15	„	19	„

When subjected to dry distillation they yield from 55 to 60 per cent. of pulverent coke, and on combustion they burn with long smoky flames.

2. Caking, long-flame gas coal, having compositions between—

Carbon	from 80	to	85	per cent.
Hydrogen	„ 5	„	6	„
Oxygen and nitrogen	„ 10	„	14	„

They yield from 60 to 68 per cent. of friable and porous coke, and emit from 32 to 40 per cent. volatile matter.

3. Bituminous or furnace coal. This type of coal is distinguished by a very black colour, is readily fragile in mass, and burns with a smoky flame, softening or intumescing in the fire. On distillation it yields between 66 and 75 per cent. of caked and swollen coke, at the same time yielding between 15 and 16 per cent. gas.

Compositions range between—

Carbon	from 84 to 89 per cent.
Hydrogen	„ 5 „ 6 „
Oxygen and nitrogen	„ 5 „ 10 „

4. Caking coals with short flames. Varieties of these coals yield on distillation from 74 to 82 per cent. of caked and very compact coke, and emit from 12 to 15 per cent. gas. Variety of composition is as follows:—

Carbon	from 88 to 91 per cent.
Hydrogen	„ 4 „ 6 „
Oxygen and nitrogen	„ 5 „ 7 „

5. Anthracitic coals. These coals burn with a short flame, and are regarded as a transition state to true anthracites. They yield from 82 to 92 per cent. of frittered or pulverent coke, and from 8 to 12 per cent. gas. In composition they approximate—

Carbon	from 90 to 93 per cent.
Hydrogen	4 „
Oxygen and nitrogen	from 3 to 5 „

6. Anthracite may be regarded as the final product of the many stages in the conversion of vegetable matter into coal. Its colour is jet black, and it possesses a vitreous lustre. In structure it is homogeneous, and on

breaking shows a conchoidal fracture. Anthracite burns almost without flame, and the carbonaceous residue remaining shows no sign of caking. Composition—

Carbon	95	per cent.
Hydrogen	2·5	,,
Oxygen	2·5	,,

Liquid Fuels.—Oils occur fairly plentifully in nature, and are given the general term "petroleum," this term including what are in reality a series of natural hydrocarbons. These are found impregnating various rocks, such as schists or clays, marls, and sands. Such a material cannot be used direct as a fuel, owing to its high content of ash; but on distillation yields tar products, so-called mineral oils, and volatile gases. A bituminous schist of the Scotch coal measures known as "Boghead mineral" yields on distillation—

Combustible gases	70	per cent.
Fixed carbon	10	,,
Ash	20	,,

When these hydrocarbons occur in sufficient quantity, naphtha and petroleum springs or deposits of solid asphalt are formed. At Baku, on the Caspian Sea, and in various parts of the United States, more particularly Pennsylvania, mineral oils are so obtained in large quantities. Crude petroleum, when distilled, yields a product containing—

Carbon	from 79 to 88	per cent.
Hydrogen	,, 11 ,, 20	,,

Many ingenious devices have been introduced for burning the oil in industrial operations. These include various forms of troughs, sprays, and the conversion of the oil into gas before combustion.

Natural gas may, in the localities in which it is found, be used for a variety of metallurgical operations. Its freedom from sulphur and its cleanliness greatly facilitate this use. Natural gas is not familiar to this country, and therefore it possesses little interest.

A typical analysis of such a gas is included—

Carbon monoxide	1 per cent.
Carbon dioxide	1 ,,
Oxygen	1 ,,
Nitrogen	2 ,,
Hydrocarbons	73 ,,
Hydrogen	22 ,,

ARTIFICIAL FUELS.

Prepared or Artificial Fuels.—The majority of fuels used in metallurgical operations undergo some process of preparation previous to actual use. In relative order these forms of preparation include drying, compression, carbonization, and gasification.

The advantages resulting from the expulsion of water from any fuel containing it are too apparent to need further mention. Peat is one of the commonest examples of a fuel subjected to such preliminary treatment.

Many attempts have been made to utilize small or refuse coal by mixing it with a suitable binding material, and compressing into blocks or "briquettes." Of various binding materials used, coal tar, pitch, and molasses have met with success.

Carbonization is effected by heating wood, coal, or other carbonaceous material without access of air. The constituents are rearranged into solid, liquid, and gaseous. The most familiar examples of carbonization are those of wood and coal, resulting in the production of charcoal and coke.

Charcoal.—Wood heated to 200° C. remains unaltered; heated to 220° C. it is slightly browned; from 270 to 300° C. it suffers decomposition; and at a temperature of 300° C. it is resolved into a fixed residue known as charcoal, and volatile products are emitted.

The woods usually used as a source for the production of charcoal are pine, fir, larch, oak, beech, ash, elm, and birch. The trees should be of mature growth, and felled in winter. They are partially barked, cut into convenient lengths, and air-dried. Rotten or worm-eaten pieces are not used. Charcoal burning may be conducted in stacks or piles known as "meilers," in enclosed chambers, or in kilns. In the latter valuable by-products are collected, and are used as a source of wood-spirit and pyroligneous acid. The majority of the charcoal used in metallurgical industries is burned in "meilers," which are built on the sheltered side of a hill or forest, and on ground sloping about 1 in 10 or 1 in 15. All irregularities between the logs are filled in with small pieces, and the surface levelled off by the same means. The covering consists of charcoal dust or sand and turf, the grassy side of which is placed inwards. Fire is introduced to the meiler by means of a central flue, and when fairly started this hole is made up and the whole allowed to "sweat"—that is, to slowly smoulder. When the sweating stage is over, or when the water has been expelled, vents are made in the meiler to admit the necessary air for partial combustion. These vents usually start from a certain point, and as fresh ones are made the old ones are closed up. Combustion is not allowed to proceed too vigorously, or loss of charcoal will be the result.

The yield of charcoal varies greatly, and depends to a large extent upon the nature of the wood, its age, dryness, and speed of charring; rapid charring, and consequently high temperature, resulting in a low yield, whilst the best results are attained with lower and more constant temperatures—that is, a temperature sufficient to char and no more. The yield by volume may vary between 50 and 70 per cent., and 80 per cent. may be regarded as the maximum. The yield by weight will vary between 15 and 25 per cent., but with careful burning between 22 and 24 per cent. by weight is usually obtained.

The composition varies. That of an average dry charcoal is given below:—

Carbon	90 per cent.
Hydrogen	3 ,,
Oxygen and nitrogen	7 ,,

Charcoal is extremely porous, and will absorb water and gases, and in this manner increase in weight, whilst the volume remains constant. Charcoal, on an average, will absorb about 12 per cent. of moisture, but if kept in the damp for several months it will take up more than its own weight of moisture. As further illustrations of the absorptive power of charcoal, its action in this respect on the following gases is given:—

It will absorb 90 volumes of ammonia.
,, ,, 55 ,, carbon dioxide.
,, ,, $1\frac{1}{4}$,, hydrogen.

This fact of the absorptive power of charcoal thereby increasing in weight whilst the volume remains constant has been quoted, as at a later stage, when exact quantities are required, further reference will have to be made to it. Charcoal was at one time extensively used for the reduction of iron in the blast furnace, and charcoal cold-blast iron is one of the purest forms of that metal obtainable. Charcoal, however, owing to its friability, does not lend itself to the production of large outputs, and its high cost, except in special cases, prohibits its use.

Coke.—Coke is the carbonaceous residue left on the dry distillation of coal, and in this respect bears the same relation to coal as does charcoal to wood. It is produced as a by-product in the manufacture of illuminating gas, but coke for metallurgical purposes is in the majority of cases specially prepared. Methods of coking may be broadly divided into three classes :—

1. Coking in heaps in the open air.
2. Coking in open-top kilns.
3. Coking in ovens.

Coking in the open air in either a "heap" or "pile" is conducted in a similar manner to the carbonization of wood in the "meiler." About 20 tons of raw coal constitute a heap or pile. Long ridges have also been employed. The coal may be piled in these ridges in lengths reaching up to 200 ft., and from 8 to 12 ft. in width on the floor line, with a height of from 3 to 6 ft. These ridges taper from the floor line to the top. The speed of carbonization is to some extent regulated by making small openings for the admission of a limited supply of air, or on the other hand by damping down with coal-dust according to requirement, but the process is never under perfect control, and is naturally a wasteful one.

Open-air coking has also been effected by building a pile around an octagonal chimney. The cover of this pile is made with wet coal or coke dust, and the products of partial combustion drawn through the apertures in the base of the chimney.

Rectangular kilns with open tops represent the methods of coking included in class 2. An open-top kiln consists of two parallel walls, varying in length from 40 to 60 ft., height 6 ft., and the width about 8 ft. Vertical and horizontal flues are placed in these walls at intervals of 2 ft., horizontal flues in each wall corresponding to each other. When charging the kiln, wooden bars are placed right through the horizontal flues in the two opposite walls, and the whole chamber filled with coal, slack, or small coal. The bars are then withdrawn, leaving a series of openings for the admission of air. The current of air may be drawn from either side, and, as the process of coking demands, this change of current is effected by closing one of the vertical flues and drawing air through the horizontal flue in that side of the wall, closing up the far end of the horizontal flue in the opposite wall and drawing the products of partial combustion through that vertical flue. The weight of coal varies according to the capacity of the kiln—generally between 200 and 300 tons—and the time occupied in coking it—between six and twelve days. These kilns yield a fairly large output of coke; they are inexpensive to install and easy to work; but the product varies greatly, and is seldom uniform throughout one batch.

It is very evident that the foregoing methods are not economical; with them a certain amount of coal is consumed in the process of coking, and much of the heat, together with all the volatile products, are lost. Hence the use of ovens, the purpose of which is to bring air in contact with the volatile gases, but not with the coal, thus ensuring the combustion of these gases, which in turn effect the carbonization of the coal, and as no air reaches the latter it is not consumed in the process of coking. Many and various types of ovens have been proposed, and are in use to effect this purpose. The extent and variety of these ovens preclude a detailed consideration of each one, and in place of it a few principles upon which ovens have been designed and a brief notice of one or two representative types will be given.

Coke ovens have been designed to attain the following objects:—

1. To prevent as far as possible the escape of heat, attained by having thick walls and building the ovens in series or back to back.

2. To regulate the admission of air so as to completely burn the volatile products without burning any of the coal; may be attained by admitting air from the top only, or by converting the oven into a retort and burning the volatile products in chambers parallel with or below the actual oven.

3. Controlling the process in such a manner as to cause the coking to proceed from outside to centre regularly in all directions.

4. To diminish labour cost and loss of initial heat by building the ovens in such a shape as to admit of a ready and quick withdrawal of the coke.

5. To collect and utilize the volatile products—tar, etc.

The most familiar coke oven is that known as the Beehive. This oven is internally a hive-shaped chamber of firebrick, usually built back to back and in long series. It is charged by means of an overhead railway, and the coke withdrawn through openings in the front of each oven. The charge of coal, varying according to the capacity of the oven from 1½ to 7 tons, is introduced immediately after the withdrawal of the preceding one —that is, whilst the oven is in a red-hot condition. The opening in the front is then bricked up, apertures being left in it to regulate the admittance of air. The volatile gases ignite on top of the coal, and carbonization proceeds downward. The draught holes are gradually stopped up, and when the flame on the top falls, the whole is made airtight. The time occupied in coking is about forty-eight hours. The red-hot coke on withdrawal is quenched with water, which treatment also effects the removal of a certain portion of the sulphur as sulphuretted hydrogen. The good qualities of the Beehive coke oven may be briefly summed up as follows: These ovens afford the least amount of side coke, have the greatest concentration of heat, and the least tendency to wear out by repeated expansion and contraction. Large quantities of coke of a thoroughly good quality are produced in these ovens. The adverse qualities of the Beehive are not many, but they are of moment, and may be indicated under three general heads:—

1. None of the by-products are collected.
2. A large amount of heat is lost.
3. It is not economical to work.

The Jameson coke oven represents an improved type of Beehive. The improvement consists in forming in the bottom, channels covered by porous tiles, which allow the by-products to drain through and collect in suitable spaces below the oven. These products are drawn by gentle suction from below the ovens and passed through condensers for retaining the ammoniacal liquor and tar.

The Coppée coke oven is a keen competitor to the Beehive. These ovens are really retorts, and the gases resulting from the distillation of the coal are burned in flues below the coking chamber. The coking chambers are 30 ft. in length, 18 in. in width, and 4 ft. high, but taper slightly from back to front. At either end of this chamber are two cast-iron doors, respectively 3 and 1 ft. in height, and in the roof are three charging apertures covered by sliding doors. The charge of crushed or slack coal is introduced through these top openings and levelled down by means of long rakes through the upper or smaller doors at either end of the coking chamber. The time taken to charge and level three tons of crushed coal is about six minutes. The coking process is complete in twenty-four hours, and the resultant coke is forced through the chamber by means of a ram, and the time occupied in so discharging one chamber is two minutes. The red-hot coke as it emerges from the chamber is quenched with a stream of water directed from a hose. A Coppée oven may therefore be discharged and recharged with fresh coal in the space of eight minutes. These ovens are built in series and worked in pairs, one of each pair being charged when its fellow is half coked. The chambers being red-hot when charged, distillation commences immediately, and the gases are drawn off by flues in the dividing wall between each chamber. As the ovens are worked in pairs, the gases from a newly charged one mingle in the side flues with those from one partly coked, thus ensuring a constant supply of gas for each chamber. The side flues lead down into horizontal ones running below the chambers and in the direction of their length. The gases are ignited in these flues, and are drawn under the full length of each chamber.

The Appolt oven may also be regarded as a retort. The actual coking chambers are tapered, and measure—at the top, 1 ft. 1 in. by 3 ft. 8 in.; at the bottom, 1 ft. 6 in. by 4 ft.; with a depth of 16 ft. A folding door forms the floor of the chamber, which opens downward, allowing the coke to fall into waggons running on rails below. As with the Coppée, Appolt ovens are charged with crushed coal from waggons through charging hoppers on the top. Each retort is surrounded by an air chamber, which communicate with one another, forming a large divided chamber. The gaseous products are drawn through openings in the retorts into this chamber, and their combustion effected by means of atmospheric air.

With both the Appolt and Coppée ovens the heating is external; no air enters the retorts, and therefore there is no combustion of the coal, resulting in an increased yield of coke. The increase in yield over that of the Beehive may be taken at between 10 and 15 per cent., but is, of course, subject in all cases to local conditions.

The Simon Carvés is one of the most familiar types of coke ovens designed to collect the by-products. In construction it is in some respects similar to the Coppée, the internal sizes of the coking chambers averaging 24 in. in width, 6 ft. in height, and 30 ft. in length. They are built in series, charged with coal from above, and the coke discharged by means of a ram. The products of distillation are drawn from each retort into one common pipe for the series, and passed through condensers and scrubbers. The uncondensed gases are returned to the ovens, and, circulating under each retort and in side flues between each pair, are ignited by the addition of the requisite quantity of atmospheric air. This air may be heated in a recuperator previous to use for the combustion of the gases.

The Simon Carvés oven gives a high yield of good-quality coke, and the by-products obtained may be valued at between 2*s.* and 4*s.* per ton of coal used.

The Properties of Coke.—Good blast-furnace coke is hard and compact; it should be clean to the hands, sonorous, and should possess a dark silver-grey lustre. It should also be free from moisture and volatile hydrocarbons, whilst high percentages of sulphur or of ash are, if present, seriously detrimental to any coke. If the coal intended for conversion into coke contain an undue proportion of either ash or sulphur, it must undergo a preliminary washing, and on completion of coking the red-hot coke should be quenched with water. Coke at ordinary temperatures will absorb from 1 to 2½ per cent. of moisture, but when in actual contact with water, coke will absorb any amount up to 50 per cent. The calorific power of a sample of coke free from ash is 8000 calories, or nearly equal to that of pure carbon. The composition of a coal and the coke produced from it are shown in the following table :—

	Coal.	Coke.
Carbon	59·61	89·58
Volatile matter	30·11	0·46
Moisture	1·26	0·03
Ash	8·23	9·11
Sulphur	0·79	0·82

In the following analyses of various cokes the first two are British, and the last three American samples:—

	Beehive.	Simon Carvés.	Connes-ville.	Poco-hontas.	Chatta-nooga.
Carbon	87·60	86·36	89·58	92·58	80·51
Volatile matter ...	1·45	2·28	0·46	0·49	1·10
Moisture	1·38	2·35	0·03	0·20	0·45
Ash	8·52	7·94	9·11	6·05	16·34
Sulphur	1·05	1·07	0·81	0·68	1·59

Gaseous Fuels.—The economy, cleanliness, and ease of manipulation of all gaseous fuels are most potent factors in favour of their adoption, and when coupled with the fact that inferior fuels and waste products may be utilized for the production of high temperatures, then the real value of gas firing is apparent. At a central generating station fuel is converted into a combustible gas, which is consumed by admixture with air at any desired part of the works. These gases are produced, in most cases, by burning the fuel in a long cylindrical column termed a producer, whereby most of the carbon of the fuel is converted to carbonic oxide, whilst the hydrogen remains free or is converted to carburetted hydrogen. Varieties of these gases are all known under the general name of "producer gas." Of these the most important, metallurgically, are those of Siemens, Wilson, and the water-gas producer.

The Wilson producer consists of a mild-steel casing, lined with firebrick, fitted with main for drawing away the gas as generated, grate bars, and ashpit. When the producer is in operation—that is, generating gas—this ashpit is closed by doors which are made airtight by luting the joints with clay. On the top of the producer, which forms a flat stage, a charging hopper is fixed and so arranged as to distribute the charges of coal evenly without admitting air. The necessary amount of air is injected by means of steam jets and directed into the ashpit below the grate bars. The steam, in its ascent through the incandescent fuel, is decomposed as follows:—

$$H_2O + C = H_2 + CO$$

—that is, water in the form of steam plus carbon at the requisite temperature yields hydrogen and carbon monoxide, both of which increase the richness of the gas. The producer is out of atmospheric contact, and no air other than that introduced by the small steam jets admitted. The fuel may therefore be regarded as undergoing a process of incomplete combustion, or, in other words, distillation. The carbon dioxide formed is converted by the excess of carbon present into the monoxide, which is the chief combustible constituent of the gas. This conversion may be represented as—

$$CO_2 + C = 2CO.$$

A typical analysis of Wilson producer gas is included in the following table:—

ANALYSES OF GASEOUS FUELS.

	Siemens.	Wilson.	Water Gas.
Carbonic oxide	24	25	36
Marsh gas	2	2	5
Hydrogen	6	12	53
Nitrogen	63	56	4
Carbonic acid	5	5	2

An analysis of natural gas has been already given, and the two following analyses are given as possessing a comparative interest. The second one is that of a gas drawn from beneath the hood of coke-fed blast furnace:—

	Illuminating Gas.	Blast-furnace Gas.
Carbonic oxide	7	26
Carburetted hydrogen	53	2
Hydrogen	36	2
Nitrogen	4	62
Carbonic acid	—	8

CHAPTER III

IRON ORES AND THEIR PRELIMINARY TREATMENT

THE metals of common use are found in nature in the form of ores. An ore consists of a metallic mineral in admixture with extraneous matter of no value, which is termed the "gangue." It is at once evident that the value of an ore is determined by its metallic content or the amount of metal that can be extracted from a given quantity of the ore. This percentage of metal determines whether the ore be "rich" or "poor"—that is, whether the metal can be extracted at a gain or loss. The ores of iron, lead, and zinc are termed "rich" when they contain 50 per cent. or over of metal. An iron ore containing less than 30 per cent. of iron cannot be worked to commercial advantage. Copper ores are considered rich at 25 per cent. metal, and are workable at 10 per cent. An ounce or so of gold intermingled with a ton of quartz or gravel is an exceedingly valuable material. A further feature in valuing an ore is the form in which the metal occurs; for instance, sulphides of iron, though of fairly plentiful occurrence, are not available for the production of iron, owing to the extreme difficulty of removing the sulphur. Other sulphides, such as those of lead and copper, form, on the other hand, valuable sources of the metals, as with these ores methods exist by which the sulphur can be eliminated.

Iron ores of commercial value may be divided into three classes, (1) oxides, (2) hydrates, and (3) carbonates, as follows :—

Oxides.	Hydrates.	Carbonates.
Magnetite and varieties. Hematite and varieties.	Brown hematite.	Spathic carbonate. Clayband. Blackband.

Magnetite or black ore represents one of the purest and richest of iron ores yet worked. When pure it contains—

Iron, 72·4 per cent.
Oxygen, 27·6 per cent.

It is, however, subject to much variation, impure varieties being contaminated with phosphorus. The ore is found in massive veins in Sweden, North America, and in the Madras Presidency, India, and to a somewhat less extent in several other localities. Magnetite, as indicated by its name, is magnetic; it is very hard and dense, and the pure varieties of this ore are the source of much high-class tool and cutlery steel.

Hematite or Red Ore.—Several varieties of this ore are found in various parts of the world, and these have received distinguishing names, such as kidney ore, micaceous ore, and specular ore. When pure, red hematite contains—

Iron, 70 per cent.
Oxygen, 30 per cent.

As with all ores, this composition is subject to much variation. It is the source of the hematite irons, and is mined in Cumberland, Lancashire, and various parts of America. Vast quantities of this ore are annually imported into this country from Spain.

Brown hematite is the descriptive term applied to iron ores consisting essentially of hydrated ferric oxide. When pure the composition may be taken as—

Ferric oxide, 85·6 per cent.
Water, 14·4 per cent.

It is often contaminated with sulphur and phosphorus, and in this country is chiefly worked in Lincolnshire, Northamptonshire, and Forest of Dean. As with red hematite, large quantities of the ore are imported from Spain.

Spathic iron ore represents a pure form of carbonate, and yields a good quality iron, very suitable for steel-making.

Clayband iron ore is of fairly frequent occurrence in Europe, the chief British localities being those of Yorkshire, Staffordshire, and South Wales. These localities indicate the use to which the pig iron produced from this ore was at one time put—that of conversion into bar or wrought iron. The immense development of mild steel is causing that metal to supersede the use of wrought iron, and consequently the manufacture of the latter is gradually decaying. Blackband ore receives its name owing to the presence of considerable carbonaceous matter giving it a black colour and a more or less stratified appearance. Both the blackband and clayband are impure forms of carbonate of iron; they contain appreciable quantities of sulphur and phosphorus, and the irons produced from them are chiefly foundry qualities.

A series of approximate analyses of iron ores is appended, and further reference will be made to them when treating of the production of pig iron:—

	Swedish Magnetite.	Red Hematite. Cumberland.	Brown Hematite.	Spathic Carbonate.	Clayband.	Blackband.
1. Ferric oxide (Fe_2O_3)	66·00	73·00	70·00	—	—	2·72
2. Ferrous oxide (FeO)	23·00	—	—	54·80	36.30	40·77
3. Manganous oxide (MnO)	1·50	0·70	0·80	1·34	1·68	—
4. Carbon dioxide (CO_2)	—	0·80	3·00	38·50	31·20	26·41
5. Alumina (Al_2O_3)	3·00	6·50	3·50	1·04	4·64	—
6. Silica (SiO_2)	5·04	9·50	10·50	1·00	7·95	10·10
7. Magnesia (MgO)	1·20	0·02	1·34	—	1·07	0·72
8. Lime (CaO)	0·23	1·00	2·50	3·26	8·68	0·90
9. Phosphoric acid (P_2O_5)	0·02	0·02	0·04	0·02	0·80	0·40
10. Sulphuric acid (SO_3)	0·01	0·03	0·02	0·04	0·72	0·60
11. Water (H_2O)	—	8·43	8·30	—	—	—
12. Organic matter.	—	—	—	—	6·96	17·38

Metallic minerals or ores occur in many varied forms. Some forms may, immediately on reaching the surface, be ready for the smelter, whilst others may have to undergo more or less preliminary treatment. This variety of occurrence is well exemplified in the case of iron ores. These may be found in the form of sands, as surface deposits, and at deeper depths as regular layers or immense beds. Iron ore in the form of sand is met with in Tasmania. Examples of surface deposits are those of the brown hematites of Northamptonshire. In this case the surface soil is removed, and the ore worked as an open quarry. Ores which are found at greater depths are extracted by regular mining, and when occurring in regular beds are worked in a similar manner to the coal deposits. The hematite ores of Cumberland are found in beds or huge pockets in the limestone. The greater portion of metallic ores occurs in the form of veins or lodes. A mineral vein consists of one or more minerals filling up a fissure in the crust of the earth, which may vary in width from less than 1 in. up to 150 ft. or more.

All ores when raised to the surface are broken into pieces of a uniform size, and hand picked. The object of this hand picking is to remove injurious material, or that which is of no value. Injurious material in the case of iron ores is removed in the form of sulphides, such as iron pyrites, and phosphides, such as apatite.

The size to which the pieces of ore are broken depends upon the density of the ore on the one hand, and on the other the after-treatment which the ore has to undergo· Assuming that the ore has to undergo the process of either magnetic or water concentration, it is then ground to powder, the fineness of which is determined by the intrinsic value of the metallic portion of the ore. Thus gold-bearing quartz is reduced to an almost impalpable powder in order to extract every particle of the precious metal. When the ore is subject to direct treatment in a furnace, the size to which the pieces are broken is determined by its density or the readiness with which the furnace gases can penetrate the ore. If the ore is porous and permits the reducing gases of the furnace to readily penetrate it, fairly large lumps may be used, and regular working follow. But if the ore is dense and offers considerable resistance to the furnace gases, only small and uniformly sized pieces must be used—the more uniform the better the working results. Magnetite, which is a good example of a dense ore, is in actual practice broken into pieces about the size of an egg.

Any preliminary treatment in the case of iron ores must by the very nature of the case be of a simple character—in other words, it must be inexpensive. This is more readily realized by comparing the treatment of gold-bearing quartz to that of an average iron ore. The metal obtained from the latter is, weight for weight, one-fifty-thousandth part the value of that extracted from the former. Costly methods are therefore not applicable in the case of ores of iron, and it does not pay to work an ore requiring much preliminary treatment. Expensive methods are only applicable in the case of metals of higher intrinsic value.

The principle, so familiar in brass foundries, of freeing the turnings and borings from iron by means of either permanent magnets or magnetic separators may be applied to any ore which is attracted by a magnet. Magnetite possesses this property, and advantage is taken of it in separating the ore from its earthy admixture or gangue. Types of separators vary much in detail, but the essential principle upon which they are constructed is that of a revolving magnetic drum, upon which a stream of finely crushed ore is directed. It is evident that at each revolution of this drum a point is reached at which the non-magnetic portion must fall off by the action of gravity. This earthy matter is allowed to fall through a shoot, and is collected in suitable trucks below. The magnetic portion revolves a little farther, and then, by means of a catch and brush arrangement, is removed from the drum, falling into a suitable truck, as in the case of the gangue. The effect of any method of concentration is to increase or "concentrate" the metallic portion of the ore, freeing it from the gangue, and thereby increasing furnace yield and output.

Weathering.—Previous to calcination many ores are subjected to atmospheric action for periods varying between three months and three years. Weathering is not applied to those ores already in a fine state of division, as the action of the elements would render the material too fine or powdery for successful furnace handling. In the case of ores associated with shale or other foreign matter hard to pick out, atmospheric action softens and considerably facilitates the removal of this impurity. This treatment is also extremely beneficial to iron ores associated with iron pyrites. The pyrites are oxidised—that is, the sulphide is converted into a sulphate, which is to a large extent dissolved out by the rain. Ores that are very compact or close in texture are rendered more porous and open, and in this state lend themselves more readily to furnace conditions.

Calcination denotes the operation of expelling by moderate heat the water and volatile constituents of an ore. In the case of iron ores calcination is chiefly intended to expel the carbonic acid and water and to convert the ferrous oxide into the ferric oxide, the reason for the latter change lying in the fact that ferrous oxide entering any furnace is liable to form scouring slags, which have a very detrimental effect on the furnace lining. A further feature is that iron associated with oxygen in the form of ferric oxide lends itself more readily to reduction than does iron in the form of ferrous oxide.

The elimination of carbonic acid and water effects a concentration of the metallic portion of the ore, and considerably simplifies the reactions of the blast furnace. Calcination, as with weathering, tends to yield the ore in a more porous condition and in a better state for charging into the blast furnace.

It is evident that if an iron ore consists essentially of ferric oxide and contains little or no water, carbonic oxide, or organic matter, calcination is in such a case unnecessary. Under these conditions only very hard or dense ores would be subjected to calcination for reasons already indicated. Magnetite iron ore is treated to the combined action of weathering and calcination in order to yield a more porous ore, and one that will readily enter into the reactions of the blast furnace. Red hematite, which, it will be remembered, contains its iron in the form of ferric oxide, but which contains, practically speaking, no carbonic acid, is not subjected to the treatment of calcination.

Calcination is conducted in open heaps, stalls, or kilns. The first method, that of open heaps, is the earliest, and is practised to some extent to-day. A suitable piece of ground is selected, and the size of the heaps marked out. This may be anything between 20 and 30 ft. wide by 50 to 150 ft. in length. Alternate layers of iron ore and coal are spread over this area until a height of from 6 to 12 ft. is reached. Combustion is started at one end, and allowed to proceed the length of the heap. It is regulated to some extent by opening passages to admit air into those portions where combustion does not proceed quickly, whilst those that are burning too quickly are damped down by fine ore. This method is analogous to that of coking coal in open piles. In it the operations are never under good control; atmospheric conditions are too variable to allow of regular and uniform results being attained, and if the temperature in any part rises too high, one of the chief objects of calcination is frustrated, for the mass partially fuses, thereby impairing porosity.

The second method, that of calcination between closed walls or in "stalls," as they are sometimes termed, is open to less objection than that of calcining in heaps. But even here the material is not altogether removed from atmospheric influences, and the labour in removing the calcined ore is excessive. Briefly, a stall consists of three walls at right angles and of moderate height. These stalls are arranged serially, and overhead tramways supply each one.

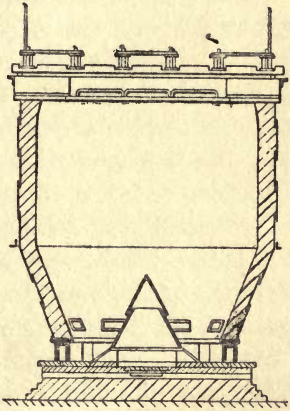


FIG. 1.

Calcination in kilns is the most economical method. Results are more uniform, fuel consumption lower, and the whole operation under much better control. There are several types of kilns, most of which utilize coal or slack as fuel. Some varieties are, however, adapted to burn waste gases. The most representative is that of Gjers, used for calcining iron ores, and familiar in the

Cleveland district. This consists of a boiler-plate shell lined with firebrick; it is cylindrical, and a section is shown in Fig. 1. Ore and coal are charged by means of overhead railways, and the calcined ore is withdrawn from the bottom. The capacity of such a kiln is nearly 1000 tons of ore per week, and the fuel consumption is about 1 cwt. of coal per ton of ore.

The foregoing notes on refractory materials, fuels, and ores are necessarily restricted, but sufficient ground has been covered to serve as preparation for the following processes.

CHAPTER IV

THE BLAST FURNACE AND HOT-BLAST STOVES

The commercial varieties of iron may be grouped into three main classes, each of which will in turn permit of subdivision. These are: (1) Pig or cast iron; (2) wrought iron; (3) steel. Wrought iron or steel can be produced by direct reduction from the ore, and such were the methods practised previous to the introduction of cast iron. But methods of direct reduction are not under good control, and the quality of the metal so produced is a matter of accident or fate, whilst the operations are tedious and costly. Therefore commercial methods for the production of steel or iron are based on the conversion of cast iron, this latter metal representing the first stage of reduction from the ore. This reduction is effected in a furnace familiarly known as a blast furnace. Blast furnaces for the reduction of iron ore are, generally speaking, long cylindrical shafts, fed with ore, fuel, and flux from the top, and supplied with the necessary air for the combustion of the fuel from the bottom. These furnaces vary in design, but the one shown in Fig. 2 may be taken as representing an average type. The cup and cone arrangement shown at the top, whilst distributing the charges evenly, serves also to close the top of the furnace and allow the gases to be drawn away through the pipe shown, which in modern plants may lead to the engine-house *viâ* the scrubbing and condensing apparatus, for the purpose of direct driving. From the throat—that is, just below the charging cone—down to where the diameter commences to contract is known as the stack; then follow the boshes; whilst the lower portion is distinguished as the hearth or well. A reference to Fig. 2 will show the relative position of these portions. Formerly the stack, hearth, and boshes were very distinct, but modern practice tends towards the adoption of a more regular curvature from throat to well. The contraction of diameter at the boshes is adopted to meet the decreasing volume of the descending charge. The molten metal collects in the well and is tapped at intervals, usually twice in twenty-four hours. It may be run into sand-beds, forming the well-known "pigs," or it may be tapped into a ladle and conveyed to a "mixer," from which it is passed as required to the Bessemer converters. In place of the sand-moulded pigs, chill moulds have been introduced, yielding a sand-free ingot of cast iron.

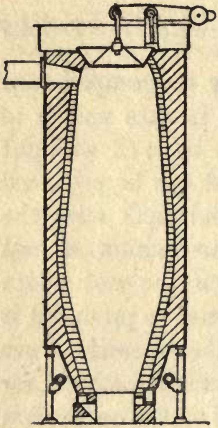


FIG. 2.

In height, blast furnaces vary according to the class of fuel used, a hard, compact fuel permitting a greater height than a soft one. Thus, charcoal-fed furnaces average 35 ft. in height, whilst coke-fed ones vary from 70 to 100 ft. in height.

Increase of height, when the character of the fuel will permit it, results in a lessened fuel consumption per ton of pig iron produced. But this increase holds good up to a certain point only, and general practice seems to have fixed an empirical maximum of 85 ft. An increase above this figure does not appear to yield a corresponding increase in economy. In capacity, blast furnaces vary from 2000 to 50,000 cub. ft., with an average capacity of 25,000 cub. ft.

Fig. 3[1] represents diagrammatically the internal form of a Cleveland blast furnace. The diameter of this furnace at the hearth is 8 ft., at the boshes 28 ft., and the charging cone is 13 ft. in diameter. The height is 85 ft., and the capacity 30,000 cub. ft. There are six tuyères, and the blast passes through them at a temperature of 1400° F. and a pressure of 5 lb. per square inch. Furnaces of this

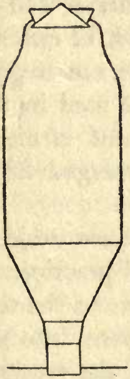


FIG. 3.

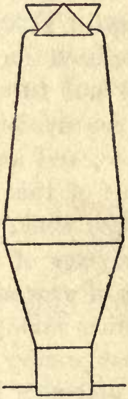


FIG. 4.

---

[1] *Iron and Steel Institute Journal*, No. 1, 1887.

type are fed with calcined Cleveland ore, the metallic content of which varies between 30 and 40 per cent. For each ton of pig iron produced, 20 cwt. of Durham coke and 12 cwt. of limestone are required. The weekly output approximates 500 tons of grey pig iron, together with 700 or 750 tons of slag.

Fig. 4[1] is a diagram of the internal form of a typical American blast furnace, having a capacity of 18,200 cub. ft. The height is 80 ft., the diameter of hearth 11 ft, that of throat 15½ ft., and the charging cone 12 ft.

There are seven tuyères, and the blast is supplied at a temperature of 1100° F. and a pressure of 9 lb. per square inch. For each ton of iron produced, 17 cwt. of Connesville coke and 10 cwt. of limestone are required. The ores used are much richer than those used in the preceding furnace, and average 60 per cent. of metallic iron. The output of this furnace has averaged 2200 tons of grey iron per week.

The tuyères of a blast furnace are subject to hard conditions of wear and tear in actual practice. From the two preceding examples of blast furnaces the temperature of the blast passing through the tuyères into the furnace is in the first case 1400° F., and in the second 1100° F. Further than this, the extremity of the tuyère projects into the furnace, and is therefore subject to the intense heat and corresponding wear and tear of the interior. Hot-blast tuyères, therefore, to give any working life at all, require shielding to some extent from the intense heat to which they are exposed, and in the majority of cases this is accomplished by surrounding the air nozzle

---

[1] *Iron and Steel Institute Journal*, No. 1, 1890.

with a water jacket. Fig. 5 shows in section the arrangement of a water-cooled tuyère, through which a constant stream of cold water is maintained. Fig. 6 shows in section a coiled wrought-iron pipe which is cast inside a conical tuyère of cast iron, and when placed in position is arranged with the inlet top and the outlet leading to the waste pipe. Figs. 5 and 6 are respectively known as Staffordshire and Scotch tuyères, but their use is not confined to locality as indicated by name, for "Scotch tuyères" are largely used in the Cleveland district. Tuyères of either of the foregoing designs possess a serious disadvantage in that a small leak of water into the furnace may go undetected for some time. The open tuyère shown in Fig. 7 is designed to permit of a more ready examination, and so facilitate the quicker detection of a leaking tuyère. In it the water is sprayed on to the part projecting into the furnace, and this form of open tuyère is one largely adopted.

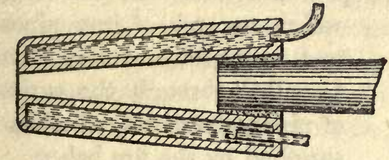


Fig. 5.

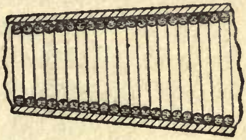


Fig. 6.

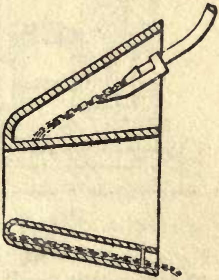


Fig. 7.

Hot-blast Stoves.—It is a natural step from the tuyères which admit the hot blast into the furnace to the stoves employed for heating that blast. J. B. Neilson, of Glasgow, was the originator of what is now commonly known as hot blast, and his first patent was granted on September 11, 1828.

The earlier types of heating stoves consisted of brickwork chambers having open firegrates, surmounting which an arch of iron pipes was arranged, and the blast travelled through the series of pipes, abstracting the heat supplied by the fire below.

A good example of a pipe stove is that known as the pistol-pipe stove, an illustration of which is shown in Fig. 8. The pipes are separated the greater part of their length by a partition, thus causing the air to travel up one half of the pipe and to return down the other. The arrows in the illustration show the direction of the air current, and this is repeated through each successive pipe of the series until it finally passes out from the end of the stove into the hot-blast main, and from thence to the furnace. Pistol-pipe stoves are usually coal fired, but they may be also fired by waste gases, in which case greater heating surface of pipe is allowed.

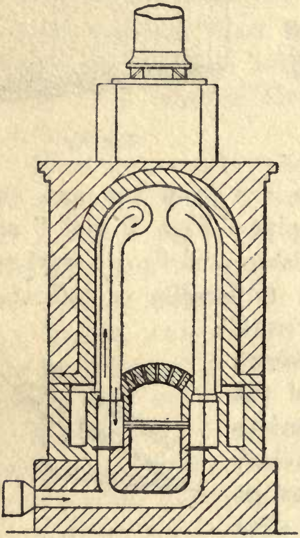


Fig. 8.

Firebrick stoves of the regenerative heating type are in more general use than are pipe stoves. These stoves, with considerably less wear and tear, give a higher temperature of blast than can possibly be attained with pipe stoves. Very briefly, the regenerative heating principle, as introduced by Sir W. Siemens, consists in passing cold air through a mass of brickwork which has previously been heated to a high temperature by drawing the waste products of combustion through it. Thus, in the accompanying model (Fig. 9), assuming that C represents a furnace and that A and B represent divided chambers filled with firebricks, and so arranged as to expose the greatest possible heating surface, while allowing a passage for a current of air, BM may represent the blast main, and E the exit for the waste products. Then if the current of waste gases is drawn from C and passed down through the brickwork in A_2, and up through that in A_1 into the exit pipe, the temperature of these gases will be very much lowered—that is to say, the brickwork will have absorbed most of the sensible heat of the gases. Supposing the current of waste gases be cut off and cold air drawn through the brickwork of A_1 and through that of A_2, and from thence into the blast

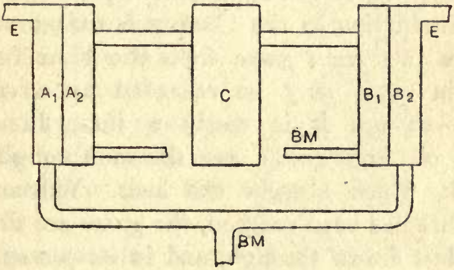
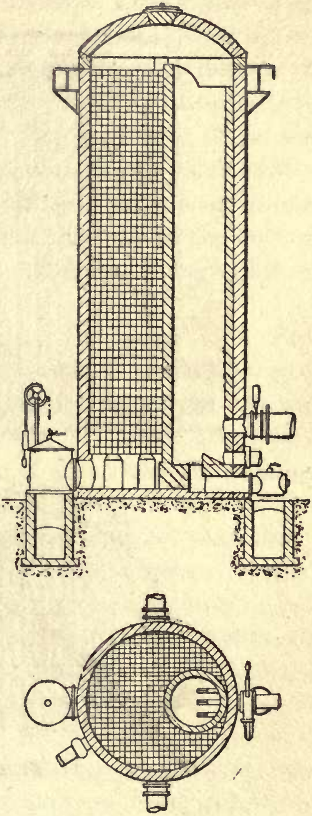


FIG. 9.

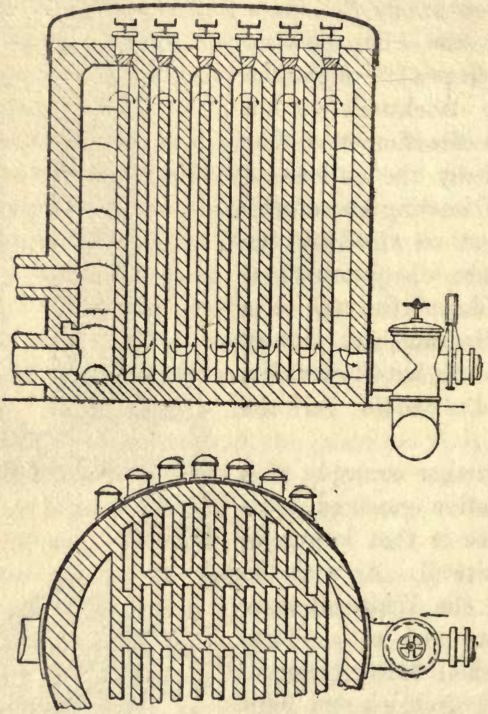
main to the furnace, that air in its passage through the chambers will abstract heat and become heated according to the amount of heat the bricks have to yield. Whilst the cold air is passing through A_1 and A_2 the waste gases are being drawn through B_1 and B_2, and when all the heat possible has been taken from A_1 and A_2, the current is reversed, the waste gases going through A and the cold air through B.

In practice this reversal of current is effected at definite intervals of time—often half-hourly ones. This brief description of the regenerative principle will serve as an introduction to the Cowper hot-blast stoves. In this stove the waste gases from the blast furnace are ignited in what may be regarded as a combustion chamber—though it is really a long flue—and the products of combustion are drawn through chequer brickwork, which absorbs the heat. When a certain temperature has been reached, the gases are shut off and the air blast drawn through, and in its passage through the chequer brickwork attains a temperature of 1500° F. Two stoves are, of course, necessary, and reversals of current are effected in the manner already indicated. Fig. 10 shows in section the arrangement of a Cowper hot-blast stove, and Fig. 11 gives a plan. These stoves consist of a circular casing from 20 to 30 ft. in diameter, and from 50 to 60 ft. in height. The roof follows the shape of a dome, and the whole is lined with brickwork. In the illustration shown the combustion flue is circular in section, but this is not universal, some types having flues of D section. At the bottom of this flue is fixed the valve for admitting the waste gases, and also one for admitting the necessary air for their combustion. When the stove has attained a sufficient degree of heat the gas and air valves are turned off, the chimney damper closed, and the hot-blast valve opened. The cold blast then enters the lower part of the chequer-work and is drawn through the intricate brickwork in an opposite direction from that followed by the current of gases in heating the stoves. The blast on reaching the top of the chequer-work is drawn down through the combustion flue, and, passing through the hot-blast valve, enters the main for the furnace.



Figs. 10, 11.

A further example of a regenerative gas-fired heating stove is that known as the Whitwell. As with the Cowper, the Whitwell stove is constructed of a cylindrical shell lined throughout with firebrick and built with a dome-shaped roof. In diameter they reach up to 25 ft., and in height up to 65 ft. Internally the Whitwell stove is very distinct from the Cowper, the essential difference lying in the arrangement of heating surfaces and in the manner of effecting the combustion of the gases. Instead of chequer-work, the regenerator is formed of vertical passages through which the gases are made to circulate, and air for combustion is admitted at several points, thus complete combustion is attained only after the gases have partly travelled through the stove. Figs. 12 and 13 show respectively the sectional elevation



FIGS. 12, 13.

and plan of a Whitwell stove. The internal arrangement is shown in these sketches, but one feature may be mentioned, and that is that stoves of the Whitwell type are much easier to clean than those of the Cowper type. To remove the accumulation of dust in the Cowper stoves a sudden shock, such as discharging a small cannon in the bottom or suddenly releasing the air, is necessary to effect a dislodgment. With the Whitwell stove the vertical passages offer no obstruction to the introduction of a cleaning tool, and such is effected through manholes in the roof; the dust is dislodged and falls to the bottom of the stove, from whence it is raked out through side or bottom manhole doors.

Blowing Engines.—The continuity of any blast furnace is naturally dependent on a constant supply of blast of uniform pressure, and of all machinery the engines for supplying blast should have least infirmities. They must, by the very nature of their work, be capable of running night and day over long periods of time, and with but few stoppages. It has been stated that thirty hours per year in stoppages for current repairs are all that any well-constructed engine should require.[1] Any consideration of types of blowing engines is outside our immediate purpose, and is a question of mechanical rather than metallurgical importance. However, in looking over the evolution of the blowing engine, it is seen that vertical direct-acting engines are replacing the earlier beam engines. The pressure of blast demanded varies widely, and a reference to the examples of Cleveland and American furnaces quoted earlier will show them to work at 5 and 9 lb. per square inch

---

[1] Kohn's "Iron and Steel Manufacture."

respectively. The actual amount of blast varies also with the capacity of the furnace, and the blowing engine may be required to deliver anything from 19,000 cub. ft. per minute.

Hoists.—Blast furnaces may be built on ground the slope of which is such as to permit of an arrangement by which the loaded trucks can be discharged on the same level as the charging stage of the furnace, but in the majority of cases hoists for raising the charges are necessary. A blast-furnace hoist may therefore take any one of the following forms: (1) Various types of hydraulic and compressed-air lifts. (2) Various types of direct-acting steam hoists. (3) An inclined plane constructed of girders and fitted with two sets of rails, upon one of which the empty truck descends whilst the loaded one ascends the other. The action is controlled by means of an auxiliary engine. (4) The water balance lift consists of two cages working between guides and suspended from the two ends of a wire rope passing over guide pulleys. When empty, the two cages balance each other. In ascending and descending, the tank on the loaded cage is emptied of its water, whilst sufficient water is run into the tank on the unloaded cage to more than balance the weight of the loaded one, and so cause it to ascend.

CHAPTER V

THE WORK OF THE BLAST FURNACE

REFERENCE to the analyses of iron ores given on page 44 will show the metallic portion of the ore to consist entirely of oxide in association with greater or less quantities of alumina, silica, lime, magnesia, etc. The work of the blast furnace therefore primarily consists in reducing the oxides of iron to the metallic condition, and in freeing the iron so reduced from its earthy admixtures. Before going into details of the chemical changes involved, the table on page 64 will give graphically some idea of the redistribution of the constituents of an iron ore effected by the action of the blast furnace. For the convenience of this table the products of the blast furnace are grouped into three divisions: (1) metal; (2) slag; (3) volatile or gaseous products.

Under certain conditions some portion of the iron enters the slag as ferrous oxide. It will also be noted that manganese and silicon are found partly in the slag and partly in the metal. According to the conditions of working, sulphur and phosphorus may pass wholly into the metal or be found partly in the metal and partly in the slag.

The volatile constituents refer to those of the ore, and not the gaseous products of the furnace.

DISTRIBUTION OF CONSTITUENTS.

Existing in the Ore as	Found in the Metal as	Found in the Slag as	Volatile Constituents.
Fe_2O_3, ferric oxide	Fe, iron	—	—
FeO, ferrous oxide	Fe, iron	—	CO_2, carbon dioxide
MnO, manganous oxide	Mn, Manganese	Also as MnO, manganous oxide.	H_2O, water
Al_2O_3, alumina	—	Al_2O_3, alumina	Organic matter
SiO_2, silica	Si, silicon	Also as SiO_2, silica	—
CaO, lime	—	CaO, lime	—
P_2O_5, phosphoric acid	P, phosphorus	—	—
SO_3, sulphuric acid	S, sulphur	Also as calcium sulphide	—

The weight of material charged into the blast furnace is considerably in excess of that of the iron produced; and referring again to the examples of Cleveland and American furnaces already quoted, it will be seen that the weight of solid material is in the first place 20 cwt. of coke and 10 cwt. of limestone per ton of iron produced, and in the second case 17 cwt. of coke and 10 cwt. of limestone per ton of iron produced. When speaking of the weight of material charged, the weight of air blown in at the tuyères ought also to be considered, which in an average coke-fed furnace may vary from 4 to 6 tons per ton of iron produced. This large amount of air, after passing through the furnace, goes to swell the amount of waste gases which are drawn off just below the charging cone. It may be taken approximately that every ton of average No. 3 iron produced is accompanied by from 25 to 40 cwt. of slag and from 120 to 140 cwt. of waste gases. These approximate figures are quoted in order to show the immense weight of material other than iron produced by the blast furnace. Actual figures are difficult to give owing to the fact that very few furnaces work under identical conditions, and fluctuations in working conditions are necessarily followed by variations in the amounts of slag or waste gases.

The Chemistry of the Blast Furnace.—Oxides of iron are readily reduced to the metallic condition when heated in contact with carbonaceous matter. Reduction also readily occurs when currents of either carbon monoxide, hydrogen, or gaseous hydro-carbons are passed through the heated oxide. Thus, if the ores consisted entirely of pure oxides of iron, the extraction of the metal would theoretically present few difficulties. But commercial ores, as has been already shown, contain appreciable quantities of constituents other than ferrous or ferric oxides, and hence the necessity arises for producing conditions which shall favour on one hand the extraction of the whole of the iron in the metallic state, and on the other the formation of a slag which shall retain the gangue and earthy constituents of the ore. The chemistry of the blast furnace may therefore be considered under two aspects: that of the reduction of iron, and that of the formation of slag.

Taking the gaseous action, and commencing at the bottom of the furnace, the first change to note is that of the combination of the oxygen of the blast with the carbon of the coke, resulting in the formation of carbon dioxide. Thus the air entering by the tuyères meets with hot coke, and the oxygen combines with carbon in the following manner:—

$$C + O_2 = CO_2.$$

This carbon dioxide is, however, instantaneously decomposed into carbon monoxide :—

$$CO_2 = CO + O.$$

The oxygen liberated combines with carbon, which is present in excess, to form carbon monoxide, thus—

$$O + C = CO.$$

If any moisture or steam is present in the blast, it is decomposed in the following manner :—

$$H_2O + C = H_2 + CO.$$

With the furnace in normal working condition there should be no free oxygen or carbon dioxide in the gases in the vicinity of the hearth. The following two analyses give approximately the composition of the gases in the locality of the hearth :—

	I.	II.
Carbon monoxide (CO)	30	37
Hydrogen (H)	0	3
Nitrogen (N)	70	60

As this gaseous current travels upwards, its composition is constantly altering, and at the same time much of its initial heat is absorbed by the cold descending charge. As the carbon monoxide of the gas comes into contact with the iron oxide of the ore in the upper portion of the furnace, reduction is effected thus—

$$Fe_2O_3 + 3CO = 2Fe + 3CO_2.$$

The iron is obtained in a spongy condition, and if the height of the furnace and the descent of the charge are proportionate to each other, reduction of the greater part of the oxide of iron is completely effected in the first 10 ft. of descent. Any oxide below this point is reduced by solid carbon, as follows:—

$$Fe_2O_3 + 3C = 2Fe + 3CO.$$

After reduction of the iron, and continuing until a state of fusion is reached, a deposition of solid carbon takes place owing to the decomposition of carbon monoxide by hot spongy iron—

$$2CO = CO_2 + C.$$

The carbon dioxide so formed travels upwards with the gases, and the solid carbon is intermingled with the spongy iron. This deposition of carbon right through the lumps of solid ore has a disintegrating effect, and the ore is converted into a black powder, sometime before combustion of the coke or fusion of the slag.

When the descending charge has reached the point at which reduction of the iron is almost complete—that is, a temperature of about 600° C.—the limestone charged as flux is decomposed into quicklime and carbon dioxide, thus—

$$CaCO_3 = CaO + CO_2.$$

The carbon dioxide will combine with free carbon to form the monoxide in the following manner:—

$$CO_2 + C = 2CO.$$

It is thus evident that from the first formation of carbon dioxide in the hearth of the furnace, and its immediate conversion into monoxide, there is a constant cycle of change. Whenever the dioxide is formed, it is dissociated by the temperature, and in the presence of an excess of carbon again forms the monoxide. This cycle of change is repeated during the ascent of the gases through the furnace, but with lessening intensity as the upper, and consequently cooler, portions are reached, and eventually a point is attained, at which some portion of the carbon dioxide is unaffected. The reduction of the iron is dependent on this change, and the activity of carbon monoxide in this respect has been already shown. Carbon dioxide is, of course, inert, further than from the sensible heat it contains, and is capable of yielding to the charge. Nitrogen is also practically inert; it has a slight effect in the formation of cyanides, which, however, does not warrant consideration here. The traces of hydrogen, probably derived from the decomposition of steam, are too small to demand consideration, and their effect may for our present purpose be disregarded.

The Descent of the Charge.—It has been already shown that the oxide of iron contained in the ore is, very shortly after its introduction to the furnace, subjected to the reducing action of carbon monoxide. This action commences a few feet from the charging level, or at an approximate temperature of 200° C., and continues with increasing vigour as the charge descends into higher temperatures. The point at which the decomposition of limestone commences (600° C.) has been indicated, and at this stage the reduction of iron is almost complete. Thus, according to the class of furnace, in from 10 to 30 ft. of descent the charge is entirely deoxidized, and now consists of spongy iron, gangue, coke, and quicklime. During the next 20 to 30 ft. of descent little chemical change occurs further than that due to the deposition of carbon by the dissociation of carbon monoxide.

Finally the charge reaches the zone of fusion, or, in other words, a temperature sufficiently high to form a slag by the union of the lime with the silica, alumina, etc., of the ore. At this temperature part of the silica, oxide of manganese, phosphoric acid, etc., is reduced, and passes over to the iron, which is already impregnated with solid carbon. The whole of the charge then melts, and trickles down into the hearth below the tuyère level, the slag, owing to the lower specific gravity, floating on the molten cast iron.

The Reduction of Silicon.—Silica is not reducible by carbon monoxide alone or by carbon alone, and reduction can only be effected by carbon in the presence of certain metals and very high temperatures. Therefore, in blast-furnace practice the amount of silicon reduced varies with the temperature of the furnace, and irons smelted at high temperatures always contain more silicon than do those produced at low temperatures. The silica, remaining unreduced, passes directly into the slag.

The Reduction of Manganese.—Manganese associated with the ore is partly reduced and passes into the cast iron, the remaining part being found in the slag as manganous oxide. As with silica, high temperatures favour the reduction of more manganous oxide, as does also the presence of basic slags. In smelting manganiferous pig irons very high temperatures are employed, in order to minimise as far as possible the loss of manganese.

The Reduction of Phosphorus.—Phosphorus, when present in the ore as calcium phosphate, is not reduced by carbon monoxide, and its reduction is effected by solid carbon in the lower part of the furnace, the lime passing over to the slag, and the reduced phosphorus to the metal. Usually, the whole of the phosphorus present in an ore passes into the cast iron.

The Reduction of Sulphur.—The sulphur present in an iron ore when smelted in the blast furnace passes partly into the metal and partly into the slag. High temperatures and basic slags favour the passage of the greater part of the sulphur into the slag. Manganese present in the ore in excess acts as a desulphurizer, owing to the formation of a sulphide of manganese.

Blast-furnace Slags.—The successful production of iron depends in very large measure upon the nature of the slag produced, which should be readily fusible for the class of iron made, and formed in sufficient quantity with the least possible addition of flux. The slag is derived from the earthy matter of the ore, the ash of the fuel, and the fluxes added to promote its fusion. It usually consists of a double silicate of alumina and lime, though in practice it is subject to variation according to local conditions. The formula approaches—

$$Al_2O_3,\ 3CaO,\ 5SiO_2,$$

having the following general composition :—

Silica	56 per cent.
Lime	30 ,,
Alumina	14 ,,

The appearance of the slag varies with the quality of the iron produced, and forms a very good index as to the working of the furnace. An excess of lime, such as is usual with a grey iron, gives a slag which is not easily fusible, and when cold has a white colour, and readily slakes in water. As the irons approach the mottled quality, the slag attains a grey colour, with possibly a greenish or bluish shade caused by traces of ferrous oxide and sulphide of manganese. It is hard and compact, and is extensively used for road metal. The slags resulting from a furnace producing white iron are, when molten, very fluid, and contain appreciable amounts of ferrous oxide. Slags of this nature are known as "scouring slags." Owing to the amount of ferrous oxide contained, they have a very scouring or corroding effect on furnace linings. These slags are, when cold, of a dark, almost black, colour. The three analyses of slags given below show the range of variation and divergence from formula :—

	I.	II.	III.
Silica	43·00	31·46	27·38
Alumina...	14·83	8·53	22·23
Lime	29·00	52·53	40·12
Ferrous oxide	2·50	0·76	0·80
Manganous oxide	1·30	2·38	0·20
Magnesia	5·57	1·38	7·27
Calcium sulphide	1·90	2·96	2·00
Alkalies	1·90	—	—

The disposal of slags is a matter of no little moment, and has given rise to what is generally known as the "slag problem." An examination of the huge slag tips in the vicinity of blast furnaces gives emphasis to the difficulties of this problem, and these constantly accumulating heaps represent an amount of labour and energy for which no return is to be seen. Some of the methods of handling slag are briefly summarized in the following :—

1. In the older style of furnaces the slag is "flushed" off between the intervals of tapping. This is effected by running the slag through a slag notch into an open sand pit, in which an iron bar, hooked at the end, is placed. When solidified, this hook offers a ready means for hoisting out the block, which is carted away and broken up on the slag tip.

2. The slag is tapped into a bogey running on rails. The body of the bogey is constructed of cast-iron segments and given a good taper to facilitate the ready withdrawal of the solidified blocks of slag. These blocks may be dumped on to the slag tip, or in other cases taken out to sea in barges and dropped.

3. The slag may be run into moulds fixed on an endless chain. These moulds travel in front of the slag spout and are filled with slag; they are then sprayed with water, and the solidified blocks of slag drop into trucks as the endless chain carrying the moulds passes round the extreme pulley.

4. The slag may be tapped into a side tapping ladle lined with firebrick.

5. The slags may be granulated by running into water. In certain cases the granulated slags may be easier to handle than the heavier blocks.

The profitable disposition of slag does not as yet cover a very extensive field. Some of the purposes to which it may be applied are included in the following:—

The compact varieties of slag and those which do not disintegrate under atmospheric influences are extensively used as road metal and railway ballast. This variety of slag can also be moulded into bricks and used for paving or building purposes.

Slag wool is formed by causing a jet of air or steam to impinge against a stream of slag as it runs from the furnace. The wool is used for purposes of non-conduction.

Other varieties of slag are used in the manufacture of cements, and phosphoric slags are used in a powdered state as fertilizers by the agriculturist.

Gaseous Products.—The gaseous products of the blast furnace offer in comparison with the slags a very rich field for profitable exploitation. Indeed, the practice of to-day confirms in large measure a prophecy made in 1848 by Mr. J. B. Budd:—

"It would appear to be more profitable to employ a blast furnace, if as a gas generator only, even if you smelted nothing in it and carried off its heated vapours by flues to your boilers and stoves, than to employ a separate fire to each boiler and each stove."

The blast furnaces of modern works may be regarded as gas generators, and as such are quite distinct from their main function of iron producing. The gases issuing from the furnace top are used in the first place for heating hot-blast stoves of the Cowper or Whitwell type in a manner already illustrated. From the heating stoves the gases are passed on to the boilers used for raising steam for the blowing engines, and should there be any surplus from these boilers, it may be used for calcining the iron ore or for general heating purposes. In the Carron Works the surplus gas is used in the iron foundry for drying moulds and similar purposes. Five typical analyses of "waste gases" from different blast furnaces are as follows:—

	I.	II.	III.	IV.	V.
Carbon monoxide ...	26·00	23·51	24·20	24·65	28·61
Carbon dioxide ...	7·80	12·88	8·77	12·01	11·39
Nitrogen	55·72	57·79	62·34	57·22	57·06
Hydrogen	6·73	5·82	1·33	5·19	2·74
Carburetted hydrogen	3·75	—	3·36	0·93	0·20

The gases themselves are not only valuable for the purposes indicated, but may, by suitable treatment, be made to yield very valuable by-products. This is especially the case with blast-furnace gases in which raw coal has been used as fuel, and it pays to extract the tar and ammonia from gases derived from such a source before burning them in either the heating stoves, under the boilers, or using them for direct driving in the case of gas engines. One of the earliest plants erected for this purpose is known as the Alexander and M'Cosh process, and it may be well to outline very briefly the chief essentials of this process. The gas is led from the blast furnace through a large gas main to the condensing apparatus, which consists of three distinct portions—namely, an atmospheric condenser, a water condenser, and scrubbers. The gas in its passage through the atmospheric condenser is very much cooled—usually from an initial temperature of 350 down to 120° F.—and during its passage through this condenser some portion of the tarry matter may be condensed. In the interior of the water condensers are arranged series of tubes through which cold water is circulated. The gases are brought into intimate contact with these cold surfaces and their temperature further reduced to an approximate one of 65° F. In general cases this lowering of temperature by passage through the water condenser effects an extraction of about 30 gals. of ammoniacal liquor per ton of coal used in the blast furnace. During their passage through the scrubber the gases are brought into intimate contact with water, which effectually washes out the tar and condenses the remainder of the ammonia. The tar and ammonia liquors are then run into tanks and allowed to separate by gravity, the tar rising to the top. The ammoniacal liquor is passed into suitable stills, and lime added in order to decompose any salts of ammonia formed. The contents are then distilled, and the ammonia, evolved as a gas, is passed into sulphuric acid. The latter is evaporated, and the crystals of ammonium sulphate extracted and dried. The average yield of crystals is about 25 lb. of ammonium sulphate per ton of coal used in the blast furnace.

The tar is distilled separately, and yields oils suitable for lighting, lubricating, and similar purposes. The solid residue consists of pitch, which may be used for a variety of purposes, and is often employed in making briquettes. The yield of tar is between 14 and 18 gals. per ton of coal used in the blast furnace.

These tars contain appreciable quantities of phenols, which in some cases are extracted and used in the manufacture of disinfectants.

In the Neilson process the gases are washed in contact with dilute sulphuric acid and in a lead-lined scrubber, which directly extracts the ammonia. The liquid is evaporated and crystallized as in the foregoing process. Before passing into the acid scrubber, the gases traverse a water scrubber to lower the temperature and remove the dust.

In the Addie process the gases are mixed with sufficient sulphur dioxide to combine with the ammonia present and form ammonium sulphite. The mixed gases are then passed through scrubbers, and the temperatures considerably reduced. The sulphite liquor is extracted, mixed with lime, and distilled.

CHAPTER VI

THE METALLIC PRODUCT OF THE BLAST FURNACE

PIG iron, which represents the metallic part of the products of the blast furnace, is classified into groups which to some extent represent the quality of the metal. We have already seen that during reduction, or on subsequent melting, the iron associates with more or less carbon, sulphur, phosphorus, manganese, and silicon. The amount of carbon present in ordinary pig irons varies from 1·5 to 4·5 per cent., with a general average of from 2·5 to 3·5 per cent. Pig irons containing special elements such as manganese or chromium in appreciable quantity, carry also proportionately more carbon, but the ordinary irons never contain more than 4·5 per cent. In every variety of pig iron, carbon is found in at least two distinct conditions, which are generally known as "free" and "combined" carbon. Free carbon or graphite is mechanically interspersed through the iron, and is well shown in a fractured pig. On the other hand, combined carbon is a definite chemical compound of iron and carbon, and as a compound has a decisive effect on the iron with which it is associated.

Graphite, representing the element carbon in a free state, can only have a mechanical effect, which will be referred to when considering the properties of pig iron. It is on the relationship of free to combined carbon that the classification of pig iron is based. For instance, when the greater part of the carbon is in the free state, as graphite, the iron is known as "grey," and when the greater part is in the combined form, the iron is "white." Intermediate stages between grey and white, containing approximately equal amounts of combined and free carbon, are known as mottled irons. Thus grey, white, and mottled are the leading features in the commercial classification of pig iron, each one of which offers any amount of sub-division. For instance, grey irons are sub-divided into numbers 1, 2, 3, and 4 foundry, or 1, 2, and 3 Bessemer, etc. Mottled varieties are distinguished as 4 and 5 forge, etc. White irons are not sub-divided into numbers denoting grade, but are recognized by their source, as Swedish white, etc. It will be readily seen that the classification adopted is a general one only, and in no case is a hard-and-fast line adopted. It is often found that numbers 1 and 2 Bessemer, or 1 and 2 foundry, vary in the slightest manner only. Further than this general classification, pig irons are often distinguished by their source. The familiar hematite pig irons are so termed owing to their being smelted entirely from English or Spanish hematite ore. The analyses of a typical series of these pig irons are given in the following table, illustrating the method of grading adopted.

ANALYSES OF ENGLISH HEMATITE IRONS.

	Bessemer Grey Irons.			Grey Foundry.	Forge Pigs.		Mottled.	White.
	I.	II.	III.	III.	IV.	V.		
Combined carbon (CC)	0·50	0·60	0·80	0·90	1·10	1·30	1·80	3·00
Free carbon (Gr)	3·50	3·30	3·10	2·80	2·50	2·10	1·40	0·10
Silicon (Si)	2·50	2·30	1·80	2·25	1·50	1·20	0·70	0·30
Sulphur (S)	0·02	0·02	0·04	0·05	0·08	0·11	0·15	0·20
Phosphorus (P)	0·04	0·04	0·04	0·04	0·04	0·04	0·04	0·04
Manganese (Mn)	0·20	0·20	0·20	0·20	0·20	0·20	0·20	0·20
Iron (Fe)	93·24	93·54	94·02	93·76	94·58	95·05	95·71	96·16

Other classifications of iron are denoted by the locality in which the ore is mined or smelted. Thus Scotch irons are often branded by the furnace or district in which they are produced; for example, Coltness, Gartsherrie, Carron, etc. English irons are similarly termed, familiar ones being Cleveland, Lincolnshire, Derbyshire, Forest of Dean, Staffordshire, etc. The last one is sometimes further distinguished as Staffordshire "all-mine"—that is to say, the iron has been smelted from a burden consisting entirely of ore. Cinder pig denotes an iron obtained from a blast furnace in which the whole or part of the burden consists of the tap cinder derived from puddling furnaces.

Basic pig iron is a phosphoric iron, low in sulphur, and fairly low in silicon, which is used as a base for the production of steel in the basic Bessemer or Siemens process of steelmaking. Charcoal and cold-blast irons are self-explanatory terms, being respectively iron produced in a charcoal-fed furnace, or one in which the blast undergoes no preliminary heating.

Ferro-chrome, when produced in the blast furnace, will contain up to 40 per cent. chromium, but higher percentages of chromium are produced in crucible furnaces. The following general analyses of ferro-chrome are instructive :—

	I.	II.
Iron	44·90	30·00
Carbon	8·60	9·10
Silicon	0·60	0·50
Manganese	0·40	0·30
Sulphur	0·05	0·05
Phosphorus	0·05	0·05
Chromium	45·40	60·00

Ferro-manganese, an alloy of iron, carbon, and manganese, may be also termed a metallic product of the blast furnace. This alloy is obtained by smelting manganiferous ores at high temperatures, the content of manganese varying from 45 to 80 per cent. With the lower percentages of manganese the alloy is termed "spiegel," which is a contraction of the word "spiegeleisen," or "looking-glass iron," due to the fact that such a material breaks with a large platy and shining fracture. As the manganese rises, the fracture becomes granular. Three typical analyses are here given :—

	Spiegel.	Medium Ferro-manganese.	Ferro-manganese.
Combined carbon ...	4·30	5·50	6·80
Manganese	15·00	50·00	80·00
Silicon	0·50	0·70	0·90
Sulphur	0·02	0·02	0·02
Phosphorus	0·25	0·25	0·25
Iron	79·93	43·53	12·03

A pig iron high in silicon is usually termed a "siliceous pig," and when specially produced such a material is known as ferro-silicon. As with ferro-manganese, ferro-silicon produced in the blast furnace requires a high temperature, a siliceous burden, and a large fuel consumption. An analysis of a ferro-silicon is given below :—

Combined carbon	0·20	per cent.
Free carbon	1·46	,,
Silicon	14·85	,,
Manganese	0·34	,,
Sulphur	0·08	,,
Phosphorus	0·12	,,
Iron	82·95	,,

Silicon spiegels are also produced, analyses of which approximate :—

Combined carbon	0·67	per cent.
Free carbon	0·98	,,
Silicon	13·00	,,
Manganese	19·00	,,
Phosphorus	0·10	,,
Sulphur	0·08	,,
Iron	66·17	,,

The Handling of Pig Iron.—The metallic products of the blast furnace, unlike the slags, offer few difficulties in the way of disposal. Pig iron is to a large extent cast into open sand moulds of D section, long rows of which lie immediately in front of the tapping hole of the furnace. The molten metal is led from the tap hole by means of suitable channels—or, as they are technicaly termed, "sows"—into the pig moulds, and when cold is broken, graded by fracture, and transferred to the storage yard. This brief outline represented a method universally followed at one time; but now the increasing outputs of modern blast furnaces, together with the increasing requirements of the steel-works, are gradually leading to the displacement of hand by mechanical labour on the pig bed. In this respect, mechanical moulding of the pigs, and the adoption of pig breakers in conjunction with suitable cranes, do much to minimize the arduous labour of the pig bed, and to assist in maintaining a high output. But it is in the adoption of mixers and pig-casting machines that the chief advances are to be noticed, although British practice still largely follows the plan of casting pigs in channels moulded by hand.

A mixer is, generally speaking, a huge storage reservoir into which the liquid metallic contents of one or more furnaces are emptied.

Mixers are used in conjunction with steel-works, supplying the Bessemer converters with molten metal as required, thus dispensing with the preliminary cupola melting necessary where mixers are not employed. In addition to supplying the steel-works with molten metal as required, the mixers serve a further purpose in that they effectually mix, as the name would indicate, the contents of several blast furnaces, thus tending towards the production of a uniform grade of iron from two or more different furnaces. The largest mixer employed in this country is that of Messrs. Bell Brothers, at their Clarence Works. This mixer has a capacity of 300 tons, and is heated with gas from three producers.

There are varieties of pig-casting machines, but the general principle upon which they are constructed is that of a travelling belt with suitable ingot, or pig moulds, fixed to it. The iron from the blast furnace is taken in a ladle to the casting machine, and the moulds are filled as they pass before the ladle. The moulds travelling away from the ladle are cooled by contact with water, and the pigs automatically dumped into trucks. The product is known as sandless pig iron, and as the chills into which it is cast modify the fracture, it is usually graded by analysis. For foundry purposes, on remelting in the cupola the chill is eliminated, and the machine-cast iron melts and casts in a similar manner to that of a corresponding sand-cast grade. An advantage of the chilled iron is its freedom from adhering sand, and it usually melts clean, producing good castings.

The following analyses of pig iron are instructive, and are introduced here preparatory to a brief study of the properties of cast iron :—

SWEDISH PIG IRON.

	Grey.	Mottled.	White.
Combined carbon	0·50	2·00	3·50
Free carbon	3·50	2·00	0·50
Manganese	0·30	0·30	0·30
Silicon	1·00	0·50	0·25
Sulphur	0·02	0·02	0·02
Phosphorus	0·03	0·03	0·03
Iron	94·65	95·15	95·40

Swedish irons rank among the purest in the world, and pig irons such as the foregoing are the source of much of the high-class crucible cast steel produced in this country. The series of hematite irons already given are typical of the better qualities of English pig irons, which find their chief outlet in the conversion into steel by the Siemens or Bessemer process.

YORKSHIRE PIG IRON.

	Suitable for		
	Acid Steel-making.	Basic Steel-making.	Common Foundry.
Combined carbon ...	0·50	0·50	0·50
Free carbon	3·00	3·10	2·90
Silicon	1·00	0·70	1·00
Sulphur	0·05	0·04	0·40
Phosphorus	0·06	2·50	2·00
Manganese	1·30	1·30	1·00
Iron	94·09	91·86	92·20

STAFFORDSHIRE ALL-MINE PIG IRON.

	I.	II.	III.	White.
Combined carbon ...	0·40	0·45	0·50	2·00
Free carbon	3·30	2·68	2·14	0·20
Silicon	1·88	1·62	1·33	0·71
Sulphur	0·02	0·04	0·09	0·19
Phosphorus	0·71	0·68	0·56	0·47
Manganese	0·40	0·54	0·25	0·50
Iron	93·29	93·99	95·13	95·93

CLEVELAND PIG IRON.

	I.	II.	III.	Forge.	Mottled.	White.
Combined carbon ...	0·10	0·20	0·48	0·80	1·25	3·05
Free carbon	3·20	3·16	3·16	2·60	1·84	0·10
Silicon	3·50	2·90	2·59	1·93	1·01	0·67
Sulphur	0·05	0·06	0·08	0·10	0·32	0·40
Phosphorus	1·67	1·69	1·57	1·55	1·57	1·60
Manganese	0·68	0·62	0·60	0·75	0·62	0·42
Iron	90·80	91·37	91·52	92·27	93·39	93·76

NORTHAMPTON, DERBY, AND SCOTCH PIG IRON.

	Phosphoric Pig, Smelted from Brown Hematite.	Derbyshire. No. III. Foundry.	Coltness. No. I.
Combined carbon ...	0·50	0·40	0·20
Free carbon	3·00	2·20	3·30
Silicon	0·80	1·26	3·50
Sulphur	0·15	0·05	0·02
Phosphorus	2·00	0·72	0·98
Manganese	1·50	0·45	1·58
Iron	92·05	94·92	90·42

AMERICAN PIG IRONS.

	No. I. Foundry.	No. II. Foundry.	No. III. Foundry.
Combined carbon ...	0·07	0·10	0·20
Free carbon	3·49	3·45	3·38
Silicon	3·15	2·40	2·00
Sulphur	0·05	0·03	0·03
Phosphorus	0·68	0·68	0·64
Manganese	0·25	0·22	0·22
Iron	92·31	93·12	93·53

In American foundry practice a siliceous pig iron known as "silver grey" is used as a softener. A typical analysis of such an iron is here given:—

SILVER GREY PIG.

Combined carbon	0·02	per cent.
Free carbon	3·13	,,
Silicon	5·50	,,
Sulphur	0·01	,,
Phosphorus	0·60	,,
Manganese	0·25	,,
Iron	90·49	,,

CHAPTER VII

THE GENERAL PROPERTIES OF CAST IRON

A review of the properties of cast iron can be most readily presented by dividing the matter into three short sections, dealing first with the general properties, secondly with the varieties of the metal used as a source for the production of steel, and thirdly with the types known generally as foundry irons.

In considering cast iron as a whole, the first and most striking feature is the high content of elements present other than iron. For instance, in the analyses recently given, the purest variety—that of Swedish white iron—contained only 95·4 per cent. metallic iron. That is to say, this iron, which, as cast irons go, is one of the purest produced, contains 4·6 per cent. of elements other than iron. Average cast irons, especially those in foundry use, contain greater percentages of foreign matter, and correspondingly lower percentages of metallic iron. Taking the analysis of Yorkshire common foundry iron given on page 84, it will be seen to contain 7·8 per cent. of elements other than iron. For the moment, this iron can be regarded as containing—

Iron	92·2 per cent.
Impurity	7·8 ,,

The nearest approach to perfect purity found in commercial irons is a Swedish *wrought* iron known as "little s," containing 99·87 per cent. metallic iron. For comparison, this and the foregoing foundry iron are diagrammatically shown in Figs. 14 and 15, where each outer square represents 100 per cent., whilst the black centres show relatively the volume of impurities.

The volume of what have just been termed impurities —a term of convenience only—very naturally determines the quality of any cast iron. Each of the constituents forming this impurity has an effect of its own on the iron in which it is contained. Further, some of the elements, notably silicon, exercise a controlling effect on others, and so, to a certain extent, regulate or limit the qualities of the metal in which they are present. Thus the properties of any variety of cast iron are a function of the constituents present, and the relationships these constituents bear to each other.

Of these constituents, the most important is that of carbon, and the amount and manner of existence of this element rules in large measure the destiny of any variety of cast iron. The analyses already given show the two forms in which carbon is usually present, and also illustrate the control this element exercises. Of these two forms, graphite represents carbon present in a free state; it can therefore be separated by mechanical methods. Generally speaking, graphite has a mechanical rather than an actual chemical influence; it is distributed through the mass of the iron just as fruit through a cake; but, unlike fruit, which flavours the cake, graphite does not affect the quality of the iron by its own individual effort. Although the greater the amount of free

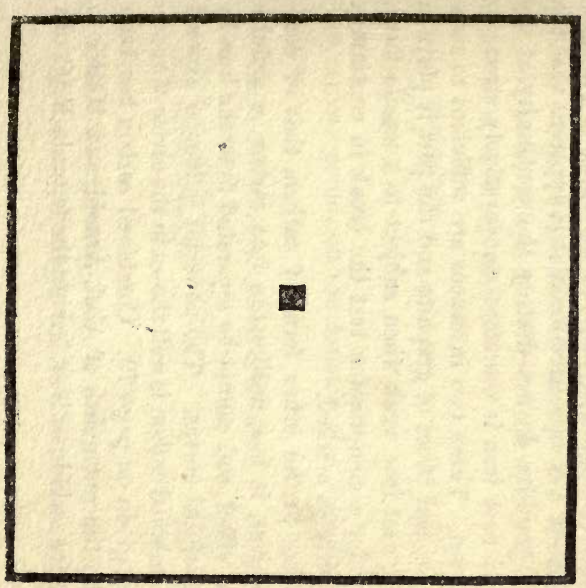


FIG. 14.—Swedish "S" Iron.

Total impurities	0·13 per cent.
Metallic iron	99·87 ,,

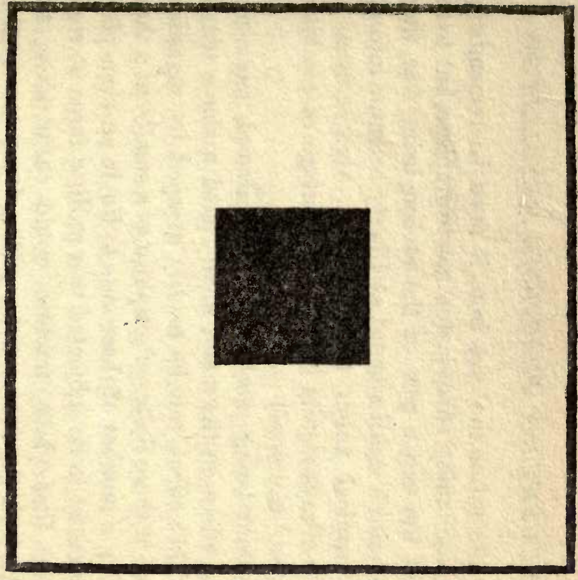


FIG. 15.—Foundry Iron.

Total impurities	7·8 per cent.
Metallic iron	92·2 ,,

carbon the softer the cast iron, it must be remembered that this softening effect is due, not to graphite, but to the fact that the major part of the carbon being free, there only remains a small amount at liberty to enter into definite chemical union with iron. A high content of graphite always results in a low percentage of combined carbon, and *vice versâ*.

Graphite being mechanically distributed, has a mechanical effect on the metal when tested under a tensile load. This effect can be readily grasped by regarding each one of these flakes of graphite as a small cut; then, supposing a number of these cuts to lie in an even plane and the metal to be subjected to a pulling force at right angles to that plane, fracture would occur along the graphitic path the moment the pulling force was equal to the cohesive force acting between the flakes of graphite. In the case of a compressive force, it is apparent that the flakes of graphite do not destroy the continuity of the mass, and cast iron is therefore comparatively strong in compression. These two instances are sufficient to show the mechanical effect of graphite and the part it plays in rendering cast iron weak when subject to a tensile force, whilst under a compression test the break in continuity is not nearly so marked.

Turning to the other form of carbon, that of combined carbon, it has, unlike the free carbon, a definite chemical effect, and cannot be separated from the iron by any mechanical means. The powerful influence exerted by the combined carbon is well shown in the series of hematite irons given on page 79. Combined carbon has been proved by the researches of Abel, Arnold, and Müller to be a definite carbide of iron, having the formula Fe_3C. In cast irons it is this carbide which gives the hardening effect—an effect readily appreciated by attempting to drill any variety of white iron in which the carbon is present entirely in the form of carbide. But in addition to this definite carbide of iron, carbon is also found in combination with manganese as a carbide of manganese —Mn_3C. If manganese be present in appreciable quantity in a white cast iron, the combined carbon will then represent a double carbide of iron and manganese. Thus, when the manganese is high, the holding power of an iron for carbon is high, an increase of manganese giving rise to an increase in the absorptive power of the iron for carbon by the very fact of this formation of double carbides. These carbides are intensely hard, and when distributed through an iron carry a hardening effect much greater than would be imagined from the content of total carbon present. The researches of Carnot and Goutal throw much light on this point. For instance, in an iron which on ultimate analysis yields—

Combined carbon	2·45	per cent.
Graphite	0·60	,,
Manganese	2·00	,,

the carbon would, on the formation of carbides, exist as follows :—

Carbide of iron and manganese, $4Fe_3CMn_3C$	7·84	per cent.
Carbide of iron, Fe_3C	24·70	,,
Carbon as indefinite subcarbide	0·32	,,
Free carbon—graphite	0·60	,,
	33·46	

Thus, with an iron containing 3·05 per cent. total carbon the effect is increased, by the formation of carbides, practically eleven-fold. It is in this light that many of the elements present in a metal must be regarded, and it is easy to imagine that even the merest trace of a foreign substance may, by the formation of a suitable compound either with the metal itself or some element present in it, be in effect considerably increased. The "trace" can in this manner be largely magnified, and it is to the formation of compounds that one must turn for the effect of the trace. These compounds may be neutral—that is to say, have very little effect on the metal in which they are distributed—but in the majority of cases they have either a beneficial or a distinctly adverse one. As an example of injurious compounds, the sulphides are specially noteworthy. The element sulphur—undoubtedly the most injurious element present in cast iron—can, when present in minute quantity only, by the formation of sulphide, make a very decisive effect, and one out of all proportion to the actual amount of sulphur present. This sulphide, in the absence of manganese, takes the form of an iron sulphide; but when manganese is present, as is usually the case in all varieties of cast iron, the sulphur associates with the manganese, forming a sulphide of manganese of the formula MnS.

Sulphur present in any variety of cast iron can be regarded in no other light than that of a most obnoxious impurity, and under no conditions can it be viewed favourably. The sulphides formed are distinctly brittle, and very slight increases in the content of sulphur result in very large increases in the brittleness. Sulphur present in excess in a cast iron favours the formation of the "white" variety, a fact readily noticed in the analyses already given, for as the combined carbon rises the amount of sulphur also increases. In this respect it must be remembered that when producing iron in the blast furnace, low temperatures favour the production of white and sulphurous irons—conditions which are intensified if the slag is acid, but which are restricted in the presence of manganese, sulphur in this case combining with the manganese and forming manganous sulphide, which passes into the slag.

Phosphorus in cast iron is present in the form of a phosphide of iron—Fe_3P. Roughly the amount of phosphide is six times that of the phosphorus present; thus a cast iron showing on analysis 0·3 per cent. of phosphorus would actually contain 1·92 per cent. of iron phosphide. Phosphorus has no effect on the carbon, and in a series of ascending irons smelted from the same ore this element remains fairly constant. Generally speaking, phosphorus in cast irons is not nearly so harmful as sulphur. Although phosphorus increases both hardness and brittleness, it tends to produce soundness, and is therefore less of an evil to the ironfounder than the steel-maker.

The fact of manganese increasing the carrying power of an iron for carbon has been referred to, and from this point of view manganese decidedly hardens the cast iron in which it is contained. This hardening action is, however, neutralized by the presence of silicon, as will be seen in a moment. Manganese presents a further anomaly in that in certain cases it can act as a softener. It has been shown that manganese and sulphur have an affinity which, when the temperature favours, results in their union and consequent passage into the slag. A manganiferous pig iron will act as a softener when melted in conjunction with a sulphurous one, for in such a case the manganese of the former combines with the sulphur of the latter, softening the iron according to the amount of sulphur removed.

The element silicon present in cast iron is generally, though erroneously, regarded as a softener, a view doubtless due to the fact that silicon exercises a very distinct control of the carbon of a cast iron. Silicon acts indirectly as a softener by producing conditions which favour the precipitation of carbon in the graphitic form, and, other things being equal, results in an iron the softness of which depends on the extent of this precipitation. When the silicon is present in excess of that required to act on the carbon, it hardens by virtue of its own action. Although silicon is regarded as a softener, and conveniently spoken of as such, it must be remembered that the softening action is an indirect one, and it is the amount and existence of the carbon which determines the grade of the iron.

Summary.—The hardness of a cast iron depends on the amount of combined carbon it contains. With a low combined carbon the iron is soft, and with a high one the iron is hard or "white." Intermediate stages represent varying degrees according to the proximity of the carbon content to the grey or white variety.

The presence of manganese allows the iron to carry more carbon, and gives rise to the formation of double carbides of iron and manganese. Low silicon and high manganese result in a white iron.

Silicon tends to throw the carbon into the graphite condition, thus resulting in a soft cast iron; but over 3 per cent. silicon hardens by virtue of its own action.

Silicon also neutralizes the tendency of manganese to throw the carbon into the combined form.

Phosphorus is unaffected by any of the constituents of cast iron; it is present in the form of a phosphide (Fe_3P).

Sulphur is present as an iron sulphide, but in cast irons containing manganese, as the majority of them do, the sulphur is found in combination with manganese as sulphide of manganese. An excess of manganese and sulphur in molten cast iron at a high temperature leads to the formation of manganous sulphide. Manganese sulphide is metallic, and is found in the cast iron, whilst manganous sulphide is a slag.

CHAPTER VIII

PIG IRON FOR THE STEEL-MAKER. CAST IRON IN THE FOUNDRY

Pig Iron for the Steel-maker.—With both the Bessemer and open-hearth methods of steel-making by what is known as the acid process, the carbon, silicon, and manganese are removed by oxidation, whilst the sulphur and phosphorus are untouched. As a matter of fact, the actual percentages of these two latter elements increase, for it is obvious that if the three former ones are removed, the percentages of iron, sulphur, and phosphorus must increase proportionately by concentration. Therefore the first essential of an iron for conversion into steel by either of these processes is freedom from sulphur and phosphorus. By freedom is meant a low percentage, for, unfortunately, absolute freedom is never obtained.

In the Bessemer process the fuel is self-contained—that is, the oxidation of the elements which are removed develops the heat necessary to carry on the operation. Therefore the cast or pig iron has to meet a further essential in that it must contain sufficient material which on oxidation will impart the requisite heat to successfully conclude the process technically termed "blowing." Of these heat-giving elements, silicon is the most important, and practice has found that between 2 and 3 per cent. of this element gives the best results.

A representative pig iron for conversion into steel by either the open-hearth or Bessemer acid process would have approximately the following analysis:—

Combined carbon	0·46 per cent.
Free carbon	3·40 „
Silicon	2·50 „
Manganese	0·50 „
Sulphur	0·04 „
Phosphorus	0·05 „

Mild steels made by these two processes, with a cast iron such as the foregoing for a base, would approximately contain the following:—

	Mild Bessemer Steel.	Mild Open-hearth Steel.
Combined carbon	0·20	0·20
Silicon	0·09	0·02
Manganese	0·90	0·50
Sulphur	0·06	0·05
Phosphorus	0·07	0·06

These processes will be dealt with at a later period, but one point worthy of notice here is that the content of manganese in the Bessemer steel is higher than that originally present in the cast iron, whilst that of the open-hearth steel is the same. During the process the manganese in either case is almost totally eliminated, but at the end of the oxidation period manganese is added, in the form of ferro-manganese or spiegeleisen, to remove the oxygen present in the metal.

The analyses of iron ores given in Chapter III. will show that the requisite conditions of low phosphorus and sulphur essential to the acid process of steel-making can only be met by the use of a pig iron smelted from hematite ore. For with the acid process neither phosphorus nor sulphur is removed, and, in fact, they increase slightly by concentration of the metal, and, as in the Bessemer process, by contact with fuel in the cupola. However, these limitations, especially that of phosphorus, do not apply to the basic process, and by the use of a basic lining in the Bessemer converter or in the open-hearth furnace, together with the subsequent addition of lime, much of the phosphorus in the original pig iron is removed. The basic process, successfully introduced by Thomas and Gilchrist, opens up to the steel-maker a vast amount of material, of which Cleveland pig iron is typical, and which could not be converted into steel by the acid process. In this country, but more especially on the Continent, large quantities of high-class low-carbon steel—often termed ingot iron—are produced from phosphoric pig iron, which may originally contain as much as 2·5 per cent. phosphorus. An analysis of iron suitable for treatment by such a process has been given on page 84.

Cast Iron in the Foundry.—A very large proportion of the pig iron produced finds an outlet in the iron foundry, and it is to the ironfounder that a consideration of the properties of cast iron will be of most interest. In general foundry practice castings are produced which have to meet many and varying conditions, as, for instance, steam cylinders and valve bodies, which have steam or water pressure to withstand; in other cases the casting may have a tensile or a transverse load to carry; or, yet again, its working life may be of such a character that it has sudden shocks or jars to meet, as instanced in the teeth of driving wheels, etc. Large quantities of castings are made which in after-life have to support heavy loads. Of these castings, columns are the most typical, and it is evident that the metal of which they are made must be strong in compression. Requirements such as the foregoing are familiar to all founders, and it is hardly necessary to enumerate others, though it may be taken for granted that a very large portion of the castings made must lend themselves readily to treatment in the machine shop. There are, of course, fair quantities of castings whose sole requisite is that they readily machine up to shape, and when finished present a good appearance to the eye. Other grades of castings are subject to no after-treatment, but go into industrial life almost as they left the sand, and in such cases the quality of the metal of which they are made is of little moment.

This variety in the product of the iron foundry leads to the use of several brands of iron rather than of one brand only, and experience proves that better results are to be obtained by so doing. In the case of special mixtures, three or even more distinct varieties may be used, and if a mixture of this kind be intelligently worked out, each constituent iron contributes or lends some special feature to the charge which the others do not give. Taking a random example of a three-pig mixture consisting of Scotch (Coltness), Northampton, and hematite irons, it would at once appear that the first is used for the manganese it adds, the second for its silicon, and the third to keep down impurities such as sulphur. Mixing may therefore be regarded as a blending of dissimilar irons to produce a result unobtainable with one grade only; and as each iron-producing locality produces a grade possessing its own peculiar features, it is evident that this blending can be carried to a fine degree of accuracy. The first essential of good mixing is that the distinctive features of the iron employed are thoroughly understood, and this can only be attained by a knowledge of the composition of the iron. The properties of any variety of cast iron are a function of its composition, and this is most concisely shown by briefly reviewing each element present from a foundry point of view only, noting the control they exercise.

The control exercised by carbon has been already shown, and if cast iron contained only iron and carbon, then there would be very little difficulty in determining a series of standards in which a given content of carbon would denote suitability for a specific purpose in the casting. Such is the case with steels which are essentially iron and carbon alloys, and the carbon standards adopted in steel-works practice are worked to a high degree of exactitude. Cast iron, owing to its more complex character, does not lend so readily to the formation of exact standards based on the content of carbon, as is the case with steel; but within limits, mixtures figured on the amount of carbon can be made to yield very fair results in the foundry. Any grade of iron between soft grey and hard white can be readily procured by suitable mixture, and as all grades, from hard to soft, are simply differences in the amount of combined carbon, this element offers in convenient form a plan for readily calculating out a charge.

Exceptionally soft mixtures, if calculated to contain 0·10 per cent. combined carbon, will yield a casting which may be most aptly described as "dead soft," and will represent the softest variety of cast iron obtainable in the form of castings. Ordinary soft castings, if worked out to a content of 0·20 per cent. combined carbon, yield a casting soft to the tool, and one that is readily machined. A casting in which tensile strength is the chief requisite will yield the best results if worked out to contain 0·50 per cent. combined carbon. If transverse strength is chiefly required, then the combined carbon is raised to 0·70 per cent.; whilst if crushing strength only is required, it is still further increased to 1·00 per cent. These figures are sufficiently comprehensive to illustrate the utility of working to a combined carbon standard; but they refer to normal irons only—that is to say, pigs poured into sand moulds and subject to the ordinary slow cooling. Sudden cooling, such as chill castings, tends to throw the carbon into the combined form, making the iron white according to degree of chill given, and for this reason mixing by means of a carbon standard is only applicable to normal sand cast irons.

The affinity of manganese and sulphur can be taken advantage of in foundry practice as a means of lessening the sulphur content of high sulphurous irons. In this manner manganese acts as a softener, and may be added to the cupola charge in the form of manganiferous pig iron, or to the ladle in the form of crushed ferro-manganese, preferably the latter. Generally speaking, manganese increases the hardness and closes the grain of an iron in which it is held, and for this reason is valuable in castings which have to be finished up dead smooth. From 1 to 1½ per cent. manganese in an iron containing normal amounts of silicon and sulphur will do all that is desirable towards producing "close grain."

Phosphorus increases the fluidity of a cast iron, and with it the capacity for taking and retaining the sharpest details of a mould. It also lessens the shrinkage, and by the prevention of blowholes increases the soundness of a casting. Phosphoric irons are therefore suitable for thin castings the surfaces of which are covered with fine and sharp detail. Castings of this character are to be met with in stove-grate and range foundries, the fine ornamental parts of gas stoves, etc. But whilst phosphorus has its advantages, it also possesses disadvantages which in the end outnumber the benefits derived from its presence. It has been stated that the phosphorus of a cast iron is present in combination with iron as a phosphide—this phosphide of iron is exceedingly brittle, and naturally has a very marked effect on the iron in which it is present—making it brittle according to the amount present. In the class of castings just mentioned, stove grate and the like, this brittleness, if not present in too great a degree, is immaterial, and is decidedly counterbalanced by the increased fluidity in the molten cast iron. With machinery castings these conditions are reversed, for here brittleness is a factor of moment, and fluidity of less import, for the castings are usually much thicker in section than are the thin plates familiar to the stove-grate founder. Therefore, machinery castings typical of the best quality of cast iron should be as free as possible from phosphorus, and should not contain more than 0·30 per cent. of this element. General machine details, gearing, and the like, should be worked out to a limit of 0·50 per cent. phosphorus. The average run of ordinary castings met with in engineering practice can with success be worked to a limit of 1·00 per cent. phosphorus, but over 1½ per cent. is only advisable for castings in which strength is of no moment.

Sulphur, unlike phosphorus, has not a single good point, and in all foundry practice this element should be kept as low as possible. Sulphur present in a cast iron in excess tends to throw the carbon into the combined form, resulting in a white iron. This tendency to produce hard irons is alone sufficient condemnation from a foundry point of view, but in addition the presence of sulphur in cast iron leads to the production of unsound and always brittle castings. The limit for castings of good quality should be 0·10 per cent. sulphur and as much lower as can be procured, whilst the limit for ordinary machinery castings should not exceed 0·20 per cent.

Cast iron containing an excess of silicon with a correspondingly low combined carbon has usually a low sulphur; grey irons are therefore always freer from sulphur than are the white irons produced from a similar grade of ore. This is owing to the fact that low temperatures in the blast furnace favour the retention of sulphur in the iron, but the higher temperatures usual for the production of grey iron favour the elimination of part of the sulphur.

The controlling effect of silicon on the carbon of a cast iron has been noted in the general properties. Where silicon is high, combined carbon is always low, and *vice versâ;* but not only is a control exercised in the case of carbon, for silicon, as already mentioned, neutralizes the hardening effect of manganese, and at the same time is a very good index of the sulphur content of a cast iron. Low silicons are usually accompanied by higher sulphurs than is the case when the cast iron contains a larger amount of silicon. From the foundry point of view, silicon can, by virtue of the control it exercises on the constituents of a cast iron, be regarded as the most important element present in the metal. With normal cast irons the shrinkage usually follows the hardness: the harder the iron the greater the shrinkage. Both hardness and shrinkage are therefore determined by the amount of combined carbon present. Carbon standards, denoting distinctive qualities of cast iron, have been given, but it is evident that as silicon controls the combined carbon, the quality of cast iron can also be regulated by a control of the content of silicon. Foundry mixtures figured on the amount of silicon meet with a large measure of success, and in general practice, especially in the States, are more extensively adopted than carbon standards. It must, however, be remembered that silicon is regarded as a standard, not through its own influence, but through the complete control it exercises on the constituents of a cast iron. In the author's hands the following standards have yielded good results when mixing on the content of silicon:—

Class of Casting.	Silicon.
Malleable cast iron	0·4 to 1·0
Chilled castings	0·7 to 1·0
Cylinders, valve bodies, etc.	1·3
General machine and engine details, gearing, etc. ...	1·5
Soft castings, pulleys, and the like	2·5
Soft thin castings	2·5 to 3·0
Hollow ware	3·0 to 3·5

The influence of silicon on cast iron has been very thoroughly investigated by Professor Turner, who published a masterly research on this subject in 1885. Mr. W. J. Keep, of Detroit, has also studied the influence exerted by silicon in foundry irons, and his results very fully confirm those of Professor Turner.

The following table is a summary of Professor Turner's results.[1]

Quality of Cast Iron.	Silicon.
Cast iron yielding maximum hardness	0·60
" " " crushing strength	0·80
" " " density in mass	1·00
" " " crushing tensile and transverse strength	1·40
" " " tensile strength only ...	1·80
" " " softness and general working qualities	2·50

From the two foregoing tables it will be seen that any of the many varieties of iron castings produced can be worked out on the silicon content alone; the range from 0·4 to 3·5 per cent. covers all the likely requirements in

---

[1] "The Influence of Silicon on the Properties of Cast Iron," *Journal Chemical Society*, 1885.

the product of an ordinary iron foundry, and well exemplifies the utility of silicon standards.

The following table, extracted from an article by Meissner,[1] is of interest here, and offers good comparison to the standards already quoted:—

Content of Silicon.	Content of Phosphorus.	Class of Casting.
3·5 to 5·5	1·0 to 1·5	Hollow ware, etc.
2·0 „ 3·0	0·5 „ 0·75	Work requiring no special strength.
1·75 „ 2·5	0·5 „ 0·60	General machinery when strength, fluidity, and softness are required.
1·5 „ 2·0	0·3 „ 0·50	Fine small castings requiring fair fluidity and softness, and mainly strength.
1·5	0·20	Castings requiring special strength.

Iron for Chilled Castings.—With cast iron used for making castings, of which chilled rolls are typical, practice has found that mixtures within the following limitations yield good results: Silicon not exceeding 1 per cent., manganese about 0·7 per cent., sulphur and phosphorus as low as possible, the latter not exceeding 0·3 per cent. This limitation closely agrees with the following, which is recommended for chilled railway wheels:—

Total carbon	3·25 to 3·75 per cent.
Silicon	0·75 „ 0·85 „
Manganese	0·50 „
Phosphorus	0·40 „
Sulphur	As low as possible.

In connection with chilled castings, the following table is instructive:—

---

[1] *Iron*, 1888, p. 548.

ANALYSES OF CHILLED CASTINGS PRODUCED AT GRUSONWERK.[1]

Silicon.	Manganese.	Phosphorus.	Sulphur.	Depth of Chill in Millimetres.
1·44	0·64	0·41	0·07	5
1·44	0·82	0·50	0·06	10
1·36	1·27	0·48	0·08	20
1·07	0·59	0·67	0·19	20
0·81	0·44	0·59	0·29	25
0·85	1·35	0·27	0·09	35
0·60	0·99	0·38	0·08	40
0·51	0·93	0·35	0·07	40
0·79	1·20	0·39	0·05	45
0·83	1·46	0·33	0·04	50
0·728	1·90	0·24	0·08	50

[1] *Iron and Steel Institute Journal*, No. 2, 1891.

CHAPTER IX

REMELTING CAST IRON

CAST iron, when required in the molten state in small quantities only, is melted in crucible furnaces of a type similar to those used by the crucible steel melter. Special qualities of iron, such as are required for chilled rolls and other special castings, are melted in a reverberatory or "air" furnace; but quite the larger portion of iron castings made are cast from metal melted in the cupola furnace. The cupola is a cylindrical shaft furnace in some respects similar to a blast furnace, in that the burden or charge of iron, coke, and flux is charged at the top, and the molten metal drawn from a tapping hole at the bottom. Cupolas have been constructed of rectangular section, but to-day cupolas of circular cross section are in almost universal use, experience fully demonstrating that the circular form is more economical.

The air necessary for combustion in the cupola is blown through tuyères, the distance of these tuyères from the bottom of the furnace being regulated by the quantity of metal required at one tapping, and also by the duration of the heat. If running for hand ladles, and only small quantities of metal are required at each tap, the tuyère level can be brought fairly low, thus diminishing the bed coke required, and tending to economy of fuel. When large amounts of metal are required at each tap, the tuyère level must, of course, be proportionally higher, in order to give a well in which the molten metal can collect. In average practice, and with ordinary types of cupolas having two rows of tuyères, a distance of from 17 to 20 in. from the lower edge of the lower row of tuyères to the bottom of the furnace is usually given.

The pressure of the blast supplied to cupolas varies from 5 oz. upwards, and in certain cases it may be necessary to reach a pressure of 14 or 16 oz. Suitable pressure is determined by the diameter and height of the furnace, and the character of the fuel employed, whether it be hard and dense or open and porous. The air may be supplied by a fan or positive blower. Generally speaking, fans are cheaper and absorb less power, but higher pressures can be reached by the blowers, and hence they are more extensively used. Fans of the Sturtevant type are, however, causing the pendulum of foundry opinion to swing, and it is now an open question as to whether a modern high-pressure fan or blower is the more effective.

The height of the cupola charging door from the tap hole varies greatly. Generally speaking, a fair height is conducive to economical working, in that it offers a descending column of cold material to absorb the heat of the ascending gases. The charging platform is supplied by hoists operated in the generality of cases by hydraulic or electric power.

Such in brief are some of the features of the cupola furnace; but as no one type can be termed universal, many designs have arisen to meet the varying requirements of different foundries. The furnaces of a foundry melting a hundred tons daily have naturally very different conditions to meet from those prevailing in a small shop casting every two or three days. Hence an examination from a metallurgical point of view of a few leading features of cupola practice is well within our subject.

Cupolas of simple form are much easier to work, require less supervision, and with any care at all seldom go wrong—or, as technically termed, "bung up." On the other hand, elaborate designs require much greater care in working and considerably more supervision if the best results they are capable of yielding are desired.

A cupola furnace of simple form and one in extensive use is sectionally shown in Fig. 16. It has a solid bottom, and blast is supplied by one tuyère placed on the opposite side to the tap hole. With all solid-bottom cupolas, on concluding the melt the contents of the furnace have to be raked out by hand. In the one shown, on completion of the melt the iron plate forming the breast—in which is also formed the tap hole—is removed, the sand lining broken away, and the red-hot coke, etc., raked out and quenched. The first advance on such a form of cupola is the introduction of the drop bottom, which dispenses with this raking out by hand on the termination of the heat. A drop bottom is shown in Fig. 17, which, as will be seen, simply represents Fig. 16 without the solid bottom. This drawing is taken at right angles to the first one, and therefore shows the tap hole and spout A, together with the slag hole and spout B at the back. Drop bottoms are more extensively used in the States than in this country, but to the author's mind they possess many advantages, and are worthy of wider adoption even on the simple forms of cupolas such as that shown in Fig. 16. With a drop bottom, after the last cast the cupola can be cleared more effectively and in much shorter time than by hand raking. In the event of more iron having been charged than is required, there is no necessity to melt it all through, for after tapping out the melted portion the bottom can be dropped, the incandescent mass quenched by directing a hose on it, and the coke and unmelted iron recovered the following morning. Drop bottoms require care in making up, but

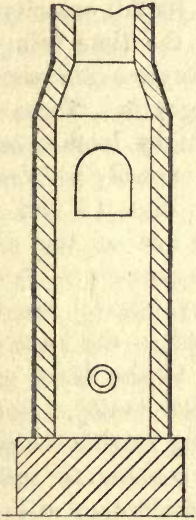


FIG. 16.

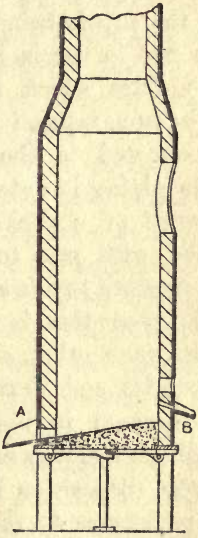


FIG. 17.

when given ordinary care there is little fear of anything going wrong, such as, for instance, a run out.

The tuyère level, as already stated, varies with the character of the work produced in the foundry. In small cupolas of the foregoing type this level can be made adjustable by having two tuyères, one near the bottom for light heats, and the other at such a distance as to admit the cupola being worked at its full capacity. The tuyère not in use is blocked for the time being. The blast nozzles which enter the tuyères are usually of wrought iron, tapered to give a tight fit. These nozzles are connected to the blast main by leather or other flexible piping in order to admit of ready withdrawal in the event of a choked tuyère. Figs. 16 and 17 are supplied with one tuyère only, but as the diameter increases more tuyère area becomes necessary. In cupolas of this type this is achieved by placing two tuyères opposite each other, and connected in the same way by iron nozzles and flexible tubing to the blast main—a style common in many foundries to-day. But with increasing diameters and increasing heights the question of tuyère disposition becomes of moment, for unless the blast penetrates to the centre, combustion will not be uniform, and the irregularity will result in uneven melting. Hence the introduction of several tuyères spaced around the cupola in such a manner that each tuyère does not give rise to intense combustion in its own vicinity only, but, in combination with the others, distributes the air in such a fashion as to result in uniform combustion over the whole area fed by the tuyères. Remembering the action of the air entering the blast furnace, it will be seen that in the cupola in which conditions are very similar a large amount of carbon monoxide is formed. In the blast furnace this carbon monoxide is required to reduce the iron ore. In the cupola the iron is already in the metallic condition, and whilst a reducing atmosphere is very desirable, at the same time it represents to some extent a loss in the heat value of the fuel. For this reason double and triple rows of tuyères have been introduced, the purpose of the upper rows being to supply atmospheric oxygen to the gases formed in the vicinity of the lower row, and by the resulting combustion of these gases attain a more economical fuel ratio. Other types of cupolas, in addition to the double row of tuyères, have smaller ones arranged spirally around the cupola, thus admitting air at many points of the furnace above the legitimate tuyère level. However many advantages such an arrangement of admitting blast may possess, it is well to remember that from the foundry point of view too perfect combustion is not good. With perfect combustion an oxidizing atmosphere ensues, and results in a corresponding oxidation of the metal passing through the furnace. Therefore in ordinary foundry practice an oxidizing atmosphere is to be avoided. The best results, judging from the quality of the metal, are certainly obtained with a reducing atmosphere present in the furnace. The best general results—that is, a combination of good-quality metal with a low fuel expenditure—are obtained by arranging the tuyère area and disposition of blast pressure in such a manner that the air admitted is slightly below the amount required for perfect combustion of the fuel, thus securing a slightly reducing atmosphere. Any criticism of a cupola cannot be founded on the degree of its combustion—that is, on its fuel ratio per ton of iron melted—but it must rather be based on the quality of the metal melted and its suitability for the purpose required. It is also evident that a ratio between the total area of the tuyères and the diameter of the furnace cannot be given. Such can only be determined by actual practice, for very few furnaces work under exactly the same conditions. But whatever the diameter and height of the furnace, the blast entering it must be effective, or, in other words, it must reach the centre. With furnaces of large diameters this condition is secured by increasing the pressure of the blast and reducing the diameter of the tuyères. In other types of furnaces this condition is attained by contracting the diameter of the cupola in the vicinity of the tuyères.

It need hardly be said that double or triple rows of tuyères are not each connected separately to the blast main, but draw their supply of air from the wind box or air belt, which is in turn fed by the blast main. In certain types of cupolas the air belt is arranged in such a manner that the air circulates round the heated part of the cupola before entering the tuyères, the aim of such a circulation being to raise the initial temperature of the air; but the increase in many cases is so slight that the advantages are not of moment. In the air belt, doors are placed opposite each tuyère to admit of the tuyère being fettled in the event of any choking or accumulation of slag. The centres of these doors may very conveniently contain small peepholes, about the size of half a crown, which may be covered with mica, glass, or a swinging disc of iron plate held in position by a small butterfly nut.

A typical form of British cupola furnace fitted with a receiver is that known as the "Stewart Rapid," which is sectionally shown in Fig. 18. The Ireland cupola, which also has a receiver, or "fore hearth," as they are sometimes termed, is shown in Fig. 19. A horizontal section is also shown in Fig. 20. It will be noted that the Stewart is fitted with a hot-air pipe from the furnace to the receiver, which is claimed to keep the iron hotter. This pipe is not fitted on the Ireland type of cupola. The Ireland, by the way, is perhaps better known on the Continent than in this country.

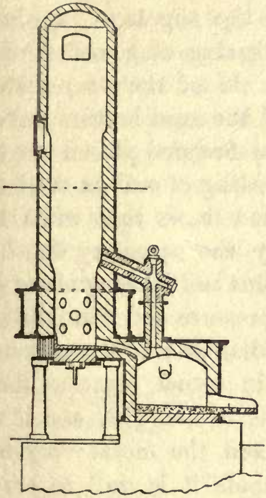
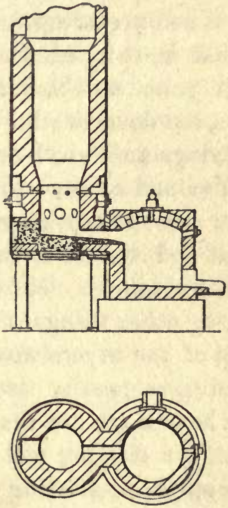


FIG. 18.


FIGS. 19, 20.

Charging the Cupola.—Systematic charging results in good working. To this end all the charges should be weighed and evenly distributed in the cupola, for an evenly spread charge means an even descent, which in turn is one of the chief things in good melting practice. When speaking of weighing the charges, it would be well to note that coke will absorb water, thus increasing in weight, whilst its volume remains constant. For this reason, where coke is exposed to atmospheric influences the better plan is to measure it rather than weigh it.

When preparing for melting, the cupola is "fettled"—that is, chipped free from adhering slag and daubed with ganister where necessary. If of the drop-bottom type, the doors are keyed up and the sand bottom put on. Shavings and wood or some live fire are placed on the bottom and covered with a sprinkling of coal to start the fire; sufficient coke is then filled in, so that when the wood and coal have burned away the necessary depth of bed is obtained. The depth of this bed is determined by, among other things, the blast pressure and the relationship of the tuyère area to the diameter of the cupola—conditions readily determined in actual practice, for if the bed be too low the metal will be sluggish, and if too high the melting will be slow and the metal very hot. Therefore, in starting a new cupola it is well to err on the side of safety by commencing with a high bed, and gradually decrease it until the right depth is found.

When the bed is burned to the tuyère level, the bottom doors are made up and the charging commenced. The pig iron for a 30-in. cupola is broken into four pieces; for cupolas of smaller diameter the pigs are broken into six, and for larger ones into three or two pieces. The pig iron should be charged first, and the scrap on top of it, but for the first charge the scrap may be put in first in order to prevent the coke being unduly crushed by the heavy pig falling on it. With a good, dense coke this precaution is unnecessary. On the top of this charge the necessary amount of coke is placed to replace that burned away in the bed; then another layer of pig, scrap, and coke, and so on until the cupola is filled to the charging doors. The blast may then be put on when convenient. The usual practice is to charge one or two hours before commencing to blow; but blowing may be started on the completion of charging without any serious disadvantage.

The relation between the weight of the bed and the subsequent charges of fuel and iron is a very variable factor, and any figures given can only hold good for the conditions they represent. In West's "Moulder's Text-book" a large number of cupola records are given; many of them refer to coal (anthracite) fed furnaces, but two typical records, in which coke alone is the fuel, are extracted.

Of these the first one is as follows:—

Fuel used for bed	Coke	1400 lb.
First charge	Pig iron	1515 ,,
	Scrap	1852 ,,
	Coke	240 ,,
Second charge	Pig iron	1515 ,,
	Scrap	1852 ,,
	Coke	240 ,,

followed by 17 charges in the order shown. The details are as follows:—

Time of starting fire	10.10 a.m.
Time of charging first iron	11.20 ,,
Blast put on	12.30 p.m.
First appearance of fluid iron	12.35 ,,
Bottom dropped	4.45 ,,
Blast pressure	8½ oz.
Flux used	Limestone.

Totals :—

Amount of iron melted	70,707 lb.
Amount of fuel consumed	6,200 ,,
Ratio of fuel to iron	1 : 11·4

The details of the second record are as follows :—

Time of starting fire	3.0 p.m.
Time of charging first iron	3.45 ,,
Blast put on	4.15 ,,
First appearance of fluid iron	4.20 ,,
Bottom dropped	5.50 ,,

The totals are :—

Amount of iron melted	14,800 lb.
Amount of fuel consumed	1,900 ,,
Ratio of fuel to iron	1 : 7·78

Mr. R. Buchanan, in an admirable paper on "The Foundry Cupola," read before the Staffordshire Association of Iron and Steel Works Managers, gave the following figures :—

Bed	Coke, 5 cwt.
First charge	Iron, 10 ,,
	Coke, 1½ ,,

The second, third, and fourth charges were the same as the first.

Fifth charge	Iron, 10 cwt.
	Coke, 1 ,,

And so on until after the second last charge of iron, when only 56 lb. of coke is put on.

The blast pressure is	8 to 10 oz.
Flux	Limestone, 24 to 28 lb. on the top of each charge of coke.

Mr. Buchanan gives the following fuel ratios extending over the period of one month:—

Light castings	1 : 7·87
Heavy castings	1 : 10·00
Average for month	1 : 8·49

Slagging the Cupola.—The materials entering the cupola which require fluxing are the ash of the coke and the sand adhering to the pig iron or scrap. In the blast-furnace section (Chapter V.), the use of lime as a flux for the silicon in the gangue of the ore was indicated. Lime, being of a basic character, will unite with acid materials at suitable temperatures, forming a fluid slag; thus in the cupola the lime acts as a flux for the acid materials forming the ash of the coke, and the acid silica of the sand adhering either to the pig or scrap iron. If the impurities to be fluxed were of a basic character, then it is evident that the flux employed would need to be of an acid character, and in such a case a siliceous material would be employed.

Lime or the raw limestone is chiefly employed in cupola practice; fluorspar may be used with equal advantage, and in districts where plentiful, oyster shells or other calcareous materials may be employed. When using limestone, it is broken into small pieces about the size of a walnut. The quantity necessary may vary from 20 to 60 lb. per ton of iron melted, the actual quantity being determined by the freedom of the coke from ash and the cleanliness of the pig and scrap iron, the chief requirements being that a fairly fluid slag result—that is, one that will admit of drawing off through the slag hole, or in its absence through the tap hole. Any cupola may be worked as long as its lining will stand, provided the slag can be drawn off at suitable intervals. Examples of cupolas continuously worked are found in Bessemer practice, where the pig iron for the converters is melted in cupola furnaces of a type similar to those employed in foundry practice.

In working a small cupola not fitted with a slag hole over a long heat it becomes necessary to tap off the slag when it has accumulated in quantity through the tapping hole—a method not to be recommended. Nearly all cupolas are now fitted with slag holes, which are placed at a distance sufficiently below the tuyère level to prevent the slag from being chilled by the blast. These holes are made up in a similar manner to the tap hole, and when the slag has accumulated in sufficient quantity to interfere with the working of the cupola, the clay or sand plug is broken through and the slag drawn off. To bring the slag up to the level of this hole, the metal is allowed to accumulate until its covering of floating slag reaches the necessary height. After a few tons of metal have been drawn off, the slag hole may, if desired, be left open until the end of the heat. Receiver cupolas have their slag holes fitted in the receiver, and the slag as it accumulates is drawn off in the same manner.

Chemical Changes in the Cupola.—The chemical changes undergone by the iron in its passage through the cupola are usually of a slight character only. One of the best records in the author's possession showing the change due to melting is as follows:—

	Analysis of Charge.	Analysis after Melting.
Combined carbon	0·46	0·49
Free carbon	3·42	3·30
Silicon	2·50	2·29
Manganese	0·47	0·45
Sulphur	0·04	0·06
Phosphorus	0·05	0·05

The chemical changes of chief interest to the founder are those of silicon and sulphur. The latter element always increases—an increase which is entirely governed by the amount of sulphur in the coke and the method of melting. Melting at a dull heat always gives a greater increase in the content of sulphur than is found with hot melting. Further, the greater the sulphur in the coke the greater the increase in sulphur after the iron has passed through the cupola. The decrease in silicon is fairly constant, varying between 0·2 and 0·3 per cent.; therefore in calculating a cupola charge on a silicon standard this loss must be allowed for. Assuming the loss to be 0·3 per cent., and the silicon content required in the castings 1·5 per cent., then the initial charge must contain 1·8 per cent. silicon.

Melting Loss in the Cupola.—The actual loss of iron on its passage through the cupola is an exceedingly difficult one to accurately determine. The material weighed on the cupola stage is usually credited as iron—some of it may be sand and dirt adhering to the pig and scrap iron—whilst the metal tapped from the cupola represents, or should represent, clean iron. Apart from this loss of weight between the dirty iron entering the cupola and the fairly clean castings and gates weighed as the product, appreciable amounts of iron may, under certain conditions, combine chemically with the slag. A combination of this character is not so apparent as when the slag contains — as it often does — enclosed buttons of shot iron. Taking into account these factors of loss due to dirt weighed with the iron charged, to combination of the iron with the slag, and to enclosed shot iron with the slag, general practice appears to indicate an average loss of 5 per cent.

CHAPTER X

MALLEABLE CAST IRON

THE term "malleable cast iron" must not be confused with that of "malleable wrought iron," for the two represent entirely distinct products. The former is applied to castings moulded in sand, poured with white or mottled pig iron, and subsequently annealed. "Malleable wrought iron" is a term applied to pig iron which has been purified by the puddling or similar process, and subsequently worked up into bars, sheets, etc.

Glancing for a moment at the origin of malleable cast iron, we find one of the earliest references to it in a treatise by Réaumur, entitled "L'Art d'Adoucir le Fer Fondu," and published in 1722. It is of interest to note that Réaumur's process for the production of malleable cast iron is practically the one followed to-day. In 1769 Joseph Ashton, of Birmingham, obtained a patent for softening cast iron by heating it in a slow fire, his process being intended for the production of nails. In 1783 George Mathews, of Brosely, patented a similar method to that of Ashton, for the production of cannon, anchors, and so forth; also stating that when annealed these articles were as malleable and tough as hammered or wrought iron.

In 1804 Samuel Lucas, of Sheffield, patented a process similar to that of Réaumur. The method introduced by Lucas ran as follows: "The pig or cast iron, being first made or cast into such a form as may be most convenient for the purpose for which it is afterwards intended, is put into a proper furnace with powdered ironstone or other substance capable of combining with the carbon of the crude iron. A heat is then applied, so intense as to effect a union of the carbon of the cast iron with the substance made use of, and continued so long as shall be found necessary to make the cast iron either partially or perfectly malleable, according to the purpose for which it may be wanted."

It will be seen that the method of Lucas consisted in depriving the cast iron of its carbon, whilst those of Ashton and Mathews were based, not on any change in the metal treated, but simply on a change in the form in which the carbon existed in the metal. As these processes or modifications of them are in use to-day, and as their product is generally termed malleable cast iron, it becomes necessary to recognize the three following subdivisions:—

(*a*) Annealed cast iron.
(*b*) "Black-heart" cast iron.
(*c*) Malleable cast iron (Réaumur or Lucas process).

Castings coming within the first group are not strictly malleable, though often described as such. In reality they represent ordinary grey iron which has been softened by annealing, a practice followed in the production of small intricate castings such as are used in textile machinery, table-forks, harness fittings, and the like. These castings are usually so small that, when the metal enters the mould, solidification rapidly follows, and the castings are chilled. By annealing in a slow fire this chill is removed and the castings are softened.

Castings coming within groups (*b*) and (*c*) may be more properly regarded as of "malleable" quality. In mechanical properties, malleable castings vary from 20 to 30 tons per square inch in tenacity, giving extensions of from 2 to 8 per cent. on 2 in. These castings possess a high resilience, or, in other words, they offer a good resistance to shock. The mechanical properties of the castings before treatment are represented by a tenacity of 10 or 12 tons per square inch, with no extension and comparatively little resistance to shock. These average figures at once show the beneficial influence of suitable heat treatment when applied to cast iron. However, any good results from heat treatment can only be attained when the cast iron is of suitable composition. The following tests recently carried out by the author illustrate this point. A cast iron containing the whole of its carbon in the graphitic condition gave as the mean of several tensile tests a tenacity of 11·4 tons per square inch. Several bars from the same cast after annealing in a non-oxidizing atmosphere for a period of four days gave a mean tenacity of 6·7 tons per square inch. In other words, the tenacity of this graphitic metal had by the process of annealing been lowered 4·7 tons per square inch. Annealing, therefore, has no beneficial effect on castings which already contain their carbon in the graphitic or free condition, and in practice the only grey irons annealed are those which in process of casting have become chilled. These comprise the small castings already referred to in class (*a*), and which are sometimes known as black-metal castings.

It has been shown in Chapter VII. that the combined carbon of a cast iron is a definite carbide of iron having a formula of Fe_3C. It is to this carbide that white cast iron owes its extreme hardness and brittleness. The external portions of grey iron castings quickly cooled—as, for instance, chilled castings—are also extremely hard, due to the carbon in the chilled portion existing in the compound form.

This carbide of iron is very susceptible to heat treatment, and at a red-heat is decomposed into its constituent elements of iron and carbon. If the heating be given for a sufficient length of time and followed by slow cooling, recombination of the iron and carbon does not again take place, and in the cold castings the carbon is entirely in the free condition. When the heating is given in an oxidizing atmosphere the oxygen combines with the carbon and gradually effects its removal. Heating in a non-oxidizing atmosphere to decompose the hard carbide gives castings coming within group (*b*), and heating in an oxidizing atmosphere gives castings belonging to group (*c*). The chief purpose of annealing in a non-oxidizing environment being to decompose the hard carbide of iron into iron and free carbon, the question naturally arises, Why not make the castings at once from iron containing all its carbon in the free condition, and so dispense with the necessity for annealing? However, the graphite or free carbon produced by decomposing the carbide of iron is not in a similar physical condition to that originally present in a sample of normal grey iron. In the latter case the graphite, as shown by a fractured surface, is present in comparatively large flakes or plates, whilst in the annealed metal the graphite is present in an exceedingly fine state of division, and equally distributed through the mass, and a fracture of such metal shows a fine velvet-black surface. The mechanical effect of this difference in physical condition and difference in distribution may be readily imagined. In the one case, the large flakes and plates of graphite readily act as cleavage planes offering most convenient routes for the passage of a fracture. On the other hand, the small finely divided graphite of the annealed metal does not offer the same conditions, for, owing to its even distribution in a fine state of division, the continuity of the metal is not destroyed in the same degree. This fine graphite resulting from the decomposition of carbide of iron has been termed by Professor Ledebur "temper carbon."

The composition of the original metal is by no means unimportant, and, as will be seen from the foregoing, the chief essential is that the whole of the carbon be in the combined form. In other words, the castings, as they leave the sand, must be of white-iron quality, and contain no graphite. The actual content of carbon is of less moment than the condition in which it is present. The original composition of the metal will also vary somewhat, according to the natute of the castings made. A much greyer iron may be used for castings of light section than for castings of large cross section, for the rapid cooling of the light casting results in the whole of the carbon being in the combined form. The slower cooling of larger castings tends to the separation of graphite, hence the iron entering such moulds must originally be white—that is, must contain its carbon in the combined form. Hence, for thick castings the silicon must be low, and should not exceed 0·4 per cent. For the average casting, good results are obtained with silicon about 0·6 per cent. Very light castings may contain as high as 1·3 per cent. silicon, but this limit should not be exceeded. The content of manganese should not be high, or it will retard the annealing operations. In good practice this element varies between 0·4 and 0·6 per cent. Sulphur and phosphorus should, of course, be as low as possible. Dr. Moldenke, an eminent authority on malleable cast iron, fixes a sulphur limit of 0·04 per cent. and a phosphorus limit of 0·225 per cent. An examination of a large number of British malleable irons by the author shows them to contain much higher contents of sulphur, whilst, on the other hand, the contents of phosphorus are decidedly lower. Average sulphurs of the malleable cast irons already analyzed work out at about 0·3 per cent., whilst the average phosphorus runs about 0·05 per cent. The content of combined carbon in average practice varies between 3 and 3·5 per cent. White irons direct from the blast furnace may be used if their compositions fall within the foregoing limits. Generally, however, in British practice, refined hematite iron is used as a source of malleable cast iron. Grey hematite is refined to eliminate the greater part of the silicon, and then cast into pigs of small cross section. These small pigs are very suitable for melting in crucibles. Melting operations in this country are usually conducted in either a crucible furnace or a cupola, reverberatory furnaces being used in comparatively few cases only. In the States, where the annual production of malleable cast iron reaches a total of 650,000 tons, melting operations are conducted chiefly in the reverberatory furnace, or, in special cases, in the Siemens open-hearth furnace. Undoubtedly the latter type of furnace is the best, but full economy can only be attained by continuous working, which naturally necessitates a very large output. (This furnace will be described when dealing with the production of open-hearth steel.) The reverberatory furnace offers specially good facilities to the malleable-iron founder in that the metal may be held in good control, and the exact grade required may be readily obtained. Good results are obtained by crucible melting, but the output is small and the fuel costs correspondingly high. The cupola, with care, yields fair results, but the metal is never of the same uniform quality as that obtained from the reverberatory furnace.

Moulding operations are similar to those of the grey-iron foundry, provision being made for the narrow range of fluidity and the high contraction of white iron. This contraction is about a quarter of an inch per foot; but as the castings during annealing expand an eighth of an inch per foot, the same shrinkage allowance on the pattern as for ordinary grey iron is given.

Annealing ovens vary in design. A common type consists of a rectangular chamber with fireholes at each corner placed below the floor level. The flames enter the chamber on the floor level, and pass towards the middle, being drawn out at the roof by means of a flue running down the centre. The dimensions of these furnaces vary with the output. An oven capable of accommodating a large number of pots would internally measure 12 by 15 ft., and 6 ft. in height. The castings to be annealed are packed in cast-iron "pots" or pans, which may be round, square, or rectangular, as most suited to the form of the casting. These pots are covered with cast-iron lids, and luted with clay to exclude air. An average size of pot for small castings is about 23 in. in depth by about 15 in. in diameter. The castings are completely isolated from each other by the packing material, and must also be packed in such a manner as to prevent distortion or warping when at a red heat. The nature of the packing material is determined by the annealing condition—that is, whether the removal of the carbon is desired, or only its change in form to that of temper carbon required. In the former case the castings are packed in an oxidizing material such as red hematite iron ore, rolling-mill scale, etc. Red hematite ore is chiefly used, and each time of annealing new ore is added in the proportion of one of new ore to four of previously used ore. The raw and spent ore are mixed well together and carefully packed round the castings in the pan, care being taken that no two castings touch each other, and that each casting lies solid in the pan. The pans are placed in the oven in such a manner that the flames can play round each one, the oven doors are luted with clay, and firing commenced. The temperature is gradually increased until about 850° C. is reached, which will take from two to three days, the oven being maintained as near this temperature as possible for a further period of three days, and then allowed to gradually cool down. The length of time, however, varies according to the thickness of the castings and the amount of deoxidation required. The carbon is removed from the outside portion of the castings first, this removal of carbon travelling slowly inwards towards the centre as the heat is continued. Naturally, the higher the temperature employed the quicker the removal of the carbon, but, as will be readily seen, a limit of heat is placed owing to the danger of deforming the castings, and therefore the maximum temperature must be below 1000° C. The carbon is removed from the cast iron by the oxygen of the ore in the following manner :—

$$C + O = CO.$$

In other words, carbon at a red heat plus oxygen forms carbon monoxide. The following analyses before and after annealing show the change taking place :—

	Iron as Cast.	After Prolonged Annealing in Iron Ore.
Total carbon	3·43	0·10
Silicon	0·45	0·45
Manganese	0·53	0·53
Sulphur	0·06	0·06
Phosphorus	0·31	0·32

As will be seen, the only change is that of carbon, but it is a change resulting in the conversion of an exceedingly brittle material into one possessing wide industrial application. The following tests of commercial malleable cast iron treated in the foregoing manner illustrate this feature :—

Tenacity in tons per square inch	27·00
Extension on 2 in.	5·75 per cent.
Contraction of area	10·00 ,,

The analysis of this metal exclusive of carbon was as follows:—

Silicon	0·65	per cent.
Manganese	0·15	„
Sulphur	0·30	„
Phosphorus	0·04	„

As already stated, the carbon removal commences from the outside of the casting first, from thence travelling inwards towards the centre; it therefore follows that an insufficiently annealed piece will have a hard core, and in any case the centre will be harder than the outside portion.

Turning to castings coming within group (*b*), which are generally known as "black-heart" castings, owing to the fact of showing a fracture in the centre of which is a core of almost velvet black surrounded by light grey edges, we arrive at what is practically a modification of Ashton's and Mathews' processes. The only essential difference between this process and that of Lucas is that the castings are annealed in a non-oxidizing environment. Apart from this feature the two processes are identical. The castings are simply heated to the requisite temperature, held there for a period, and then slowly cooled. Were it not for the excessive scaling, the castings could be annealed by packing direct on the floor of the oven and allowing the flames to play through them. In practice the castings are laid in pans and packed with a non-oxidizing material, such as sand, in a similar manner to that followed in the oxidation process. Lids are luted on to the pans to exclude air. When filled, the ovens are heated up to a temperature of about

850° C., maintained at that temperature for two days, and then allowed to slowly cool down to a black heat. Usually the slower the cooling the better the result.

The rationale of the process lies in the decomposition of the carbide of iron into iron and free carbon, the carbon being deposited in a very fine state of division, which is described by Ledebur as "temper carbon." It is stated by some authorities that if the heating be unduly prolonged the carbon tends to assume the flaky appearance familiar to the grey irons. The mechanical properties of black-heart castings are represented by a tenacity of about 20 tons per square inch, though much higher tenacities are occasionally met with. The castings are easily machined. Within limits they will bend through a fairly wide angle, and will to a certain extent harden and temper.

Very briefly the influence of heat treatment on cast iron has been dealt with. Notwithstanding the early introduction of malleable cast iron, many of the reasons underlying its production are to-day in a more or less hypothetical state. In many instances, practice or rule of thumb has preceded scientific reasoning, but to-day there is a large amount of scientific thought and experiment being devoted to malleable cast iron, which in the course of time will add much to our knowledge of the subject.

The further treatment of cast iron is a question worthy of very careful study, for comparatively slight differences in mode of treatment result in large differences in the properties of the metal. Quite recently the author obtained from an iron, the original tenacity of which was

12 tons per square inch, one result yielding 24 tons per square inch, and another of 2·5 tons per square inch. These figures, of course, represent different treatments, but are extremely instructive in showing the susceptibility of cast iron to heat treatment.

CHAPTER XI

WROUGHT IRON

A DISTINCTION has already been drawn between malleable cast iron and malleable iron. Malleable or wrought iron is the very converse of cast iron; it is fairly tenacious and extremely ductile. At a suitable temperature it passes into a more or less pasty condition, in which state it readily lends itself to the operation of welding, and does so in a better manner than any other variety of iron or steel. When heated to a full red and quenched in water it will not harden, differing in this respect from steel, which under such treatment assumes an adamantine hardness. The tenacity of malleable iron varies between 18 and 24 tons per square inch, its extension ranging between 15 and 30, or, in specially good qualities, 50 per cent. on a length of 2 in.

Wrought iron always contains more or less unexpressed slag, which gives to a fractured surface a fibrous appearance. This so-called fibre offers a rough index as to the properties of the metal, and if it be fairly uniform, it shows that the product has been regularly worked up. and that the slag is evenly distributed through it. On the other hand, an irregular " fibre " denotes a corresponding irregularity in manufacture. The slag present in a wrought iron is easily recognized under the microscope, showing either as elongated streaks or as more or less rounded dots, the distinction being due to the manner in which the microscopic section is cut from the mass of metal. Thus a section cut in the direction of rolling or forging shows the elongated streaks whilst one cut at right angles to the rolling direction shows the dots, Fig. 21 represents the structure of wrought iron as seen in a section cut in the direction in which the metal was rolled. The streak-like masses of unexpressed slag will be readily noted. Fig. 21 represents a section taken at right angles to that of Fig. 22. It will be seen that here the slag lines are cut through, and consequently appear as rounded dots.

It must be remembered that this slag is invisible to the naked eye, and that the foregoing drawings represent a high magnification. From the fact of the distribution of slag in the manner indicated, it is apparent that wrought iron will possess a higher tenacity in the direction of rolling than it does in a direction at right angles to that of rolling. In technical language, wrought iron is stronger with the grain than it is across it. The following tests by Seaton illustrate this :—

Material.	Tenacity in lb. per square inch.	Extension per cent. on 8 in.
Yorkshire plate, with the grain	54,000	20
,, ,, across the grain	49,000	14
Staffordshire plate, with the grain	50,000	12
,, ,, across the grain	41,000	8

When tested in a direction at right angles to that of

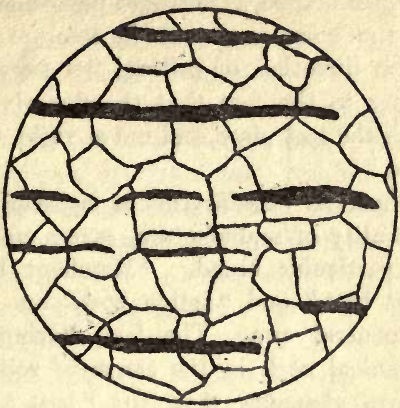


FIG. 21.—Longitudinal section of wrought iron.

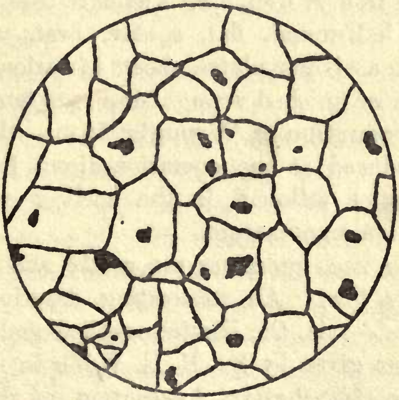


FIG. 22.—Transverse section of wrought iron.

rolling or forging, the fine hair lines of slag will act, in a greater or less degree, as cleavage planes, or as starting points for the commencement of fracture; but when tested in the direction of rolling, the tenacity will be greater owing to the fact that the fine slag lines are parallel with the test piece, and not at right angles to the tensile force.

The commercial classification of malleable iron varies with the locality of manufacture, many makers having their own particular brand. "Merchant bars," "best iron," "best best," and "treble best," are some of the terms in general use. The last, having undergone more mechanical work in the shape of rolling, is of a more uniform character than the "best best," which, however, has had more work put on it than the "best" iron receives. The "sections of finished iron vary according to requirement, usual ones being Z iron, T iron, angle or L iron, H iron, etc. Amongst bars, usual shapes are round, half-round, flat, square, oval, octagon, etc. Plates such as boiler plates, sheets of various gauge, and other forms of finished wrought iron, are familiar.

The Production of Wrought Iron.—Wrought iron can be produced at one operation direct from the iron ore, a practice followed in the earliest period of the history of iron manufacture.

However, such processes are costly, and the yield is exceedingly low. An interesting description of two such methods—viz. the Hindoo method and the Catalan process—was given by Mr. H. E. Webb in a paper read before the Manchester Association of Engineers in February, 1892.

The wrought iron of commerce is, with hardly an exception, produced by indirect methods—that is, by the purification of pig iron. The processes vary somewhat in character, but all are based on the elimination of the impurities of pig iron by oxidation. This oxidation may be effected in a hearth or in a reverberatory furnace. In the former case the metal is in actual contact with the fuel, the oxygen of the blast combining with the impurities and being eliminated in the form of oxides. In the latter case, that of the reverberatory furnace, the metal is not in actual contact with the fuel, and the oxygen is supplied by means of an iron oxide such as mill scale. The furnaces in which these operations are conducted are variably known as the Walloon, the Lancashire hearth, Franche Compté, and the familiar puddling furnaces of Britain. The Walloon and Lancashire hearth are chiefly employed in Sweden, using as a base the exceedingly pure pig irons smelted from Swedish ore, and yielding a product of excellent quality and high purity.

The Lancashire hearth consists of a rectangular chamber supplied with two, or in some cases three, tuyères; horizontal flues lead from this chamber to the stack, and are used for heating the pig iron before drawing it forward into the hearth. Charcoal is used as a fuel, and as the pig iron melts it trickles down before the blast, which oxidizes part of the carbon, silicon, and manganese. The molten metal collects in the bottom of the chamber and is allowed to partially solidify; it is then broken up by means of an iron bar and brought to the top of the fuel again; this process being repeated until the metal is practically decarbonized. It is then collected in the form of a sponge weighing about 200 lbs., withdrawn from the hearth, and worked down by process of rolling into bars 3 in. by ½ in. According to Greenwood, the consumption of charcoal amounts to 150 lb. per 100 lb. of bars produced, and the loss in weight of the pig iron employed is about 15 per cent. The high purity of the product has been already referred to, and is well shown in the following analysis of a typical sample:—

SWEDISH LANCASHIRE HEARTH IRON.

Combined carbon	0·05	per cent.
Graphite	0·00	,,
Silicon	0·01	,,
Manganese	0·10	,,
Sulphur	0·01	,,
Phosphorus	0·02	,,

The analyses of irons produced by the Walloon process are almost identical with those of the Lancashire hearth. The principle of the Walloon process is very similar to that of the Lancashire hearth, but the type of furnace employed does not yield so large an output, whilst the bars are hammered down to finished size, thus producing a better finish than those of the Lancashire hearth, which are rolled down to size. Walloon iron is also claimed to possess more "body," and is said, when used as a source for the production of steel, to yield a metal of higher quality than that obtained from Lancashire hearth iron.

The Franche Compté process is essentially that of the foregoing ones—namely, melting the pig iron in a charcoal hearth, the impurities being slightly oxidized by the blast, partially cooling and breaking up the mass in order to bring the broken pieces again within the oxidizing influence of the blast until the whole is decarbonized, the final operation consisting in collecting the spongy mass into balls and working them down into bars or rods.

The Walloon, Lancashire hearth, and Franche Compté all depend on a white iron as a basis on which to commence purification. As previously shown, the pig irons of Sweden are exceptionally pure, but the white pig irons of Britain are high in sulphur, and therefore do not readily lend themselves to the production of wrought iron by any of the foregoing processes. It is, or rather was, usual to refine grey pig iron; in other words, to partially decarburize and convert the remaining carbon into the combined form before purification in the finery, this method forming what is known as the South Wales process. Briefly, the refinery consisted of a rectangular hearth, formed by means of a water-cooled casting and supplied by tuyères, coke being employed as fuel. The grey pig iron melted in the oxidizing atmosphere of the refinery is totally converted into white iron, each charge so treated weighing about 5 cwt. This product is cast into a metallic mould, forming "plate iron," which may be broken up whilst hot and passed on to the finery, or instead of casting in a mould the refined iron may be tapped, and by means of suitable channels run direct into the finery. The influence of refining is shown in the following analyses:—

	Before Refining.	After Refining.
Combined carbon	1·80	2·20
Graphite	0·80	None.
Silicon	1·91	0·30
Manganese	0·50	None.
Sulphur	0·20	0·15
Phosphorus	0·85	0·80

The subsequent treatment of the refined metal in the finery is very similar to that of the Lancashire hearth—that is, the metal collecting in the bottom of the finery furnace is frequently broken up and brought into the proximity of the tuyères until the purification is complete, or, in technical language, until the metal "comes to nature."

The ball is withdrawn and shingled under a steam hammer into a flat slab, this shingling expressing the cinder intermingled with the sponge. Whilst hot the slab is nicked, so that it may be afterwards broken into pieces of about 28 lb. in weight each, these pieces being known as "stamps." An iron "staff" is formed by welding a piece of iron of similar quality to the stamps on to an iron bar. Stamps are placed on this staff and heated to a welding heat in a hollow fire; when of the right heat the whole is welded together under the hammer. The slab thus formed is nicked and doubled, and the two parts welded together again. It is reheated and reduced to a billet, and whilst still hot sheared from the staff and afterwards rolled down into the desired shape or section.

The puddling process was introduced by Henry Cort in 1784, and rapidly superseded the open-hearth method of conversion. Cort's process for the production of malleable iron lay in the use of a reverberatory furnace, the bottom of the melting chamber being dished out in the form of a basin in order to contain the metal. When first introduced, the hearth of the furnace was formed by a sand basin, and hence the oxidation taking place was due entirely to atmospheric action, this action being assisted by constantly agitating the metal and exposing fresh surfaces to the influence of the furnace atmosphere. This process worked on a sand bottom was known as "dry puddling," so termed owing to the fact that during the process the metal never became very fluid, and was consequently more or less "dry." Dry puddling necessitates the use of a white iron, hence the process had to be worked in conjunction with a refinery. According to Scrivenor, dry puddling, when first introduced, was accompanied by a waste of 20 cwt. of pig iron per ton of malleable bars made. When the process became better known it required from 30 to 35 cwt. of pig iron to make one ton of bars, and later a yield of one ton of malleable bars from 26 cwt. of pig was considered good practice.

The sand bottom of the furnace had to be repaired before each charge, and these delays curtailed the output. Each charge consisted of not more than 2½ cwt. of metal, and four of these charges represented twelve hours' work. White iron only was used, and it was customary to refine grey pig iron previous to its treatment in the puddling furnace. Drawings and descriptions of the refinery furnace, or "running-out fire," are given in Dr. Percy's "Metallurgy of Iron." The refined iron so obtained was charged on to the sand bed of the furnace, and when it assumed a pasty condition was constantly agitated and broken up in order to expose fresh surfaces to the oxidizing influences of the furnace. The metal, when decarburized, was balled and shingled down into blooms ready for working up into plates or bars. Later the sand bottom was replaced by a lining of iron oxide, which materially assisted the oxidation. The refined iron was charged on this bed of oxide, usually leaving a clear space in the centre. Whilst heating up, the surfaces of the pigs were partially oxidized. When the charge assumes a pasty condition it is drawn forward to the centre, and by means of bars broken up and the oxide already formed thoroughly mixed with the metal. The rabbling is continued until the metal "comes to nature." This stage denotes the removal of the impurities, chiefly carbon and silicon, with smaller amounts of sulphur and phosphorus, by the oxidizing atmosphere of the furnace, which removal is materially assisted by the oxygen present in the iron oxide formed during the heating of the pig, and subsequently worked into it. This process was ultimately developed into the "wet" method of puddling, or, as is otherwise known, the pig-boiling process.

Yorkshire Wrought Iron.—Bowling, Low Moor, and Farnley wrought irons have long held a wide reputation for high quality. The forging properties of these irons are excellent, and they will admit of many reheatings and smithings without deterioration. The welding properties are also high, and the mechanical properties, as shown in the results yielded by the testing machine are, for wrought iron very good. The process of manufacture may be briefly sketched as follows: Pig iron obtained by smelting the Yorkshire clay ironstone in blast furnaces supplied with cold blast is refined and cast into "plate metal." A puddling furnace charge consists of 3 cwt. of this plate metal, which is heated previous to its introduction to the furnace. The furnaces used have smaller beds than usual and higher stacks, thus giving better draught, and consequently higher working temperature. Nine or ten heats are worked from each furnace per turn of 12 hours. From the time of melting down to balling up, the metal is almost continuously rabbled, and when "it comes to nature" the impurities are almost totally eliminated. Each ball weighs from 80 to 90 lbs. These balls are shingled under a "helve" into blooms of 12 in. square by about 2 in. in thickness.

When cold the blooms are broken under a falling weight and classified according to the appearance of the fracture. The broken blooms are, after classification, piled, reheated, and welded into billets, further reheated and rolled down into the desired plate, section, or bar. Sir Lowthian Bell, in his "Principles of the Manufacture of Iron and Steel," gives the following analyses of the original pig, refined iron, and final product as obtained at the Bowling Works:—

	Cold-blast Pig Iron.	Refined Metal.	Finished Iron.
Carbon	3·656	3·342	0·226
Silicon	1·255	0·130	0·109
Sulphur	0·033	0·025	0·012
Phosphorus	0·565	0·490	0·064

The wet method of puddling, or the pig-boiling process, depends upon the reaction between the impurities of the pig iron and the oxygen added in the form of various oxides of iron. Unlike the dry process, grey or mottled pig iron may be employed, the variety chiefly used being that of forge quality.

The lining of the hearth and the additions of oxide made during the process are termed "fettling." Fettling materials embrace various oxides of iron, one of the most familiar being that of the hammer slag squeezed out of the balls of iron from the puddling furnace.

The chief purpose of the hammer slag is to provide in the puddling furnace a bath of fluid cinder into which the globules of pig iron trickle as they melt. The "fettling" of which the furnace hearth is formed is known as "bull dog," and is obtained by calcining tap cinder—that is, slag tapped from the puddling furnace. "Blue billy," a form of ferric oxide obtained as a residue in the manufacture of sulphuric acid from iron pyrites, is also used. It should, of course, be fairly free from sulphur. "Pottery mine" is a variety of blackband ore obtained from the pottery district of Staffordshire. When calcined it consists of ferric oxide, and forms a very suitable material for the fettling of a furnace hearth. Ferric oxide in the form of red hematite ore may be also employed for the same purpose.

The shell of the working bottom of the furnace is formed of cast-iron plates, on which the bed of fettling is laid. When laying a new bed, a refractory fettling consisting of small pieces of pottery mine or similar material is evenly spread over the surface of the plates. The whole is levelled down by a covering of rolling-mill scale or other form of fine iron oxide, and a heat applied sufficient to soften the materials and make them frit together.

A ball of scrap iron is then charged into the furnace, heated to a welding heat, and worked repeatedly over the whole surface of the bed. This ball of scrap iron, in the strongly oxidizing atmosphere and high temperature of the furnace, is converted into magnetic oxide of iron, which, by constantly working over the surface of the bed, "flows" and unites the whole into a smooth, even mass. A good bed is essential to successful working, and in working life all worn places are made good by means of a scrap ball in the manner indicated.

The pig iron is charged on to the hearth of the furnace, together with a specified quantity of fettling, usually hammer slag, and the operations from this point may be divided into four stages: First, the melting-down stage, which occupies about half an hour, and effects a partial removal of the silicon; also converting the grey iron into the white variety by changing the free carbon into the combined form. Portions of the phosphorus and manganese are also oxidized. During the second stage, lasting from seven to ten minutes, remaining portions of the silicon, manganese, and phosphorus are removed. The molten charge is thoroughly mixed with the added fettling, and the metal "cleared." The third stage, known as the "boil," lasts about half an hour, during which nearly the whole of the carbon and further portions of the phosphorus are removed. The metal gradually begins to thicken, and is vigorously worked or rabbled in order to bring all portions of it into intimate contact with the fettling. The carbon of the metal uniting with the oxygen of the fettling forms carbon monoxide, which burns on the surface of the metal as the bubbles of gas rise to the top and burst. During this ebullition of gas the metal rises in the furnace, and part of the slag or cinder is run out into an iron slag waggon. The violence of the reaction begins to subside and the metal settles down, gradually "coming to nature." The metal is now in the form of a sponge or more or less porous cake of wrought iron. The temperature is raised to a welding heat, and the fourth or last stage of the process commences. This consists in working up the porous cake into a ball, the latter being thoroughly worked in order to ensure uniformity. This ball is then divided into smaller balls weighing from 80 to 90 lbs. each, which are taken to the "helve," or steam hammer, under which the intermingled cinder is expressed and a bloom of wrought iron obtained. The blooms are rolled down, without reheating, into "puddled bars," which are subsequently worked up by piling and welding into various industrial shapes. A quantity of slag remains in the furnace, to which fresh additions of hammer slag are, if necessary, made when charging the pig iron previous to commencing another operation. The amount of fettling used per ton of wrought iron made, varies with the quality of the original pig and the particular method of working followed. In the production of best Staffordshire iron, the quantity of fettling per ton of bars made is stated by Professor Turner at slightly over 10 cwts. The yield also varies according to the exact procedure adopted and the character of the pig iron employed. Under certain conditions this yield may be made to exceed that of the weight of pig iron charged. Such a result naturally represents specially good working conditions and a perfect adjustment between the fettling and the pig iron, showing that as the impurities of the metal have been oxidized, metallic iron has been reduced from the fettling, so increasing the yield of wrought iron. Generally, however, there is a loss, which, under ordinary conditions, may vary from 5 to 10 per cent. of the weight of pig iron charged.

As already stated, the balls from the puddling furnace are shingled under a helve, or, in a more modern works, under a steam hammer, in order to express the involved cinder and to produce a bloom. From the hammer the bloom passes on to a set of rolls, and is rolled down into rough bars which are known as puddled iron, When cold, these bars are sheared into suitable lengths and formed into "piles," the size and weight of which vary according to the shape and weight of the ultimate product. These piles are heated to a welding heat in a reheating furnace, and rolled down into the desired form of plate, rod, bar, or angle.

The Reactions of the Puddling Process.—The oxygen of the fettling and the impurities of the pig iron react on each other, resulting, in ideal cases, in a simultaneous reduction of iron from the fettling and elimination of impurity from the metal. In the first place, the graphitic carbon of the grey or mottled pig iron is converted into the combined form, from which state it is subsequently oxidized to carbonic oxide. Silicon and manganese enter the slag as oxides, and the contents of sulphur and phosphorus are largely reduced. Thus the operation is of a basic character, in that it effects the removal of the acid phosphorus and sulphur. The theoretical explanations as to the removal of these elements are by no means clear; but, nevertheless, the fact remains that during the process of puddling, some 50 per cent. of the sulphur and 70 or 75 per cent. of the phosphorus are eliminated. This, of course, in addition to nearly the whole of the carbon, silicon, and manganese. These changes are well shown in the following analyses:—

	Mottled Iron.	When melted.	Twenty minutes after melting.	Puddled Bar.
Combined carbon ...	1·45	2·80	1·17	0·15
Graphite	1·38	none	none	none
Silicon	1·24	0·82	0·05	0·14
Phosphorus	0·65	0·60	0·30	0·14
Sulphur	0·11	0·09	0·05	0·04
Manganese	0·63	trace	trace	0·10

The foregoing brief description of the production of wrought iron has been included chiefly for its metallurgical interest, and in order to show at a later stage the relationship between this and the more modern methods adopted for the purification of pig iron. The pig-boiling process was developed chiefly in the direction of mechanical puddling. Special types of furnaces were also designed, including rotating types, gas-fired, etc.; but none of these appliances were largely adopted, owing to the rapid advance of the Bessemer process, and within more recent times that of the Siemens process of steel-making. With the advance of steel, wrought iron naturally began to decline; ingot iron and mild steel are now regular products of the steel furnace, and have replaced in very large measure wrought iron. Whilst wrought iron is still made in fairly large quantities, its manufacture is year by year gradually declining, whilst, correspondingly, that of steel is advancing.

CHAPTER XII

THE CEMENTATION PROCESS

Before passing on to a full consideration of steel, it may be well to briefly examine the cementation process for the production of converted bar, or "blister steel." The latter name is due to the fact that the surface of the bars on completion of the process are covered with large blisters. This method ranks as one of the oldest of those employed in steel-making, and is to a limited extent in use to-day. The high purity of Swedish wrought iron has been recently shown. (See analysis of Lancashire-hearth iron, which represents the type of iron usually employed in the cementation process.)

Externally a cementation, or converting furnace, resembles a glass furnace. It contains two pots, which are capable of holding from eight to fifteen tons of metal each, according to the size of the furnace. These furnaces are, or rather were, built in rows, from four to six in each row. A rough sketch (Fig. 23) will convey some idea of the arrangement of this furnace. A, A represent the pots, which are generally 12 ft. in length, 3 ft. in width, and 3 ft. in depth, but vary according to the capacity of the furnace. At C the manhole is shown through which the charging and drawing operations are conducted.

This manhole is bricked up when the furnace is in operation. The firegrate is shown at B. This grate runs the full length of the pots, and is fired at both ends. The flames from the grate circulate around the pots, and are drawn away by means of flues D. The pots are supported in masonry bearers, the aperture between each bearer forming flues for the circulation of the flames from the firegrate. When preparing for converting, the pots are packed with alternate layers of Swedish wrought-iron bars and charcoal; each bar, in fact, is surrounded by charcoal. The pots are luted over with a thick layer of "wheelswarf"—that is, the refuse, consisting chiefly of siliceous material, but containing also small particles of metallic iron and iron oxide, which collects in the troughs below the grindstones employed in grinding hardware and cutlery goods.

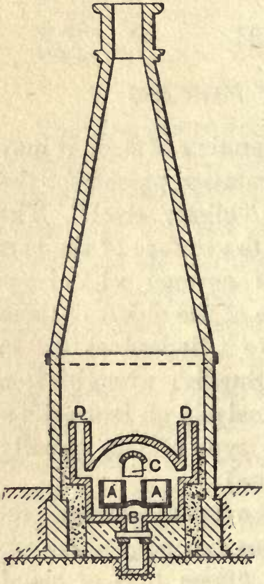


Fig. 23.

This layer of "wheelswarf," at the temperature of the furnace, partially fuses over and forms an airtight covering for the pots.

The effect of heating carburized iron in the presence of oxygen to a temperature below its fusing point has been shown in the case of malleable cast iron. At a red heat, in the presence of oxygen, carbon is removed from the casting. Conversely, decarburized iron, when heated in the presence of carbon, absorbs that element and becomes carbonized. As in the malleable cast iron, the outside layers contain the least carbon, so in the converted bar the outside layers contain the most carbon, the action in both processes commencing at the outside and working gradually towards the centre. As the carbonization in the cementation process proceeds from the outside, it is evident that the depth of carbon penetration is determined by the length of time to which the bars have been heated in contact with carbon (charcoal). Any degree of carburization can, within certain limits, be therefore obtained by regulating the duration of the heat. In practice, seven grades of carbonization or "tempers" are produced, ranging from No. 1, which contains the least carbon, and is therefore the mildest. Owing to its mildness, No. 1 converted bar is sometimes referred to as "Irish temper." As the numbers pass upwards from 1 to 6, the content of carbon increases, No. 6 usually containing about 1·7 per cent., and is known as "flake bar," owing to the flaky appearance of its fracture. The highest temper made is known as "double converted," or glazed bar, and contains about 2 per cent. of carbon. As already seen, the temper is determined by the length of time to which the pots are heated. Usually mild heats receive eight days' firing, medium heats about ten days, and hard heats from eleven to twelve days. An opening is provided in the pot for inserting trial bars; these are withdrawn from time to time, and the progress of the carbonization noted by examining a fracture. When the required temper is obtained, the furnace is banked and allowed to cool down slowly. When cold, the pots are drawn, and the bars classified according to the appearance of the fracture. A medium converted bar presents a core of unchanged iron, known as "sap," surrounded by layers of hard steely material, which increases in hardness towards the edges of the bar. High tempers contain little or no "sap," the carbon having penetrated right through to the centre. The analyses given below show the change taking place during cementation :—

	Before converting.	Converted to Medium Temper.
Combined carbon	0·05	1·10
Silicon	0·02	0·02
Manganese	0·10	0·10
Sulphur	0·01	0·01
Phosphorus	0·02	0·02

As will be seen, the only change taking place is that due to carbon, and therefore by this method some of the purest commercial steels are produced. These steels, known as shear steels, are produced by piling and welding converted bars together, the blows of the hammer breaking up the hard exterior portions of the bars and distributing them with the softer cores of sap, thus producing a more uniform structure. The faggot so obtained is rolled or hammered down into the required bar, and is known as "single-shear" steel. Double-shear steel represents the foregoing faggot nicked and broken into two halves, reheated and welded together again before rolling or hammering down to shape. The treatment is only a physical one, its effect being to produce a uniform structure by working up and equally distributing the hard and soft portions.

Converted bar is also remelted in steel-melting crucibles, and poured into ingots for the production of high-quality "cast steel."

CHAPTER XIII

STEEL

Steel.—In the preceding chapter it has been shown that wrought iron heated in contact with carbon absorbs the latter element and becomes steel; evidently, then, steel is an alloy of iron and carbon. However, this is not intended as a definition, for "steel" is one of the most difficult of metallurgical products to define; in fact, it cannot be accurately defined. Thus, alloys of iron and carbon include cast and malleable cast iron, wrought iron, etc. In Sheffield—the home of the crucible steel industry—a product consisting of 75 per cent. pig iron and 25 per cent. boiler-plate punchings has been legally defined as steel, and the maker justified in marking it "cast steel." Carrying this decision to its logical conclusion, it follows that any ironfounder introducing 25 per cent. of wrought iron into his cupola mixtures is entitled to call his castings "steel"—a most absurd proposition, and one finding no foundation in fact. Further, the distinguishing feature of hardening when quenched in water from a high temperature cannot now be confined to all classes of steels, for mild steels and ingot irons are not sensibly hardened by such treatment. Thus, whilst a steel containing

1 per cent. carbon heated to redness and plunged into cold water becomes hard enough to scratch glass, a similar steel containing 0·1 per cent. carbon is comparatively unaffected by such treatment. Other difficulties lying in the way of an exact definition are found in the large variety of special steels now produced, instances of which are found in armour plate and projectile steels, and in the modern types of high-speed cutting-tool steels, self-hard steels, and the like, which may contain large quantities of metals other than iron, such as chromium, tungsten, vanadium, manganese, nickel, molybdenum, and so forth. Therefore, excluding these special varieties, ordinary steel may be described as iron containing from 0·1 to 2 per cent. of carbon in the combined form, which has been submitted to complete fusion and poured into an ingot or mould for the production of a malleable or forgeable metal. As showing the inadequacy of this definition, it will at once be seen that it does not embrace shear steels which have never been submitted to complete fusion, but it is nevertheless fairly descriptive of a product, an exact definition of which it is almost impossible to give. Ingot iron represents iron of practically the same composition as wrought iron, but which has been produced in a steel-melting furnace. Mild steel contains about 0·2 per cent. carbon, this element increasing as the harder varieties are approached, being highest of all in the tool steels. The mechanical effect of this carbon is shown in the following table :—

Material.	Analysis.				Tenacity in Tons per square inch.	Extension per cent. on 2 inches.	Contraction per cent. of Area.
	Carbon.	Silicon.	Sulphur.	Phos-phorus.			
Mild steel ...	0·10	0·03	0·02	0·02	20·0	50·0	70·0
Tool steel ...	1·00	0·03	0·02	0·02	60·0	5·0	10·0

The controlling effect of carbon on the properties of pig iron has been shown, an effect which is even greater in the case of steels, as shown in the table just given If, by increasing the content of carbon from 0·1 to 1 per cent., an increase of 40 tons in tenacity is obtained, it is evident that any intermediate percentage will, in a corresponding manner, give intermediate mechanical properties. Within limits, an increase of carbon is accompanied by an increase in tenacity and a decrease in ductility, each increment of carbon showing distinctly these increases and decreases. It follows—still within certain limits—that a specific content of carbon denotes a steel specially suitable for a particular purpose, and in actual practice varying "tempers" represent varying carbons. The following classification embraces the most familiar tempers of Bessemer, Siemens, and crucible steel:—

Class of Steel.	Content of Carbon.	Purpose.
Bessemer steel.	0·20	Ship and boiler plates, sheets, etc.
	0·25	Axle steel.
	0·30	Tyre steel.
	0·30 to 0·40	Rail steel.
	0·50	Spring steel.
Siemens or open-hearth steel.	0·20	Boiler plate.
	0·65	Spring steel,
	1·30	Tool steel.
Crucible steel.	0·90	Chisel steel.
	1·10	Large files, drills, and similar tool steels.
	1·20	Turning tool steels.
	1·40	Saw file steels.
	1·50	Razor steels.

This classification is general only, but it clearly shows the practical application of varying contents of carbon. A limit of carbon is necessarily found where the content is such as to render the product too hard and brittle for industrial use. For instance, white cast iron containing the maximum proportion of combined carbon is, owing to its extreme hardness, impossible to machine with ordinary tools, and, owing to its high degree of brittleness, is limited in industrial application.

Steel heated to redness and quenched in water under certain conditions becomes hardened. This hardening effect increases with an increasing content of carbon, for whilst a steel of 0·1 per cent. carbon is unaffected, one of 1 per cent. carbon becomes so hard that it will scratch glass. On reheating a hardened steel to the temperature at which it was quenched, and slowly cooling it, it again becomes soft, or, in other words, the steel is "let down." The amount of this "letting down" can be regulated by the temperature to which the steel is heated after hardening. On this latter fact the process of tempering is based, for by heating hardened steel to certain definite temperatures the metal is softened to the extent of the heating given, and varying degrees of hardness are thereby readily obtained. The object of tempering is to obtain a certain combination of hardness and ductility, in order to permit a tool carrying a cutting edge, and at the same time prevent its fracture under shock. This combination of two opposite properties varies with the class of tool and its subsequent use. The actual range of tempering is a very narrow one, commencing at 100° C. and being complete at 400° C. The range being narrow, it need hardly be stated that the process of tempering demands delicate care, and in reheating the exact temperature must be caught. As already shown, these temperatures vary with the degree of hardness and ductility required. In practice, temperatures are judged by the colour of the oxide formed on the heated surface, the colours varying in intensity as the heat is increased, thus commencing with a faint yellow, passing through straw to full yellow, and, as the heat increases, to brown, purple, full blue, and dark blue respectively. The highest of these colours, as will be seen, is far below the hardening or quenching temperature.

Oil-hardened steel, or, as it is otherwise termed, oil-tempered steel, represents steel quenched from the hardening temperature in oil instead of water. The hardening effect is less intense than when quenched in water, and the ductility and toughness therefore greater.

The remaining constituents may be briefly noted as follows: Manganese is present in all commercial steels, varying from traces only, up to 1 per cent. It promotes soundness, to some extent increasing the elastic limit and breaking load, also neutralizing the effect of sulphur when that element is present in excess. Silicon also tends to the production of a sound metal by virtue of its deoxidizing properties, but it is usually present in insignificant quantity in forging steels, whilst in casting steels it may be present to the extent of 0·3 per cent. Phosphorus produces an exceedingly brittle metal, rendering it also "cold short." Specially pure steels contain from 0·02 to 0·03 per cent. Usual specifications limit the content of this element to 0·06 per cent., and at 0·1 per cent. a danger limit is reached. Phosphoric steels, whilst cold short, may be worked at a suitable temperature. On the other hand, steels containing appreciable amounts of sulphur are decidedly "red short"—that is, will not permit of working at a red heat. In high-quality steels the content of sulphur runs about 0·01 per cent.; ordinary specifications are limited not to exceed 0·04 per cent. As already noted, the presence of manganese neutralizes the harmful influence of sulphur, a fact to which attention was drawn in the case of cast irons.

The Constitution of Steel.—The control exercised by carbon is recognized in works practice to such an extent that in many cases steels are classified in grades which vary by only 0·1 per cent. Excluding mild steels, the following table[1] shows how the carbons are varied to suit special requirements :—

---

[1] Author, "Technics," vol. iii., No. 13.

Content of Carbon in Steel.	Purpose for which the Steel in the form of a hardened or tempered Tool is suitable.
0·50	Springs.
0·60	Stamping dies.
0·65	Clock springs.
0·75	Hammers, shear blades, axes for wood, mint dies.
0·80	Boiler punches, screwing dies, cold setts.
0·90	Edge tools, slate saws.
0·95	Circular saws, pens.
1·00	Cold chisels, crosscut saws.
1·10	Drills, large files, handsaws.
1·20	Granite and marble saws, mill chisels.
1·30	Harder drills, cutters, spindles, turning tools, and medium files.
1·40	Saw files.
1·50	Turning tools for chilled rolls, razors, and surgical instruments.

From the foregoing it is evident that any study of steel is naturally resolved into an examination of the influence of carbon on iron. This influence has been very clearly shown by Professor Arnold, who in 1895 published a masterly research,[1] which forms a classical contribution to metallurgical knowledge. By combining different methods of investigation and working on a series of exceptionally pure steels with carbon as the only variable, Professor Arnold arrived at a series of results as to the constitution of steel which are of immense practical value, a value further enhanced by the fact that they were obtained by combining thoroughly practical conditions with the best scientific methods of investigation. Probably the chief result of this work lies in the establishment of certain properties associated

---

[1] "The Influence of Carbon on Iron," *Institution of Civil Engineers*, vol. cxxiii.

with a steel containing 0·89 per cent. carbon, and this will be referred to in a moment.

In Figs. 21 and 22, p. 137, the appearance of wrought iron under the microscope is shown; in other words, the structure of the iron is reproduced. This examination of structure is included in the science of metallography, and its purpose is to reveal the internal arrangement of a metal or alloy. Structure is essentially distinct from the appearance shown by a fractured surface. The latter reveals only the appearance after breaking by force, such as a blow or pull, and what appear to the eye as parts are really groups of parts more or less distorted by the force required to effect fracture. In examining structures mechanical disturbances are therefore avoided. Usually a small piece of metal is gently machined from the mass; this piece, one face of which must be a plane, is termed the section, and two of these sections taken at right angles to each other are essential when studying the distribution of the various constituents in the solid mass. The plane surface of the section is freed from scratches by rubbing on emery papers of succeeding fineness, finishing on "00" or "000." This face is then ready for final polishing, which is effected by rubbing on a wet cloth lightly sprinkled with diamontine, and finishing on kid skin containing a little rouge. When free from scratches the section is ready for etching or the development of its structure. Etching mediums vary in character, but as a rule consist of dilute acids, which, acting differentially on the various constituents of the metal, throw certain of them into greater prominence than others. In the case of pure metals the crystal junctions are more rapidly attacked than the crystals themselves. All metals are crystalline, assuming the metal to be chemically pure; then in mass it will be built up of a series of crystals, and a section through the mass will show the boundaries or crystal junctions.

Taking as an example slag-free and nearly pure iron its structure is that shown in Fig. 24. This particular photograph represents an area in which carbon is absent. Carbon present in a steel is in combination with iron as a definite carbide, Fe_3C. In the simultaneous presence of manganese, chromium, or certain other metals, double carbides are formed. For convenience, these hard carbides are micrographically known as "cementite." On the other hand, pure iron, such as that shown in Fig. 24, is known as "ferrite." A definite mixture of "ferrite" and "cementite" is known as "pearlite." Pearlite often consists of alternate striæ of ferrite and cementite, and in such a form gives a magnificent play of colours resembling those of mother-of-pearl; hence the term pearlite, which, in reality, is a contraction of Dr. Sorby's "pearly constituent."

"Pearlite" is not a constituent of hardened steels, and the following consideration is confined exclusively to unhardened steels.[1] Typical pearlite is shown in Fig. 25, the high magnification being necessary in order to resolve the structure and to clearly show the laminations. In the research already referred to, Professor Arnold has clearly shown that as carbon increases ferrite is replaced by pearlite. Evidently, then, in a series of steels of ascending carbon content, a point will be reached at which the whole of the structure is represented by pearlite. This point has been firmly

---

[1] Treated steels are discussed in Chapters XVIII. and XIX.

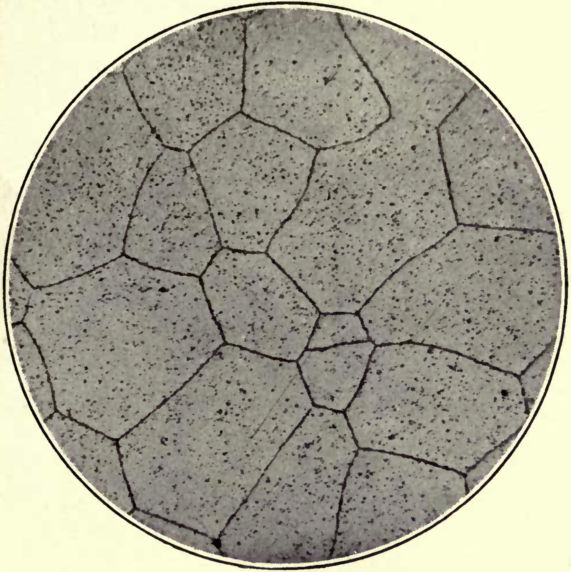


FIG. 24.—Ferrite. × 150.

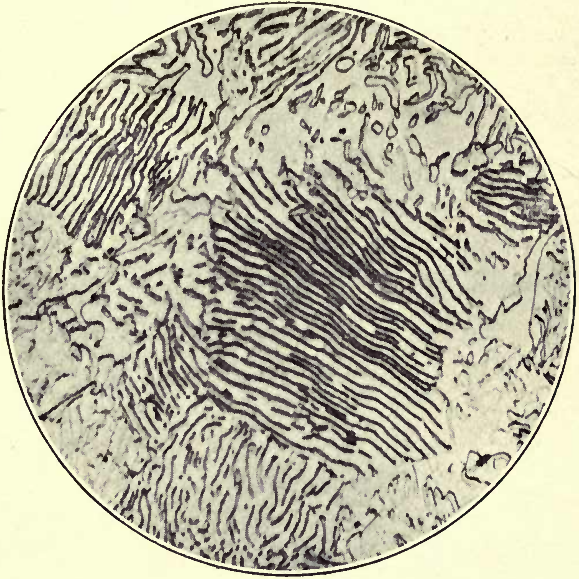


FIG. 25.—Pearlite. × 1000.

[*To face p.* 164.

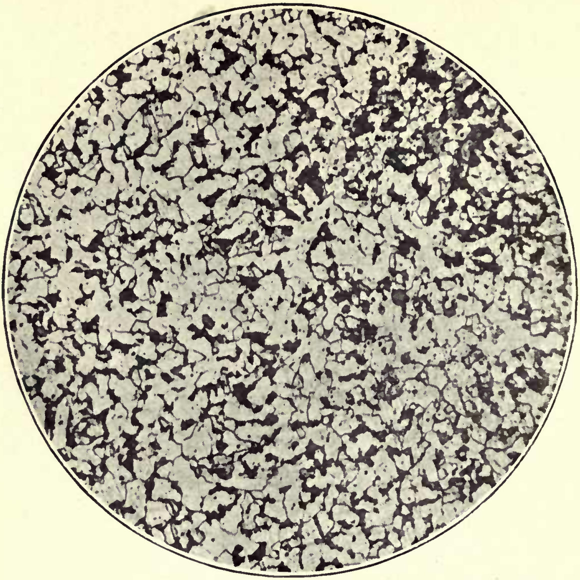


FIG. 26.—Unsaturated Steel. Pearlite and ferrite. × 150.

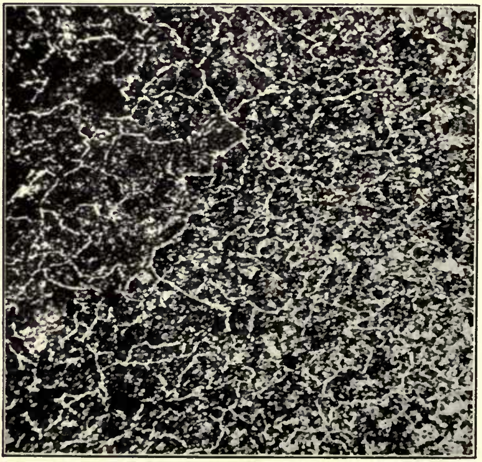


FIG. 27.—Supersaturated Steel. Pearlite and cementite. × 150.

[*To face p.* 165.

established by Professor Arnold at 0·89 per cent. carbon. Such a steel in the normal condition consists entirely of pearlite, and corresponds with the saturation point of iron for carbon. Steels containing 0·89 per cent. carbon are therefore distinguished as "saturated;" steels containing less than 0·89 per cent. carbon as "unsaturated," and steels containing more than 0·89 per cent. carbon as "supersaturated."

The saturation point of 0·89 per cent. carbon refers distinctly to iron carbon steels, for in the presence of elements capable of forming double carbides this point is slightly lowered. As an example of unsaturated steel, Fig. 26 is given, and examination will show it to consist of crystals of ferrite interspersed by dark knots of pearlite.

At this magnification the two constituents of pearlite are not resolved, and it therefore appears as a dark mass. Successive increments of carbon are accompanied by the disappearance of ferrite until the saturation point is reached. Exceeding the saturation point, cementite appears structurally free, and is sectionally shown as a white network embracing areas of pearlite as in Fig. 27. Still further increments of carbon result in an increasing thickness of the network, and the appearance of isolated streaks of cementite in the pearlite areas. Fig. 28 reproduces the structure of converted bar containing 1·5 per cent. carbon—and allowing for the lower magnification—a comparison with Fig. 27 will show the disposal of the surplus cementite. Translating the two last figures into the solid, it will be seen that each area of pearlite is enveloped by a membrane of cementite. As the membranes increase in thickness with an increasing content of carbon, a point will finally be reached at which the structure sectionally presents cementite in juxtaposition with pearlite. Such a structure is met with in white cast iron, which contains the maximum amount of combined carbon. An examination of Fig. 29, which is reproduced from a typical sample of white cast iron, will show this characteristic cementite and pearlite structure. The white areas represent cementite, and the dark ones pearlite.

Cementite is an essentially hard and brittle compound, but when interspersed with ferrite in the form of pearlite its brittleness is in some measure neutralized by adjacent ductile ferrite. Therefore cementite under these conditions exerts a "stiffening" effect on the metal in proportion to the amount of pearlite present. When the saturation point is exceeded, and cementite appears structurally free, then actual brittleness is shown. Whilst a supersaturated steel will yield a high maximum stress it is nevertheless brittle under shock, for by means of a sudden blow fracture will readily travel along the hard cementite cell walls. Maximum brittleness is shown in the cementite pearlite structure of white cast iron.

The mechanical value of structural changes due to steadily increasing contents of carbon is well shown in the following table:—[1]

---

[1] J. O. Arnold, "Influence of Carbon on Iron."

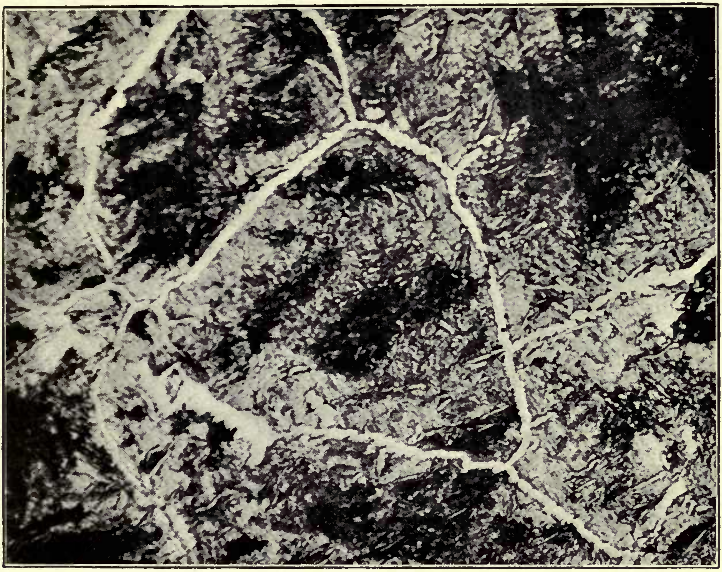


Fig. 28.—Converted Bar. Supersaturated steel. × 58.

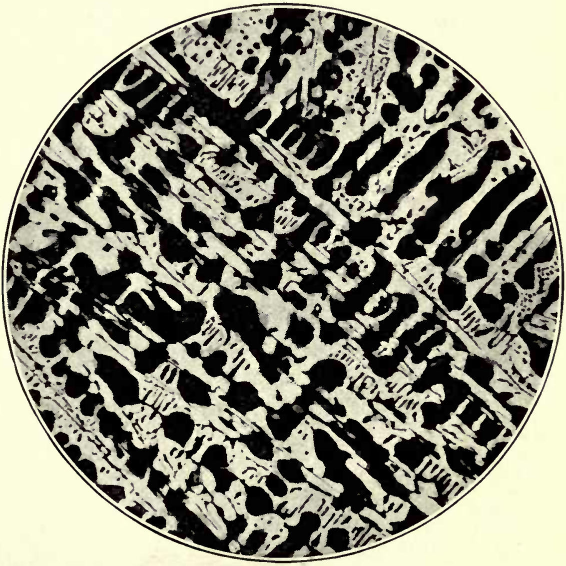


Fig. 29.—White Cast Iron. 3·4 per cent. carbon. × 150.

[*To face p.* 166.

MECHANICAL PROPERTIES—"NORMAL STEELS."

Carbon.	Elastic Limit. Tons per square inch.	Maximum Stress. Tons per square inch.	Elongation.	Reduction of Area.
0·08	12·19	21·39	46·6	74·8
0·21	17·08	25·39	42·1	67·8
0·38	17·95	29·94	34·5	56·3
0·59	19·82	42·82	19·9	22·7
0·89	24·80	52·40	13·0	15·4
1·20	35·72	61·65	8·0	7·8
1·47	32·27	55·71	2·8	3·3

Normal steels represent the rolled bars heated to 1000° C. and cooled in air. The object of this treatment being to bring all the steels into one uniform condition. Following the tenacities and comparing them with the foregoing notes, it will be seen that as pearlite replaces ferrite, maximum stress increases, and continues to do so until a structure consisting of pearlite and very thin meshes of cementite is reached. Further increase in the content of carbon, resulting in a greater dispersal of free cementite, is associated with a decrease in maximum stress. The white iron of Fig. 29 will yield a maximum stress of 10 tons per square inch, no elongation and no reduction of area.

CHAPTER XIV

THE CRUCIBLE PROCESS

THE exact procedure followed in any steelmaking process varies according to locality, hence essential features only can be considered here, minor details being necessarily omitted. Steelmaking processes may be broadly divided into three groups: (1) Bessemer. (2) Open-hearth. (3) Crucible. The two former are essentially chemical processes, in that during the operation certain chemical changes occur which practically eliminate the whole of the impurities of the pig iron used. On the other hand, the crucible process is not a chemical one; in fact, it is rather a mechanical one, for the method simply consists of melting together dissimilar materials to produce a desired result. From this point of view it may be compared to mixing in cupola practice, for just as in the cupola certain dissimilar brands of pig iron are charged in order to obtain a certain grade of metal, so in the crucible process of steelmaking certain dissimilar materials are charged together into the melting pot and melted in order to obtain the desired grade of steel. The process is therefore simply one of mixing and melting, and skill in employing it depends on the careful selection and adjustment of the charges, followed by careful melting practice. The crucible method of steelmaking is old, but is nevertheless one which yields exceedingly high qualities of steel. The chief products of this method are found in high-class tool, file, razor, and similar grades of steel. To a somewhat limited extent it is employed for the production of steel castings, but the relatively higher cost, compared with the open-hearth or surface-blown type of Bessemer converter, is such that it cannot compete except in the case of castings of special quality.

Special steels of the self-hardening type and high cutting speed are almost exclusively the product of the crucible process. It will be seen that the term "cast steel," by which the crucible product is denoted, embraces a metal of exceedingly high quality, and one therefore realizing a much higher price in the market. It may, however, be noted that not all the "cast steel" of commerce represents crucible metal, for not infrequently steel made by other methods is marked "cast steel" in order to realize the higher price of this material. Such a practice is, of course, literally correct, for any steel produced by the usual methods is of necessity cast steel; but the practice is commercially wrong, in that by virtue of priority the term is conceded solely to crucible metal. An illustration of this kind emphasizes the necessity for more binding definitions of the various types of steels; the definitions in present use are more or less of a loose character.

The Crucible Process.—A series of "melting holes" constitute the steel-melting house. The holes are oval in section, and each accommodates two crucibles, as shown in the accompanying sketch, Fig. 30. The melting holes are formed by ramming ganister between firebrick sides and a wooden pattern, the exterior of which corresponds to the interior of the melting hole. Similar furnaces employed in brass-foundry practice are circular in section, and accommodate only one crucible, though the latter may be of much larger capacity than is usual for steel. When fully employed, steel-melting holes are usually relined once a month; the range of holes forming one melting house are shut down for a day, known as "building day," and relined altogether. As shown in the sketch, the top of the melting hole corresponds to the floor level; the cover for the hole is formed by a square firebrick, held in a wrought- or cast-iron frame fitted with a projecting handle. Generally a series of twelve holes form one melting house, and are in charge of a steel melter, or "teemer." Two "pullers out" and two "cokers" attend to the crucibles and fires respectively; an "odd man" takes charge of the annealing grate, a "potmaker" supplies the crucibles, a "cellar lad" makes the stands and lids, and also "mops" the crucibles clear of slag when casting.

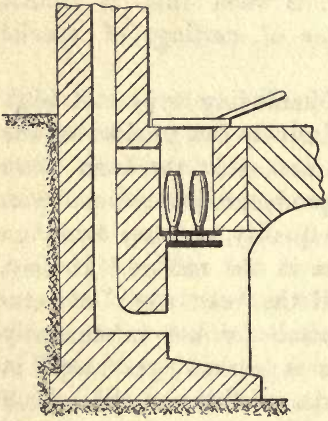


FIG. 30.

The crucibles employed are usually clay ones. Plumbago crucibles are used in certain districts, but they never yield the same reliable product as the clay ones do.

In the section devoted to refractory materials, four typical analyses of fireclays were given (see page 17), which are specially suitable for the manufacture of steel-melting crucibles. A mixture of clays always gives a better result than one clay alone, and in practice several varieties of fireclay are employed, to which additions of coke dust are made. The four crucible clay mixtures given below are made from the clays already given :—

CRUCIBLE CLAY MIXTURES.

	a	*b*	*c*	*d*
Clay No. 1	10	20	21	35
,, No. 2	45	40	20	0
,, No. 3	21	17	35	20
,, No. 4	21	17	14	30
Coke dust	3	6	10	15

The first mixture *a* gives a crucible specially useful for the production of high-grade steel; in other words, a crucible that imparts comparatively little carbon or silicon to the steel. This mixture takes much more working up than do the following three. Mixtures *b* and *c* are especially useful in ordinary works practice. They make up into crucibles that will stand a fair amount of handling, and only part with normal amounts of silicon, at the same time, other things being equal, yielding cast steels of good quality. Mixture *d* is suitable for making up into crucibles that will have fairly rough usage to meet. It therefore finds its chief application in steel-foundry practice. It throws more silicon and carbon into the steel than do the three preceding mixtures, but gives a strong crucible capable of standing four heats.

The working life of an average clay crucible is represented by a day's work of three heats. Naturally, no clay crucible when in use should ever go cold, for in the event of its doing so it cannot be reheated again with safety. Steel-melting crucibles are in the majority of cases made by hand, and, as already shown, one potmaker is employed to each set of twelve melting holes. The daily output of the potmaker will therefore be twenty-four pots per day, plus allowance for breakages and running pots. Uniformity in texture of the clays employed is one of the first essentials, and this is attained by suitable grinding and sifting. The necessary amounts of each clay and also the coke dust to make up a batch of thirty pots are weighed out and mixed together in a suitable floor tray. Water is added to bring the mass to the requisite consistency, and the whole is well kneaded by treading with the bare feet. It is essential that the mass be well incorporated, and therefore the "treading" process must be very thoroughly performed, and continued until the mixture arrives at what is technically termed "nature." For 600 lb. of clay this treading occupies about three hours, but generally the time varies according to the mixture employed. For instance, the mixture *a* takes far more treading than does the one marked *d*. On the completion of the treading process the clay is cut into blocks of about 29 lb. in weight. These blocks, or "balls," as they are termed, are worked by hand on a slab, being given a rocking and twisting motion until they are entirely free from air bubbles. An experienced man can tell by the feel of the ball when the air bubbles are expelled.

The apparatus employed for forming the crucibles consists of a cast-iron flask, the inside of which corresponds to the outside form of the crucible, and a plug or core to give the internal form. The inside of the flask is finished dead smooth. The bottom plate of the flask is loose, and through the centre a small hole is drilled. The plug or core may be of cast iron, cored out inside to lessen its weight, or it may be formed of hard wood. In either case the outside is finished perfectly smooth. In the bottom of the plug and in the centre a pin is inserted corresponding to the hole in the loose bottom plate of the flask. Both the flask and the plug are well oiled to prevent the clay sticking to the moulds. One of the aforementioned balls of clay is dropped in the flask, the plug inserted, and centred by means of the centre pin. The plug is then driven home by a few blows from a large wooden mallet, and the clay so forced up between the inner and outer moulds. The plug is given a dexterous twisting movement, and is withdrawn. The flask is lifted by means of two trunnion handles on to a post fixed in the floor and slid downwards, leaving the crucible standing on its bottom plate on the post. The top edge of the crucible is finished off, and the top diameter reduced a little by drawing it in towards the centre. Two sheet-iron clips are placed around the crucible in order to carry it without deformation, and it is taken away and stored in a warm atmosphere to harden. When hardened, the crucibles are placed on shelves fixed round the melting house, and remain there for two or three weeks. The weight of a newly made crucible averages 29 lb., on air drying 25 lb., and after annealing the weight is lessened to about 21 lb. In addition to crucibles, covers or lids and stands are made. Both stands and lids are usually made of a cheaper mixture of clay than that employed for the crucibles themselves.

Annealing.—The crucibles, previous to use, must be heated slowly and uniformly. This is achieved by annealing them overnight in a slow fire. Annealing grates are built to take about thirty crucibles; a layer of fire is spread over the grate and the crucibles placed mouth downwards, the spaces between each one being filled by very small coke. The combustion is very slow, and is so arranged that the pots shall be ready for the following morning. The crucible lids previously mentioned are dish-shaped, and are used in some measure to protect the contents of the crucible from adverse furnace influences. The stands are conical, about 3 in. high, and are used to raise the crucible from the furnace bars. They also serve a further purpose, namely, that of stopping up the hole left in the bottom of the crucible by the centre pin of the plug. To ensure this the pots are "sanded"—that is, after placing on the stands in the furnace a handful of sand is thrown in the bottom of each one. This sand, selected as being fairly fusible, effectively binds crucible and stand together.

The life of the crucibles, as stated earlier, is usually three heats, though with special mixtures of clays they may be worked to yield four heats—that is, of course, providing they do not cool between. But in no case do they exceed this number—that is, in actual steel-melting practice.

Turning from crucibles to the actual melting operations, the first feature of interest lies in the methods of mixing the charges. Turning back for a moment to the cementation method of converting bar iron into steel, it will be remembered that the heterogeneous structure of the converted bar iron is broken up under the hammer, giving a product known as single or double shear steel as the case may be. Instead of working the converted bars down under the hammer, they may be rendered homogeneous by melting in a crucible and casting into an ingot, which is subsequently hammered or rolled down into the desired section, a practice which gives an exceedingly high quality of cast steel, and is largely followed for the better grades of cutlery steels.

The Carbonization of Wrought Iron in the Crucible.—Wrought iron may be at once converted into steel of any desired temper by melting it with the requisite amount of carbon in the form of charcoal.

Wrought iron so heated and melted in contact with charcoal absorbs carbon. Evidently, then, the greater the quantity of charcoal present the greater the amount of carbon absorbed, and the harder the resulting steel. Charcoal is not pure carbon, a fact shown on page 30. On the same page attention is also drawn to the property possessed by charcoal of absorbing the various atmospheric gases and aqueous vapour. Although charcoal increases in weight when absorbing moisture, its volume remains constant, a fact which may be utilized by measuring charcoal instead of weighing it. In any case, however, the charcoal should be stored in a dry place. The method of mixing is most conveniently shown as follows: An ingot weighing 50 lb. is desired to contain 1·1 per cent. carbon, and it must be made from wrought iron containing 0·05 per cent. carbon, and charcoal containing 87·5 per cent. carbon; 50 lb. = 800 oz.

Let x equal the weight of charcoal, and naturally

$800 - x$ will equal the weight of wrought iron in ounces. However, it is only necessary to find the weight of charcoal required. The carbon content of the ingot is required to be 1·1 per cent., allowing a loss of 0·08 per cent. on melting; the theoretical carbon of the ingot should be 1·18 per cent. (Carbon per cent. × weight of charcoal) + (carbon per cent. × weight of wrought iron) = (carbon per cent. × weight of ingot).

$$\begin{aligned} \text{Then } 87{\cdot}5\,x + 0{\cdot}05\,(800 - x) &= 800 \times 1{\cdot}18 \\ 87{\cdot}5\,x + 40 - 0{\cdot}05\,x &= 944 \\ 87{\cdot}45\,x &= 904 \\ x &= \frac{904}{87{\cdot}45} = 10{\cdot}3. \end{aligned}$$

10·3 oz. of charcoal are required to bring the theoretical carbon up to 1·18 per cent. As a matter of fact, the charcoal does not impart all its carbon to the iron, for some of it is lost by oxidation. An average loss appears to be 10 per cent., but the actual loss may vary with different furnace conditions, and should therefore be determined for differing conditions. Assuming a loss of 10 per cent. in our present example, then—

$$\text{As } 100 : 10{\cdot}3 :: 10 : x$$

$$x = \frac{10 \times 10{\cdot}3}{100} = 1{\cdot}03,$$

or 1·03 oz. of additional charcoal to cover loss by oxidation, therefore total weight of charcoal required is 11·33 oz.

Another method of carbonizing wrought iron is by melting it with converted bar (blister steel). This method may be illustrated in the same manner as the foregoing one:—

Materials to be used—

Converted bar	containing	1·30	per cent. carbon.
Wrought iron	,,	0·05	,, ,, ,,

From these materials a 50 lb. ingot is required, containing 0·65 per cent. carbon. Allowing a loss of 0·05 per cent. carbon, the theoretical carbon required is 0·7 per cent.

Let x = weight in pounds of converted bar;
then $50 - x$ = weight ,, ,, of wrought iron;

$$\begin{aligned} \text{then } 1{\cdot}3\,x + 0{\cdot}05\,(50 - x) &= 50 \times 0{\cdot}7 \\ 1{\cdot}3\,x + 2{\cdot}5 - 0{\cdot}05\,x &= 35 \\ 1{\cdot}25\,x &= 32{\cdot}5 \\ x &= \frac{32{\cdot}5}{1{\cdot}25} = 26. \end{aligned}$$

That is, 26 lb. of converted bar and 50 − 26 = 24 lb. of wrought iron to yield a theoretical carbon content of 0·7 per cent.

An opposite form of crucible calculation is embodied in the following: It is assumed that 50 lb. of wrought iron, 6 oz. of ferro-manganese, and 10 oz. of charcoal are charged into a crucible and melted together. What will be the theoretical content of carbon, assuming each of the constituent materials to contain the following amounts of carbon?—

Wrought iron	0·05 per cent.
Ferro-manganese	7·00 ,,
Charcoal	87·5 ,,

The weight of the resulting ingot may be taken at $50\frac{1}{2}$ lb.

800 oz. wrought iron contain $\left(\frac{800 \times 0{\cdot}05}{100}\right) = 0{\cdot}40$ oz. carbon

6 „ ferro-manganese „ $\left(\frac{6 \times 7}{100}\right) = 0{\cdot}42$ „

10 „ charcoal $\left(\frac{10 \times 87{\cdot}5}{100}\right) = 8{\cdot}75$ „

Total weight of carbon $= 9{\cdot}57$ oz.

That is, the carbon distributed through the ingot weighs just over $9\frac{1}{2}$ oz. Calculating this into percentage as follows:—

$$\text{As } 808 : 100 :: 9{\cdot}57 : x$$
$$x = \frac{9{\cdot}57 \times 100}{808} = 1{\cdot}184,$$

which is the theoretical percentage of carbon in the ingot.

As a last example of crucible calculations, one in which the theoretical content of each element present in the resulting ingot is required may be taken. It is assumed that 38 lb. of mild-steel scrap, 12 lb. of white iron, and 4 oz. of ferro-manganese are melted together. The analyses of these materials are as follows:—

	Mild-steel Scrap.	White Iron.	Ferro-manganese.
Carbon	0·20	4·00	7·00
Silicon	0·01	0·10	0·90
Manganese	0·50	0·30	80·00
Sulphur	0·05	0·02	0·02
Phosphorus	0·05	0·03	0·25

The theoretical composition of the ingot is required, its weight being 50 lb. 38 lb. = 608 oz.; 12 lb. = 192 oz.; 50 lb. = 800 oz.

CARBON.

(1) $\frac{608 \times 0{\cdot}2}{100} = 1{\cdot}216$ oz. from scrap.

(2) $\frac{192 \times 4}{100} = 7{\cdot}680$ oz. „ white iron.

(3) $\frac{4 \times 7}{100} = 0{\cdot}280$ oz. „ ferro-manganese.

Total 9·176 oz. carbon.

$$\frac{9{\cdot}176 \times 100}{800} = 1{\cdot}147 \text{ per cent. carbon.}$$

SILICON.

(1) $\frac{608 \times 0{\cdot}01}{100} = 0{\cdot}0608$ oz. silicon from steel scrap.

(2) $\frac{192 \times 0{\cdot}1}{100} = 0{\cdot}1920$ oz. „ „ white iron.

(3) $\frac{4 \times 0{\cdot}9}{100} = 0{\cdot}0360$ oz. „ „ ferro-manganese.

Total 0·2888 oz. silicon.

$$\frac{0{\cdot}2888 \times 100}{800} = 0{\cdot}0361 \text{ per cent. silicon.}$$

MANGANESE.

(1) $\frac{608 \times 0{\cdot}5}{100} = 3{\cdot}040$ oz. manganese from steel scrap.

(2) $\frac{192 \times 0{\cdot}3}{100} = 0{\cdot}576$ oz. „ „ white iron.

(3) $\frac{4 \times 80}{100} = 3{\cdot}200$ oz. „ „ ferro-manganese.

Total 6·816 oz. manganese.

$$\frac{6{\cdot}816 \times 100}{800} = 0{\cdot}852 \text{ per cent. manganese.}$$

SULPHUR.

(1) $\frac{608 \times 0{\cdot}05}{100} = 0{\cdot}3040$ oz. sulphur from steel scrap.

(2) $\frac{192 \times 0{\cdot}02}{100} = 0{\cdot}0384$ oz. „ „ white iron.

(3) $\frac{4 \times 0{\cdot}02}{100} = 0{\cdot}0008$ oz. „ „ ferro-manganese.

Total 0·3432 oz. sulphur.

$$\frac{0{\cdot}3432 \times 100}{800} = 0{\cdot}0429 \text{ per cent. sulphur.}$$

PHOSPHORUS.

(1) $\frac{608 \times 0{\cdot}05}{100} = 0{\cdot}3040$ oz. phosphorus from steel scrap.

(2) $\frac{192 \times 0{\cdot}03}{100} = 0{\cdot}0576$ oz. „ „ white iron.

(3) $\frac{4 \times 0{\cdot}25}{100} = 0{\cdot}0100$ oz. „ „ ferro-manganese.

Total 0·3716 oz. phosphorus.

$$\frac{0{\cdot}3716 \times 100}{800} = 0{\cdot}0464 \text{ per cent. phosphorus.}$$

The crucible method of steel-making has been referred to as one of simple mixing and melting. However, slight chemical changes take place during melting, and the actual composition of the resultant ingot differs to some extent from the calculated composition of the charge. Taking the last example as an illustration of these changes, the following two analyses show respectively the one obtained by calculation and the one obtained by actual analysis, the difference being, of course, due to changes taking place during melting :—

	Calculated Composition.	Actual Analysis.	Loss.	Gain.
Carbon	1·147	1·147	—	—
Silicon	0·036	0·180	—	+0·144
Manganese	0·852	0·430	−0·422	—
Sulphur	0·042	0·060	—	+0·018
Phosphorus	0·046	0·046	—	—

In this table carbon has been taken as constant for the sake of simplicity. Any change in this element is due to the nature of the crucibles employed in melting. For instance, if the coke dust of the crucible is high, then the content of carbon in the steel will actually increase; on the other hand, with a low coke dust a slight decrease of carbon may result; and in other cases where the proportion of coke dust is such as to yield a slight amount of carbon to the metal, no change will occur. Therefore the carbon loss or gain must be determined in individual cases, for no definite rule can be given. The increase in the content of sulphur is due entirely to the quality of coke used. With a pure coke—that is, one containing from 0·6 to 0·8 per cent. sulphur, an increase of about 0·02 per cent. may be expected; but with higher contents of sulphur in the coke this figure is exceeded. Phosphorus as a rule remains stationary, and closely agrees with the calculated figure. Silicon increases from four to six times the amount originally present, and manganese decreases from 40 to 50 per cent. The increases of silicon is due to the "killing fire," which will be referred to later, and the loss of manganese may also be traced to the same source.

Melting.—On commencing operations the melting holes are cleared of clinker and a shovelful of live fire placed in each one. Two stands are placed on the firebars of each furnace, and on them the crucibles from the annealing grate are placed. The crucibles are covered by their lids, and the melting holes filled with coke to the level of the crucible lids; when fairly warm, the pots are sanded as already described. When the fires are well burnt up the crucibles are charged, a portion of the previously weighed charge being introduced to the crucible by sliding it down a funnel-shaped "charger." Firing is continued, and the remaining portions of the charges added. In from three and a half to four hours the contents of the crucible will be "clear melted." If drawn and poured at this stage the resulting ingot would be completely riddled with "blow-holes." To eliminate these blow-holes, or, in other words, the occluded gas which causes them, 4 or 5 oz. of ferro-manganese are added, and the steel "killed" or given another fire until it is "dead melted." The time of this firing varies, according to the temper of the steel, from twenty minutes to half or even three-quarters of an hour. The chemical reactions taking place during the killing fire are rather complicated, but they may be briefly described as follows: The manganese present throws silicon from the walls of the crucible into the steel, a joint reaction which appears to effectually expel the gases of the steel, leaving less to escape during solidification. Howe, in his "Metallurgy of Steel," does not hold this view, but argues that the absorption of silicon increases the solvent power of the steel for gas, thus enabling it to retain in solution, on solidification, the gas which it retains when molten. Practical experience, however, does not hold to this view, but rather to the one that the gases are expelled by the "killing fire." The necessity for the addition of manganese in the form of ferro-manganese is dispensed with if sufficient manganese is initially present in the materials charged. Ferro-manganese, as its name indicates, is an alloy of iron and manganese containing carbon. When the manganese is present in smaller quantity, the alloy is termed "spiegeleisen," or "spiegel." An analysis of an 80-per-cent. ferro-manganese has been already given. The following represents two further varieties of iron manganese alloys:—

	"Spiegel."	Medium Ferro-manganese.
Carbon	4·30	5·50
Manganese	15·00	50·00
Silicon	0·50	0·70
Sulphur	0·02	0·02
Phosphorus	0·25	0·25
Iron	79·93	43·53

The best results in crucible practice are attained by using the 80-per-cent. alloy. The presence of manganese in a steel tends to ensure the absence of oxygen. A steel containing oxygen in the form of ferrous oxide is known as a "dry ingot," owing to the fact that it will neither forge nor roll, but crumbles to pieces under such treatment.

The ingot moulds into which the steel is poured vary in shape according to the after-treatment of the ingot. Ingot moulds for crucible steel are of cast iron and made into two halves; previous to casting, the half-moulds are laid face down on a gantry and a pan of burning coal tar placed beneath. The pan is gradually moved from one end of the gantry to the other, in order to give an even deposit of fine soot on each mould. This process is termed "reeking," and the unconsumed carbon in the form of soot effectually prevents the ingots sticking to the moulds. Instead of "reeking," the moulds may be oiled, coated with fireclay cream or wet plumbago, and afterwards dried; but the first method is the one usually followed. After reeking, the two halves of the mould are placed together and fastened by means of rings and wedges. They are placed on end in a small casting pit or teeming hole at a slight inclination towards the teemer, in order that he may be able to strike the bottom first and not catch the sides of the mould with the stream of metal. The bottom of these teeming holes is formed of sand; in other words, an adjustable bottom which enables the ingot mould to be placed at a convenient height for teeming. When the steel is dead melted the crucibles are withdrawn by the puller-out, who passes them on to the teemer, removing the lid as soon as the latter grips the pot with his teeming tongs.

For ingots of more than normal weight the pots are doubled—that is, the contents of one pot are added to another before teeming the ingot. For still heavier ingots two "doubled" pots may be required, in which case two teemers are necessary, the second one following on just before the first has finished, in order that no break occurs in the stream of metal entering the mould. Before the development of the Bessemer and open-hearth processes of steel-making, heavy ingots were produced from the crucible furnaces by emptying the contents of as many crucibles as necessary into a ladle, from which the metal was delivered into the ingot mould, a practice, however, not largely followed at the present time.

Tool steels or steels of high temper are the usual product of the crucible process. Ingots of these steels contain at the top end a contraction cavity known as a "pipe." Before rolling or hammering down, the "piped" ends are broken off and returned as scrap to the furnaces. On the other hand, mild steels may actually rise in the moulds after teeming, to prevent which the usual practice is to insert a cast-iron stopper in the mould, and lying on the top of the metal. In other cases the space between the metal and the top of the mould is filled in with sand, a plate placed on the top, and held in position by means of wedges passing through two eyes cast in the moulds for this purpose.

CHAPTER XV

THE BESSEMER PROCESS

The Bessemer process of steel-making is, in comparison with the method last considered, essentially a chemical one, for, commencing with molten cast iron, an entirely distinct product is obtained at one operation. Essentially the process consists of blowing a large volume of compressed air through a bath of molten pig iron, the oxygen of the air combining with carbon, silicon, and manganese, to form oxides, which in the case of carbon are evolved as gases, whilst in the case of silicon and manganese slags are formed. Assuming the sulphur and phosphorus of the pig iron to be low, it will be seen that on removal of the carbon, silicon, and manganese, a product approaching wrought iron in composition is obtained. This oxidation of the impurities is accompanied by a considerable increase in temperature, an increase sufficient to maintain even dead mild steel in the fluid condition and permit of its being poured into ingot moulds. Bessemer originally described his invention as a method of producing wrought iron without fuel, but, as just shown, the fuel necessary to the operation is self-contained—that is, it is derived from the combustion of the carbon, silicon, and manganese. Of these three elements, by far the most important heat-producing one is silicon. As the sulphur and phosphorus are not removed, then evidently a pig iron initially low in these elements must be selected for conversion into steel; hence the use of Bessemer pig irons fairly free from phosphorus and sulphur.

The Process. — In selecting charges, an average content of 2·5 per cent. silicon gives the best results. With a content higher than this, the heats are likely to be "hot" and require scrapping, whilst with a lower one there is some danger of cold blows. The molten metal may be taken direct from the blast furnace, or from a mixer into which the metal from several furnaces is poured, thus ensuring more uniform charges; or the pig iron may be melted in a cupola furnace, tapped, and led by means of runners to the converter. Direct metal taken from a mixer is, however, the more usual and the most economical method. The converter consists of a mild-steel shell mounted on trunnions, supported on pedestals so that a semi-rotary motion may be given. It is lined with silica bricks or ganister, usually the latter, and the internal form is that of an arch in every position, familiarly known as a pear-shaped vessel. The tuyères are placed in the bottom of the vessel, and force the air vertically upwards through the charge. Below the tuyères is an air chamber receiving the blast from one of the trunnions, which is hollow and acts as a blast main. On the other trunnion the requisite turning gear is fixed. For convenience in lining or repairing, modern converters are constructed in three portions, known respectively as the bottom section (which contains the tuyères), the belly, and the nose. The various portions are bolted or keyed together, and may be readily removed for repairs. The detachable bottom is due to Holley, and as this portion of the converter receives the most wear and tear, its ready removal and replacement facilitates rapid and continuous working.

When ready for a molten charge, the vessel is turned on its axis into a horizontal position, and the requisite weight of metal poured in, care being taken that the level of the metal does not reach the tuyères whilst in this position. Blast is admitted, and the vessel returned to a vertical position, oxidation of the impurities commencing immediately. The pressure of the blast—from 20 to 25 lb. per square inch—prevents any metal entering the tuyères. The rising temperature, due to the oxidation of the silicon, gradually increases the size and luminosity of the flame. The violence of the reaction, as evidenced at first by showers of sparks, and later by splashes of slag, also increases, denoting a period known as the "boil." The flame then gradually subsides and eventually "drops," denoting an almost complete decarbonization of the metal in the converter. The drop of the flame is carefully looked for, and immediately it occurs the vessel is turned down and the blast shut off, any further blowing resulting in an oxidation or burning of the iron. The time occupied in blowing varies, according to the quality of the pig iron and depth of metal in the converter, from fourteen to twenty minutes. Assuming the original pig iron to contain 4 per cent. total carbon, 2·5 per cent. silicon, 0·4 per cent. manganese. 0·04 per cent. sulphur, and 0·04 per cent. phosphorus, then, after blowing and on the drop of the flame, the metal lying in the vessel will have approximately the following composition: carbon, 0·04 per cent.; silicon, 0·02 per cent.; manganese, trace; sulphur, 0·06 per cent.; and phosphorus, 0·06 per cent., thus showing a complete removal of carbon, silicon, and manganese, together with a slight increase in the amount of sulphur and phosphorus. The latter is due to concentration of the iron, sulphur, and phosphorus. As will be seen, such a material is exceedingly pure. It is, however, contaminated with more or less oxygen in the form of ferrous oxide, and if cast into ingots at this stage would result in a more or less "red-short" steel. In other words, the ingots on forging would work dry and tend to crumble to pieces under the hammer. Much of the early Bessemer steel was so affected, and the remedy was found in Mushet's conception of the addition of manganese to the oxygenated metal, an addition which removes the oxygen and results in a forgeable steel. Not only is the addition of manganese necessary, but a certain amount of carbon is also essential. The latter, of course, varies with the character of the steel desired, but the two necessary additions are made in the form of either ferro-manganese or spiegeleisen, the former for mild heats and the latter for hard ones. Analyses of both these materials having been given, it is only necessary to add that the ferro is added in the solid, though red-hot, condition, whilst the spiegel is added in the molten condition, it being usually melted in a small auxiliary cupola.

After this addition the contents of the converter are emptied into a casting ladle, which is rotated over a series of ingot moulds for casting. On solidification the ingots are stripped and taken to the soaking pits, subsequently passing to mill or forge.

The following analyses show the changes occurring during the conversion of the pig iron into finished steel:—

DETAILS OF AN ACID BESSEMER SPRING STEEL HEAT.

Material.	Combined Carbon.	Graphite.	Silicon.	Manganese.	Sulphur.	Phosphorus.	Iron.
Pig iron	0·46	3·42	2·54	0·47	0·04	0·05	93·12
Cupola metal ...	0·47	3·38	2·26	0·45	0·06	0·05	93·33
Blown 5 minutes ...	3·02	—	1·67	0·13	0·07	0·06	95·05
Blown 10 minutes ...	0·98	—	0·26	0·04	0·07	0·06	98·59
Blown 15 minutes ...	0·04	—	0·03	—	0·07	0·06	99·8
Finished steel ...	0·53	—	0·08	1·08	0·06	0·07	98·18

The foregoing constitutes a brief outline of what is known as the acid Bessemer process, so termed owing to its being conducted in a converter lined with an acid material (ganister). This method does not eliminate phosphorus; in fact, as indicated, a slight increase takes place, due to concentration, and therefore phosphoric pig irons are inadmissible.

The Basic Process.—The acid or highly siliceous character of the slag formed in the foregoing process precludes any removal of phosphorus during the blow, and, naturally, a basic slag essential to this removal cannot be formed in an acid-lined vessel, owing to the action of the slag on the lining. The chief difference between an acid and basic process is therefore found in the linings of the converters. The latter must be of either a neutral or basic character in order that the basic additions shall not unduly attack it. The usual lining is burnt dolomite, mixed with anhydrous tar, and rammed around a wooden model having the internal form of the vessel. The bottom section is formed by ramming the dolomite on the perforated bottom plate, through which the required number of tapered pins are inserted, and which on removal form the tuyères. The converter and bottom section are dried and heated as usual previous to blowing.

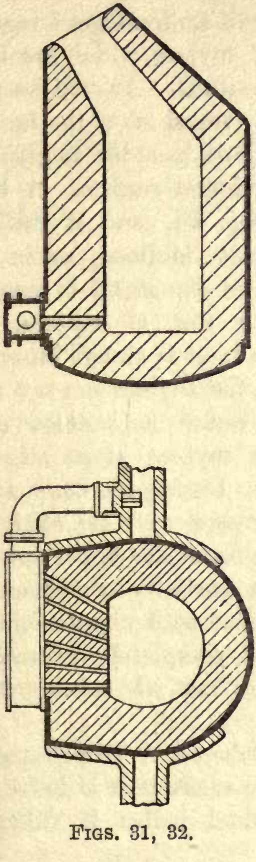
This process was originated by Messrs. Thomas and Gilchrist, and apart from the difference in linings and addition of lime during the blow, the method is very similar to the acid process. The usual casting, stripping, and soaking arrangements are adopted. A much larger quantity of slag is produced, which, owing to its content of phosphorus, possesses a certain agricultural value. This slag is removed by pouring from the converter into iron bogies running on rails, and is subsequently taken to the crushing house for pulverizing into a form suitable for use as a fertilizer.

The Blow.—About 3½ cwt. of lime per ton of metal to be blown is added to the hot converter, the molten charge of pig iron introduced, the blast admitted, and the converter rotated into the vertical position. The deoxidizing action of the blast is similar to the acid blow, the phosphorus not being removed until the flame drops, indicating the elimination of carbon. Hence blowing is continued a few minutes further during a period known as the "after blow," in which the phosphorus is removed. There are no visible indications when this stage is complete; hence samples are taken by turning the converter down, withdrawing a small ladle of metal, and casting it in an iron chill. This bar is then forged down to about half an inch thick, quenched and broken, its fracture indicating whether the phosphorus removal has been carried sufficiently far. A large crystalline fracture indicates the presence of phosphorus, whilst a fine granular one denotes a low content of phosphorus. In the event of the former, further additions of lime are made to the converter and the blow continued. This test is, of course, rapidly conducted, and an experienced operator readily judges by the fracture whether the blow has been carried far enough, or if it is necessary to carry it further. Assuming the elimination of phosphorus sufficient, the slag is poured off as completely as possible, the ferro-manganese added, and the steel poured into the casting ladle.

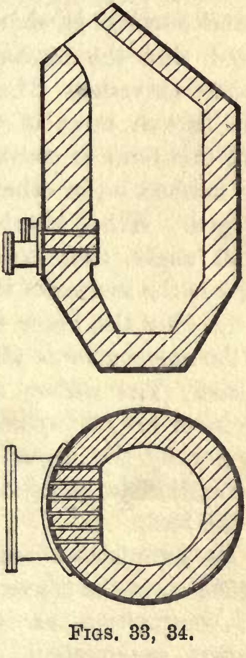
The pig iron used, known as basic pig, should not be high in silicon. An average content is 1 per cent., whilst the phosphorus varies from 2 to 3 per cent. with a fairly low sulphur. Such a pig iron, after treatment, will yield a steel containing approximately 0·06 per cent. phosphorus and any desired carbon, though usually basic steels are of the mild or soft variety.

Modifications of the Bessemer Converter.—Bessemer, in his original experiments, tried every possible method of blowing molten pig iron in order to obtain a decarburized metal. From these experiments with vessels of various forms, and with tuyères fixed in every possible position or angle, he evolved the process of bottom blowing as followed to-day. Departures from this process have not, as a rule, proved successful when followed for the production of ingots. However, in one field—that of steel castings—certain modifications of the process have met with success, more especially in the case where very fluid steel is required for light castings. In ordinary foundry practice better results are obtained when small amounts of hot metal are obtained at frequent intervals than are to be had from large amounts obtained at long intervals. Hence the success of the small or "Baby" converter in foundry practice. Apart, however, from the convenience of a regular supply at short intervals, the steel may be obtained exceedingly hot; indeed, by suitable manipulation it may be obtained far hotter, and therefore more fluid, than either crucible or open-hearth steel. This high initial temperature also permits of the steel being cast from small ladles or shanks, as in the case of cast iron. Of these small converters, the most successful are the Robert and Tropenas, both of which are "side blown," this success referring, of course, solely to foundry practice, and not to the production of ingots.

The Robert Converter is illustrated in Figs. 31 and 32, representing respectively vertical and horizontal sections. The back of the vessel is flattened, giving a D-shaped section, and here the tuyères are placed horizontally, but inclined to the radial, as shown. As a rule the surface of the metal lies near the tuyère level, but this may be adjusted by inclining the vessel either to or from the tuyères. Blast at a pressure of from 3 to 4 lb. per square inch, regulated by means of a valve or the inclination of the vessel, is admitted through the tuyères and impinges on the surface of the metal, or but slightly below it. Whilst blowing, a rotary motion is imparted to the vessel by the inclination of the tuyères. The surface of the metal is approximately the tuyère level; in certain cases it may be higher, but seldom exceeds a height of 3 or 4 in. above the tuyères. This high tuyère level permits some of the air to escape unconsumed, and



FIGS. 31, 32.



FIGS. 33, 34.

burn on the surface of the bath the carbon monoxide formed in the bath by the oxidation of the carbon. This combustion of carbon monoxide to carbon dioxide gives rise to considerable heat, which is absorbed by the bath, and it is to this reaction that the higher temperature of any variety of side-blown metal is due.

The Tropenas Converter differs from the foregoing in that it has a double row of tuyères, which are horizontal when the converter is vertical. As will be seen from Fig. 33, the bottom of the vessel takes the form of a truncated cone, and is so designed in order to give the maximum depth with the maximum surface. A horizontal section is shown in Fig. 34, and it will be noted that the tuyères are not inclined, as in the Robert converter. The surface of the metal is usually the bottom edge of the lower row of tuyères, and with this form of converter the blast is always blown on the surface, or, in other words, the tuyères are not submerged. When blowing, the vessel is inclined at a small angle, thus making the tuyères slope slightly towards the surface of the bath. During the early stage of the blow the lower row of tuyères only are used, but on the appearance of the carbon flame the upper row are opened. The carbon monoxide partially consumed by the lower row of tuyères is supplied with supplementary oxygen by the upper row, and completely burned to carbon dioxide, generating further heat, which is absorbed by the bath.

Recarbonization with both Robert and Tropenas steel is effected in the converter if the entire heat is desired of one composition, or in individual ladles if different qualities are required.

The chemical changes taking place in a two-ton Tropenas converter are given in the following table:—[1]

---

[1] A. Simonson, *The Foundry*, July, 1903.

	Cupola Metal.	After 5 Minutes' Blowing.	After 12 Minutes' Blowing.	After 14 Minutes' Blowing.	After 18 Minutes' Blowing.	End of Blow.	Finished Metal.
Graphite	3·180	2·920	—	—	—	—	—
Combined carbon	0·350	0·340	2·900	2·300	0·860	0·100	0·240
Silicon	2·310	1·620	0·466	0·382	0·084	0·074	0·326
Sulphur	0·037	0·037	0·035	0·036	0·038	0·038	0·037
Phosphorus	0·054	0·053	0·054	0·054	0·051	0·050	0·058
Manganese	0·610	0·600	0·101	0·040	0·040	0·042	1·080

CHAPTER XVI

THE OPEN-HEARTH PROCESS

THIS process, like the Bessemer, is based on the oxidation of the impurities of pig iron, the necessary oxygen being added in the form of iron ore to a bath of molten pig iron. The method is slow, occupying from seven to twelve hours per charge, as against twelve to twenty minutes per blow of the Bessemer converter. On the other hand, much larger weights can be manipulated per charge, and the quality of the final product is decidedly higher. The process is fairly elastic, admitting of a wide variety of product from the mildest to the hardest of steels, whilst the capacities of the furnaces vary from 2 to 50 tons, certain special types exceeding this latter weight. To Martin is due the idea of producing steel by the fusion of pig iron in admixture with steel or wrought-iron scrap in an open sand basin. In the early Siemens process, pig iron and ore alone were used, hence a combination of the two methods became known as the Siemens-Martin process. The system of regeneration introduced by Sir William Siemens is described on p. 57, and the exceedingly high temperature attainable in the Siemens furnace is due entirely to this preheating of gas and air. The fuel employed is generally known as "producer gas," and is generated by the incomplete combustion of coal. Gas producers vary in design, modern tendencies leading towards mechanical feeding and poking and the recovery of by-products before the gases are burnt in the furnace. Gaseous fuels are treated in Chapter II., and the analyses there given of Siemens and Wilson gases may be taken as typical of the general run of producer gases. It may be added that one ton of coal will generate from 150,000 to 160,000 cub. ft. of gas at ordinary pressure and temperature.

The Furnace.—The body of the furnace is a rectangular structure, cased in mild-steel plate, and braced together by tie rods. These tie rods may be provided with springs to take up the expansion, or if springs are not fitted the nuts may be eased as the furnace heats up. The internal portions of the furnace must be of the best silica brick, in order to successfully meet the high temperature, and also to withstand the cutting action of the flames. The various parts of the furnace may be considered separately as follows:—

The Hearth.—A shallow rectangular trough, the sides of which are known as the banks. The hearth of an acid furnace is formed first by two or more courses of silica bricks on the bottom plates, the sides being "stepped" to follow the required contour of the banks. On these bricks thin layers of silica sand are gradually fritted until the requisite thickness is obtained. When complete, every portion of the hearth should drain to the tap hole.

The Roof in the earlier types of furnaces was designed to deflect the flame on to the hearth below, somewhat after the fashion of the ordinary reverberatory furnace.

These conditions, however, were too severe on the bricks of the roof, and later-day furnaces are all built with comparatively high roofs, the necessary slight deflection of the flame being obtained by the inclination of the ports.

The Ports for admitting air and gas vary considerably in design. Their purpose is to ensure a suitable mixing of air and gas in the furnace, leading to complete combustion of the gas. Present practice appears to favour the air entering above the gas with the ports at a slight inclination, so that air and gas mix just above the level of the hearth. Other designs are found in furnaces having gas and air ports side by side; one gas port with an air port on either side; or two gas ports on one level, with two air ports near the roof.

The Regenerators.—For each furnace two sets of regenerators are provided—that is, two for gas and two for air. According to the direction of the current, one pair are used for heating the gas and air previous to their combustion on the hearth, whilst the products of combustion are drawn through the other pair. The regenerator chambers are formed of chequer brickwork, so arranged as to present the largest possible surface for, on one hand, absorbing heat and, on the other, imparting heat. The success of the furnace as an economical steelmaker is determined by the efficiency of the regenerators: they should have ample cross section, so as to permit of a low velocity, thereby giving sufficient time for (*a*) heat absorption, or (*b*) heat transference. Further, their design should be such that the current does not find a free or short path, but is broken by the chequer work in all directions. As a rule, the air regenerator is of larger capacity than the gas one, in order that the air will enter the furnace at a higher temperature than the gas. With regard to actual capacities, the following statements are of interest:—

"Siemens estimated that the chequer brickwork in one air and one gas chamber should weigh sixteen or seventeen times as much as the fuel burned between reversals. Grüner states that the weight of one gas and one air chamber should be 50 kilos. of brick for each kilogramme of coal burned in the producer between any two reversals. In practice, he found regenerators to vary from 59 to 103 cub. ft. for 100 lb. of coal gasified per hour. Ledebur considers that in practice the contents of one air and one gas chamber vary from 56 to 130 cub. ft. per 100 lb. of coal gasified per hour. Campbell states that the contents of one air and one gas chamber should be at least 50 cub. ft. per ton of metal in the furnace, while double this amount is better."[1]

From the foregoing it will be seen that in order to attain the best results the capacities of the regenerators should err on the larger rather than the smaller side.

Dust Pockets.—The products of combustion on leaving the furnace carry with them certain amounts of dust, particles of slag, and so forth, which if carried on to the regenerators are liable to be deposited in the spaces of the chequer work, thereby reducing their efficiency. This dust may be trapped by means of a chamber placed between the ports and the regenerators.

Stack.—Each furnace is provided with its own stack, the internal area of which is of importance, and according

---

[1] Hess, "Proportions of Regenerative Gas Furnaces," *Proceedings of the Engineers' Club of Philadelphia*, vol. xxi., No. 1.

to Hess[1] the height should rarely exceed from 100 to 130 ft. The same authority also states: "The burning of 100 lb. of coal in the producer will give 36,500 cub. ft. of stack gases at 760 millimetres pressure and 522° F., the gas burning with 20 per cent. excess of air. Both Toldt and Ledebur recommend an average velocity of the stack gases of about 16½ ft. per second. This would require 0·6 sq. ft. for each 100 lb. of coal burned per hour. A stack section of 0·9 sq. ft. for each 100 lb. of coal per hour would correspond to a velocity of 11 ft. per second in the stack gases."

Valves.—The valves for controlling the furnace are of two types, "inlet" and "reversing." The inlet valves

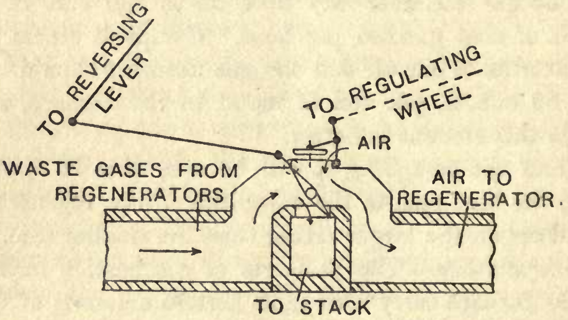


FIG. 35.

are usually of the mushroom pattern, one each for gas and air. Reversing valves—of which there are also two, one for gas and one for air—are used for changing the direction of the current through the furnace. The purpose of these valves may be illustrated roughly by means of the accompanying diagrams. Thus Fig. 35 represents the air

---

[1] "Proportions of Regenerative Gas Furnaces."

admission and air reversing valve, and, as shown by the position of the latter, the products of combustion from one set of regenerators on the left are passing into the flue leading to the stack. It will also be noted that the air for preheating is passing through the flue on the right to the air regenerator. By changing over the reversing lever the direction of the current is reversed. Thus Fig. 36 represents the gas admission and gas reversing valve, the latter fixed in the opposite position from that of Fig. 35 in order to illustrate the change of direction.

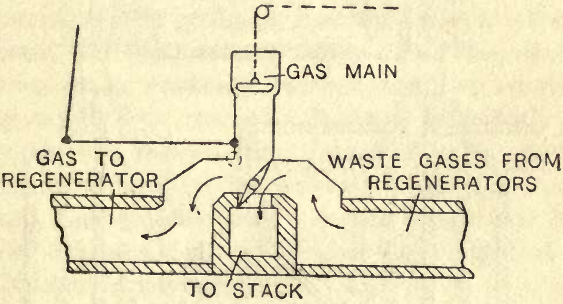


FIG. 36.

Summary.—From the foregoing description of the various parts of the furnace the action of the whole will be readily seen. A typical open-hearth furnace, with its regenerators, flues, and valves, is sectionally shown in Fig. 37. The stack flue A draws the products of combustion from the two regenerators on the right, as shown by the position of the reversing valves B and C. The gas and air pass through their respective flues and regenerators on the left, meeting at the ports and burning on the hearth. On changing over the reversing valves B and C, the direction of the gas and air is reversed, and both pass through the regenerator chambers, which have been previously heated by the waste gases. In practice, reversing is effected at intervals of half an hour, and by thus alternating the direction of gas and air with the waste gases from the hearth, the regenerators alternately serve to impart heat to the ingoing current, and abstract it from the outcoming one.

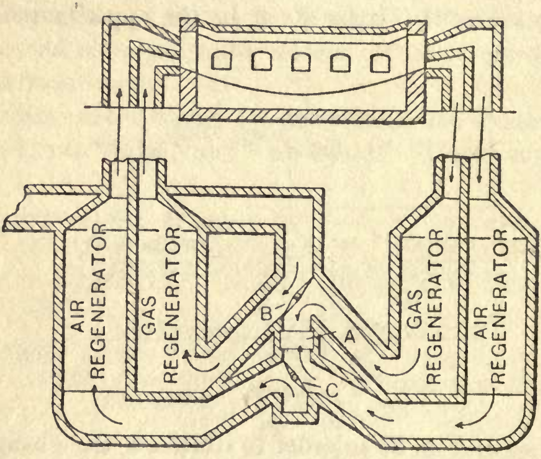


Fig. 37.

In starting a new furnace every portion must be thoroughly dry before any gas enters. This preliminary drying is effected by means of coal fires in the hearth, all valves being open to allow the escaping heat to pass through the flues and four regenerator chambers. Efficient drying will take a week or longer, according to the size of the furnace. When dry, the next step is to sweep all air from the flues, which may be effected by passing gas from the producer and allowing it to escape from the last manhole in the flue. After escaping in this fashion for some time the gas is tested, and if it burns steadily for some minutes it is then ready for passing into the furnace. Previous to sweeping the air from the flues, fires are made on the hearth near the gas ports, which serve to ignite the gas when admitted into the furnace. Combustion is allowed to proceed slowly at first, in order to gradually heat the furnace. The first reversals are comparatively long ones, the reversing intervals being gradually reduced until an interval of thirty minutes is reached. When a sufficiently high temperature is reached, thin layers of silica sand are evenly distributed on the bricks to form the working hearth. The surface of each layer is fritted over before another one is added, and the hearth in its final form should drain to the tap hole.

Outline of the Siemens Acid Process.—The hearth of the furnace having been formed to the required contour by fritting successive layers of silica sand, as recently described, a further preliminary before actual steelmaking is found in the "pig wash." The tap hole is carefully made up, the furnace brought up to a melting heat, and a small charge of pig iron spread on the banks of the furnace. When melted, the iron is well rabbled over the sand bottom, in order to harden it and bring it into condition for steel melting. No attempt at a carbon or silicon removal is made; the pig wash is simply a mechanical and preliminary process to steelmaking. When the rabbling is judged complete, the metal is tapped, cast, and returned to the furnace in subsequent charges.

Pig iron used in the acid process has been already dealt with; the chief essential is that both sulphur and phosphorus be fairly low. The charges vary according to circumstances, but may be usually taken as two-thirds of pig iron and one-third of scrap steel. After charging, the first stage of the process is naturally the melting one, and will take, as a rule, about three hours. During melting a slight oxidation of carbon and silicon will take place; when the bath has gathered sufficient heat, or the iron is clear melted, it is gradually brought to the boil by additions of iron ore. Additions of iron ore are cautiously continued until the surface of the bath resembles a boiling fluid, a stage marking the reaction of the oxygen of the iron ore on the carbon of the molten metal. This action may be expressed as follows:—

$$3C + Fe_2O_3 = 3CO + 2Fe;$$

or three parts of carbon combine with one part of ferric oxide to form three parts of carbon monoxide and two parts of iron. It will thus be seen that the purpose of the iron ore added is to maintain the slag in such a condition as regards its content of oxide of iron that it will act vigorously on the metal below, removing from it carbon, silicon, and manganese. This removal is shown in the following table representing the history of a typical acid open-hearth heat:—

	Carbon.	Silicon.	Manganese.	Sulphur.	Phosphorus.
Analysis of charge ...	2·90	1·90	0·60	0·04	0·05
Melted metal 3 hours after charging... ...	2·50	1·10	0·25	0·04	0·05
1 hour after melting ...	1·87	0·30	none	0·04	0·05
2 hours ,, ...	1·48	0·10	none	0·04	0·06
3 ,, ,, ...	0·81	0·05	none	0·05	0·06
4 ,, ,, ...	0·56	0·04	none	0·05	0·06
5 ,, ,, ...	0·39	0·03	none	0·05	0·06
6 ,, ,, ...	0·13	0·01	none	0·06	0·06
Finished steel	0·20	0·02	0·56	0·06	0·06

The steady fall in carbon will be noted—a fall which can be arrested at any desired point, thus permitting the manufacture of a range of steels from the hardest to the softest. When making the latter type the usual plan is to drop the carbon as rapidly as possible. Limitations to speed are found in the fact that a too violent boiling ejects metal from the furnace, and that a too rapid addition of ore lowers the temperature of the bath below working conditions. Within these limits the bath is maintained at a brisk boil, and when the carbon is reaching the vicinity 0·2 per cent., spoon samples are taken. This sample is chilled in water to a red heat only, and then allowed to cool in air. The fracture of this sample indicates to a trained eye the approximate content of carbon, and the further conduct of the bath is decided. Instead of judging the fracture, the sample may be drilled and the carbon estimated by the colour test, a method accurately performed in fifteen minutes or less. The latter is the more general plan, and certainly the better one.

It will have been noted from the analyses in the table that while manganese is removed early in the process, the finished steel contains 0·56 per cent. of this element. The open-hearth process, like the Bessemer, is an oxidizing one, and during the operation oxygen is absorbed by the metal. This oxygen must be removed before a satisfactory steel can be produced, and, as in the Bessemer process, its removal is effected by the addition of manganese in the form of either spiegel or ferro-manganese. It is usual in open-hearth practice to add sufficient ferro-manganese to equal an addition of 1 per cent. manganese on the charge. Of this manganese added, from 40 to 50 per cent. is lost by oxidation. To save oxidation losses the ferro is often added to the ladle on tapping the steel; however, by far the better plan is to add it in the furnace previous to tapping. This method gives an opportunity for thoroughly rabbling the bath before tapping, and ensures a more effective removal of oxygen.

No matter when the ferro is added, it introduces to the steel a certain amount of carbon, which may be calculated from the analysis of the ferro and the weight added. Evidently, then, in working for an exact carbon content in the finished steel, the carbon of the bath must be lowered sufficiently to allow for that added by the ferro-manganese. Further, the carbon indicated by the sample represents conditions existing when the sample was taken. Thus, if the rate of fall in carbon per hour is 0·2 per cent., and 15 minutes have elapsed since the sample was taken, then the carbon in the bath will be 0·05 per cent. lower than that registered by the sample. Therefore, in working for exact contents of carbon, two allowances are necessarily made: (1) for the carbon added by the ferro-manganese, and (2) for the time occurring between the determination of the carbon and the time of sampling—features which in practice offer no difficulty. When working for mild steels there is no danger of running the carbon too low, but with harder heats such as spring steel, the carbon may be dropped lower than required. An accident of this kind does not often occur, but if it does it may be readily rectified by adding more carbon in the form of pig iron—a process known as "pigging back." An excess of the actual carbon required is added in order to give the bath time to recover the chilling influence of the cold addition. Samples are taken as usual and the bath caught at the desired point.

As shown in the table, silicon is removed comparatively early in the oxidation process, and in normal practice there is no return of silicon to the bath. Occasionally, however, silicon in the finished steel may be higher than required or expected—a feature at one time thought to be due to a "sand boil;" in other words, a detachment of some portion of the bottom or banks, and a corresponding reduction of the silica to silicon which passes into the steel. The researches of Messrs. McWilliam and Hatfield have, however, completely cleared this point.[1] Their observations on many heats, in which a wide variety of carbon contents were made, show that silicon can vary irrespective of the condition of banks and bottom. Thus the following tables show variations with the bed in bad and good conditions respectively :—

---

[1] *Journal of the Iron and Steel Institute*, No. 1, 1902.

TABLE I.—BOTTOM AND BANKS OF FURNACE IN BAD CONDITION.

No. of Charge.	Carbon.	Silicon.
1	0·65	0·12
2	0·26	0·06
3	0·55	0·08
4	0·53	0·15
5	0·36	0·15
6	0·36	0·06

TABLE II.—BOTTOM AND BANKS OF FURNACE IN GOOD CONDITION.

No. of Charge.	Carbon.	Silicon.
7	0·68	0·16
8	0·25	0·12
9	0·47	0·26
10	0·36	0·14
11	0·33	0·14
12	0·22	0·08

These results, selected from a large number of charges, show that the silicon varies irrespective of the carbon or the condition of the furnace. Messrs. McWilliam and Hatfield found, however, that the source of the variation lay in the condition and composition of the slag. It was found that steels finishing with thin slags were always low in silicon, and those with thick ones were high in silicon. This condition of slag could be varied at will, until with practice the percentage of silicon in the finished steel could be approximately estimated from the condition of the slag at the end of the heat. The content of silica in a thin slag was found to be about 51 per cent., in a medium one about 54 per cent., and in a thick slag resulting in steels correspondingly high in silicon about 57 per cent. The fluidity of the slag is not in itself the cause of the more complete elimination of the silicon, as the slags in several cases were made more fluid with other bases, in order to leave the silicon at the point called high, and the silicons in the steels were invariably high. The fluidity of the slag is therefore only taken as a measure of its basicity when the bases in different slags are fairly parallel. These features are shown in the following table of results:—

Slag.			Finished Steel.	
Ferrous Oxide.	Ferric Oxide.	Silica.	Carbon.	Silicon.
18·6	5·2	55·8	0·36	0·14
26·3	1·6	51·6	0·28	0·06
21·7	4·2	53·6	0·29	0·10
19·9	trace	57·2	0·22	0·23
21·2	trace	53·6	0·29	0·08

The authors' results, showing that the percentages of silicon in the steel increase when the slag contains more than a certain amount of silica, would indicate the reduction from the slag of a silicate of manganese—a feature receiving confirmation from the fact that an increase in silicon is associated with a rise in manganese.

Sulphur and phosphorus are not removed in the acid process; as a matter of fact, these elements increase slightly by concentration. On the charge there is a loss owing to the removal of carbon and silicon—a loss which to some extent is compensated for by the iron reduced from the ore entering the bath. Hence, of the materials charged into the furnace, a yield of ingots equal to 95 per cent. is usually obtained. These figures represent ordinary practice; in some cases it is exceeded and higher yields obtained.

The Basic Open-hearth Process.—Generally speaking, this method is not suitable for the production of high or medium carbon steels, owing to the fact that it is almost impossible to effect a removal of the phosphorus before the carbon. Hence the bath cannot be stopped at any desired carbon content, for if this content is fairly high there is a danger of considerable phosphorus remaining in the steel. From a consideration of the acid process the thought will naturally occur, why not remove the carbon and with it the phosphorus, and then recarburize to the desired extent by means of pig iron or other carbonaceous material? To this idea a limitation is found in the fact that carbon added to a bath in the presence of basic slag reduces the phosphoric acid of the slag, and the released phosphorus again enters the steel. Recarburization must therefore be effected outside the furnace, a method which, if attempted in the ladle, does not always yield a uniform and satisfactory product. The ordinary basic process is therefore more adaptable for the production of mild steel such as boiler plate, etc., from phosphoric pig iron. On the Continent large quantities of so-called ingot iron are produced by it.

The process is fairly similar to the acid one, the chief difference being found in the lining of the furnace, which must consist of a basic material. Owing to the friability of basic bricks the furnace cannot be built entirely of them, hence it is usual to build the sides and roof of ordinary acid (silica) brick. As a matter of fact, the first course of the hearth is laid with silica brick in order to get a firm acid foundation on which to build the side walls. Owing to the fusibility of a basic and acid material when in contact at high temperatures it is found advisable to have a layer of neutral material between them, such a neutral substance being found in chromite or chrome iron ore. The hearth may be built in of basic brick, or it may be rammed to the requisite contour with basic material mixed with tar, and afterwards hardened and glazed by heat. A more suitable method is to ram a thin layer of the basic material—burnt dolomite, for instance, mixed with anhydrous tar,—and harden this by heat. When this is effected, successive thin layers are spread over the bottom and banks, each layer being fritted by heat before the addition of a further one, until the required thickness and contour are obtained.

To maintain the slag in as basic a condition as possible, lime is added at intervals during the working down of the charge. Before charging, a mixture of lime and iron ore is spread on the bottom, and a few shovelfuls distributed amongst the charge. When melted and on the boil these additions are regulated by the condition of the bath. Whilst it is necessary to have a basic slag, if too much lime is added the slag becomes pasty and unworkable. When reaching the end of the process samples are taken as usual, and the amounts of carbon and phosphorus estimated by fracture or rapid analytical tests. When the removal is judged complete the bath is tapped, and the requisite ferro-manganese added to the ladle. As in the case of carbon, the addition of ferro to the bath in the presence of the basic slag tends to return the phosphorus to the steel.

Modifications of the Open-hearth Process.—Many modifications of the process have been proposed, those of most moment relating to an increase of the output by the use of molten pig iron direct from the blast furnace or mixer. Of these, the process introduced by Mr. Benjamin Talbot is probably the most noteworthy. Mr. Talbot described his method very fully in a paper read at the spring meeting of the Iron and Steel Institute in 1900. Later, in 1902, before the same institute, details as to the development of the process were given. An outline of the process was also given before the Engineering Conference[1] in June, 1903, from which the following notes are taken. The method known as the continuous process derives its name from the fact that the furnace is worked continuously during an entire week without completely emptying it. The process is most conveniently worked in a tilting furnace of large dimensions, and owing to the continuous heat a basic lining is preferable. In practical working the process is carried out as follows: On Sunday evening the furnace is charged with a mixture of scrap and solid pig iron, or partly solid and partly molten pig iron. This "filling charge" is worked down in the usual way until a bath of finished steel is obtained, which, in a furnace of 75 or 100 tons' capacity, will take about twelve hours. When ready for tapping the furnace is tilted and a definite part of the charge run into a steel ladle, the necessary ferro additions being made to the ladle as the steel runs in.

---

[1] Section IV., "Engineering Conference," *Proceedings of the Institution of Civil Engineers*, vol. cliv.

This steel is cast into ingots and the furnace turned back into the upright position. A certain amount of lime and oxide of iron is added to form slag with which to oxidize the metalloids of the incoming molten pig metal. After these additions are incorporated with slag, a further addition of molten pig iron is made to the steel remaining in the furnace. The reaction between the slag covering of the bath and the molten metal introduces results in the rapid oxidation of the metalloids. Silicon, carbon, and phosphorus are quickly removed, although it may be noted that when the silicon is high the carbon removal is not effected so quickly; hence it is preferred that the pig iron added should be low in silicon. The combustion of the carbon in the form of carbonic oxide materially diminishes the amount of fuel per ton of steel, and the removal of the metalloids by the oxides contained in the ferruginous slag results in the precipitation of iron into the bath, thereby increasing the yield of steel.

After the first reaction has subsided, the bath is sampled and worked down until it again represents finished steel. Another definite amount is then cast, and the process continued through the week. At the week-end the furnace is emptied at short intervals and any necessary repairs made. The weekly output varies with the size of the furnace and the quality of the pig metal used. In the States a 200-ton furnace, working hematite iron, has yielded 1400 tons of steel in the week. At Pencoyd, using a 70-ton furnace, more than 750 tons of steel have been made in a week from pig iron containing 0·8 per cent. phosphorus. At Frodingham (Lincolnshire), with a furnace of 100 tons' capacity, more than

600 tons of steel have been obtained in the week, using pig iron containing nearly 2 per cent. phosphorus.

The continuous process may be worked in fixed furnaces provided arrangements are made to draw off a portion of the charge only—leaving in the furnace a bath of finished steel, to which molten pig metal may be added. This involves two tapholes at different levels, one of which will when required drain the furnace, whilst the second or working taphole is so placed as to draw off a part only of the bath. The process is exactly the same as when tilting furnaces are used, except that a fixed furnace necessarily involves "tapping," and the two tapholes may in practice give rise to difficulties not met with in the case of tilting furnaces.

The following figures, extracted from a paper by Surzycki,[1] show results obtained from a 25-ton fixed furnace worked by the Talbot method.

CONSUMED.		
Cold pig iron	140·80	tons
Molten pig iron	1809·50	,,
Ferro-manganese	20·9	,,
Scrap	19·8	,,
Iron ore (Krivoi Rog)	458·1	,,
Lime	144·3	,,
Aluminium	0·08	,,
Burnt dolomite	107·7	,,
Chrome ore	2·0	,,

PRODUCED.		
Good ingots	2003·7	tons
Scrap	41·8	,,

Working days, 26.
Production per day, 77·07 tons.
Yield, 107·72 per cent.

The Bertrand Thiel process involves the use of two open-hearth furnaces. In one, the "primary" furnace, phosphoric pig iron is melted and given a preliminary treatment with oxides and limestone, in order to remove as much as possible of the silicon and phosphorus before

---

[1] *Journal of the Iron and Steel Institute*, No. 1, 1905.

finishing in the secondary furnace. In this furnace suitable proportions of steel scrap, iron ore, and lime are charged and raised to a high temperature. The partly refined metal from the primary is introduced into the secondary, and a vigorous reaction between the highly heated ore, lime, and fluid metal follows. If the primary furnace is on a higher level than the secondary its contents may be tapped and led down a runner, but if both furnaces are on the same level, transfer is effected by means of a ladle. In any case care is taken to prevent slag from the primary entering the secondary furnace. Messrs. Darby and Hatton have in a recent paper reviewed the later developments of this process. As originally worked by Bertrand, six to seven 20-ton charges of soft steel per 24 hours were considered good practice for a pair of furnaces. At Brymbo, with a more highly phosphoric pig, seven similar charges per day, during a week's working have been attained; whilst at the Hoesch Works in Dortmund ten charges have been regularly produced per day. The following return (p. 218) by Mr. Springorum represents a week's operation at the latter works.[1]

In the case of two works employing this process and working on high phosphoric pig, it was found advisable to employ a gas-heated tipping mixer, in which the blast furnace metal is collected and retained for use as required. In the mixer some desulphurization takes place and the percentage of silicon is reduced. Figures given show the silicon to be reduced from 0·654 per cent. to 0·473 per cent., whilst sulphur falls from 0·076 per cent. to 0·040 per cent. The mixer is a costly piece of apparatus,

---

[1] *Journal of the Iron and Steel Institute*, No. 1, 1905.

WEEK ENDING APRIL 8, 1905. 61 CHARGES. 1147 TONS, 6 CWTS. INGOTS PRODUCED. YIELD, 104·5 PER CENT.

1905.	Number of Furnaces.	Number of Charges.	Composition of Charges.												Production.					Consumption of Iron Ore, etc., per Metric Ton of good Steel.					
															Good Material.										
			Molten Thomas Pig Metal.		Ferro-Manganese.		Ferro-Silicon and Spiegeleisen.		Light and Plate Scrap.		Broken Moulds.		Total.		Per 24 Hours.		Per cent. of Metals Charged.	Weight of Charge.		Swedish Iron Ore.	Mill Scale	Lime.	Limestone.	Gas Producer Coal.	Basic Material.
April.			T.	C.	T.	C.	T.	C.	T.	C.	T.	C.	T.	C.	T.	C.		T.	C.	C.	C.	C.	C.	C.	C.
3	2	10	143	19	2	8	1	14	29	18	...	...	177	19	186	2	104·53	18	12	3·74	1·26	1·88	0·86	5·00	1·08
4	2	11	158	1	2	11	1	6	30	6	...	...	192	4	200	17	104·50	18	5	3·48	1·18	1·86	0·86	4·64	1·10
5	2	10	143	4	2	10	1	6	34	18	2	8	184	6	192	10	104·48	19	5	3·58	0·88	1·76	0·84	4·84	1·04
6	2	10	145	4	2	10	2	13	34	12	...	...	184	19	193	6	104·52	19	6	3·40	1·14	1·76	0·82	4·82	1·04
7	2	10	144	12	2	10	4	4	25	18	...	8	177	12	185	12	104·50	18	11	3·98	1·26	1·84	0·82	5·02	1·08
8	2	10	143	15	2	14	1	4	34	4	...	16	182	13	190	19	104·55	19	2	3·36	1·10	1·78	0·84	4·88	1·04
144 hrs.		61	878	15	15	3	12	7	189	16	3	12	1099	13	1149	6	104·51	18	16						

= 8 tons per hour over the whole period.
= 4 tons per furnace hour over the whole period.

and in order to get a better return it was decided to carry refining in it still further, only raising the temperature sufficiently high to melt the slag while adding a considerable quantity of iron ore and lime. The average temperature as determined by the Wanner pyrometer was 1545° C., whilst that of the secondary furnace in full heat was 1720° C. The following table gives results obtained:—

	Average Composition of Pig Metal charged into Mixer as Primary Furnace.	Average Composition of Refined Metal from Mixer as Primary Furnace ready for Secondary Furnace.	Average Composition of Final Steel from Secondary Furnace.
Carbon ...	3·25	2·10	0·169
Silicon ...	0·636	0·160	0·042
Sulphur ...	0·053	0·043	0·028
Phosphorus	2·42	0·930	0·032
Manganese ...	2·40	0·78	

In order to further test the elimination of sulphur in the primary furnace, irons were obtained containing high percentages of this element, and the following are notable instances:—

Percentage of Sulphur in Pig Metal.	Percentage of Sulphur in Primary Metal.	Duration of 18-ton Charge in Primary Furnace. Hrs.	Min.	Percentage of Carbon in Primary Metal.
0·308	0·067	2	45	2·2
0·209	0·070	2	15	1·6
0·240	0·078	2	40	1·8
0·370	0·100	3	0	0·9

The percentage of sulphur in the finished steel from the secondary furnace did not in any case exceed 0·05 per cent.

With both the Talbot and Bertrand Thiel methods large outputs are obtained, to which the use of fluid metal largely contributes. Further, it will be noted that, by following the basic process, originally impure pig metal may be used for the production of good-quality steel.

CHAPTER XVII

THE PRODUCTION OF SOUND STEEL

Theoretically, an ingot top or the feeder on a steel casting should sink or "pipe," due to shrinkage of the molten metal. If, however, instead of sinking, a rise or increase in volume is shown, then clear evidence of internal unsoundness or sponginess is exhibited. This feature is more familiar to dead mild steels than to harder varieties. When unsoundness of this type is due to blowholes, the process of rolling down into bar or plate is relied on to close up the blowholes, a method known as "wash welding" being sometimes followed. It is open to some doubt whether these blowholes are ever perfectly welded; they often give rise to long lines known as "rokes," but in any case reliable data on the subject is absent. Certainly, prevention is better than cure, and the obvious feature lies in making ingots free from blowholes, which is easier to write of than achieve in the melting shop.

One of the first essentials lies in having the steel thoroughly dead melted or "killed" before casting. The purpose of the killing fire was indicated in describing the manufacture of crucible steel. A properly killed steel pours quietly, and after casting gently settles down in the mould. Wild or fiery metal, as indicated by name, is troublesome to cast, and does not settle down in the mould. Wild metal is in some cases represented by an over-oxidized metal, and is most likely to occur in Bessemer steel.

A distinction must be drawn between a "pipe" and a "blowhole." The former is due entirely to contraction or shrinkage involved in passing from the liquid to the solid state. Thus an ordinary steel ingot starts to solidify from the sides and bottom, due to contact with a cold mould. This gradually solidifying mass, in contracting, draws from the last fluid portion of metal to meet its own deficiency. Hence the cold ingot will contain a cavity in the portion last to solidify, somewhat after the form of Fig. 38. Pipes in ingots are always found near the top, because the section of metal is equal throughout the length. Were the ingot irregular in form, then the pipe would occur in the heaviest part. This may be illustrated by taking the case of a casting in which the distribution of metal is irregular, as, for instance, in Fig. 39. Here the light arms evidently solidify first. The heavy rim, being the last to set, cannot feed from the arms, therefore unless the part A sinks, an internal cavity will occur, as shown. With steel the outer faces

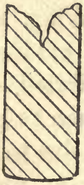


FIG. 38.

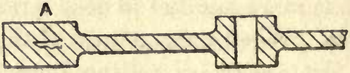


FIG. 39.

rapidly solidify, hence the chances are that shrinkage is not supplied by sinking of the upper face, but rather by the sides drawing, as it were, from a central well, thus leading to the formation of a central cavity. Piping, then, being in a sense mechanical, may be obviated by purely mechanical means, or, in foundry parlance, by the use of feeding heads. Thus, in Fig. 39 a feeder at A would, by keeping the top face open, serve as a reservoir to supply the shrinkage of the casting. Small ingots are "topped"—that is, the part containing the pipe which serves as a feeder is broken off and scrapped. In order to minimize the waste due to "topping," large ingots have a feeder smaller in size than the mould, but sufficiently large to feed the ingot. These head moulds are formed of fireclay, externally fitting the interior of the mould, and containing a hole the diameter of which varies according to the size of the ingot. When casting, the ingot mould is filled nearly to the top, and the fireclay mould, previously heated to a white heat, is inserted and filled. This method remedies pipe in the ingot, and the head acts as an efficient feeder. The same principle is applied to very large ingots, in this case the fireclay head being replaced by a "compo" mould, and the resulting head subsequently machined off. Various devices have been applied to lessen the pipe in large ingots, and in them compression largely figures.

The Harmet method involves solid compression, applied from the bottom of the ingot, the tapering sides of the mould also imparting a side pressure. A novel method, described by Julius Riemer in *Stahl und Eisen*,[1] consists in keeping the upper portion of the

---

[1] Vol. xxiii., No. 21.

ingot fluid by directing a flame of producer gas on to it. Both gas and air are regenerated, and the flame directed down the mould some time before casting. Casting is effected from the bottom, hence the rising surface meets the flame and is kept well fluid. When the mould is filled, the flame, acting on the top, maintains a fluid bath, from which the solidifying ingot draws to replace its own shrinkage. This ensures a more uniform subsidence, diminishes the tendency to form a long narrow pipe, and hence decreases waste. Figures quoted show this waste to be small.

Blowholes form a class entirely different from such defects as piping. The latter is a natural result of a heavy fall in temperature, whilst the former represent the setting free of gases absorbed during the melting process. Molten iron readily absorbs or occludes gases, and, as we have already seen, the contents of either the open-hearth furnace or Bessemer converter are towards the end of the oxidation process almost pure iron; in other words, the bath of metal offers very favourable conditions for the absorption of gases. In considering the character of these gases, oxygen naturally arises first, owing to the strong affinity between iron and oxygen. But there is every reason to suppose that the oxygen absorbed when the iron is molten remains stable at low temperatures as an oxide, and in the absence of a deoxidizing agent this ferrous oxide is intermingled with the iron. This is supported by the fact that oxygenated steel is "dry" under the hammer, and the crumbliness thus induced is not necessarily due to the presence of blowholes, but rather to a non-coherent or "red-short" metal. Further, if free oxygen is present in quantity in the gas contained in a blowhole, its skin would show an oxide film. Now, the majority of blowholes have bright surfaces, and comparatively few show coloured tints, ranging from a straw to a blue colour, due to oxidation films. These coloured blowholes owe their oxidized film, not to free oxygen liberated by the iron, but to air[1] mechanically trapped during casting—a feature readily studied in foundry practice. Further actual analyses of the gases seldom show more than mere traces of oxygen; thus E. Münker[2] reports some sixty-seven analyses of gases evolved by molten pig iron, and the highest content of oxygen in the series is found at 0·8 per cent. Average analyses of gases in blowholes give results somewhat of the following order:—

Hydrogen	75 per cent.
Nitrogen	23 ,,
Carbon monoxide	2 ,,

The actual amount of these gases absorbed depends to some extent on the temperature and composition of the bath. Whilst fluid, the gases are retained, but after casting and the consequent fall in temperature they are evolved. This gas, set free by a fall in temperature, bubbles through the pasty mass, the trapped bubbles representing blowholes in the cold ingot. As the temperature continues to fall, less movement is offered, and the gas cannot force a passage through the stiffening metal. Hence more bubbles are trapped; finally a stage is reached at which the mass becomes rigid, and the

---

[1] Air = a mechanical mixture of oxygen and nitrogen, containing by weight 23 per cent. oxygen and 77 per cent. nitrogen.

[2] *Stahl und Eisen*, vol. xxiv., No. 1.

formation of blowholes becomes impossible. Wahlberg, in a valuable paper on "The Influence of Chemical Composition on the Soundness of Steel Ingots,"[1] embodying a series of researches by Brinell, enters very fully into the question of blowholes. This section of the paper is summarized as follows:—

"1. The evolution of gases is due to the process of gradual cooling to which the ingot is subjected after casting, since with a decreasing temperature, the steel becomes less capable of retaining the gas absorbed while hot. The tendency of the gases to free themselves, therefore, constantly increases as the cooling down proceeds.

"2. The capacity of steel to retain the absorbed gases is increased by the presence of manganese and silicon, and, consequently, the higher the percentage of these two elements the further the cooling process will be continued without any evolution of gas taking place.

"3. The higher the percentage of silicon and manganese the sooner will the upper surface of the ingot solidify, on account of no evolution of gases taking place.

"4. The evolution of gases in the central and lower parts of the ingot will be almost completely intercepted when the top surface becomes perfectly solid, since there is then no room for any portion of the liquid steel to give way to the pressure of the gases evolved. No more gas is liberated, except that which the gradual shrinkage within the still liquid mass of steel permits, until the solidification of the ingot is finally complete."

---

[1] *Journal of the Iron and Steel Institute*, No. 1, 1902.

A consideration of the foregoing leads to the following conclusions:—

1. If no internal movement is possible in the solidifying steel, the gas cannot disengage itself and so lead to the formation of blowholes.

2. The presence of silicon and manganese lead to the retention of the gases until solidification is complete, hence preventing the formation of blowholes.

In the same order, methods of prevention include (1) liquid compression, and (2) prevention by additions to the steel, the latter being the more general of the two. These additions include manganese, silicon, and aluminium. Each of these elements acts powerfully on oxygen or oxides of iron, removing oxygen by combining with it to form a slag. This feature has been shown in the case of manganese additions to the Bessemer and open-hearth steel. We have already seen that the gases of a blowhole contain little or no free oxygen. Chemically, aluminium will remove carbonic oxide, for in 1891 Professor Arnold showed that at a white heat carbonic oxide is decomposed by aluminium, forming alumina and free carbon. There is, however, no chemical reason to suppose that aluminium removes hydrogen or nitrogen from the steel. Judged by results, the presence of either manganese, silicon, or aluminium tends to retain any hydrogen or nitrogen absorbed during melting, dissolved in the steel—that is to say, the presence of these elements increases the solvent power of the steel for hydrogen and nitrogen, and these gases remain *dissolved;* they are not evolved on solidification. In considering the activity of these elements, Brinell found that to produce an ingot of perfect density, in the absence of silicon, 1·66 per cent.

of manganese is necessary. In the absence of manganese, 0·32 per cent. of silicon is required; and, with no manganese or silicon, 0·0184 per cent. of aluminium is sufficient to produce a perfectly sound ingot. These figures relate to the content remaining in the steel, and they forcibly show the powerful influence of aluminium. To express the same thing in another form, Brinell gives the action of aluminium as 90 times that of manganese, and 17·3 times that of silicon. Aluminium is therefore specially suitable for the production of very pure steels, for by adding sufficient to leave about 0·02 per cent. in the steel, a perfectly sound ingot results. With careful melting and the suitable adjustment of silicon, manganese, and aluminium, no trouble need be feared from unsoundness. However, of late various elements have been proposed for the elimination of blowholes. Thus, Weber[1] advises the use of metallic borides in conjunction with ferro-titanium. It is claimed that boron, having a strong affinity for oxygen, forms boron-trioxide, not only with free oxygen present, but also with such oxides as are reducible by boron. The boron-trioxide also forms borates with any oxides unreducible by boron. The titanium added combines with any nitrogen present to form a stable nitride, thereby eliminating blowholes.

The Influence of Casting Temperature.—This influence is generally viewed solely from the point of soundness. Whilst it is perfectly true that a too high or too low casting temperature does lead to unsoundness, such a feature is the least evil. The author's researches convince him that the influence of casting temperature must be regarded chiefly from the point of mechanical

---

[1] *The Iron Age*, vol. lxxii.

properties. Thus, if a series of steel castings are poured from one ladle, commencing with an exceptionally high-casting temperature and finishing with the lowest at which the metal will flow, the mechanical properties of the series will be found to rise until the fair-casting heat is reached, and then fall with each successive fall in temperature. The varying mechanical properties obtained from steels poured from one ladle within a few minutes of each other are not restored to one level by subsequent treatment.

Thus, in the following table,[1] the bars were annealed together, each bar receiving exactly the same treatment:—

No.	Analyses.					Max. Stress. Tons per sq. in.	Elongation. Per cent. on 2 in.	Reduction of Area. Per cent.
	Carbon.	Si.	Mn.	S.	P.			
80A	0·29	0·07	0·16	0·07	0·06	24·2	9·5	18·0
81A	,,	,,	,,	,,	,,	27·2	24·0	32·3
82A	,,	,,	,,	,,	,,	27·0	12·5	17·5
83A	,,	,,	,,	,,	,,	25·5	8·0	12·0

These steels were poured from one large ladle at intervals of a few minutes; they are of exactly the same analysis, and apart from variations of casting temperature, in exactly the same condition. The elongations are worthy of careful note. The tests of 81A are exceptionally good, yet 83A was poured from the same ladle. These results have been repeated many times, and when the steel is poured at an excessive temperature, similar ones are always obtained. Owing to the high melting point

---

[1] *Journal of the Iron and Steel Institute*, No. 1, 1904.

of mild steel the general tendency will be not to err on the high, but rather on the low side. Here an important pecularity presents itself, for if a crucible steel is heated to the fair-casting heat, a few test bars poured, and the crucible then allowed to stand until the steel will just flow, and another set poured, the two sets of bars, when subsequently tested in tension, yield similar values, yet the bars poured at the cold heat will be brittle. Further, although tension tests do not differentiate between the two sets, this brittleness survives through annealing or forging. Nowadays the majority of engineers recognize a type of brittleness which is not shown by the tensile test. Professor Arnold has devised a most valuable test for detecting this brittleness.[1] A test piece $\frac{3}{8}$ in. square by 6 in. long is gripped in the vice of the machine and the free end bent backwards and forwards, a definite number of reversals being given per minute. In the following table some results by this test are given in comparison with the results obtained from tension tests. The steel was cast at a "fair" and "low" heat, and the tests represent values obtained from the two heats in the cast, annealed, and forged condition :—

---

[1] *Proceedings of the Institute of Civil Engineers*, vol. cliv., Supplement.

No.	Analyses.					Casting Temperature.	Condition.	Tensile Tests.		Alternation of Stress Test.[1]
	Carbon.	Si.	Mn.	S.	P.			Max. Stress. Tons per sq. in.	Elongation. Per cent. on 2 in.	Reversals to complete Fracture.
97	0·36	0·22	0·89	0·02	0·02	Fair	As cast	35·8	12·5	68
98	,,	,,	,,	,,	,,	Low	,,	34·2	11·5	48
97A	,,	,,	,,	,,	,,	Fair	Annealed	27·0	17·5	122
98A	,,	,,	,,	,,	,,	Low	,,	28·2	18·5	62
99	0·37	0·18	0·87	0·03	0·02	Fair	Forged	40·9	27·5	546
100	,,	,,	,,	,,	,,	Low	,,	40·1	28·0	172

The tensile results of this table show no difference due to varying casting temperature. The alternation stress results, however, present some noteworthy features. Thus, the low heat, even after annealing, is not brought to the same value as the fair heat in its cast or raw condition. The low heat in its forged state is very little better than the fair heat after annealing. This result is of high importance, for this type of steel is largely used in engineering structures. Although No. 100 possesses an extension of 28 per cent., it is none the less exceedingly brittle, and such a steel, if in service, subject to alternations of stress, is very liable to fracture at comparatively low stresses. Herein, then, lies the vital importance of casting temperature, for under the conditions noted, tensile tests do not discriminate between ductile and brittle material.

---

[1] 270 reversals per minute, $\frac{9}{16}$ in. stroke.

CHAPTER XVIII

METALLOGRAPHY OF THE HEAT TREATMENT OF STEEL

THE properties of steel or iron are very largely determined by the "condition" of the metal, a feature illustrated in the following table :—[1]

	Carbon.	Manganese.	Condition.	Max. Stress. Tons per sq. in.	Elongation. Per cent. on 2 in.	Reduction of Area. Per cent.
1	0·08	0·06	Cast	18	20	30
	0·08	0·06	Forged	22	45	60
2	0·36	0·88	Cast	28	18	18
	0·36	0·88	Forged	41	28	54

Each pair of results represents material of precisely the same chemical composition, but in each case the influence of condition is distinctly shown in the tensile test results. Chemical analysis does not, as a rule, indicate the condition of a steel, and recourse must be had to microscopical examination for evidence of the treatment applied to a metal. Taking as a first example the nearly pure iron of the foregoing table, the structure of the cast product is shown in Fig. 40, whilst Fig. 41 is that of the same iron after forging. Therefore the effect of work, such as

---

[1] Author, *Technics*, vol. ii., No. 12.

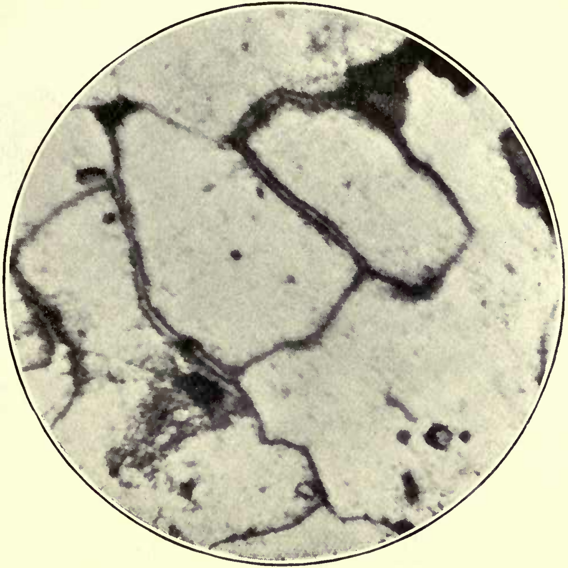


FIG. 40.—Ferrite (as cast). × 360.

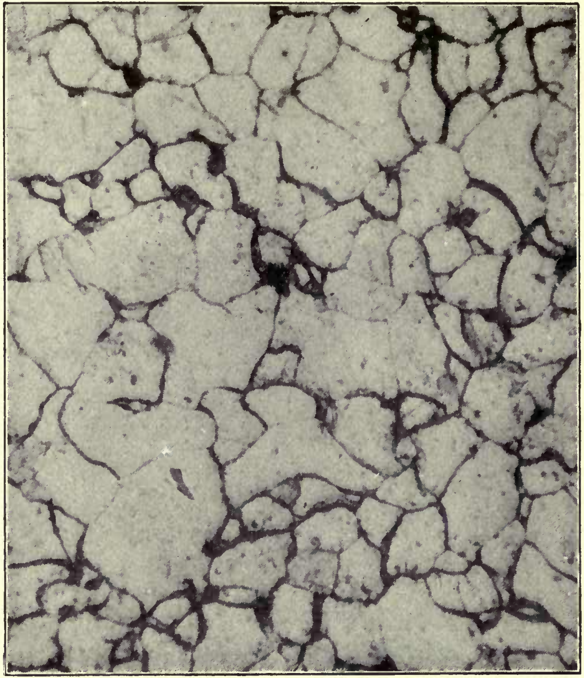


FIG. 41.—Ferrite (as forged). × 360.

[*To face p.* 232.

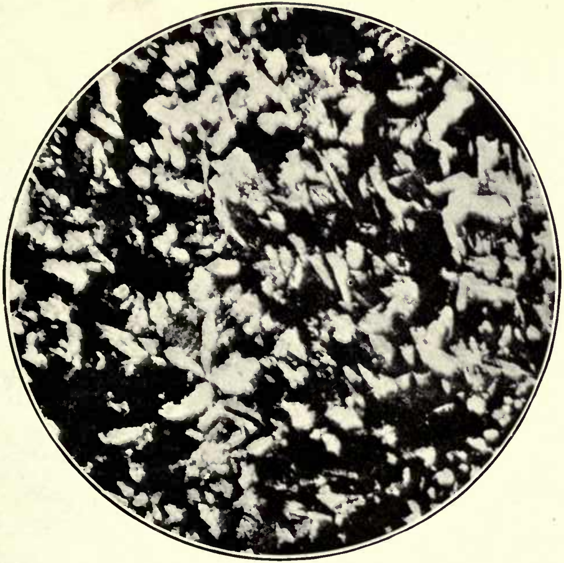


FIG. 42.—0·36 per cent. Carbon Steel (as cast). × 58.

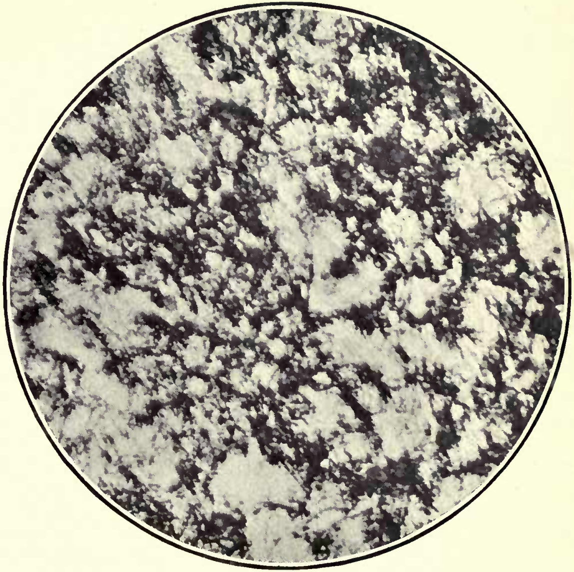


FIG. 43.—0·36 per cent. Carbon Steel (annealed). × 58.

[*To face p.* 233.

forging, is to dovetail the crystals one into another. This interweaving most effectually strengthens intercrystalline cohesion. Taking as a second example the steel of the foregoing table, its structure as cast is reproduced in Fig. 42. It will be noted that this structure is distinctly sharp, and that the areas of pearlite (black) and ferrite (white) do not merge at all. Such a steel, if used in the cast condition, is always annealed before use, a process which consists in heating the castings to a temperature between 800° and 900° C., which is maintained for seventy hours, and then followed by slow cooling. The structural changes induced by this treatment are shown by a comparison of Figs. 42 and 43. It will be noted that the sharp boundaries between the pearlite and ferrite are broken down, and that these constituents tend to merge one into the other without showing a sharp dividing line. The object of annealing is, however, of a twofold character, for in addition to destroying the sharp boundaries, it also relieves internal strains due to inequalities in the thickness of the castings, the latter purpose being largely a function of slow cooling.

Carrying the examination of this steel further, the structural influence of forging is shown in Fig. 44. A comparison of Figs. 42 and 44 will show that the large crystallization is replaced by a much smaller type. The distribution of ferrite and pearlite in relatively small areas gives a "broken-up" appearance, a feature which, in addition to the stronger internal cohesion, accounts for the higher tensile properties. In studying Figs. 42, 43, and 44, it should be remembered that they represent one steel, and that whilst the structures differ in arrangement, chemical analyses of the three are identical.

These examples are sufficient to illustrate the influence of forging and of annealing. Next in order comes the influence of heat treatment, or, more correctly, the influence of the rate of cooling from a high temperature. It is generally recognized that, with all crystalline bodies, the slower the rate of cooling the more perfect the type of crystallization—a feature specially marked with metals and alloys. Iron, which crystallizes at a lower temperature than its solidification point, offers a good example for studying the influence of the rate of cooling. Thus, Figs. 45, 46, and 47 represent the structures of three pieces of Swedish iron heated to 1000° C., but all cooled at different rates. In cooling from 1000° C., Fig. 45 occupied five hours; Fig. 46, half an hour; and Fig. 47 was, by quenching in water, almost instantaneous. Slow cooling gives a large and regular type of crystallization; the quicker cooling of Fig. 46 shows a small but still fairly regular type, whilst the rapid cooling of Fig. 47 gives a distorted and irregular crystallization. Chemically, the three structures are the same, and as far as mineralogical hardness is concerned, the three structures are equal, quenching developing no greater hardness than that possessed by the slowly cooled sample. With a pure iron of this type, containing only one constituent, ferrite, the influence of varying rates of cooling is only evidenced on the crystallization, and, micrographically, is studied by comparing the contour of the crystals and the appearance of the junctions as indicated. When, however, carburized iron is substituted for carbonless iron, well-marked structural changes are induced by varying thermal treatment.

In discussing constitution (Chapter XIII.), the

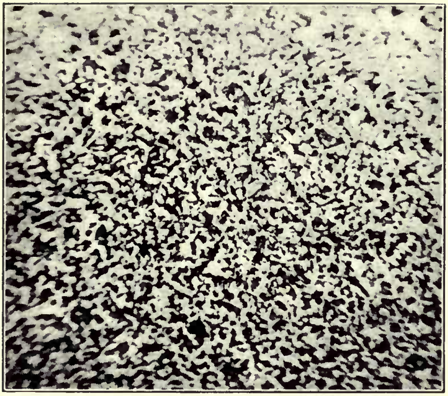


FIG. 44.—0·36 per cent. Carbon Steel (forged). × 58.

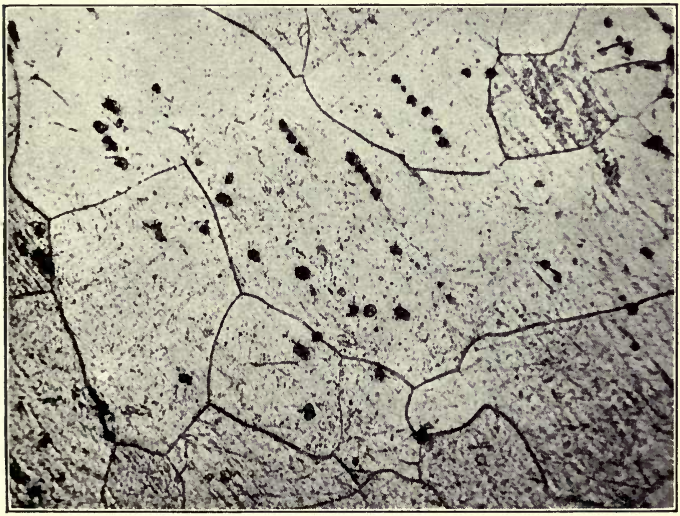


FIG. 45.—Ferrite (slowly cooled from 1000° C.). × 150.

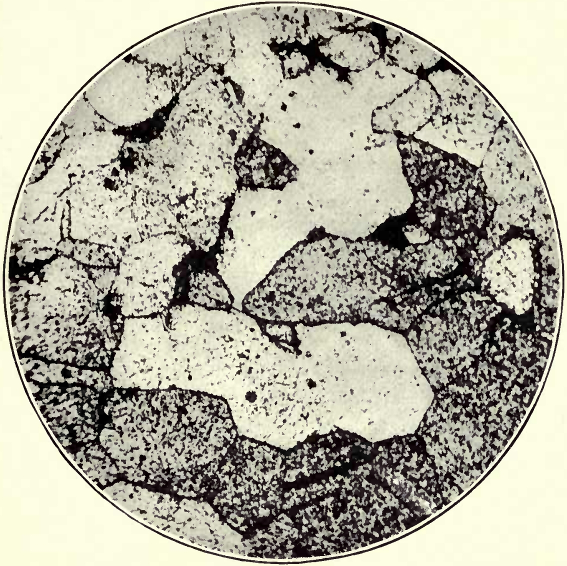


FIG. 46.—Ferrite (quickly cooled from 1000° C.). × 150.

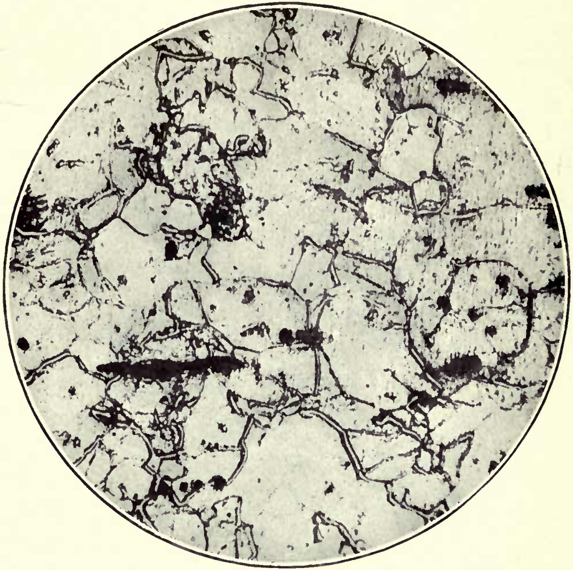


FIG. 47.—Ferrite (quenched from 1000° C.). × 150.

[*To face p.* 234.

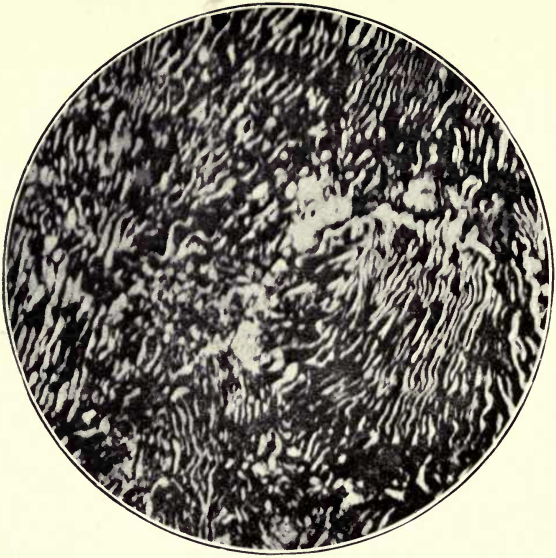


FIG. 48.—Segregated Pearlite. × 1000.

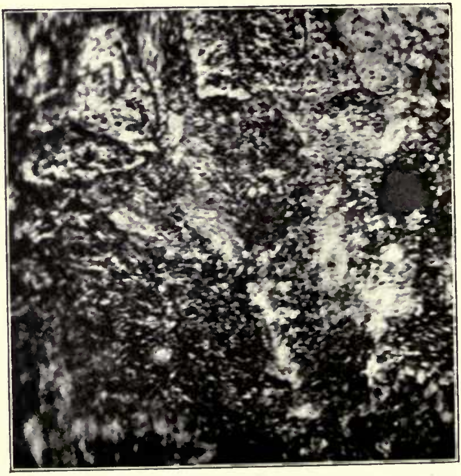


FIG. 49.—Unsegregated Pearlite. × 1000.

constituents of unhardened steels were shown to be ferrite and pearlite, or pearlite and cementite, according to the amount of carbon in the steel. Laminated pearlite has also been shown, but, as a matter of fact, pearlite may be found in every possible state of division, between coarse and exceedingly fine. With pure iron, slow cooling produces the largest and most geometrical crystals; so with the pearlite of a steel, slow cooling gives the necessary time for its constituents, ferrite and cementite, to segregate, resulting in laminated pearlite. On the other hand, rapid cooling, but not actual quenching, retards to some extent this segregation, and as would be naturally expected, the pearlite is in a fine state of division, the fineness increasing with the rapidity of the cooling. Unsegregated pearlite is therefore common to all steels rapidly cooled, whilst the segregated or laminated type is familiar to slowly cooled steels. These two types impart very different properties, and it is usually found that a steel containing well-laminated pearlite possesses high ductility; whilst a similar one, containing its pearlite in the unsegregated form, will show less ductility, but yield a much higher tenacity. The essential difference between these types of pearlite was described by Professor Arnold in 1895.[1]

Fig. 48 shows coarse pearlite developed in a "saturated" steel by slow cooling from a full red heat. The same steel, heated to a full red and cooled in air, has the structure shown in Fig. 49, which is typical of unsegregated pearlite. A comparison of the two illustrates the influence of differing rates of cooling.

The type of pearlite shown in Fig. 49 is often

---

[1] *Proceedings of the Institution of Civil Engineers*, vol. cxxiii.

described as "sorbite," a term indicating a distinct constituent. However, careful examination leads to the conclusion that sorbite, instead of representing a distinct entity, represents only pearlite in an exceedingly fine state of division; in other words, it has been produced under conditions of cooling which have retarded visible segregation of its constituents, ferrite and cementite. Until present ideas are replaced by exact knowledge, sorbite should not be regarded as a constituent, but as a type of structure induced by particular treatment. Viewed in this light, the term "sorbitic pearlite" is permissible, since it describes a type of structure, but does not necessarily indicate a definite constituent.

A further example of differing rates of cooling is found in a comparison of Figs. 50 and 51. These structures represent a tool steel of 1·2 per cent. carbon, both cooled from 1000° C., Fig. 50 taking five hours, and Fig. 51 taking half an hour, to reach atmospheric temperature. Segregated and unsegregated pearlite will again be recognized. Fig. 51 shows a central area of faintly laminated pearlite surrounded by cementite. Another example of rapid cooling in the case of a tool steel is shown in Fig. 52, the centre of which shows no segregation, but faintly laminated pearlite will be noted in other parts of the photograph.

Steels high in carbon, if given a prolonged heating at about 1000° C., tend to deposit carbon in the free state. This is achieved by the decomposition of cementite into free carbon and ferrite; the former being found in an amorphous and not a crystalline condition. With metals of very high carbon content, such as white cast iron, this decomposition of cementite has an industrial value, as

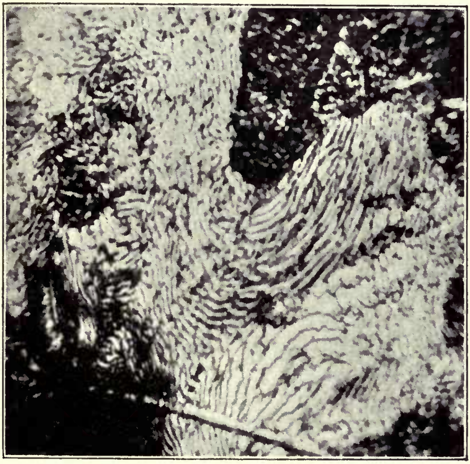


FIG. 50.—Tool Steel (slowly cooled from 1000° C.). × 1000.

[*To face p.* 236.

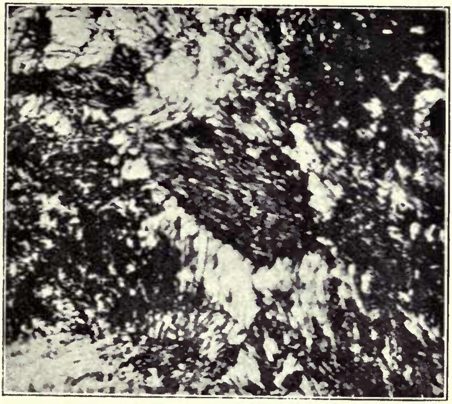


FIG. 51.—Tool Steel (quickly cooled from 1000° C.). × 1000.

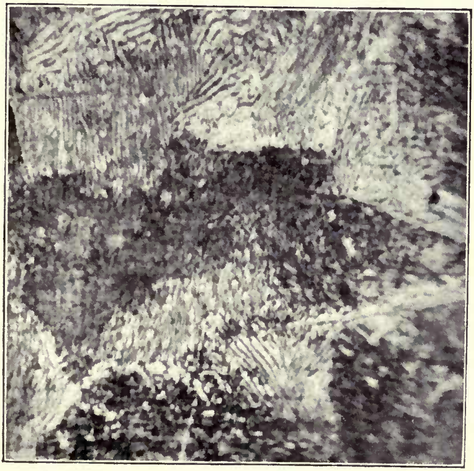


FIG. 52.—Tool Steel (rapidly cooled). × 1000.

[*To face p.* 236.

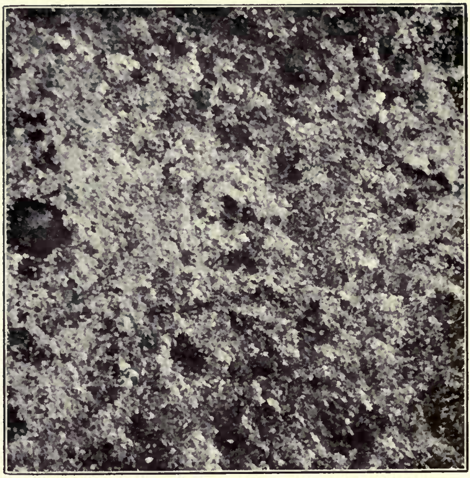


FIG. 53.—Annealed White Iron. × 58.

FIG. 54.—Table Knife. × 1000.

[*To face p.* 237.

noted in Chapter IX. Where simple decomposition occurs—*i.e.* unaccompanied by a removal of carbon—the resulting structure is that of Fig. 53. A comparison of Fig. 53 with Fig. 29 (Chapter XIII.), which represents unannealed white iron, will show the structural changes induced by annealing a metal high in carbon. This splitting up of the hard and brittle cementite doubles the tensile strength, but apart from this gain in tenacity, the annealed product is comparatively soft and readily worked by tools.

CHAPTER XIX

THE METALLOGRAPHY OF HARDENED STEELS

THE *structural* charges noted in the preceding chapter are of comparatively simple character, and, with the exception of Fig. 53, involve only differences in arrangement or pattern of structure. When, however, a tool steel is quenched from a high temperature, certain *constitutional* changes occur which impart very decisive properties to the metal. This intense hardness, acquired by quenching, forms one of the most interesting and fascinating problems of steel metallurgy, and, it is hardly necessary to add, has given rise to many equally fascinating theories. But the exigencies of daily work forbid the acceptance of any theory, no matter how alluring, until that theory admits of practical demonstration. As some of the published theories of hardening have not met this practical test, their inclusion will serve no useful purpose.

With ordinary carbon steel it is a practical axiom that the greater the hardness required the higher must be the carbon content.[1] The series of standards given in Chapter XIII. will show that in practice carbon varies

---

[1] Too much emphasis cannot be laid on the fact that in practice carbon is varied to suit the desired hardness; unfortunately, many writers ignore this fundamental.

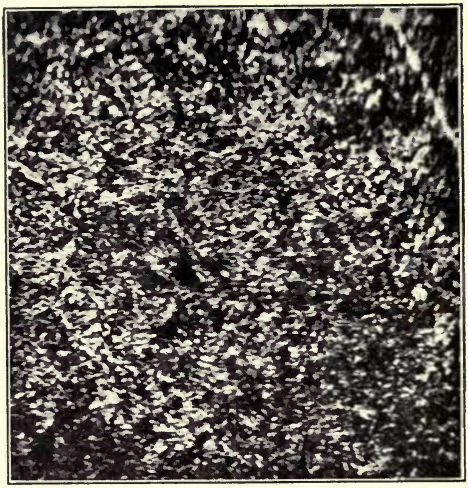


FIG. 55.—Hack Saw. × 1000.

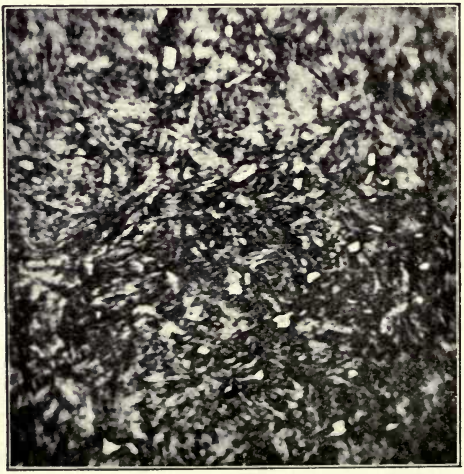


FIG. 56.—File. × 1000.

[*To face p.* 239.

from 0·5 to 1·5 per cent., and that this range includes a wide variety of hardened and tempered tools. The first feature of moment is therefore found in the carbon content; a second one lies in the fact that the intense hardness imparted by quenching outright in water may be modified by subsequent tempering. The tempering range has been indicated in Chapter XIII., and its purpose shown to lie in an effort to obtain a combination of hardness and ductility, or, more correctly, hardness and resilience. For instance, an ordinary table-knife is required, not only to carry a cutting edge, but also to possess certain springing properties. Similar requirements are found in saws; all tools of this description may be bent to a certain extent, and on removal of the bending force possess the property of resuming their original position. A fully hardened steel will not bend at all, but, when the force is sufficient, fracture sharply; on the other hand, a fully annealed steel will bend through a certain angle, but show no tendency to spring back.

Tempering may, as indicated, be achieved by reheating fully hardened steel, or, instead of hardening outright in water, the articles may be quenched in oil, a procedure which may be regulated to give a tempered product. An example of the latter is found in springs, which, whilst depressed by a certain load, will on removal of the load resume their original position.

As a first example of a commercial steel a table knife is selected, and its structure shown in Fig. 54. It consists of two constituents, dark and white, and the same constituents differently arranged will be noted in Fig. 55, which is the structure of an ordinary hacksaw blade. Both the foregoing steels possess, to some extent, springing properties. The following two represent hard steels, which will not bend, but fracture readily under a blow. Thus, Fig. 56 is the structure of an ordinary 14-in. flat file, whilst Fig. 57 is that of a razor. These illustrations run in ascending order of hardness and carbon content. The table-knife and saw represent tempered steels, whilst the file and razor are but slightly tempered. Razors have no shock to meet; their sole requirement is found in a keen cutting edge, and, in conjunction with surgical instruments, these tools represent the hardest class of the more familiar tool steels.

An examination of the four structures will show that whilst none of them are specially definite, yet each one is built up of two constituents.

Taking next the influence of heat on these structures, the saw blade, after heating to a dark blue,[1] presents the structure shown in Fig. 58. A comparison of this with Fig. 55 will show that this temperature has resulted in some internal change, for the white areas are now more pronounced, and show a tendency to gather together. The file, similarly treated, presents a structural rearrangement as shown in Fig. 59, where the collection of white areas will be chiefly noted. As already noted, a hardened steel heated to full red and slowly cooled is softened. Such treatment in the case of the razor is shown in Fig. 60, which represents the structure of Fig. 57 after annealing.

The Constitution of Hardened Steel.—In 1895 Professor Arnold published his discovery of the "saturation

---

[1] The term "blue heat" represents the colour observed on a polished surface, on reaching which the samples were withdrawn and cooled in air.

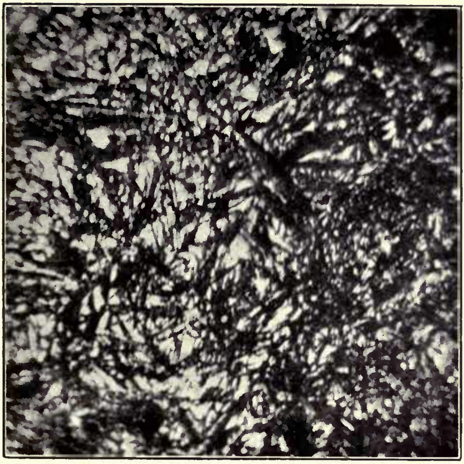


Fig. 57.—Razor. × 1000.

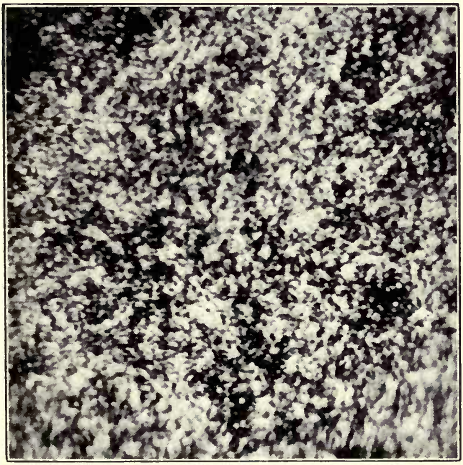


Fig. 58.—Tempered Saw. × 1000.

[*To face p.* 240.

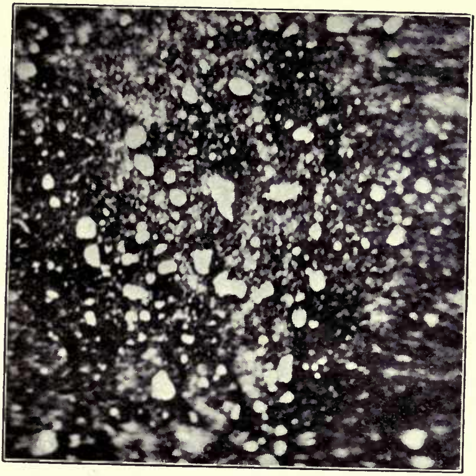


FIG. 59.—Tempered File. × 1000.

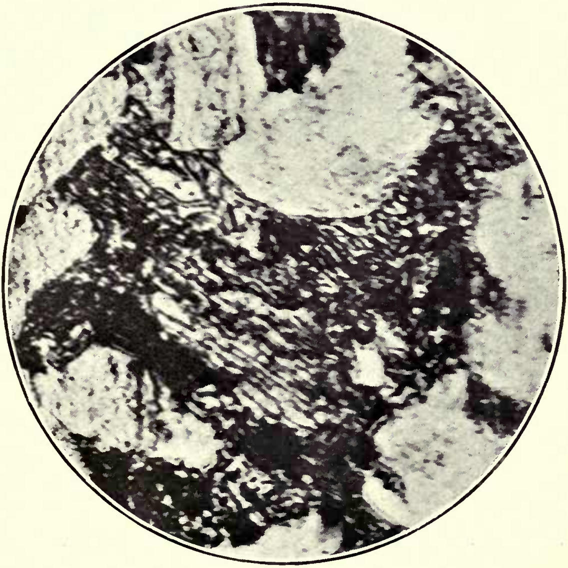


FIG. 60. Annealed Razor. × 1000.

[*To face p.* 240.

point," and showed that an annealed steel containing 0·89 per cent. carbon structurally consisted of pearlite. He also showed that such a steel, when hardened, contained only one constituent formed by the union of the ferrite and cementite of the pearlite, and therefore corresponding to the formula $Fe_{24}C$. This constituent, forming the whole of a saturated hardened steel, is termed "hardenite." An unsaturated steel when hardened consists of hardenite and ferrite, as shown in Fig. 54, the white areas of which are ferrite. A supersaturated steel when hardened consists of hardenite and cementite, as shown in Figs. 56 and 57, the white portions of which are cementite.

In 1902 Messrs. Arnold and McWilliam published a research[1] on the structure of hardened steel, from which the following summary is extracted :—

"The clear and definite constituents of hardened steel consist of:

(*a*) Hardenite, of which the whole consists only in the case of 0·89 per cent. carbon steel;

(*b*) Ferrite, which segregates more or less in unsaturated steels, in spite of the rapid action of quenching, and

(*c*) Cementite, which segregates more or less in supersaturated steels, in spite of the rapid action of quenching. The indefinite portions of hardened steels consist in unsaturated carbon steels of hardenite containing more or less unsegregated ferrite, or, in supersaturated steels, of hardenite containing more or less unsegregated cementite."

From the foregoing it is evident that the carbon of

---

[1] *Journal of the Iron and Steel Institute*, No. 1, 1902.

a steel is at high temperatures in the form of hardenite, which is in a large measure preserved by sudden cooling. Evidently, before this hardenite can form, certain changes must occur on heating. Taking first an unsaturated steel, which normally consists of pearlite and ferrite, such a steel will, on reaching a temperature of about 700° C., undergo a change in the condition of its pearlite, which passes into *hardenite.* A further rise in temperature results in the interpenetration of hardenite and ferrite, until finally a state of equilibrium is reached. If quenched from this state, the condition of equilibrium is not fully maintained for some ferrite segregates, the extent of this segregation being determined by the rapidity of quenching, being greater in oil-hardened than in water-hardened samples. If, instead of quenching, the steel is slowly cooled, the changes are as follows:—

On falling to a temperature of about 750° C., hardenite and ferrite begin to segregate into distinct areas, and at about 680° C. hardenite decomposes into pearlite.

A saturated steel will on heating undergo the pearlite change at about 700° C., and the piece will then consist entirely of hardenite. The pearlite of a supersaturated steel will, on reaching a temperature of 700° C., pass into hardenite as before; continued increase in temperature results first in the slow segregation of cementite, and on reaching a temperature of 900° C., cementite and hardenite interpenetrate, reaching a state of equilibrium at about 1000° C. As in the case of unsaturated steel, this condition is not completely preserved on quenching for cementite segregates as shown in Figs. 56 and 57. If, instead of quenching, the supersaturated steel is slowly cooled, cementite and pearlite form, as shown in Fig. 60.

FIG. 61.—1·2 per cent. Carbon Steel (quenched from 800° C.). × 1000.

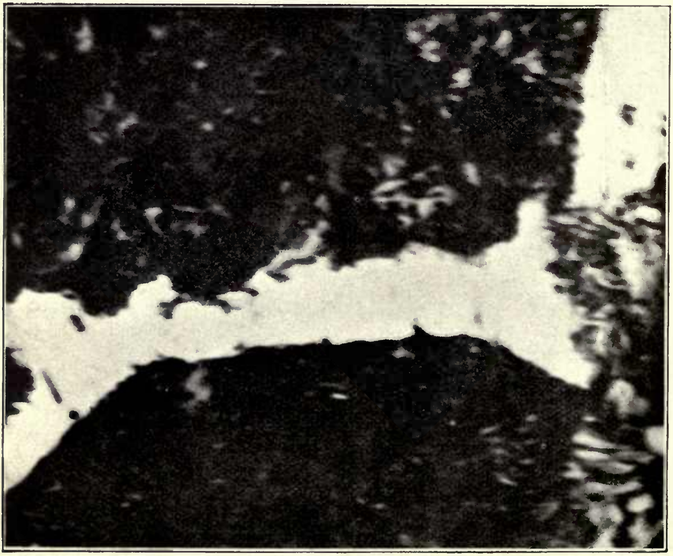


FIG. 62.—Hardenite and Cementite. × 3000.

[*To face p.* 243.

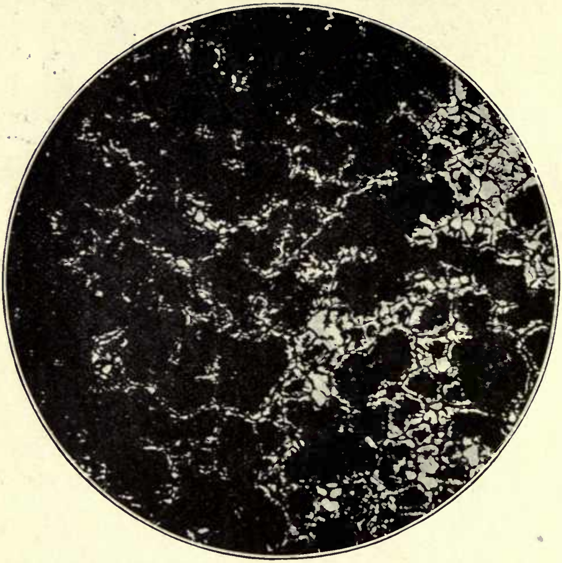


FIG. 63.—1·2 per cent. Carbon Steel (quenched from 700° C.). × 150.

FIG. 64.—1·2 per cent. Carbon Steel (quenched from 600° C.). × 1000.

[*To face p.* 243.

The foregoing is essentially based on the results of Messrs. Arnold and McWilliam's research already quoted. It is only just to state that it gives only one aspect of the hardening of steel, and there are many others. However, the aspect given is, so far as present knowledge goes, the most lucid, and it has the further advantage of meeting with practical corroboration. Wide reading, still wider experiment, and shop experience convince the author as to the truth and practical value of the aspect given.[1]

The following illustrations selected from a large number of experimental results are instructive: A 1·2 per cent. carbon steel quenched from 800° C. gives the structure shown in Fig. 61, consisting of hardenite interspersed by tiny particles of cementite. Fig. 62, at a magnification of 3000 diameters, shows hardenite traversed by a cell wall of cementite. The steel of Fig. 61, cooled from 1000° C., and quenched on reaching 700° C., presented the structure shown in Fig. 63. When quenched from 600° C. under the same conditions, the resulting structure was that of Fig 64, showing finely divided pearlite and cementite. These quenching temperatures of 800°, 700°, and 600° have a direct bearing on constitution; thus Fig. 61 shows hardenite broken up by ill-defined cementite characteristic of a properly hardened steel. Fig. 63, quenched at a temperature nearer the change point, shows a more decided separation of cementite; whilst in Fig. 64 this separation is complete.

---

[1] It is not advisable to enter here into any of the various theories of hardening. The author has discussed some of them in *Technics*, vol. ii., No. 12; vol. iii., No. 13.

CHAPTER XX

SPECIAL STEELS

STEELS are essentially alloys of iron and carbon, but in many cases a third element is added in order to obtain properties not possessed by the dual alloy, as, for example, in modern high-speed steels. Steel is exceedingly sensitive to the presence of certain elements, but as a starting-point, the influence of these elements on pure iron must be considered. Too much emphasis cannot be laid on this starting-point, for obviously before the influence of a special element on steel is considered, its effect on iron should be known. Having determined this, the next step lies in determining the effect of the element on iron plus carbon, and evidently an infinite number of alloys will be required if complete knowledge is desired. Such knowledge is not easily attained, and though a large amount of research has been done the field is by no means exhausted.

A series of extremely pure alloys has been prepared by Professor Arnold, and the results published in a paper on the "Physical Influence of the Elements on Iron."[1] The following table gives the actual amount of the special element, the contents of iron and carbon,

---

[1] *Journal of the Iron and Steel Institute*, No. 1, 1894.

together with the total impurites and the mechanical properties of the alloys :—

	Alloy.	Special Element.	Carbon.	Iron.	Total Impurities, including Carbon.	Elastic Limit. Tons per sq. in.	Max. Stress. Tons per sq. in.	Elongation.	Reduction of Area.
1	Iron ...	99·87	0·04	99·87	0·13	14·39	21·77	47·0	76·5
2	Carbon ...	1·35	1·35	98·21	0·44	46·53	57·50	5·0	5·6
3	Nickel ...	1·51	0·11	98·19	0·30	22·45	26·80	35·3	62·0
4	Manganese	1·29	0·10	98·17	0·54	22·72	32·16	35·0	65·0
5	Copper ...	1·81	0·10	97·90	0·29	30·80	34·80	30·5	62·2
6	Chromium	1·10	0·17	98·62	0·28	19·75	27·18	40·0	72·1
7	Tungsten...	1·41	0·08	98·29	0·30	20·00	27·24	42·5	76·6
8	Aluminium	1·86	0·03	97·99	0·16	17·00	27·04	35·0	63·7
9	Silicon ...	1·94	0·08	97·77	0·29	20·40	31·68	36·0	62·4
10	Arsenic ...	1·57	0·04	98·27	0·16	17·75	27·10	28·5	34·1
11	Phosphorus	1·36	0·07	98·47	0·17	28·98	28·98	—	—
12	Sulphur ...	0·97	0·08	98·85	0·16	2·54	2·54	—	—
13	Iron ...	99·82	0·08	99·82	0·18	14·28	20·08	16·0	33·8

The sulphur alloy represents results obtained from cast test pieces, the iron following being also in the cast condition for purposes of comparison. These two sets of results show very forcibly the influence of a high content of sulphur. The remaining alloys represent forged material, and in order to obtain perfectly comparative conditions the whole of the bars were normalized by heating to 1000° C. and cooling in air. This treatment removes any distortion induced by rolling, and places the whole of the bars in the *same* condition.

The high ductility of the iron will be noted. The addition to this iron of 1·35 per cent. carbon raises the maximum stress from 21·8 to 57·5 tons per square inch, and reduces the elongation from 47 to 5 per cent. Excluding phosphorus and sulphur, none of the other elements produce such a remarkable change in properties.

On the whole, the elongations are lower and the maximum stresses higher than those of pure iron, but in comparison with carbon these differences are comparatively slight. A further point of moment is found in the behaviour of the copper and arsenic alloys. These elements are often regarded with suspicion, yet an iron containing 1·81 per cent. copper yielded a maximum stress of 34·8 tons and an elongation of 30·5 per cent., whilst the arsenic alloy gave a maximum stress of 27·1 tons and an elongation of 28·5 per cent.

Of possibly greater moment is the influence of these elements on the hardening power of the iron. Thus a bar of the carbon alloy—which represents a typical tool steel—if quenched in water from a red heat, would acquire an intense hardness, and any attempt made to bend would result in fracture. The following bending tests are therefore of much interest, for by again taking iron as the base, the hardening power of each element is well shown. The whole of the bars were quenched from over 1000° C. in cold water:—

Alloy.	Special Element.	Bending Angle of Hardened Bar.
Iron	99·87	180° unbroken
Nickel	1·51	180° „
Manganese	1·29	180° „
Copper	1·81	180° „
Chromium	1·10	103° broken
Tungsten	1·41	180° unbroken
Aluminium	1·35	180° „
Silicon	1·94	180° „
Arsenic	1·57	29° broken
Phosphorus	1·36	0° „
Sulphur	0·97	0° „
Iron	99·82	125° cracked

The behaviour of a hardened carbon steel under the foregoing test is familiar: it would fracture without bending, hence the value of the foregoing results, for it will be noted that in the presence of decisive quantities of nickel, manganese, copper, tungsten, aluminium, and silicon, the hardened alloys behave in a similar manner to the hardened iron—that is, they all bend double.

Professor Arnold's results, and also those of other experimenters, thus clearly show carbon to be the most energetic of the elements usually added to iron; and further, carbon alone confers water-quenched hardness. Therefore, whether a special element is introduced into a tool steel which has to be subsequently hardened, or into a structural steel which enters working life in the unhardened condition, the effect of the addition must be viewed, not on iron alone, but on iron plus carbon.

Taking structural steels first, a third element may be added to the iron carbon alloy, for the purpose of raising its elastic limit, without seriously lowering its extension. Further, it may be added to increase the resistance to alternating stress, to impact, or shock. If the elastic limit can be raised without impairing ductility or resistance to shock, then structural members, girders, stanchions, bolts, and so forth, can with safety be decreased in weight. Such a decrease will often compensate the increased cost of the special steel; but even with no decrease in cost, the higher factor of safety is good compensation, a remark especially applicable to the steel parts of high-speed engines. In such parts requiring rigidity without brittleness, nickel steels are exceptionally serviceable. The content of nickel is usually 3 per cent., with carbon from 0·2 to 0·4 per cent., and manganese about 0·5 per cent. It may be well to note here that nickel, like iron, has a strong affinity for oxygen, hence ferro-manganese must be used in the manufacture of nickel steels, and a distinct amount of manganese left in the finished product in order to ensure a readily forgeable material. Typical commercial nickel steels are given in the following table:—[1]

	Condition.	Analyses.			Yield Point. Tons per sq. in.	Max. Stress. Tons per sq. in.	Elongation. Per cent. in 2 in.	Reduction of Area.
		Carbon.	Manganese.	Nickel.				
Q. F. nickel steel ...	Annealed	0·320	0·512	2·95	21·7	39·3	34·0	58·6
Sheffield nickel steel ...	Annealed	0·280	0·516	3·01	21·9	39·2	32·5	49·3
German nickel steel ...	Oil tempered	0·310	0·625	4·175	23·7	50·4	21·5	54·3

From these results it will be seen that the simultaneous presence of nickel and carbon gives a product of comparatively high tensile strength and practically unimpaired ductility.

Chromium is chiefly added to tool steels, although chrome carbon steels find a large application in the form of tyres, springs, etc. An exceedingly valuable structural steel is found in one containing carbon, chromium, and vanadium, the last element being usually present in very small amounts from 0·1 to 0·2 per cent.

---

[1] "Heat Treatment Experiments with Chrome Vanadium Steels," Sankey and Kent Smith, *Institution of Mechanical Engineers*, December, 1904.

The following tests illustrate the influence of a comparatively small quantity of vanadium in the presence of chromium and carbon.[1]

Analysis.				Yield Point. Tons per sq. in.	Max. Stress. Tons per sq. in.	Elongation. Per cent. in 2 in.	Reduction of Area.
Carbon.	Manganese.	Chromium.	Vanadium.				
0·22	0·29	1·02	0·17	36·2	48·6	24·0	56·6

The high yield point and tensile strength, associated with the comparatively high ductility, render this steel exceptionally valuable for engine details or other parts subject to alternating stresses. Vanadium has been proposed as an addition to tool steels, but its chief value lies in the direction indicated. With chromium and vanadium constant at 1 and 0·2 per cent. respectively, and carbon varying from 0·2 to 0·5 per cent., a range of products varying from mild forgings to spring steels is obtained. Vanadium steels work well under the hammer and offer no difficulty in welding. They yield excellent cold-bending tests, and resist in a remarkable manner alterations of stress.

Turning to the tool steels, the chief special elements added are found in chromium, tungsten, and molybdenum, which may be present singly or in combination. A type of chrome steel is as follows: Carbon, 1 per cent.; chromium, 2·5 per cent.; such a steel being suitable for files and drills. Tungsten is added in varying quantities

---

[1] "Heat Treatment Experiments with Chrome Vanadium Steels," Sankey and Kent Smith, *Institution of Mechanical Engineers*, December, 1904.

to tool steels. Thus, chisel steels of 0·8 per cent. carbon are, for certain classes of work, considerably improved by the addition of from 0·5 to 1 per cent. tungsten. Turning tools and drill steels have tungsten added in amounts varying from 5 to 10 per cent. Tungsten steels are also used for magnets, the simultaneous presence of carbon and tungsten yielding a high retentiveness. Such a steel will contain 0·8 per cent. carbon and 8 per cent. tungsten.

The old type of self-hardening steels contained decisive quantities of tungsten, and occasionally chromium, in addition to fairly high quantities of carbon, silicon, and manganese. A type of such a steel is as follows:—

Carbon	1·75	per cent.
Tungsten	10·00	,,
Manganese	1·75	,,
Chromium	1·00	,,
Silicon	0·60	,,

Owing to the high contents of carbon, silicon, and manganese, such a steel, if hardened in the usual way—*i.e.* by quenching in water—would crack; but if heated and then air cooled, a sharp and fairly permanent cutting edge would be retained. These tools yield good results when employed on hard material. Analyses of Mushet self-hardening steel, given by Hadfield,[1] are as follows:—

Carbon.	Tungsten.	Manganese.	Silicon.
2·3	6·12	2·57	1·05
2·0	8·22	1·72	1·60

---

[1] *Journal of the Iron and Steel Institute*, No. 2, 1903.

—thus showing a wide range of composition. The development of the self-hardening steel has resulted in the air-hardening steel. These steels are hardened by quenching from a dazzling white heat in a blast of air. Not only are quenching temperatures much higher than for self-hard steels, but the compositions are very different, the most noticeable change being in the lowering of carbon, silicon, and manganese. However, whilst a lowering is effected in this direction, not a few of these steels contain as much as 30 per cent. of elements other than iron. For instance, one well-known type contains 20 per cent. tungsten and 7 per cent. chromium, and the author has met with others containing even higher contents of tungsten. According to Gledhill,[1] 16 per cent. tungsten appears to be a limit of cutting efficiency. An analysis of the A. W. steel, given by Gledhill, is as follows: Carbon, 0·55 per cent.; chromium, 3·5 per cent.; and tungsten, 13·5 per cent. In the general run of these steels, carbon is found to vary from 0·5 to 0·8 per cent, silicon from traces to 0·4 per cent., chromium from 2 to 8 per cent., and tungsten from 7·5 to 14 per cent.

Here again a wide range in composition is indicated, which is further emphasized by, in certain steels, the presence of molybdenum. Concerning the action of this element on iron, comparatively little is known, the only investigations being those of Guillet. However, its effect in air-hardening steels seems to be very similar to that of tungsten, except in that of activity. Molybdenum appears to be far more active than tungsten, and in

---

[1] *Journal of the Iron and Steel Institute*, No. 2, 1904.

practice 2 per cent. molybdenum is equal to 8 per cent. of tungsten. Further, the presence of molybdenum appears to lower the quenching temperature, such steels being usually heated to 1000° C. only before quenching in air blast.

INDEX

57

THE END

PRINTED BY WILLIAM CLOWES AND SONS, LIMITED, LONDON AND BECCLES.

Mineralogy, Mining, Metallurgy, &c.

WORKS BY HILARY BAUERMAN, F.G.S.

SYSTEMATIC MINERALOGY. With 373 Illustrations. Crown 8vo, 6*s*.

DESCRIPTIVE MINERALOGY. With 236 Illustrations. Crown 8vo, 6*s*.

WORKS BY ARNOLD LUPTON, M.I.C.E., F.G.S., ETC.

MINING. An Elementary Treatise on the Getting of Minerals. With a Geological Map of the British Isles, and 596 Diagrams and Illustrations. Crown 8vo, 9*s*. net.

A PRACTICAL TREATISE ON MINE SURVEYING. With 209 Illustrations. 8vo, 12*s*. net.

THE ANALYSIS OF STEELWORKS MATERIALS. By HARRY BREARLEY and FRED IBBOTSON, B.Sc.(Lond.), Demonstrator of Micrographic Analysis, University College, Sheffield. With 85 Illustrations. 8vo, 14*s*. net.

THE ART OF ELECTRO-METALLURGY. By G. GORE, LL.D., F.R.S. With 56 Illustrations. Crown 8vo, 6*s*.

ENGINEER'S VALUING ASSISTANT: being a practical Treatise on the Valuation of Collieries and Other Mines, etc. By H. D. HOSKOLD. With an Introductory Note by the late PETER GRAY. 8vo, 7*s*. 6*d*. net.

METALS: their Properties and Treatment. By A. K. HUNTINGTON, Professor of Metallurgy in King's College, London, and W. G. M'MILLAN, late Lecturer on Metallurgy in Mason's College, Birmingham. With 122 Illustrations. Crown 8vo, 7*s*. 6*d*.

LABORATORY NOTES ON PRACTICAL METALLURGY: being a Graduated Series of Exercises. Arranged by WALTER MACFARLANE, F.I.C. Crown 8vo, 2*s*. 6*d*.

THE CRYSTALLISATION OF IRON AND STEEL: an Introduction to the Study of Metallography. By J. W. MELLOR, D.Sc. Crown 8vo, 5*s*. net.

METALLURGY. By E. L. RHEAD, Lecturer on Metallurgy at the Municipal Technical School, Manchester. With 94 Illustrations. Fcap. 8vo, 3*s*. 6*d*.

ASSAYING AND METALLURGICAL ANALYSIS for the use of Students, Chemists, and Assayers. By E. L. RHEAD, Lecturer on Metallurgy, Municipal School of Technology, Manchester; and A. HUMBOLDT SEXTON, F.I.C., F.C.S., Professor of Metallurgy, Glasgow and West of Scotland Technical College. 8vo, 10*s*. 6*d*. net.

THE STUDY OF ROCKS: an Elementary Text-book of Petrology. By F. RUTLEY, F.G.S. With 6 Plates and 88 other Illustrations. Crown 8vo, 4*s*. 6*d*.

LONGMANS, GREEN, AND CO.
LONDON, NEW YORK, AND BOMBAY.