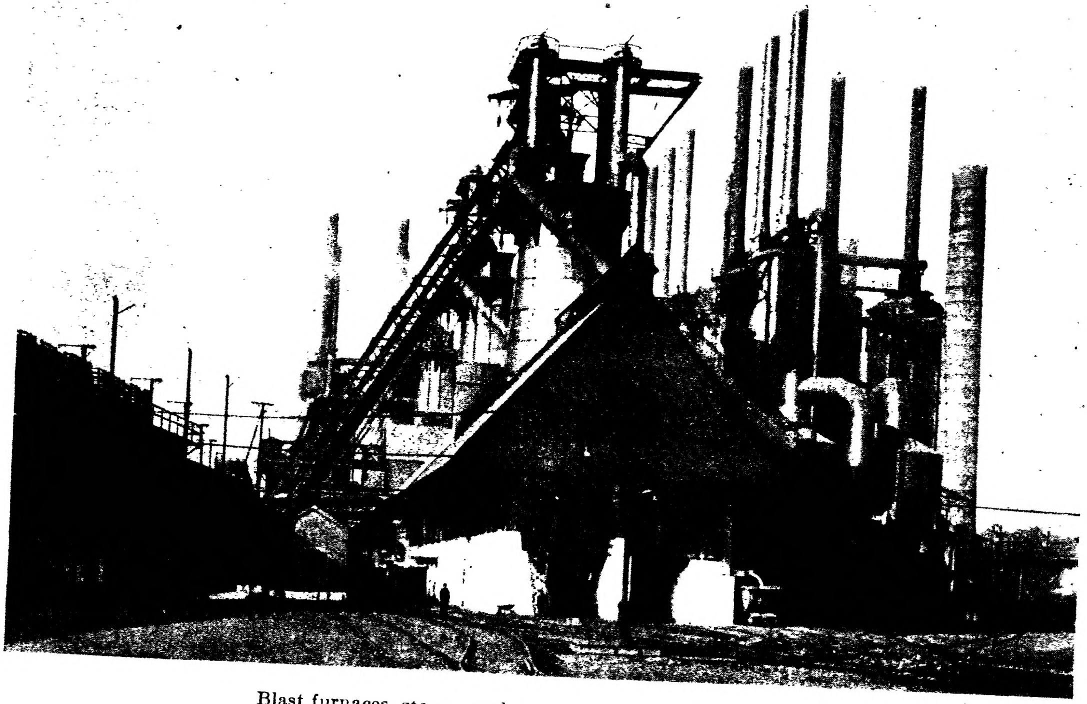
METALLURGICAL TEXTS

THE METALLURGY OF IRON AND STEEL

The quality of the materials used in the manufacture of this book is governed by continued postwar shortages.



Blast furnaces, stoves, and part of gas-cleaning apparatus.

(*Frontispiece*)

THE METALLURGY OF
IRON AND STEEL

BY

BRADLEY STOUGHTON, PH. B., B. S.

Professor of Metallurgy, Lehigh University

FOURTH EDITION

TENTH IMPRESSION

McGRAW-HILL BOOK COMPANY, INC.
NEW YORK AND LONDON
1934

PRINTED IN THE UNITED STATES OF AMERICA

PREFACE TO THE FOURTH EDITION

For the Fourth Edition of this book a complete new manuscript has been required. Only a very few of the pages included in the three other editions have been reproduced here. This is due not entirely to the material of the old pages being out of date, but also to a necessity of rearrangement of all the matter. One of the objects of this rearrangement is to present the subject very largely from the historical standpoint. Experience has shown that this method of presentation seems to be at once more interesting and more easily absorbed by a beginner.

Throughout the whole book the difficulty has been to condense the necessary material into the space available for a textbook. The problem has, therefore, been one of treating the different subjects in such a way as to give each one an amount of attention proportionate to its relative importance. The emphasis on the different subjects has necessarily been considerably altered for two reasons: In the first place, the basic open-hearth process is now so predominant from the tonnage standpoint, and the study of its physical equipment and chemical progress so very important from the standpoint of quality, that a great deal of space should properly be devoted to it. The second consideration in allocating space has been the availability of other books on the subjects treated. For example, the last few years have seen the publication of a number of excellent books, both in English and in German, on the subject of forging and rolling. This section of the Third Edition was, therefore, curtailed to make space for other subjects which cannot adequately and easily be found in recent reference or textbook form elsewhere, such as, for example, the electrometallurgy of iron and steel.

The subject of alloy steels deserves at least one whole book devoted entirely to it. At least one or two good books have appeared each recent year on some one or two of the alloy steels, but there has been nothing covering comprehensively the high points of alloy steels in general. Therefore, only the high points are treated here, leaving the details for those special treatises which have already appeared and others now in course of preparation which the author knows will soon be published.

The subjects of welding, testing, metallography, and corrosion were prepared for inclusion in this edition, but threatened greatly to exceed the space available in a textbook which could be sold at a moderate price. They were, therefore, reluctantly omitted, although this reluctance is somewhat modified by the fact that they are available in other textbooks not devoted wholly to iron and steel metallurgy.

BRADLEY STOUGHTON.

BETHLEHEM, PA.,
December, 1933.

PREFACE TO THE FIRST EDITION

The purpose of this book is to serve as a textbook, not only for college work but for civil, mechanical, electrical, metallurgical, mining engineers and architects and for those engaged in work allied to engineering or metallurgy. America now produces almost as much iron and steel as the rest of the world together, although less than eighteen years ago she held second rank in this industry. It seems fitting that the record of this progress should be brought together into one volume covering every branch of the art of extracting the metal from its ores and of altering its adaptable and ever varying nature to serve the many requirements of civilized life.

I take pleasure in acknowledging here, with sincere thanks, the assistance of many who have aided in the make-up of the volume and especially the Adams Co.; American Electric Furnace Co.; American Sheet and Tinplate Co.; Bethlehem Steel Co.; Brown Specialty Machinery Co.; Connersville Blower Co.; Crocker-Wheeler Co.; Francis G. Hall, Esq., Holland Linseed Oil Co.; Chas. W. Hunt, Esq., secretary, American Society of Civil Engineers; Prof. James F. Kemp, Mackintosh, Hemphill & Co.; Morgan Construction Co.; National Tube Co.; S. Obermayer Co.; J. W. Paxson Co.; Henry E. Pridmore; John A. Rathbone, each of whom has kindly loaned electrotypes. Also Dr. H. C. Boynton, the Brown Hoisting Machinery Co.; Buffalo Furnace Works; H. H. Campbell, Esq.; Prof. William Campbell, Carnegie Steel Co.; W. M. Carr, Esq., Central Iron and Steel Co.; Crucible Steel Co. of America; Fiske & Robinson; *The Foundry;* Harbison-Walker Refractories Co.; Joseph Hartshorne, Esq.; Prof. Henry M. Howe, Lackawanna Steel Co.; Marion Steam Shovel Co.; Mesta Machine Co.; Morgan Engineering Co.; Prof. A. H. Sexton, William Swindell & Bros.; United Coke and Gas Co.; United Engineering and Foundry Co.; Wellman-Seaver-Morgan Co.; Whiting Foundry Equipment Co. And O. S. Doolittle, Esq., for information upon paint; Frank E. Hall, Esq.; and W. J. Keep, Esq.

But especially am I indebted to the following gentlemen, each of whom has read a section of the book and made suggestions for its revision which have been very valuable to me: Messrs. W. Arthur Bostwick; Stanley G. Flagg, Jr.; Alfred E. Hammer; Joseph Hartshorne; J. E. Johnson, Jr.; Carleton S. Koch; Frank N. Speller; Herbert L. Sutton; and Hugh P. Tiemann.

BRADLEY STOUGHTON.

January, 1908.

CONTENTS

THE METALLURGY OF IRON AND STEEL

CHAPTER I

INTRODUCTION AND EARLY HISTORY

The story of man's first use of iron is lost in the remote past, for two reasons: First, it antedates by an unknown number of centuries the time of recorded history; and, second, iron is so rapidly rusted and attacked by the elements that no samples of early manufacture remain to give evidence of their existence, unless they happened to have been placed in a locality where the climate is dry and relatively noncorrosive and where they have been protected by the exclusion of air and moisture. However, a rare example of written history exists in a Chinese manuscript which dates from before 1500 B. C. and perhaps even 2500 B. C. This describes what were called "south-pointing chariots," used by a Chinese war lord to point his way homeward from a campaign in the fog-infested regions to the north. Perhaps these south-pointing chariots were applications of the principle of the modern mariner's compass, also said to have been originally developed during the lost age of civilization of ancient China. It has been suggested that the magnetic attraction of these south-pointing chariots was due to the natural magnetic iron mineral known as *lodestone*. However, it is very doubtful if the relatively feeble magnetism of lodestone would have sufficed, and it is at least possible that steel corresponding roughly to that of our modern compass needles was made and used by the ancient Chinese. If so, the fact indicates an almost modern knowledge of the art of steel compounding, heat treatment, and production of permanent magnetism. It is very probable that the first manufacture of iron and steel was carried on in the Far East, such as China and India, and thence found its way into Egypt. But the comparatively dry atmosphere of Egypt affords so much better opportunities for preservation of early specimens of iron and steel that we have many ancient iron objects from that country. This includes a piece of high-carbon hardened steel tool, now contained in the British Museum and discovered in a crevice in one of the pyramids. It was apparently made and hardened more than three thousand years ago. This is an indication not only of knowledge possessed by the ancients but also of the possibility of the long retention of hardness in a heat-treated steel object.

Where Ancient Iron Was Obtained.—Many meteorites fall to the earth from other heavenly bodies in the course of a year. Most of these consist of iron containing about 8 per cent of nickel and not much of other ingredients or impurities. Many of these meteorites are of very large size and doubtless were so in the past. They could easily afford chippings and samples of a strong and tough metal, which primitive man could and did hammer into various weapons and implements. In America this is believed to have been the only source of iron available to the natives, including even the civilized tribes in Mexico and Central and South America. In Europe, however, existed an early smelting process which is of considerable interest to us because it is in chemical principle identical with the process of smelting iron from its ores prevalent in the upper half of the most modern iron blast furnace. It was also a source of supply for iron and steel in civilized countries even well into the nineteenth century and the principal means of production until about the eighteenth century. Briefly, it consisted in subjecting an iron ore to the action of heat and a reducing agent, such as the hot gases from burning charcoal (see Fig. I-1). The iron ore used was probably

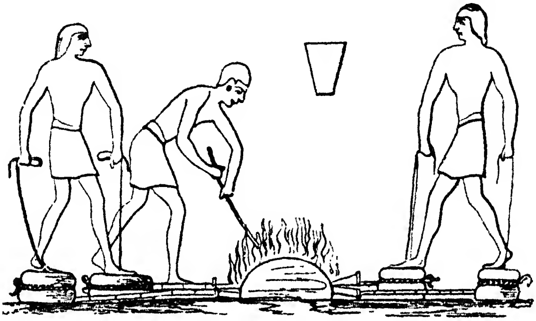


FIG. I-1.—Egyptian iron-smelting furnace. From wall painting in the tomb of Rekhmara at Thebes. Eighteenth Dynasty, 1535–1450 B. C. (*Ludwig Becks, "Geschichte des Eisens," vol. I, 1891.*)

always an oxide, because these ores were very common in a pure form and because they are the simplest to reduce.

Description and Chemistry of the Ancient Process.—The common oxides of iron are Fe_3O_4 and Fe_2O_3, often mixed with silica rock, combined water, and clay, as impurities. The Fe_3O_4 will attract a magnet slightly and is, therefore, known as *magnetite.* Sometimes magnetic currents in the earth caused the magnetite to be permanently magnetized and thus attract other iron bodies to it. This is the famous lodestone, which figures in "Arabian Nights" and other ancient tales. The Fe_2O_3, when relatively pure, is called *hematite.*

These oxides of iron will give up oxygen readily to a reducing agent, such as carbon monoxide gas, hydrogen, carbon, etc., even below a red heat—say 600°F. A brisk charcoal fire blown by a crude form of bellows or blowpipe was all that ancient man needed to produce lumps of hot metal out of any fairly pure iron ore. The metal could not be produced in a liquid condition at these temperatures but could be dragged out of the fires in a pasty and spongy mass, hot enough to be welded to a similar piece of metal, so that serviceable balls of iron could be accumulated. When enough iron had been welded together, this piece would be hammered while hot into various useful implements for warfare or agriculture. For two or three thousand years before the Christian era the Chinese, East Indians, Egyptians, and other races practiced this industry on a small scale with furnaces and appliances usually of the simplest forms. Not only swords and plowshares but even razors and needles were made, tempered, and used at least as early as the day of Alexander—about 350 B. C. No important change in principle was made in the process until the fourteenth century, and even after that the crusaders used the famous "swords of Damascus," probably traded to them through this ancient city but manufactured farther east. And the armies which followed Columbus to America were supplied with "Toledo blades," doubtless made in Spain by the same type of ancient process. It was also commonly practiced in many other parts of Europe and apparently in the British Isles at least before the Christian era.

Iron and Carbon.—The ancients understood that iron could be produced either soft or hard, pliable (ductile[1]) or strong,

---

[1] A ductile metal is one that can be squeezed or pulled so that it will permanently change its shape without breaking.

springy or malleable,[1] but did not understand the principles. Carbon and heat treatment are now known to be the factors which produce revolutionary changes in the properties of the metal, so much so that seemingly trifling modifications effect changes great enough to make an apparently different metal. Carbon has the peculiarity of conferring on iron great strength, which, strange to say, it does not itself possess, and also hardness, which it possesses only in its diamond allotropic form. So important is the influence of carbon in regulating and controlling the characteristics of the ferrous metals that they are classified according to the amount and condition of the carbon in them (see page 12).

Iron with very little or no carbon is relatively soft, malleable, ductile, and low in strength. This metal could be obtained by the primitive reduction process, provided the red-hot iron was not left too long in contact with the charcoal, because solid iron at a red heat will absorb solid carbon or carbon from carbon monoxide gas. The absorption is slow: Carbon will penetrate hot iron at the rate of about $\frac{1}{8}$-in. travel in 24 hr. However much or little ancient man knew of the theory of this process, he was acquainted with the fact that the characteristics of iron could be greatly changed by heating it for some hours in contact with charcoal, and he learned to regulate the different properties conferred on the metal by the length of time it was exposed to this contact.

Today metallurgists know that as little as 0.75 to 1.0 per cent of carbon will make revolutionary changes in the properties of iron: It is much less soft than the pure metal; does not hammer into shape so easily, either when cold or at a red heat; and cracks when hammered or pulled into a new shape at atmospheric temperature. It is about two or three times as strong as pure iron; is much less ductile; and acquires an entirely new property of being hardened by quenching in water from a bright red heat.

Heat Treatment of Steel.—Pure iron is not greatly hardened by this heat treatment. If, however, as much as 0.75 to 1 per cent of carbon is incorporated with the iron, then its properties are revolutionized by rapidly cooling it from a bright red heat. This rapid cooling is usually accomplished by plunging the heated metal into oil or water (see Fig. I-1*A*). So great is the hardness

---

[1] Metal is malleable when it can be hammered into different shapes without breaking.

produced in the metal by this treatment that man in his superstitious state of mind ascribed to the phenomenon a mystic significance and frequently surrounded the process by secret or religious rites. The relatively pure metal was given the name of *iron*, whereas the iron containing carbon, which could be hardened by sudden cooling, was called *steel*.

In Table I-I, taken from Howe, "The Metallography of Steel and Cast Iron" (page 598), is seen how carbon affects the hardness of steel in its "annealed," or slowly cooled, condition and also how much more potent is the effect of rapid cooling in hardening steel when the carbon is higher.

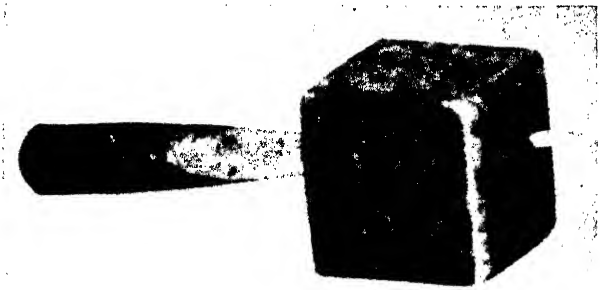


FIG. I-1*a*.—Effect of heat treatment on steel. A piece of steel was cut in two; one part was heated to bright-red heat and very slowly cooled. The other part was forged into a punch and hardened by quenching in water from a bright-red heat. Its brittleness was then relieved by warming (called tempering), after which it was ground to a fine point and then driven through the piece which had been softened by slow cooling. It will be seen from the photograph that the point of the hardened piece was scarcely injured and that the soft steel was scarcely cracked during this penetration.

The Knowledge of Ancient Man.—Ancient man knew then how to smelt iron out of its oxides; knew when and how to produce it free from carbon or to incorporate carbon with it; and knew how to heat treat the iron to which carbon had been added so as to make it suitable for weapons and other cutting tools. He also knew that the rapid cooling of the steel gave it both hardness and brittleness and that it had to be warmed somewhat to decrease the brittleness to the point where the metal could be used without breaking under shocks. He even knew that by warming a little more effectively he could modify the hardness to the point where he had a very elastic or springy material. He also knew that swords could be made with the back of low-carbon material and the edge partially saturated with carbon, so that, after heat treatment, he would have the toughness of the back portions to support and strengthen the more brittle cutting edge. This was accomplished either by welding a strip of high-carbon steel to form the cutting edge along a piece of softer iron or else by making the whole blade of soft, low-carbon metal and then increasing the carbon in the edge that was to do the cutting by leaving it for many hours in contact with red-hot carbon, which resulted in nearly 1 per cent of carbon being absorbed by the metal. However, the art of early man was often the result of chance. Swords and other implements of the very highest quality were sometimes made and were usually reserved for royalty. But lack of understanding of the nature of the

TABLE I-I.—INCREASE OF THE BRINELL AND SHORE HARDNESS WITH THE CARBON CONTENT

Carbon content, per cent	Shore scleroscope hardness			Brinell or ball hardness	
	Annealed	Normal merchantable	Hardened	Annealed	Hardened
2.04	......	......	...	286	Cracked
1.75	40 to 45	50 to 55	110		
1.72	......	......	...	286	477
1.50	37 to 40	47 to 50	110		
1.25	35	44	110	262	627
1.00	30 to 35	40	107	259	627
0.80	28 to 30	38	105	235	648
0.66	......	......	...	202	578
0.65	......	......	...	235	652
0.60	27	36	102	225	628
0.50	26	34	96	204	579
0.45	......	......	...	194	555
0.40	25	32	90	175	478
0.35	24	30	82	156	402
0.30	23	28	70		
0.25	22	27	58	143	311
0.20	21	26	50	115	196
0.15	20	25	43		
0.10	19	24	35	97	149
0.05	18	23	25		
0.01	......	......	...	75	107 112

processes occasionally resulted in uncertainty and irregularity, so that many of the early products of metallurgical art were of poor quality compared with our present-day standards. Damascus was the ancient city at which Europeans often purchased swords of very high quality. The name *Damascus swords* was therefore often applied to these weapons but incorrectly, because they were doubtless made in Persia or some other point east of Damascus. The name *damascene* was also incorrectly applied to the watermarks which indicated that these swords had been extensively worked and rewelded, because, at that time, such configurations could not be made in any other way. This extensive working was one reason for the toughness and durability of the metal.

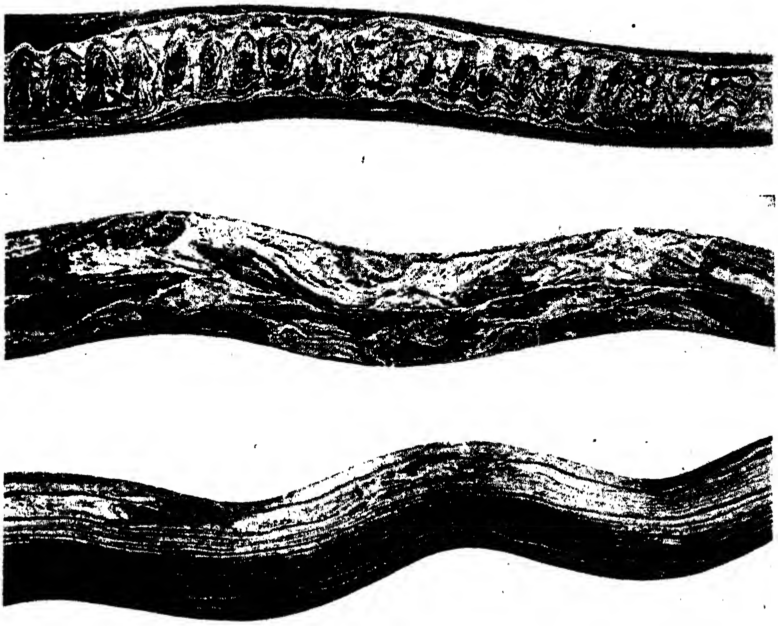


Fig. I-2.—Early sword blades. The patterns are made by welding pieces of steel of different degrees of carbon and twisting, folding, and rewelding them in various ways. The best blades are said to contain from 4,000 to 4,000,000 layers in a thickness not more than ¼ in. After producing the layers, the steel is finished, polished, and etched with lime or lemon juices, or, more rarely, with acids. (*Courtesy of George C. Stone.*)

Steel by "Cementation."—Steel makers of the past two centuries, and perhaps earlier, attempted to control the amount of carbon absorbed by wrought iron at a red heat: They heated the iron in closed vessels in contact with charcoal; the temperature and time were accurately controlled. Even under these circumstances the carbon varied in various pieces in the same "pot." How early ancient metallurgists practiced cementation in this way is not known. Some think that the Romans did it before the date of the Christian era. In any event the result then must have been a haphazard product, however produced.

Fig. I-3.—Persian watered steel sword blades from the collection of George C. Stone in New York. All these signatures are of "Assad Ullah, the servant of Shah Abbas." He was the most famous of the Persian swordsmiths and did most of his work between A. D. 1580 and 1630.

Carbon and Melting Temperature.—Pure iron will not melt until a temperature of about 1535°C. has been reached. When the iron contains about 1 per cent of carbon, melting begins at 1150°C. but is not completed unless, and until, a temperature of 1450°C. is reached. With 3 per cent of carbon, melting is complete at 1320°C. The lowest melting temperature is obtained with iron containing 4.25 per cent carbon, where the alloy melts at about 1130°C. With less or more carbon than this, the melting temperature is higher. It is generally believed that the ancients were never able to get a high enough temperature to melt low-carbon iron. Iron with low carbon became commonly known as wrought iron, because it could not be melted and cast but must always be wrought into shape under a hammer or similar implement. Some metallurgists believe that the ancients put iron into a refractory pit with about 1 per cent of charcoal and then placed the pot in the midst of glowing coals, which were blown vigorously until the mass melted to liquid steel. Such melted steel could be cast into shape and used for cutting tools. Definite evidence of this practice by the ancients is lacking. It is true that a suitable crucible can be brought to a temperature of 1500°C. when in direct contact with a briskly blown charcoal fire, but enormous difficulties exist in the way of carrying out such a process. Iron containing 3 or 4 per cent of carbon can easily be melted and cast into molds. It is known as *cast iron*, and the objects produced are known as *iron castings*. It is so brittle that it cannot be worked either hot or cold without cracking. To summarize: Cast iron cannot be wrought; wrought iron cannot be cast.

There was recently discovered in China a cast-iron stove made before 200 B. C. Whether this is the earliest cast-iron object ever made or how general the practice was of making and melting cast iron or by what process the melting was performed is unknown.

The Fourteenth Century Discovery of Cast Iron.—If iron ore is reduced with charcoal in a low hearth or fire, the metallic lump can be dragged out of it almost as soon as formed. On the other hand, if the furnace be shaped like a shaft and this shaft be filled with material to the top, then the reduction of the iron may take place in the upper levels. The reduced metal will slowly descend in the furnace as the charcoal in the bottom is burned. The nearer the iron gets to the bottom, where the charcoal is burning,

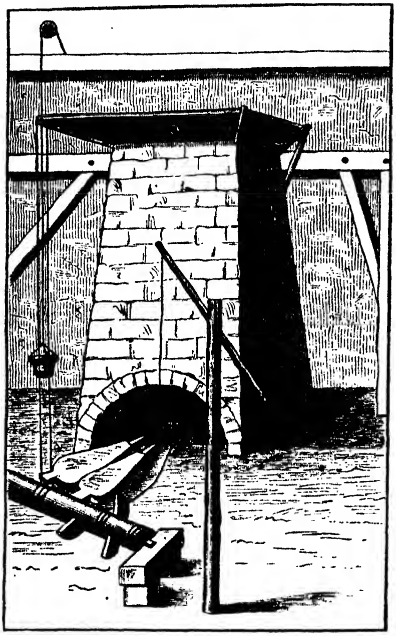


FIG. I-4.—Stückofen. (*From "Geschichte des Eisens," vol.* II, 1893–1895.)

the hotter it will become and the more carbon it will absorb. For both reasons it incurs the liability of being melted. Some time about the early part of the fourteenth century, either through chance or through design, some furnaces in use in the Rhine Valley (see Figs. I-4 and I-4*a*) had reached such a height of stack, and the rapidity of burning the fuel had reached such an intensity, that iron ore was wholly reduced in the upper levels. Then the metal, on reaching the lower levels of the furnace, became saturated with carbon and, finally, melted. It flowed out of the furnace in a molten stream. The furnace was called a *blast furnace*, because of the large volume of air which was forced into it at a relatively high pressure. This process is more rapid and cheaper than the production of solid lumps of metal which have to be welded together. The product melts easily and it is put into service either by remelting and casting or else by casting directly from the furnace into sand molds in which it solidifies as stove plates, kettles, parts of machinery, etc. In

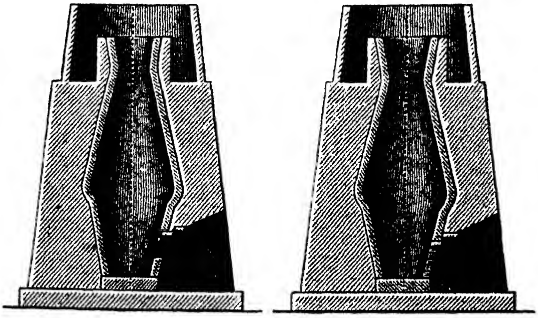


FIG. I-4*a*.—Stückofen. (*From "Geschichte des Eisens," vol.* II, 1893 1895.)

later times the metal was allowed to run out of the furnace along a main runner, then into side runners, and thence to overflow into small impressions, having the general appearance of a back of a comb with its teeth (see Fig. I-5). It also has the general appearance of a sow with pigs, and the name *pig iron* ultimately became universal for the material, cast at the furnace in this way, when broken apart and sold.

The Ferrous Metals.—Because iron and steel are used industrially more than all other metals added together, it is customary to divide metals into two classes, *viz.*, ferrous and nonferrous metals. Ferrous comes from the Latin word *ferrum,* meaning iron, as does also the chemical symbol Fe. All the products defined in the previous paragraph contain at least 94 per cent of iron; also, almost all modern alloy steels contain 75 to 95 per cent of iron; and all of them contain at least 50 per cent of iron. Therefore, the term *ferrous metals* is appropriate. There is also a group of metals which we might appropriately call *ferrous accessories,* because the chief use for them is to serve as a "physic," or else as an alloying element, in steel manufacture. For example, silicon and manganese are added to almost all liquid steels in order to rid them of objectionable gases. More silicon and manganese are used for this purpose than for all their other uses combined. The following table summarizes these

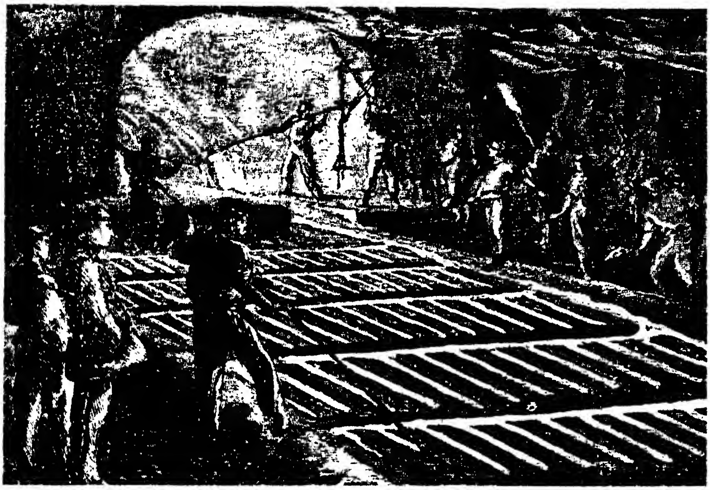


FIG. I-5.—Casting from a blast furnace into pig beds. (*From Richard Peters, Jr., "Two Centuries of Iron Smelting in Pennsylvania."*)

facts and gives a bird's-eye view of the position of iron and steel among metals:

TABLE I-II.—FERROUS AND NONFERROUS METALS

Ferrous metals	Ferrous accessories			Common nonferrous metals	Precious nonferrous metals
	Class A[1]	Class B[2]	Class C[3]		
Pig iron	Manganese	Nickel	Zinc	Copper	Gold
Cast iron	Silicon	Chromium	Lead[4]	Lead	Silver
Wrought iron	Aluminum[4]	Tungsten	Nickel	Aluminum	Platinum
	Vanadium	Molybdenum	Chromium	Zinc	
Steel	Titanium	Cobalt	Tin	Tin	
Alloy steels		Copper[4]	Cadmium	Nickel	
			Aluminum	Cobalt	
				Tungsten	
				Mercury	

[1] Class A ferrous accessories are used both as steel physics and to produce alloy steels.

[2] Class B ferrous accessories are used for making alloy steels.

[3] Class C ferrous accessories are used for coating iron and steel to protect them from rust and other oxidations.

[4] Copper, lead, and aluminum are the only ferrous accessories which are more used independently of steel than in connection with it.

Early Definitions.—Beginning several centuries ago the following ferrous products were, therefore, established in the daily life of man:

Pig Iron.—The product of the blast furnace; iron with usually 3 or 4 per cent of carbon and often other impurities; melted rather easily; not strong or reliable in tension; brittle; cannot be forged either hot or cold without breaking; often cast into some useful shape, when the name of *cast iron* is given to it. The *objects* thus cast are known as *iron castings.*

Wrought Iron.—Iron too low in carbon to be hardened by quenching; always containing admixtures of slag which are small in size but visible to the eye; can easily be forged (hence the name). It is stronger than cast iron; ductile; easily welded when cleaned pieces are hammered together at a white heat (actually about 1200 to 1400°C.).

Steel.—Iron containing enough carbon to be appreciably hardened when quenched but not enough to be brittle like cast iron.

These simple definitions meet satisfactorily the requirements of science and technology. They continued in vogue until the latter part of the nineteenth century, when the Bessemer and open-hearth processes were developed. These processes can make a product either high or low in carbon, as desired. Usually it is too low in carbon to be capable of appreciable hardening on quenching, but it is always produced in a liquid state, so that it does not contain intermingled particles of slag. The slag particles are characteristic of wrought iron, owing to the latter's final stage of pastiness when taken out of the furnace. Even when the Bessemer or open-hearth metal could *not* be hardened by rapid cooling, the manufacturers, nevertheless, desired to call it steel, because they could sell it more easily and get a better price. Thus the early definition of steel was sacrificed to commercial considerations. Metallurgists, however, do not despair of some day seeing the revival of a more logical classification for varieties of iron and steel.

LATER DEVELOPMENTS IN ORE SMELTING

The old so-called *direct process* of reducing ore to a relatively pure, malleable product has long been superseded by a smelting process which produces a liquid metal. The direct process is technically so simple and advantageous that it is "reinvented" at frequent intervals, but it is doubtful whether it will ever compete industrially until it can produce in a single operation, without the necessity of transferring to another furnace for remelting, a finished product capable of being cast or wrought into serviceable objects. Otherwise the product can command a price no higher than that of scrap of like analysis. Today practically all the iron ore smelted is made in the blast furnace into the impure liquid product known as pig iron.

The Blast Furnace.—The crude blast furnace of the fourteenth century has been developed from a chemical vessel which would produce a few tons of pig iron per month to a twentieth century type which can produce 1,200 tons per day. This development has proceeded along the lines of both evolution and revolution. The *evolution* has consisted in increase in efficiency of the original apparatus, such as the substitution of steam blowing engines for cruder devices, mechanical hoisting, and top charging; also a change in furnace design and other improvements whereby a larger amount of fuel could be burned per minute, for it is the speed of burning the fuel which determines the rapidity of the process. There have been two major *revolutions* in the operation: The first was a gradual change, whereby coke replaced charcoal as a fuel. This occurred first in England about the middle of the eighteenth century. The second revolutionary innovation was introduced in the beginning of the nineteenth century, when Neïlson first used preheated blast.

Mechanical Features of the Blast Furnace.—Except in size and details of design, the modern blast furnace embodies the same general principles as the fifteenth century model. Figure I-6 represents a furnace in vogue fifty years or so ago, illustrating the prominent features: At the throat of the furnace all raw materials are introduced, and the furnace is kept full at all times up to this point during its campaign of a few years. The charge is introduced by means of the bell *B*. The fuel is burned in the lower level where the tuyères blow in the preheated air for combustion. It is the burning of the lower portion of the fuel column which permits the charge to sink in the furnace and necessitates regular addition of new material at the throat. The blast furnace itself consists of a tall cylindrical stack lined with an acid (siliceous) refractory fire brick.

Furnace Parts.—The different parts of a blast furnace are designated by names which were the same fifty years ago as they are today. They are indicated in general in Fig. I-6 and summarized as follows: The lower part of the furnace which serves as a reservoir for the melted products is known as the *crucible* or *hearth*. It contains the *iron notch* or *tap hole* located a few inches above the bottom of the furnace, so that most of the liquid contents will be drained out of it when the tap hole is opened. The *slag notch* (also called *monkey*) is located far enough above the bottom of the furnace to allow below it a reservoir large enough to be packed with a column of coke and permit sufficient interstices between the coke particles to contain at least 200 tons of melted pig iron. The slag notch must be a few inches below the level of the *tuyères*, so that it may be opened at intervals and the slag drained out before it reaches the point of running back into the tuyère notches. The tuyères surround the top of the hearth at regular intervals. They project about 12 in. inside the furnace and are protected by copper tuyère coolers through which water flows to keep them from melting. The *bustle pipe* surrounds the furnace and distributes the heated blast to the several tuyères. The *bosh* is the sloping portion of the furnace extending from the top of the hearth to the bottom of the stack.

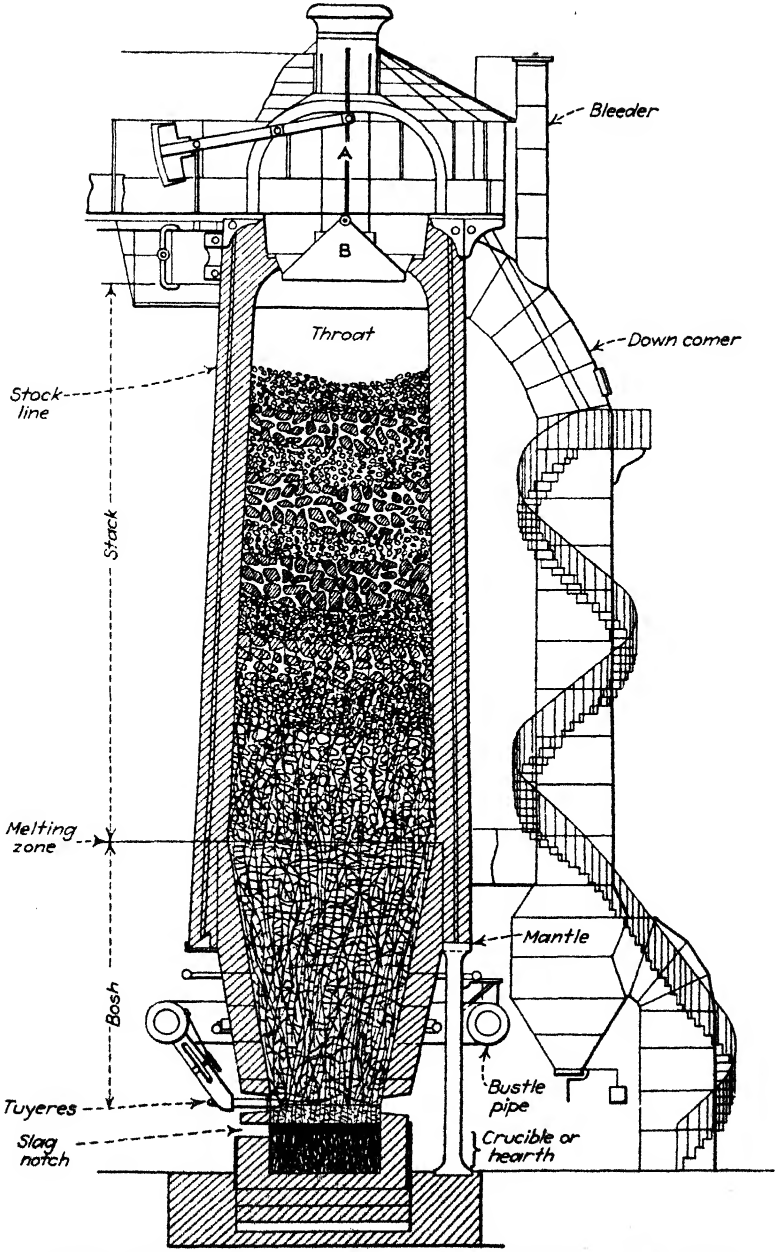


FIG. I-6.—A nineteenth century blast furnace sectioned to show interior.

The *inwalls* of the bosh are fitted with several rows of hollow steel castings in wedge shape, through which water is caused to circulate in order to cool the brickwork of the bosh. Everything is supposed to be melted in that zone of largest furnace diameter which marks the top of the bosh. Below the top of the bosh there should be no solid material except the coke itself. A column of coke extends from the top of the bosh to the very bottom of the hearth of the furnace. Beginners sometimes find it difficult to believe that the coke extends all the way down into the hearth through the liquid metal, and many practical men have doubted the possibility of this, but it has been demonstrated many times by inserting a bar through the tap hole. The *mantle* surrounds the furnace and is supported by columns, so that the upper part of the stack is not supported by the structure of the bosh and hearth, which, because of its high temperature, is not well adapted for support purposes. The *stack* extends from the top of the bosh to the *throat.* In the upper part of this stack there should be complete reduction of iron ore to spongy iron without melting. The *stock line* is the top of the solid materials in the furnace, and this line should be kept at a fairly constant level for reasons to be mentioned later. Above the throat is the charging mechanism which usually consists of two *bells*, one situated above the other. A modern furnace has four *downcomers* spaced equally around the periphery of the throat. Above these downcomers extend the *bleeders,* which permit of release of pressure, which may exist in an emergency, at the throat.

Charcoal vs. Coke as Fuel.—Charcoal was regularly used as a blast-furnace fuel up to a century ago. It is still used on occasion when one or the other of the following reasons exist: first, in a few rare cases, such as Sweden, where coke is excessively costly and supplies of charcoal can be obtained from near-by forests. This is a question of economics. It is becoming rarer, however, and, even in Sweden, is being partly replaced by heat obtained from electricity. The second reason why charcoal continues to be used is because it is a purer fuel than coke and produces a higher quality of cast iron, though at a higher cost. The sulphur in coke is its impurity which is most objectionable in iron smelting. The sulphur can be largely carried away in the slag when a high temperature is used in the furnace and a slag rich in calcium oxide is employed. This is costly but is cheaper practice than employing charcoal as fuel—first, because charcoal costs more per unit and, second, because charcoal is a relatively weak material. Therefore, it will not support a heavy column of material in the furnace, so that charcoal furnaces must be much smaller in size. This means, of course, smaller tonnage per 24 hr. with consequent increase in costs, especially labor costs. Some industries, however, are willing to pay an extra price for charcoal pig iron, because they believe that the product of this furnace gives a higher quality of cast iron, *e.g.*, for making chilled cast-iron rolls. One reason offered for the superior quality of charcoal iron over coke iron is that it is manufactured at a lower temperature. Indeed, this principle has been carried to the point where some charcoal-iron manufacturers do not even use preheated blast, and the resulting material, known as *cold-blast charcoal iron*, is desired by some users. It happens that the manufacture of charcoal and its by-products is carried on in the United States in connection with the smelting of iron ore with charcoal. The consequence is that industrially the plants seem

FIG. I-7.—Remains of the old charcoal iron furnace at Oxford, N. J. At this furnace, in 1834, hot blast was first used in America in an iron blast furnace.

to be more important from the chemical standpoint of the production of methyl alcohol and acetate of lime, so that economically the industry is more chemical than metallurgical. For this reason, and also because the operations are very small in comparison with other iron and steel processes which have to be discussed all too briefly in one book, we shall not deal further with charcoal smelting.

Preheated Blast.—In an iron blast furnace only about one-half of the calorific value of the fuel is usefully employed, while the remainder goes out of the top in the form of sensible heat and of combustibles, especially carbon monoxide, in the top gases. The sensible heat as well as the combustible value of this gaseous product can be used. James B. Neilson invented, in 1824, a method of using some of the calorific value of the top gases for the purpose of preheating the blast driven into the furnace. An illustration of his original apparatus[1] is shown in Fig. I-8. It will be seen that the blast is driven into the furnace through iron pipes. Around the pipes is situated a fire chamber in which the top gases from the furnace are burned and thus preheat the entering blast. This principle of countercurrent flow, in which

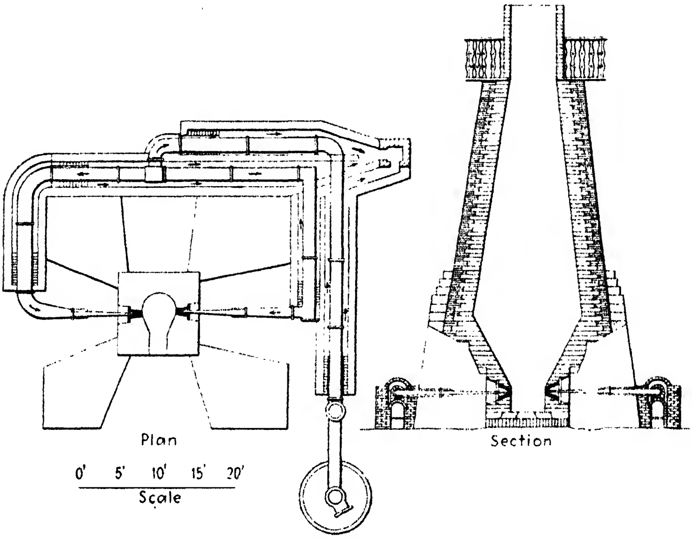


FIG. I-8.—Neilson's original iron blast-heating stove. (*From Fred Clements, "Blast Furnace Practice," vol.* II, 1929.)

---

[1] Taken from Clements, "Blast-furnace Practice," vol. II, p. 325.

the outgoing gases of any furnace are used to preheat the entering air, is known as the *recuperative system*. This recuperative method of preheating blast-furnace blast has long been superseded by a process known as a *regenerative system*. In the regenerative system there are always two or more regenerative chambers, containing a checkerwork of brick or some similar structure, whereby fire brick offers a large surface to hot, burning gases. The surfaces of the brick absorb the heat until the whole chamber has become a calorific reservoir. Then the next phase of the regenerative operation takes place, as follows: The burning gases are diverted to a second fire-brick chamber, and the air which is to be driven into the blast furnace is passed through the heated chamber, thereby absorbing the heat which has been impounded in the surface of the fire brick. A blast-furnace plant of the late nineteenth century usually included four hot-blast stoves. After a stove had been heated up by gas burning in it, it could be used for about an hour to preheat the blast. Usually it required 2 to 3 hr. to heat it up again before it next went on air. Four stoves were necessary, because the gases from the top of the furnace contain a good deal of dust, consisting of fine coke and ore particles carried over from the furnace charge. This caused the fire-brick channels between the bricks to become partially choked and the surface of the bricks to be glazed, which required occasional cleaning. Nowadays (because blast-furnace gas is more carefully cleaned before burning in the stoves), three stoves suffice for each blast furnace.

References

J. Newton Friend: "Iron in Antiquity," London, 1926.

H. Garland and C. O. Bannister: "Ancient Egyptian Metallurgy," London, 1927.

William Pulsifer: "Notes for a History of Lead," New York, 1888.

James M. Swank: "History of the Manufacture of Iron in All Ages, and Particularly in the United States from 1585 to 1892," Philadelphia, 1892.

Richard Peters, Jr.: "Two Centuries of Iron Smelting in Pennsylvania," 1921.

François Liger: "La ferronnerie ancienne et moderne," 2 vols., Paris, 1873.

Albert Sauveur: "The Metallography and Heat Treatment of Iron and Steel," 3d ed., Cambridge, 1926. This book covers well the theory and principles of physical metallurgy, metallography, and heat treatment of steel.

H. M. Howe: "Iron, Steel, and Other Alloys," 1903. This book contains three chapters upon the manufacture of iron and steel and ten upon

its constitution and properties, especially from the standpoint of metallography.

H. H. Campbell: "The Manufacture and Properties of Iron and Steel," 4th ed., New York and London, 1907. This is a great reference book by one of the best of the practical American metallurgical engineers. It is the best American reference book upon the manufacture of iron and steel but is not intended especially for beginners or those without technical education.

A. Ledebur: "*Handbuch der Eisenhüttenkunde*," 5th ed., Leipzig, 1906. This is an excellent reference book for those who read German and contains a very complete account of the metallurgy of both iron and steel and of their properties. There are also classified lists of the literature upon each of the branches of the subject.

Sir I. Lowthian Bell: "Principles of the Manufacture of Iron and Steel," London, 1884. This book well accomplishes its aim—*viz.*, to elucidate the principles of iron and steel manufacture—and no man can be either so well informed or so ignorant as not to understand the metallurgy of these metals better after reading it.

H. P. Tiemann: "Iron and Steel (A Pocket Encyclopedia)," New York and London, 3d ed., 1933. There is a wealth of general information in this book arranged for ready reference because in alphabetical order. It is in fact an encyclopedia of the iron and steel industry, with a sufficient explanation of all the terms and processes and products likely to be met with by those interested in the industry or trade.

H. M. Boylston: "An Introduction to the Metallurgy of Iron and Steel," New York, 1928.

Allison Butts: "A Textbook of Metallurgical Problems," New York, 1932 These problems not only teach how to calculate many very important things in connection with furnaces and their efficiency but give a good insight into the principles of the processes themselves.

Verein deutscher Eisenhüttenleute: "Anhaltszahlen für den Energieverbrauch in Eisenhüttenwerken," Dusseldorf, 1931.

James M. Camp and C. B. Francis: "The Making, Shaping, and Treating of Steel," 4th ed., Pittsburgh, 1925. This is an excellent practical treatise on the making, treating, and properties of iron and steel, according to the practice of the Carnegie Steel Co.

Bernard Osann: "Lehrbuch der Eisenhüttenkunde," 2 vols., Leipzig, 1915 and 1921. Contains an extended bibliography.

"Directory to the Iron and Steel Works of the United States," embracing the blast furnaces, rolling mills, steel works, forges, and bloomeries in every state and territory. Prepared and published by the American Iron and Steel Institute. The first edition of this book appeared in 1873, and the nineteenth in 1920. The data given are very complete and are classified for convenient reference.

"Ryland's Coal, Iron, Steel, Tin-plate, Metal, Engineering Hardware, and Allied Trades' Directory (for Great Britain only) with Brands and Trade Marks," published by Eagland & Co., Ltd., London, 1922.

Donald M. Liddell: "The Metallurgists and Chemists' Handbook," 3d ed., New York, 1930.

V. EVERETT KINSEY and THOMAS E. HOPKINS: "Index to Iron and Steel Patents," Pittsburgh, 1930.

The Journal of the Iron and Steel Institute, vol. I, London, 1869. This periodical appears twice a year and contains not only many original articles of great value but an almost complete collection of abstracts of the literature of iron and steel that is published anywhere, classified under headings for convenient reference. Anyone beginning research in any branch of iron and steel metallurgy should commence with this journal, as soon as the textbooks have been consulted.

Stahl und Eisen, vol. I, Dusseldorf, 1881. This is the best German periodical on iron and steel and contains not only many valuable original articles and abstracts but also translations. It is particularly useful in this latter connection, because of its translations of many articles from the Swedish.

Revue de Métallurgie, vol. I, Paris, 1904. This is a very valuable periodical for those who read French, not only for its original articles but also for its abstracts. Upon the more scientific side of metallurgy, *i.e.*, the properties and constitution of iron and steel, alloy steels, etc., it is without an equal.

Science Reports of the Tohoku Imperial University, Sendai, Japan, vol. I, about 1910. These contain reports in English of some of the most important physicometallurgical investigations now being conducted anywhere.

The Mineral Industry. Its statistics, technology, and trade, vol. I, New York, 1892, to vol. XLII, 1933. This contains a review every year of the technology and trade of each of the metals listed alphabetically, as well as the statistics of production, price, etc. The articles usually include a review of the progress of the metallurgy during the year.

The Iron Age, vol. I, New York, 1869. This is the oldest and largest of the American iron and steel technical magazines and not only deals with the scientific and technical side of the subject but also acts as a sort of weekly newspaper upon the condition of the iron trade and recent happenings of interest.

Transactions of the American Institute of Mining and Metallurgical Engineers, vol. I, New York, 1871. The American Institute is the leading aggregation of both mining engineers and metallurgists in America. These transactions contain many original articles of value.

Mining and Metallurgy. Monthly publication of the A. I. M. E.

Year Book of the American Iron and Steel Institute. Contains annually accounts of recent American practice and innovations.

Steel, formerly the *Iron Trade Review*, Cleveland, Ohio. Although this magazine aims to deal principally with iron trade conditions, it contains also a great many technical articles of importance.

Jernkontoret Annaler, vol. I, Upsala, Sweden, 1846. For many years this has been the standard iron and steel technical magazine of Sweden, representing the iron and steel makers there.

Proceedings and also *Specifications of the American Society for Testing Materials*, vol. I, of *Proceedings*, Philadelphia, 1899 to 1902. The *Standard Specifications* are published every third year, as 1918, 1921, etc. The *Proceedings* contain many published monographs and researches on iron, steel, and their properties, testing, and treatment. The specifications are widely recognized and used.

Transactions of the American Society for Steel Treating, vol. I, Cleveland, Ohio, 1920. Much of the earlier publications is elementary in character, but recent volumes contain valuable data, especially on the practical side of heat treating.

Metal Statistics. Published annually in New York. Gives some prices, production statistics, etc.

Comité des Forges de France. The *Bulletin* and some other publications of this society, which appear somewhat irregularly, give valuable data on the iron and steel industry of France.

Metals and Alloys, New York, 1929. Containing many technical articles as well as metallurgical abstracts and digests.

Metal Progress. Published monthly by the American Society for Steel Treating and containing articles of great value on iron and steel manufacture, physical metallurgy, and heat treatment.

CHAPTER II

FIRST APPLICATIONS OF CHEMICAL THEORY IN FERROUS METALLURGY

The primitive process of producing a fairly pure iron, mixed with particles of slag equivalent to about 1 or 2 per cent of the weight of the mass, continued for a long time after its economic usefulness was superseded by cheaper products. The production of a liquid metal, maintained in a liquid condition until all the chemical changes to which it is to be submitted have been completed, permits handling a product in enormous quantities at a minimum of cost. On the other hand, there seems to be a very slight, almost imperceptible, falling off in quality of iron when it is submitted to oxidation at a high temperature. The extent of this superiority is so slight that it has eluded a thorough proof of its extent; nevertheless, many makers of steel objects of the highest quality at first held somewhat tenaciously to the use of raw materials which had never been melted or subjected to very high temperatures. However, as pig iron gradually became lower and lower in price as compared with wrought iron, some iron masters of England, which long held the supremacy in the production of the largest amount and the highest quality of iron and steel, finally turned their attention to making wrought iron out of pig iron, instead of producing it directly from iron ore. This involved a definite complication of processes and a duplication of chemical operations. This will be evident from the following summary: In the upper half of the blast furnace the old direct process is repeated, with production of a fairly pure iron direct from the ore without melting. This reduction should be entirely complete before the ore has traveled halfway down the furnace stack. Then follow a melting of the metal and its admixture in the lower part of the furnace with impurities, especially carbon, which makes it brittle and unworkable in a forge either hot or cold. In order to make wrought iron out of this brittle material, it had to be freed from its objectionable impurities. A method of doing this was finally developed in the eighteenth century. The final development of the process was due to the genius of Henry Cort and resulted in the so-called *pig boiling*, or puddling, process which is used today for wrought-iron manufacture.

Chemical Law of Melted Metallurgy.—The reduction of metals from their ores, as well as the elimination of impurities from crude metals, depends upon the following chemical law, which prevails wherever melted elements or compounds are subjected to either reducing or oxidizing influences: *Reduced elements tend to dissolve in one another; oxidized elements tend to separate from reduced elements.*

It happens that almost all reduced elements are heavier per unit volume than oxidized elements; therefore, the law of gravity tends to help in the separation of the two, although the fundamental basis of the separation is chemical, *viz.*, that the oxidized elements tend to dissolve in each other, and the reduced elements tend to expel all oxidized elements from them. This is exemplified in the blast-furnace operation when the melted iron saturates itself with carbon and with all the silicon, manganese, phosphorus, and sulphur[1] which are present in the reduced condition. It may be applied likewise in the removal of carbon, silicon, manganese, phosphorus, and sulphur if melted iron is subjected to slightly oxidizing conditions which convert the impurities into an oxidized form and leave the iron in reduced form.

Chemical Strength of Metals.—Elements can be arranged in a series beginning with the one which has the greatest chemical affinity for oxygen and continuing in sequence. This may be illustrated by determining the amount of heat evolved when an element unites with oxygen to form a definite compound. It is almost universally true that, the greater the amount of heat developed, the greater will be the chemical affinity involved. Table II-I is an example of this sequence of affinities and represents the relative affinity of the elements included therein as existing at atmospheric temperature. It happens that their chemical affinities at other temperatures are usually proportional to their affinities at atmospheric temperature. Carbon is the great exception in this respect and we shall discuss it in detail later.

---

[1] Sulphur will dissolve in iron if it is in the form of iron sulphide, FeS, but not if it is in the form of calcium sulphide, CaS, or sulphur dioxide, SO_2.

For the present, we may illustrate the application of the facts comprised in this table somewhat as follows: If we should submit a mixture of those oxides listed in Table II-1 to reducing influences of gradually increasing intensity, we should begin to reduce the elements from their oxides commencing with the ones at the bottom of the list and proceeding upward. This would result in the elements' dissolving in each other as fast as reduced. In practice we adjust the intensity of our reduction by the temperature, because carbon is more intense in its reducing effect the higher the temperature.

TABLE II-1 HEATS OF FORMATION OF THE OXIDES
Calories per Kilogram of Oxygen

Element	Oxide	Heats of formation
Ca	CaO	9,485
Al	Al_2O_3	8,120
V	V_2O_3	7,399
Si	SiO_2	6 280
Mn	MnO	5,438
Zn	ZnO	5 205
Cr	Cr_2O_3	5,080
P	P_2O_5	4,568
Sn	SnO_2	4,315
Cd	CdO	4 075
Fe	Fe_2O_3	3,994
W	WO_3	3,990
Mo	MoO_3	3,655
H	H_2O	3,617
Ni	NiO	3,613
Co	CoO	3,600
S	SO_2	2,216
Cu	CuO	2,180

Impurities Present When Iron Is Smelted.—To illustrate an application of the facts comprised in this table, we may assume that an iron ore contains some of the frequent impurities, such as oxides of copper, phosphorus, manganese, silicon, and aluminum. Obviously, all the copper oxide would be reduced and go into the iron. Carbon would go into the iron because it is already present in the coke in reduced form. Phosphorus, manganese, and silicon would not go into the iron provided we gaged our intensity of reduction with that exactness which would cause reduction of the iron oxide without the reduction of the oxides above it in Table II-I. This we can do in the direct process, where the iron ore is reduced without melting. But, in order to produce liquid metal, we must have a temperature higher than that necessary for the mere reduction of iron oxide, with the result that phosphorus and a certain amount of manganese and silicon are unavoidably reduced from their oxides and consequently go into the iron. This is indeed the means whereby the blast-furnace operator produces pig iron with silicon less than 1 per cent, or as high as 10 per cent, if desired. There is always a great abundance of silicon dioxide present, both in iron ores and in the ash of the coke. Therefore, it is only necessary to increase the intensity of reducing influences to introduce a greater quantity of silicon into the melted metal. The oxide of aluminum is so far above that of iron that, although we frequently have Al_2O_3 (clay) in our ores, nevertheless, the reducing intensity in the blast furnace is never strong enough to reduce aluminum into the iron.

The Application of the Chemical Law to Pig-iron Purification.—This same law may also be applied in the reverse direction to the removal of the impurities in pig iron: The common impurities in pig iron are carbon, silicon, manganese, phosphorus, and sulphur. If the iron be melted and subjected to slightly oxidizing conditions, the first elements to be oxidized will be those highest in Table II-I, *viz.*, silicon, manganese, and phosphorus. These oxidized bodies, being lighter than the iron, will float upon it and dissolve in each other to form what is known as a *cinder* or *slag*. When the temperature gets somewhat higher, carbon also will be oxidized and forms carbon monoxide gas which bubbles out of the iron and produces a boiling effect.

Pig-iron Boiling or Puddling Process.—This is the principal method of manufacturing wrought iron today. It was invented by Henry Cort in the year 1780 and later developed by S. B. Rogers and Joseph Hall. In this process the pig iron is melted in a reverberatory furnace (see Fig. II-1) the hearth of which is lined with oxide of iron. During the melting there is an elimination of silicon and manganese and the formation of a slag which automatically adjusts itself to a very high content of iron oxide by absorption from the lining. After melting, the heat is reduced and a reaction is set up between the iron oxide of the slag and the remaining silicon, manganese, carbon, phosphorus, and sulphur of the bath, whereby the impurities are oxidized and all removed to a greater or less extent. The slag, because of its basicity (by iron oxide), will retain all the phosphorus oxidized, and therefore the greater part of this element may be removed. The sulphur is the least removable of the impurities. The oxidation of all the impurities is produced chiefly by the iron oxide in the slag and the lining of the furnace, although it is probable that excess oxygen in the furnace gases assists the slag.

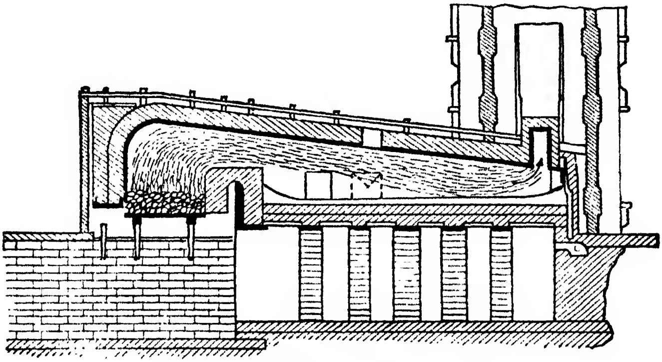


Fig. II-1.—500-lb. puddling furnace.

The purification finally reaches that stage at which the utmost heat of the furnace is not sufficient to keep the charge molten, because iron, like almost every other metal, melts at a higher temperature the purer it is. The metal therefore "comes to nature," as it is called; *i.e.*, it assumes a pasty state. The iron is rolled up into several balls, weighing 125 to 180 lb. apiece, which are removed from the furnace, dripping with slag, and carried over to an apparatus, where they are squeezed into a much smaller size and a large amount of slag ejected from them. The squeezed ball is then rolled between grooved rolls to a bar,

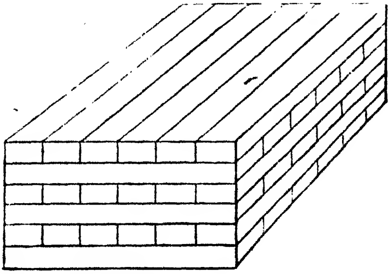


Fig. II-2.—Method of piling muck bar.

whereby the slag is still further reduced, so that the bar contains at the end usually about 1 or 2 per cent. This puddled bar or, "muck bar," is cut into strips and piled up, as shown in Fig. II-2, into a bundle of bars which is bound together by wire, raised to a welding heat, and again rolled into a smaller size. This rolled material is then known as "merchant bar," and all wrought iron, except that which is to be used for manufacture into crucible steel, is treated in this way before sale. The effect of the further rolling is to eject more slag, and also to make a cross network of fibers, instead of a line of fibers all running in the same direction, *i.e.*, lengthwise of the bar. The fibers are produced by the action in rolling of drawing out the slag into strings as shown in the micrograph (Fig. II-3).

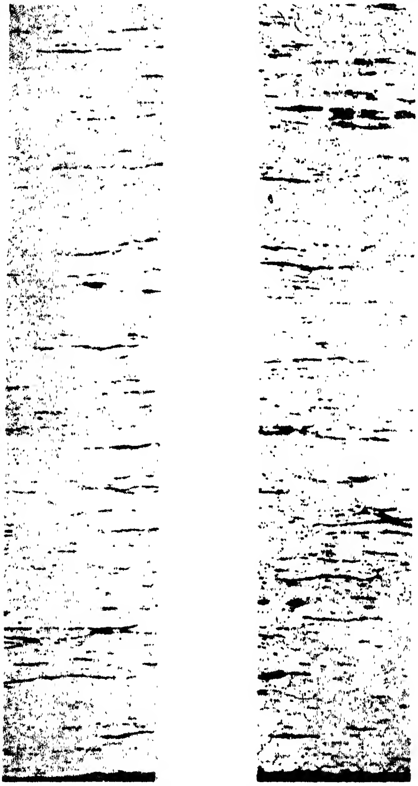


FIG. II-3.—Microstructure of wrought-iron pipe made by the Aston process. Magnified 50×. Section on left is unetched; that on right is etched. (*From Rawdon and Knight, U. S. Bureau of Standards, Research Paper* 124, *December*, 1929.)

Puddling Furnaces.—There are many different varieties of puddling furnace, varying in capacity from 300 to 1,500 lb. and even more, but the commonest is probably the 500-lb. furnace, built either single or in pairs, back to back, the latter arrangement having the advantage of reducing loss of heat by radiation, which is always a very large factor. Puddling furnaces are heated by gas or bituminous coal. The commonest method is a deep bituminous-coal fire, giving a long flame, and with a large area of grate in relation to the area of the hearth in order that a high temperature may be maintained.

Fettling.—The hearth is lined or "fettled" with oxide of iron in the form of roll scale, or high-grade iron ore, or "bulldog," *i.e.*, roasted puddle cinder, and this oxide, together with the metal oxidized during the melting, supplies the base which automatically maintains a very basic slag and also serves as the principal oxidizing agent of the impurities. The fettling is repaired between melts as often as is necessary and suffers wear with each operation.

Puddling.—Pig iron is usually charged by hand through the working doors of the furnace, and the puddler's assistant fires vigorously in order to melt it down as fast as possible, which usually takes about 30 to 35 min. As soon as it is melted, there follows a short stage of 7 to 10 min., during which iron oxide in the form of roll scale or very high-grade iron ore is added, in order to make a very basic slag, the charge being thoroughly mixed and cooled, for which purpose the damper is put on and sometimes even water is thrown on to the bath. The object is to reduce the temperature to the point where the slag will commence to oxidize the impurities, and especially the phosphorus and sulphur, ahead of the carbon. At low temperatures, phosphorus oxidizes ahead of carbon; at higher temperatures, carbon in preference to phosphorus (see Table II-II for slow removal of carbon at first). As soon as the carbon reaction is started, light flames begin to break through the covering of slag, produced by burning carbon monoxide:

$$Fe_2O_3 + 3C = 3CO + 2Fe; \quad (1)$$

$$CO + O = CO_2. \quad (2)$$

The slag must be very basic at this time lest the carbon monoxide reduce phosphorus and sulphur and cause them to return to the metal.

As the carbon monoxide forms more and more abundantly, the charge is more violently agitated by its escape, and the "boil" is in progress. The formation of gas in its interior causes the charge to swell greatly, and it thus rises in the furnace and a large amount of slag pours out of the slag hole and into a waiting buggy. About one-half of all the slag produced during the process is removed at this time. The boil continues from 20 to 25 min., and during this time the puddler stirs or "rabbles" the charge vigorously with a long iron rabble, shaped like a hoe. Toward the end of the boil the metal begins to come to nature, and points of solid metal project through the cover of slag, while other pasty masses form on the bottom of the furnace. Both of these things must be corrected immediately by the puddler (1) lest the iron that is exposed to the furnace gases become too much oxidized, (2) lest the iron sticking to the cold bottom

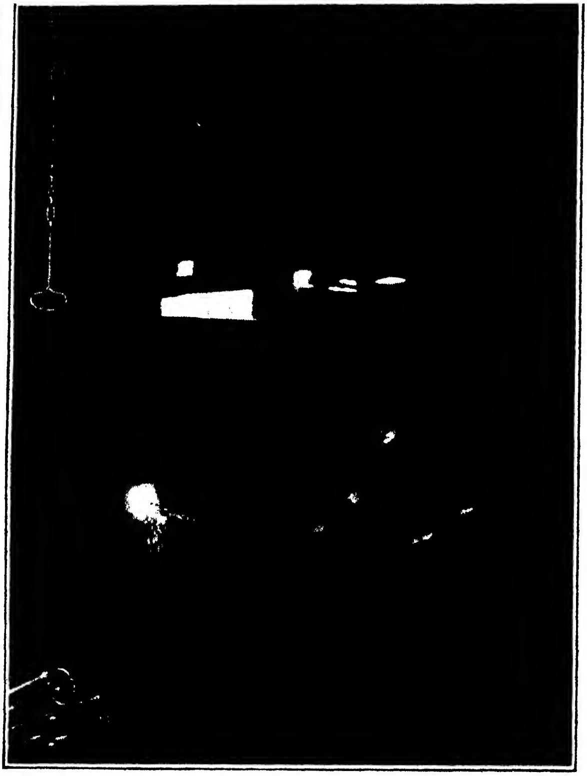


FIG. II-4.—Puddling. (*Courtesy of Central Iron and Steel Co.*)

become too much chilled, or (3) lest the charge be not uniform in composition. Finally, all the charge comes to nature and the "balling" period begins and occupies about 15 to 20 min. During this period the bath is divided into three or four portions, which are each rolled up into a ball, consisting of a large number of particles partially welded together. The balls are rolled up near the fire bridge in order, first, to protect them from direct contact with the flame and, second, to keep them as hot as possible until the puddler can draw them, so that the slag may be fluid and thus more easily squeezed out of the metal. The balls are then squeezed in turn, and the furnace hearth repaired for another charge. The total time between operations is usually from 1 hr. 10 min. to 1 hr. 40 min.

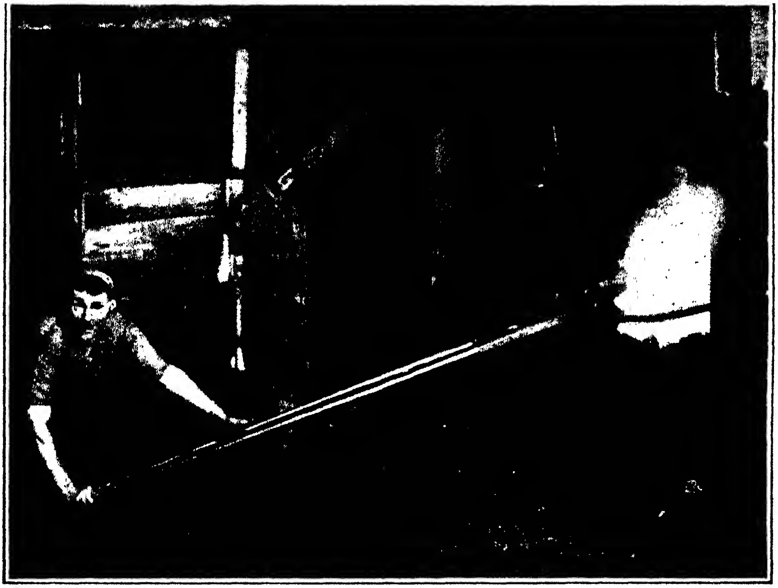


Fig. II-5.—Removing the puddle ball. (*Courtesy of Youngstown Sheet and Tube Co.*)

Squeezers.—A very common form of squeezer is that shown in Fig. II-6, the distance between the inner and outer circle being greater on the entering side than on the outgoing side. As the inner circle revolves, the corrugations on the surface carry the ball around, giving it at the same time a movement of rotation. By the time the ball exists on the opposite side, it has been squeezed and kneaded sufficiently to get rid of a large amount of slag. In European countries the squeezer is rarely used and the ball is "shingled"—reduced under a hammer—to weld its particles together and force out the slag.

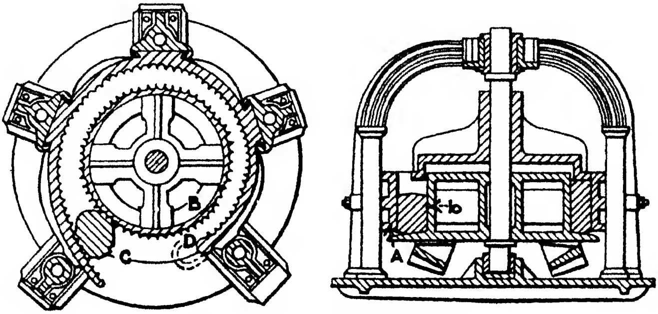


Fig. II-6.—Rotary squeezer.

Chemistry of the Process.—The removal of the impurities during the puddling process is shown in Table II-II, which is quoted because it records probably the first successful attempt ever made to study in this way the chemistry of an iron or steel process. A similar study is graphically represented in Fig. II-7.

Table II-II.—Removals in Hand Puddling
(By Calvert and Johnson, *Philosophical Magazine*, 1857)

	Time after charging		C, per cent	Si, per cent	S, per cent	P, per cent
	Hr.	Min.				
Sample 1	0	0	2.275	2.720	0.301	0.645
Sample 2	0	40	2.726	0.915		
Sample 3	1	00	2.905	0.197		
Sample 4	1	5	2.444	0.194		
Sample 5	1	20	2.305	0.182		
Sample 6	1	35	1.647	0.183		
Sample 7	1	40	1.206	0.163		
Sample 8	1	45	0.963	0.163		
Sample 9	1	50	0.772	0.168		
Puddled bar	..	..	0.296	0.120	0.134	0.139

During the melting-down stage, the silicon and manganese in the puddling charge are almost entirely eliminated, and these reactions are as complete as they will be by the end of the "clearing" stage which follows it. Much phosphorus and sulphur are also removed. The boil period is, of course, the period during which the carbon escapes, together with some phosphorus and sulphur which were not removed during the first two periods.

Fuel.—The temperature of the puddling process is as high as can be obtained in furnaces of this type without preheating the air.[1] The result is a very large waste of heat up the chimney, although sometimes economy in this respect is obtained by placing boilers, or else furnaces to heat metal for the rolls, where they will receive the waste heat of the puddling furnaces. The two greatest items of expense in the puddling process are the fuel used and the excessive labor, which, on account of the strength and endurance demanded, receives a high price. The amount of fuel burned per ton of iron produced will usually be about one ton of a soft bituminous coal, or a little more, although better figures than this are obtained in some cases.

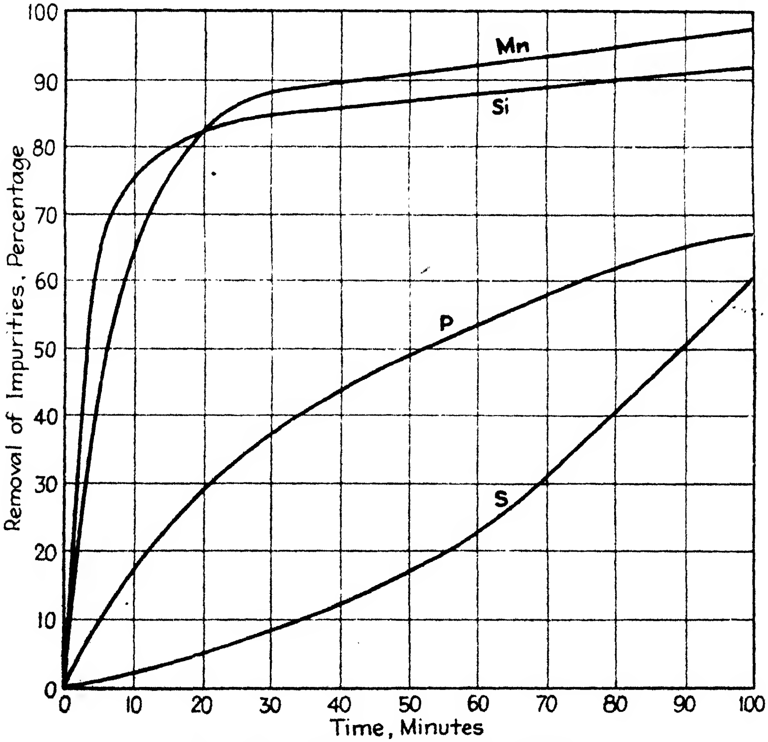


Fig. II-7.—Removals in hand puddling.

---

[1] Indeed, in some cases the air is preheated by the regenerative process, although this is not the usual practice.

Losses.—The loss in the puddling process usually averages from 4 to 6 per cent of the weight of the metal charged. The following table gives a typical example of loss:

Table II-III.—Table of Losses in Hand Puddling

Element Burned	Percentage of Loss
Silicon	1.00
Carbon	3.50
Sulphur	0.20
Phosphorus	0.50
Manganese	0.30
Total	5.50
Iron reduced from oxide[1] =	1.00 per cent gain
Net loss	4.50

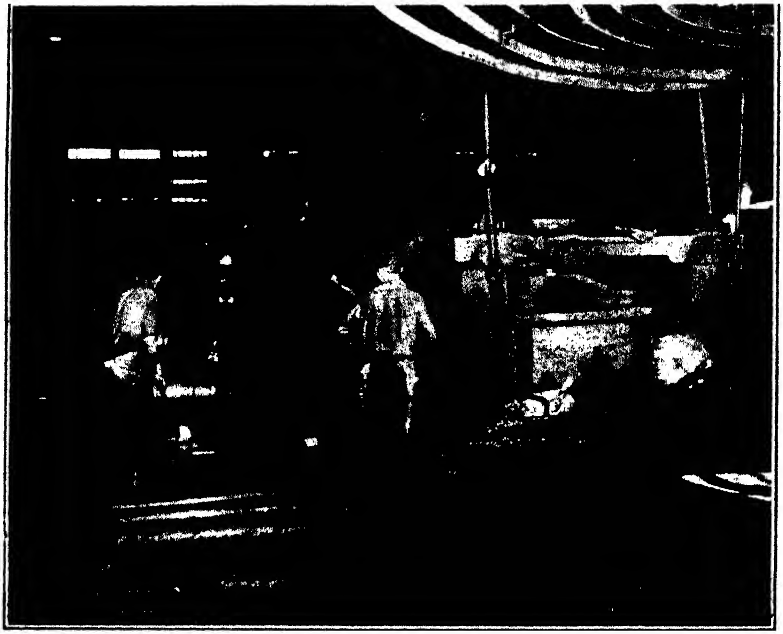


Fig. II-8.—Squeezing puddle balls and rolling puddle bar.

Slag.—The slag which runs from the tap hole during the boil is known as *boilings*, while that tapped out at the end of the process is known as *tappings* or *tap cinder*. The characteristics

---

[1] There is much iron oxidized and carried off in the slag, but there is also much reduced by impurities. The figure here given represents the excess of reduction over oxidation; in some cases it runs as high as 6 per cent or more.

of the boilings are that they contain a larger amount of phosphorus than the tappings, and also that globules of metallic iron are carried off in the violent agitation of the boil. An analysis of the two varieties, giving a mean composition from seven heats, is as in Table II-IV.

TABLE II-IV.—SLAG ANALYSES. PUDDLING PROCESS

Components	Boilings	Tappings
Ferric oxide, Fe_2O_3	6.94	12.90
Ferrous oxide, FeO	62.61	64.62
Silica, SiO_2	19.45	15.47
Phosphoric anhydride, P_2O_5	6.32	3.91
Not determined, MnO, S, CaO, etc.	4.68	3.10
	100.00	100.00
Total iron	53.55	59.29

The amount of slag will depend chiefly upon the amount of silicon in the pig iron. It will average in weight about one-half the weight of the charge, where the silicon is high, as in English practice (say 1.70 to 2 per cent), and about one-quarter to one-third in American practice, where the silicon is about 1 per cent.

Bundled Scrap.—In the United States a good deal of wrought iron is made every year by bundling scrap up into a pile roughly resembling Fig. II-2.[1] This is then tied up with wire, heated to a welding heat, and rerolled into "puddle bar." This is an inferior grade of product.

RECENT PROGRESS IN WROUGHT-IRON MANUFACTURE

The greatest handicaps to wrought-iron manufacture are (1) labor and (2) the small size of the operations of manufacture as compared with those for steel. The labor problem is not only that workers of skill and endurance are required but more particularly that the type of labor is not attractive to men of intelligence and it has become increasingly difficult to secure iron puddlers. The first attempt to meet this was the use of puddling furnaces which could be mechanically rocked and tilted or rotated so as to avoid the severe labor of puddling and balling. These furnaces perform their work satisfactorily and produce a high

---

[1] See p. 27.

grade of wrought iron. Their use, however, has never become general.

The Aston Process.—The Aston process is a decided departure from the method of purification by puddling. It consists in blowing pig iron in an acid Bessemer converter until its silicon, manganese, and carbon are eliminated. The liquid bath is then poured into a liquid bath of slag, which has been separately melted in a suitable furnace and carried in a ladle to a convenient point for the pouring operation. This quenching of molten iron in molten slag is called a *shotting* operation. It results in the iron solidifying and inclosing within it particles of slag. The pasty iron is removed from the slag bath and squeezed and rolled in the ordinary manner into the desired shape. The chemical composition of this Aston process wrought iron is found to be very close to that of hand-puddled iron, but with the advantage that the Aston process iron has been more uniformly freed of carbon, and the so-called *carbon streaks* sometimes found in puddled wrought iron are absent. The amount of entangled slag in the new iron is approximately the same, and it never contains relatively large particles of slag which are sometimes found in hand-puddled wrought iron. The mechanical properties, such as tensile, torsion, and impact tests are about the same in the two irons. It is also probable that the corrosion resistance of the Aston metal will be the same as that of hand-puddled iron, although definite data on this point cannot be determined except

FIG. II-9.—The Aston "shotting" process. (*From Aston, American Institute of Mining and Metallurgical Engineers, September,* 1929.)

by service tests lasting over a number of years, because so-called *accelerated tests* for corrosion are admittedly unreliable.

Reference

SAMUEL BALDWYN ROGERS: "An Elementary Treatise on Iron Metallurgy," London, 1858.

CHAPTER III

THE AGE OF STEEL

The Cementation Process.—Steel was made in a primitive age, before any written records existed, by the absorption of solid carbon by solid red-hot iron. This process was known as the *cementation process*. The carbon cemented or soaked into the iron and converted it into steel in a period usually extending over some hours in length. This ancient process existed for the manufacture of the very highest quality of tool steels, probably into the beginning of the present century. The metal, when properly made, had a very high quality. It has been believed by some that its toughness and durability might be partly ascribed to the fact that low temperatures had always prevailed at each stage of its manufacture. However, the superiority, if any, was very slight and the process has apparently become obsolete.

"Cast," or Crucible, Steel.—The second steel process to be developed was the melting of wrought iron in crucibles with some carbonaceous material which contributed carbon to the liquid mass and resulted in an iron containing in the general neighborhood of 1 per cent of carbon. Obviously, the purity of the product would depend upon the purity of the raw materials used, because no purification was practicable. Aside from possible isolated instances in early days, the process was devised before 1740 and first commonly used and developed by Benjamin Hunsman of Sheffield, England. In England clay crucibles are used and in America crucibles of graphite which hold about 100 lb. apiece and last longer than the clay crucibles. The furnaces are either coke or anthracite beds into which the crucible is placed, or regenerative gas furnaces capable of heating the crucible and charge to about 1700°C. It requires about two or three hours to melt the solid material, and it is then held molten and liquid in the furnace for a period of one-half to one hour longer in order that it may entirely free itself from solid particles, such as slag in the wrought iron or other oxides, and in order that it may be entirely free from gas. The success of the process is very largely dependent on the skill of the operator, including the proper killing, pulling out of the furnace, and pouring. The name of cast steel was early given to the process developed by Benjamin Hunsman, because it was poured into ingots or molds while liquid, in contradistinction to the cemented steel which was impregnated with carbon at a yellow heat while solid.

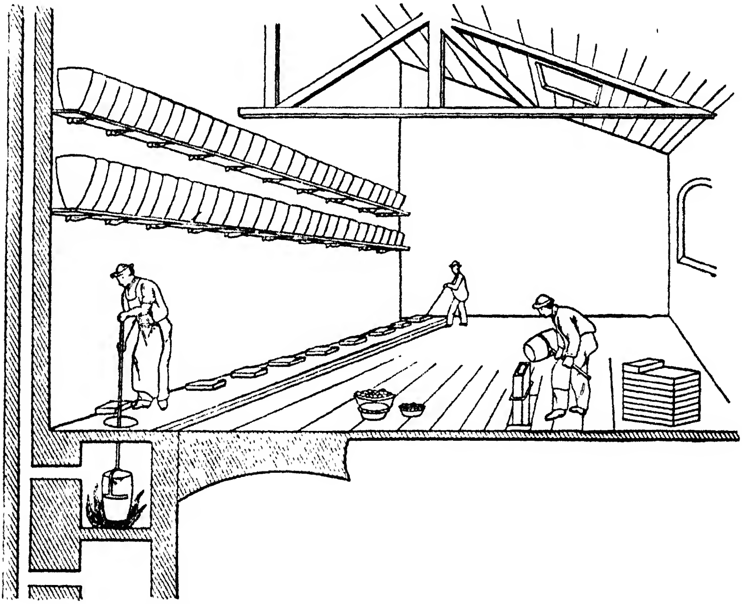


FIG. III-1.—Section through Sheffield melting house.

The Situation Previous to the Age of Steel.—In the first part of the nineteenth century steel could be made only on a somewhat small scale, because of the excessive amount of labor involved in the processes in vogue. The manufacture of wrought iron is also one which does not lend itself to a so-called *tonnage production.* The civilization of man was advancing to a point where great advances in industry, transportation, methods of communication, and convenience could be made, provided a cheap material for structural purposes could be obtained on a large scale. Cast iron did not meet this need because it was too brittle, and wrought iron and steel could not be made in sufficiently large quantities. Cast iron was used for many purposes which we now consider unsuitable, such as, for example, highway bridges. Railroad rails were made of wood with a wrought iron or steel strap thereon or else were made of wrought iron with a strip of steel over the head. Ships, buildings, most bridges, most fences, and almost all containers were of wood. Hardware, tools, machinery, railroad rails, agricultural implements, and weapons were made of iron and steel but the extent of industrial production was enormously limited by the small amount of metal that it was possible to produce with the limited processes then in vogue.

A Technical Revolution.—A new era began when man learned how to secure high temperatures in iron and steel manufacture. Then he learned that the secret of economy in operation and large tonnages in production inhered in keeping the metal liquid at all times until it has undergone all the chemical changes which are to be wrought in it. The full benefit of this practice required about fifty years' development in the United States and it is only now coming into full practice in England and Europe. It involves producing pig iron in a liquid form, transferring it in that condition to a furnace where it is purified, and then delivering it in a final state of purification and chemical adjustment to be cast into ingots, which are not allowed to become cold until they have been rolled into finished products, such as railroad rails, I beams, plates, and a hundred other common forms. The chemical adjustment includes producing metal as low as possible in its harmful impurities, such as phosphorus and sulphur, as well as more elusive components, such as oxygen, nitrogen, or other gases, and specks of oxide and like entangled particles. The product also contains when finished some carbon, usually for strength but sometimes also for hardness, with usually manganese and sometimes silicon, which act as scavengers to help purify the steel and incidentally contribute desirable properties. When alloy steels are to be made, then we must add nickel, chromium, etc., to the other ingredients.

The Attainment of High Temperature.—Between 1850 and 1860 Henry Bessemer in England experimented with a process of blowing unheated air through, or on the surface of, liquid pig iron. We have seen that pig iron contains 5 per cent or more of impurities, notably carbon, silicon, manganese, phosphorus, and sulphur. All of these except sulphur can be oxidized at a red heat more readily than can iron. Bessemer, therefore, conceived the idea of blowing air into the liquid metal and burning out of it its impurities. He calculated from chemical information that the amount of heat generated by this combustion would be more than sufficient to keep the whole mass in a liquid state until purification was complete. The same basic idea had occurred previously to an American by the name of William Kelly, who built a small vessel and attempted to work the process. Many Americans have claimed that Kelly is the real inventor, because he started his work about eight or nine years before Bessemer did. However, Kelly and his backers had abandoned their efforts and never developed their process until after the Bessemer process was being successfully used in England and Sweden.

In spite of the ridicule of many practical iron men, who expected that a mass of liquid iron would be quickly chilled and frozen if exposed to a blast of cold air, Bessemer's efforts resulted in success. The bath was so much hotter after burning its contained silicon, manganese, and carbon that it remained liquid even though purer than at the beginning. Bessemer, however, received a very serious check because of three things: First, the metal became so charged with oxygen that it was brittle and unworkable when they tried to roll it after solidification. This was finally remedied by putting about 1 per cent of manganese into the liquid bath to purge it of the greater amount of its oxygen before it solidified. This effect was beneficial, although the complete elimination of oxygen has never been accomplished up to the present time by any of the purification processes. The second handicap met in the Bessemer process was that sulphur, which is eliminated in puddling to the extent of about 60 per cent of its content, was not reduced at all in the Bessemer process. Sulphur dissolves in iron as ferric sulphide. The puddling slag, containing a large proportion of iron oxide, will also dissolve ferric sulphide and, therefore, take a share of it from the iron. Furthermore, iron oxide will expel some sulphur from iron, perhaps by the formation of ferrous sulphate, from which sulphur trioxide is later volatilized. Unfortunately, none of these desulphurizing influences existed in the operation performed by Bessemer. Third, phosphorus, three-quarters of which is eliminated in puddling, was not lowered by oxidizing in the Bessemer blow. This was most surprising, because phosphorus is above iron in the electropotential series[1] and should be oxidized

---

[1] See Table II-I (p. 25).

first. The explanation proved to be that phosphorus formed an acid radical, phosphoric anhydride, which would not remain in a slag which was predominantly acid, as was the case of the Bessemer slag because of the large percentage of silicon dioxide produced by the oxidation of the silicon in the pig iron, together with silicon dioxide dissolved from the lining by MnO and iron oxide. Phosphorus is readily oxidized and carried into the slag in the puddling process, where the slag is basic by virtue of the predominant amount of iron oxide contained in it. But where there is not enough basic radical to satisfy all acids, the stronger acid drives the weaker one out of combination. So that phosphorus could not be held in a silica slag.

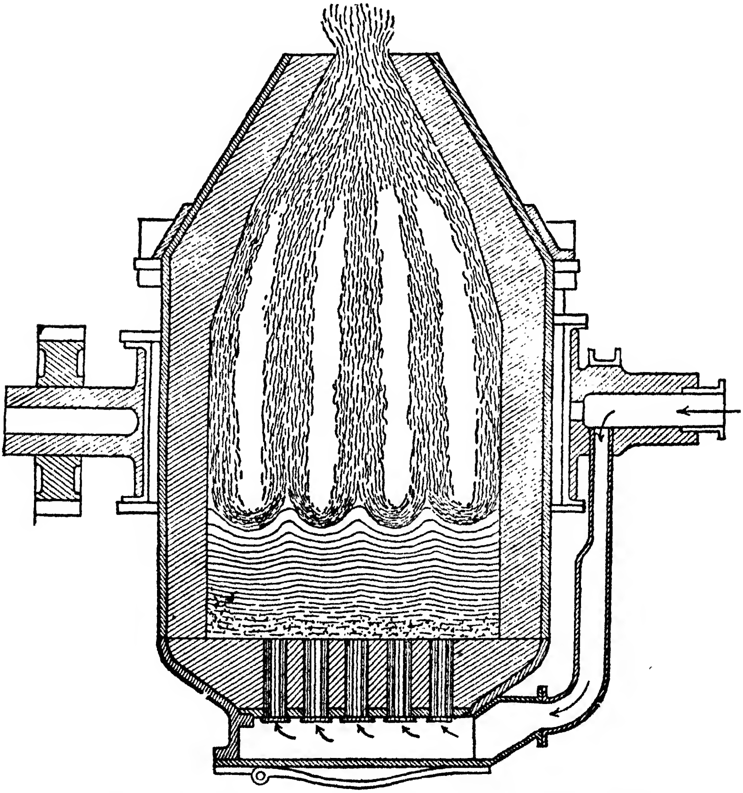


FIG. III-2.—Section through Bessemer converter while blowing.

Bessemer Process.—In a modern United States Bessemer process perhaps 25 tons of melted pig iron are poured into a hollow pear-shaped converter lined with siliceous material. Through the molten material is then forced 30,000 cu. ft. of cold air per minute. In about 4 min. the silicon and manganese are all oxidized by the oxygen of the air and have formed a slag. The carbon then begins to oxidize to carbon monoxide, CO, and this boils up through the metal and pours out of the mouth of the vessel in a long brilliant flame. After another 6 min. the flame shortens or "drops"; the operator knows that the carbon has been eliminated to the lowest practicable limit (say 0.04 per cent) and the operation is stopped. So great has been the heat evolved by the oxidation of the impurities that the temperature is now higher than it was at the start, and we have a white-hot liquid mass of relatively pure metal. To this is added a carefully calculated amount of carbon to produce the desired degree of strength or hardness, or both; also about 1.0 per cent of manganese and 0.15 per cent of silicon.[1] The manganese is added to remove from the bath the oxygen with which it has become charged during the operation and which would render the steel unfit for use. The silicon is added to get rid of the gases which are contained in the bath. After adding these materials, or "recarburizing" as it is called, the metal is poured into ingots, which are allowed to solidify and then rolled, while

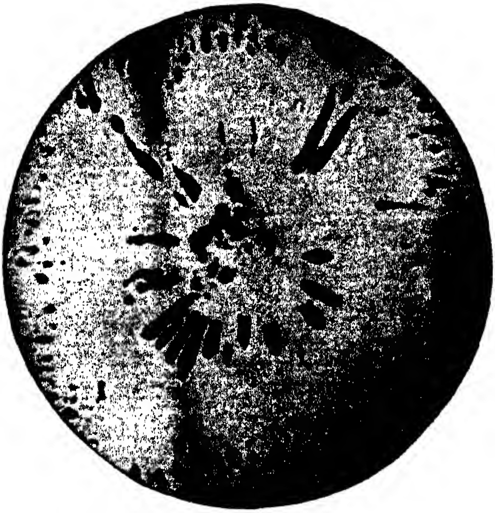


FIG. III-3.—Blowholes or gas bubbles in steel.

---

[1] In the case of making rail steel.

hot, into the desired size and form. The characteristics of the Bessemer process are: (*a*) great rapidity of purification (say 10 min. per "heat"); (*b*) no extraneous fuel is used; and (*c*) the metal is not melted in the furnace where the purification takes place.

A New Definition for Steel.—Wrought iron was defined as iron too low in carbon to be capable of hardening by quenching, and also iron entangled with minute particles of slag. Large tonnages of Bessemer metal soon began to be produced with carbon as low, or almost as low, as that in wrought iron. But the Bessemer metal did not contain particles of slag, because the bath remained liquid until the purification process was complete and the slag separated from the metal by gravity. The low-carbon Bessemer metal was not steel, according to the old definition, because it would not harden. On the other hand, it was not wrought iron because it did not contain slag. The manufacturers of the new metal wanted to call it steel, because steel commanded a higher price in those days than did wrought iron. On the other hand, a great deal of steel had been made for thousands of years by the cementation of wrought iron. It, therefore, contained slag and also enough carbon to be hardened. For fifty years a struggle waged between scientific metallurgists who wanted to call low-carbon iron "wrought iron," and manufacturers who wanted to call it "steel" if it had low carbon and no slag. The situation has finally been clarified greatly by the practical obsolescence of the cementation process, so that slag occurs only in steel made in the years previous. At very best, however, the definition of steel is awkward, because it must include any metal which contains enough carbon to be hardened by sudden cooling, and yet not enough carbon to make it cast iron.[1] Steel must also be defined as iron with little carbon and no slag. The Europeans have endeavored to get around this awkward situation by calling the low-carbon, slagless material "ingot iron," because it is cast liquid into ingots as distinguished from being pulled out of the furnace in a pasty mass. However, even in Europe, the low-carbon, slagless material is often called steel.

A New Era in Industry.—The Bessemer process was the first method of making in very large quantities a material which would satisfy the demands of modern industry for railroads,

---

[1] The exact boundary between the carbon in steel and in cast iron will be discussed in Chap. XI.

ships, buildings, highways, automobiles, agriculture, machinery, mining, airplanes, etc. Without steel in large quantities, it is doubtful whether our civilization of the twentieth century could have been developed. Therefore, the name *steel age* has been given to our present era, beginning with the latter part of the nineteenth century.

A New Era in Labor in the Iron and Steel Industry.—About seventy years after the technical discovery of ways to maintain higher temperatures in larger furnaces in steel manufacture there came another revolutionary change which was no less influential in raising the industry to a higher plane in civilization: For centuries the 12-hr. shift had been in vogue at blast furnaces. As the steel industry grew in magnitude, the same system was applied to many departments of its manufacture also. By this system two shifts of laborers covered the 24 hr. of the working day, sometimes continuously for seven days per week all the year around, although this was not customary except at blast furnaces. These hours of employment, together with the severe type of work required around the furnaces and rolling mills, gave labor at iron and steel works the reputation of being more brutal than that in most other industries, with the result that good labor was difficult to attract and was often obtained only by paying enormously high wages. This did no good to the industry. Shortly after the ending of the World War some European countries and Great Britain began to adopt 8-hr. shifts at iron and steel plants, sometimes by agreement and sometimes by national law. About 1922 a study of the 12-hr. shift was undertaken by two committees in the United States: The first was a committee of engineers appointed by and representing some of the national engineering technical societies. Within a short time a committee of executives of the industry began a similar independent investigation. The engineers' committee reported that the 12-hr. shift could be discontinued with benefit to the industry and the workmen and with only a small percentage increase in the cost of the product. The executives' committee, on the other hand, reported that their investigation showed that the change was not desired by the workmen themselves and would substantially increase the cost of iron and steel. Using the book published by the engineers' committee[1] as the basis for his reasoning, the President of the

---

[1] "The Twelve Hour Shift in Industry," New York, 1922.

United States finally secured the voluntary agreement of the governing bodies of some of the largest iron and steel companies to make a trial of abandoning the 12-hr. shift. Shorter hours have been in vogue ever since and this has proved a boon to the industry both technically and financially. While not claiming that this is the sole reason for recent improvements, nevertheless the greatest advance in the technique and quality of product in the history of the industry has been coincident with the era of shorter hours of labor during the past few years. There has also been a notable decrease in the number and seriousness of accidents in the same period of time, although a special reason for this is the earnest attention and "safety campaigns" which have been in vogue almost everywhere. At the present time (1934), when the industry is beginning to approach normal operation after a serious depression, there is a movement on foot to establish a 6-hr. day in the plants, so that four groups of laborers will cover the 24 hr. It is thought that work can thereby be given to a greater number of men. I believe that this is not so. Having visited many plants in 1922 to study the question of the best hours of labor, and having written that section of the book already mentioned which deals with the iron and steel industry, my opinion is that 6 hr. of work are too few to bring the best results to either the laborers or the industry, and even if there may be a greater number of men receiving wages on 6-hr. shifts—which is doubtful—the total number of dollars which the industry can earn and pay in wages will be less if the 6-hr. shift is adopted.

The Open-hearth Process.—Another Englishman, by the name of William Siemens, also developed a method of obtaining high temperature, by using gas for fuel, and by preheating the gas and the air previous to their combustion in the furnace. Siemens successfully developed the idea of some one else for preheating, by means of the so-called *regenerative system,* which is described in detail in the legend under Fig. III-4. The furnace used to contain the liquid bath was similar to a puddling furnace in general details and was called the open-hearth furnace. Siemens' first industrial furnace was installed in 1868. It had a siliceous lining and a slag predominant in silica, so that it was only capable of removing from pig iron the silicon, manganese, and carbon. The metal was held in a shallow pool on the long hearth and the impurities were oxidized by the slag, which floated on the metal and to which iron oxide was added to hasten the purification.

The purification was much slower than in the puddling process, because a furnace lining of iron oxide would not stand the high temperature of the open-hearth operation and, if attempts were made to oxidize very rapidly by iron ore added to the slag, the action in the furnace was so violent as to boil the slag and metal out of the doors.

The Siemens-Martin Process.—The Martin brothers in France modified the Siemens process by melting steel scrap together with pig iron, to form the bath for purification. Steel scrap is obtainable at a moderate price and is, of course, much lower in impurities than pig iron. If, therefore, the raw materials are part pig iron and part scrap, it is obvious that the period of purification will be shorter. This makes the whole operation shorter in time, even though steel scrap is a little slower to melt than is pig iron. The process was shortly developed to use almost invariably a portion of each raw material. It became known as the Siemens-Martin process, which it is frequently called in England and Europe.

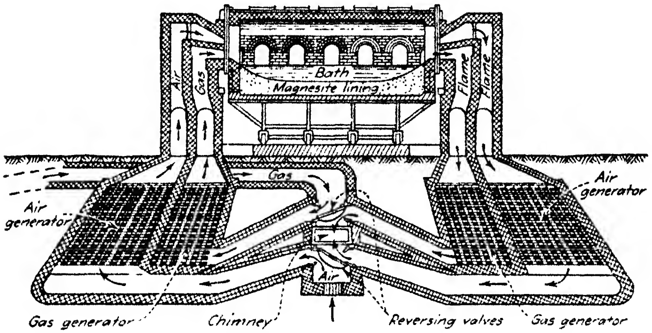


FIG. III-4.—Schematic diagram of basic open-hearth furnace, showing method of regenerative heating. The four regenerators are indicated in plan view, standing in front of the furnace, which is shown in elevation. Each regenerator is filled with a checkerwork of brick, except for free spaces below and above the checkers (see Fig. V-3). Before the furnace is started, the bricks of the regenerators are heated by a wood fire. The air enters the outer regenerator on the left; the gas enters the regenerator next it. They are heated by the hot surfaces of the checker brick, enter the furnace, unite, and burn. Then they pass out through the downcomers to the two regenerators on the right. In this way the right-hand regenerators are heated still hotter, by the waste heat of the furnace. The direction of the current of air, gas, and products of combustion is reversed every 15 min. or so, whereby all four regenerators are kept always hot. The result is that the air and gas enter in a preheated condition, which gives high temperature and combustion efficiency, while the products of combustion leave the apparatus at a relatively low heat and thus promote fuel economy. (*Taken from L. W. Spring, "Non-technical Chats on Iron and Steel."*)

Basic Process.—But the most important development in the open-hearth process was the use of a slag very low in silica and, therefore, capable of purifying the metal from phosphorus, and partly purifying it from sulphur, as well as taking out the silicon, manganese, and carbon. Two English chemists, S. G. Thomas and P. G. Gilchrist, had shown that it was slags rich in bases and low in silica which could hold phosphorus away from the metal. It was also shown that, if the slag was rich in bases, then the lining of the furnaces must be predominantly basic, or else the slag would dissolve and liquefy the lining. This principle was applied to the Bessemer process and it was soon used also in an open-hearth furnace. This enables the process to employ a much cheaper raw material, and, although the operation itself takes longer, the result is a cheaper product, which is at the same time lower in objectionable impurities, such as phosphorus and sulphur. It is, unfortunately, higher in another impurity, oxygen, owing to the fact that the basic slags are themselves more highly oxidized and leave the steel in a more oxidized condition at the end of the operation. However, the basic open hearth is now the predominant process in every steel-making country in the world and produces more than twice as much steel as all the other processes added together. The last ten years has witnessed a great scientific advance in the method of making basic steel, for the object and with the result of improving it in its weakest point as regards quality, *viz.*, the oxidized character of the product after purification.

Duplexing.—Since purification is so rapid in the Bessemer process and so slow in the open-hearth process, and since the open-hearth process has the advantage that it can employ a basic process better than can the Bessemer, it is obvious that silicon, manganese, and carbon might be oxidized out of the metal in a few minutes in the Bessemer converter and the melted product then poured into a basic open-hearth furnace, where the phosphorus could be removed. This is a so-called *duplex process* which has many advantages and which uses some three million tons of steel per year in normal times in America.

Electric Furnace.—The Bessemer and open-hearth operations are at all times oxidizing, because it has been shown to be impossible to carry on combustion at high temperatures without subjecting the iron to either free oxygen or carbon dioxide gas, both of which oxidize it. But the nineteenth century saw the development of a process whereby heat was obtained from the conversion of electric energy and this heat applied to metal melting and purification processes. The heat obtained in this way has two outstanding advantages over heat from combustion of fuel; *viz.*, (1) it may be generated in a furnace whose atmosphere is reducing in character instead of oxidizing; and (2) it may employ higher temperatures than are feasible with combustion heat.

Superrefining.—A process has, therefore, been developed whereby liquid steel from the basic open-hearth process can be poured into an electric furnace and there subjected to a reducing influence which will greatly decrease (although it never can entirely eliminate) the oxygen in the metal, and where, incidentally, sulphur may be reduced to any desired extent. In this way, a top notch of quality is put on basic open-hearth steel.

Other Electric Processes.—While the greatest tonnage of electric steel is made by the superrefining of open-hearth metal, nevertheless, there is a good deal made by melting steel scrap in electric furnaces, adjusting its composition to the desired proportions, casting it into ingots, and then rolling or forging it into parts for automobiles, airplanes, cutting tools, and other high-quality uses. One of the most important ways in which this type of electric process is employed is in the making of alloy steels.

Summary of Iron and Steel Manufacture

In Fig. III-5 are summarized the important modern American processes of iron and steel manufacture. The American industry is chosen, because the United States produces more iron and steel than all the other countries together. While there is one important European process—the basic Bessemer—which is not now used here, nevertheless, the outline in Fig. III-5 is representative of America's largest single manufacturing industry, and the basic Bessemer process may be added to it by those who desire a bird's-eye view of the processes in vogue in England, Germany, and France.

At best this array of different processes is complicated and illogical, because first we extract iron from its ore; then we dissolve about 6 per cent of impurities in it; then we transfer it to one or more other furnaces and refine most of these impurities out of it again. And we do not always refine in the same furnace but sometimes use one furnace, sometimes another, and sometimes two or three in succession, as, for example, when we first partly purify pig iron in a Bessemer converter, then take phosphorus out of it in a basic open-hearth furnace, and finally superrefine in the electric furnace. This complexity has grown up from economic demands and conditions and not through lack of logical design. It arises from the two following conditions: (1) because we do not know how to produce a pure product in a liquid form by direct reduction from iron ore, therefore the roundabout method is less costly, provided the materials are kept always liquid from start to finish; and (2) industry demands some materials of the highest quality, and others at a low price. Therefore, different methods must be used to produce different types of steel.

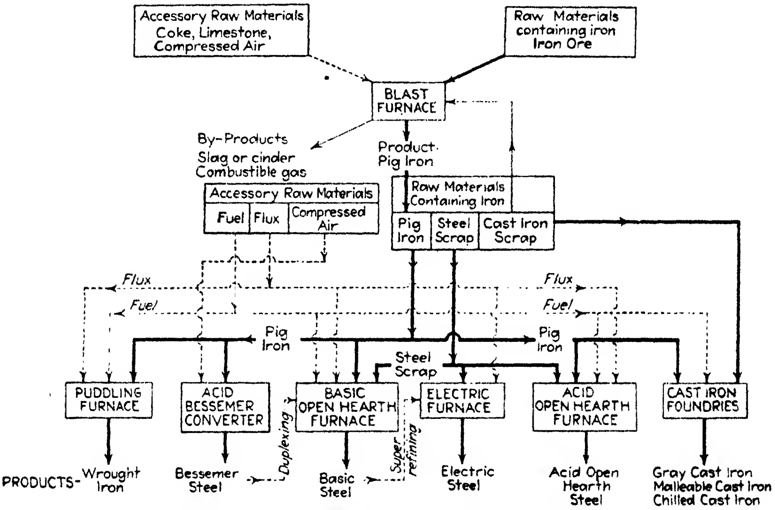


FIG. III-5.—General scheme or skeleton of iron and steel manufacture.

Accordingly, the present complicated series of processes will doubtless remain in vogue, unless, and until, some inventor discovers a means of producing pure iron or steel direct from ore in such condition that it may be rolled directly into final shape without the expense of remelting first. Considering now the present industry:

Raw Materials for Smelting.—All iron ore used goes to the blast furnace for reduction, except a minor amount used as flux in the puddling and open-hearth furnaces. We also charge into the blast furnace some pig-iron scrap, chiefly that made incidentally to the operations, such as "skulls" which solidify around the runners from the furnace or inside the ladles. Therefore, ore and iron scrap are the primary raw materials of the smelting operation—*i.e.*, the raw materials which contain the metallic constituents. In addition there must be raw materials for accessory purposes, such as: fuel (usually coke); flux, limestone being practically universally used for this purpose; and air. For every ton of pig iron made in America, under good average conditions, there are used a little less than 2 tons of ore; 100 to 200 lb. of pig-iron or cast-iron scrap; 1,500 lb to 1 ton of coke; ½ ton of limestone, and 3 to 4 tons of atmospheric air.[1]

Steel Scrap Used in Iron and Steel Manufacture.—The amount of steel scrap used in open-hearth practice is almost unbelievably great to one who learns of it for the first time. With the 20,000,000 tons of pig iron normally used per year in America in open hearth furnaces, there will be mixed from 21,000,000 to 22,000,000 tons of steel scrap. The wonder is where such an amount of scrap can constantly be obtained. About 10 to 20 per cent of it comes from the steel-manufacturing and rolling processes themselves, from ingots too short to be rolled and similar scrap sources, also steel pieces made and rejected by the customer because of improper chemical analysis or other qualities, "croppings" and "trimmings" from the pieces being rolled or forged, etc. The remainder comes from structures, etc., which are torn down, old automobiles, machinery, etc. It is a constant surprise that, with all the scrap used every year, there still seems to be an unfailing supply at a price lower than that of pig iron. Steel scrap is also used sometimes for melting in electric furnaces and purifying to steel, especially alloy steel. Some is used occasionally for melting with cast iron to make what is called *semisteel* in iron-foundry practice. Steel scrap must, therefore, be considered as one of the most important raw materials of the steel industry.

Cast-iron Scrap.—Cast-iron scrap to the extent of nearly 50 per cent of the final product is used in iron foundries. Its sources are "return scrap"—*i.e.*, scrap made in the foundry itself, including rejected castings—also machine-shop scrap and worn-out parts, such as old railroad freight-car wheels and parts of discarded machinery.

---

[1] At 70°F. and atmospheric pressure, each 1,000 cu. ft. of air weighs 75 lb.; 3 long tons of air have a volume of 90,000 cu. ft. It requires about 100,000 cu. ft. of air to make 1 long ton of pig iron.

Accessory Raw Materials Used in Finishing Processes.—Fuel as ordinarily defined—meaning coal, gas, oil, etc.—is not used in the Bessemer converter or the electric furnace. Iron-ore flux is used in puddling and open-hearth furnaces. Limestone flux is used extensively in the basic open-hearth and basic electric furnaces and is sometimes used in cast-iron foundry cupolas. It is used sparingly to adjust the composition of the slags in the acid open-hearth furnace and acid Bessemer converter. Compressed air is used in Bessemer converters and in foundry cupolas. Modern open-hearth plants also blow air in regulated volumes to control combustion. These facts are shown in the accompanying summary (Fig. III-5), except that the supply of accessory raw materials is indicated only where they are used regularly and somewhat extensively.

Relative Quality of Different Steels.—Electric steel commands the highest price and enjoys a reputation for highest quality, due chiefly to its relative freedom from oxygen, entangled oxides, and sulphur. It is never entirely free from these defects but more so than the next steel in quality, which is acid open-hearth steel. Acid open-hearth steel is, in turn, freer from oxygen and entangled oxides than basic steel and stands second in quality when it is fairly low in phosphorus and sulphur, which requires that it be made from pig-iron and steel scrap low in these impurities, because the acid process does not remove any phosphorus or sulphur during its purification operation. Bessemer steel stands lowest in quality, chiefly because it is usually relatively high in phosphorus and sulphur.

Relative Tonnage.—Basic open hearth is now predominant in tonnage, because (1) from cheap raw materials it makes a product low in phosphorus and sulphur; and (2) intensive study and research during the past few years have very greatly improved its quality by lessening its chief defects, *viz.*, a tendency to hold relatively large proportions of dissolved oxygen and entangled oxide particles.

Since the year 1924, more than 80 per cent of American steel has been made by the basic open-hearth process, and this has continued through good times and bad, as shown by Fig. III-6, which is taken from a recent address by Dr. George B. Waterhouse before the American Institute of Mining and Metallurgical Engineers. The next process in relative tonnage is the Bessemer (shown also in Fig. III-6), and it should be added that a few million tons of steel per year which is credited to the basic open-hearth process is really "duplex" steel; *i.e.*, it is made from pig iron first "blown" in a Bessemer converter and then dephosphorized in a basic open-hearth furnace. The basic open-hearth and Bessemer processes together produce about 97 per cent of American steel. This leaves the acid open-hearth and electric furnaces as "quality" steel producers, as distinguished from "tonnage" steel producers. By this we do not imply that basic steel is not also of very fair quality. Indeed, it enjoys a reputation for occasional superiority over acid steel in respect of toughness and ductility under static stresses, *i.e.*, stresses that are constant as distinguished from those which are variable, alternating, or vibratory. To Dr. Waterhouse we are also indebted for Fig. III-7, which shows that acid open-hearth steel has been decreasing in production, especially during the past fifteen years, while the production of electric furnaces has been overtaking it

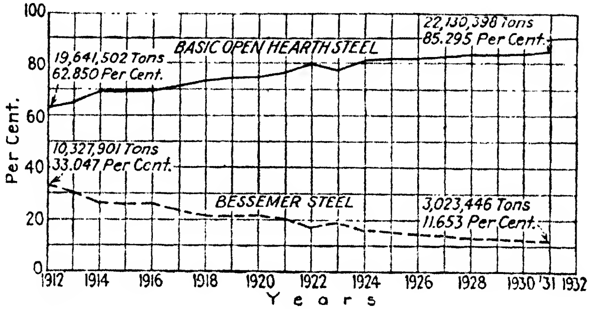


FIG. III-6.—Trends in basic open-hearth and Bessemer steel in America. (*Courtesy of Dr. George B. Waterhouse.*)

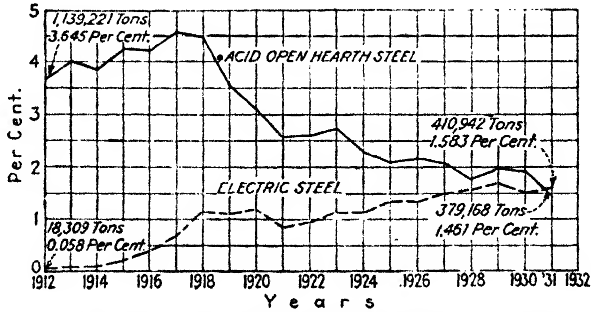


FIG. III-7.—Trends in acid open-hearth and electric steel in America. (*Courtesy of Dr. George B. Waterhouse.*)

and has at last surpassed it during a time of serious industrial depression.

Crucible Steel.—Some metallurgists and some authorities among steel consumers insist that crucible steel, because of its uniformity in high quality, is superior to all other steel. They argue that there are temptations to take short cuts to production and to resort to doubtful practices in electric-furnace manufacture which are not so likely to arise in crucible practice. At the same time, they admit that electric steel, when properly made and with all possible precautions observed, is as high in quality as the crucible product. It is the author's opinion that sometimes electric steel is not made so well as it should be, but that it can be at least as good as any steel ever produced. Figure III-8 shows that the production of crucible steel in America has now dropped to an almost insignificant amount. It is, therefore, omitted from the summary in Fig. III-5. If it were to be added there, it would appear under the puddling furnace, since its raw material is wrought iron. Germany and France make between 10,000 and 20,000 tons of crucible steel each in a normal year.

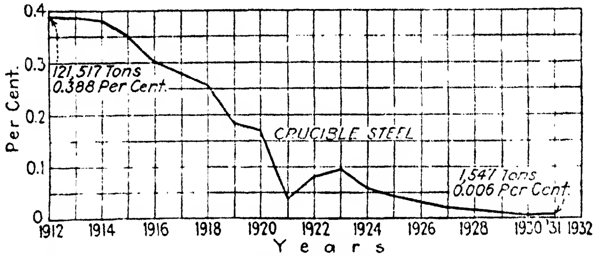


FIG. III-8.—Trend in crucible-steel manufacture in America. (*Courtesy of Dr. George B. Waterhouse.*)

Wrought Iron.—Wrought iron is made to the extent of about 500,000 tons in a normal year in America. It costs about 10 to 20 per cent more than the cheapest steel. Its chief claim to superiority over steel is in its resistance to corrosion, which is discussed in more detail in the following paragraph. It is also valued for its toughness and for a fibrous structure which it seems to have.[1] It is chiefly used for boilers and boiler tubes, water pipes, bars and small structural shapes, and wire, also for corrugated roofing and building sheets. It is chiefly valued in the railroad field, and many railroad-designing engineers insist

---

[1] See II-3, p. 28.

that it is superior to steel in fatigue resistance, especially because a microscopic crack which appears on the surface of a rotating member does not seem to develop, or grow so rapidly in wrought iron as it does in steel. This opinion persists among some of the highest authorities although attempts to prove it by comparative scientific investigations have not led to conclusive results. The properties of wrought iron are better in a longitudinal direction, *i.e.*, when stressed in lines parallel to the slag fibers, than they are in a transverse direction. This is true in both tensile and impact tests Wrought iron welds easily by the old hand-welding process, which, however, has a decreasing importance, because modern methods of welding are replacing hand welding even in field operations and cruder types of repair shops. An important advantage of wrought iron is its rough surface to which paint will adhere more firmly. It is also said to take a thicker and better coating of zinc in the galvanizing process. The properties of wrought iron are nearest to those of pure iron of any commercial material, notwithstanding its slag, because its impurities in chemical combination are small. The slag is mechanically mixed with the metal and does not alter some of its mechanical and physical characteristics. It is therefore preferred to low-carbon steel for electrical conductivity and magnetic purposes. When under strain greater than it can withstand, wrought iron stretches more uniformly over its entire length than does steel, although the elongation close to the point of fracture may not be so great.

Corrosion of Wrought Iron vs. Corrosion of Steel.—There is a prevalent conviction that steel corrodes more rapidly than wrought iron. This opinion rests on no very exact experimental evidence, although there are not lacking incidents of very long service by wrought iron in situations where steel corroded rapidly. One point, however, stands out very clearly in this connection, *viz.*, that wrought iron containing "carbon streaks" or wrought iron made from so-called "bundled scrap" is more corrosive than steel made well. Likewise, steel which has been badly made and contains blowholes, segregation, or other inhomogeneities, will corrode much more rapidly than steel made well or than good wrought iron. A number of scientific tests carried on over a period of years have indicated, however, that there is not a great difference in speed of corrosion between well-made wrought iron and well-made steel, although the results

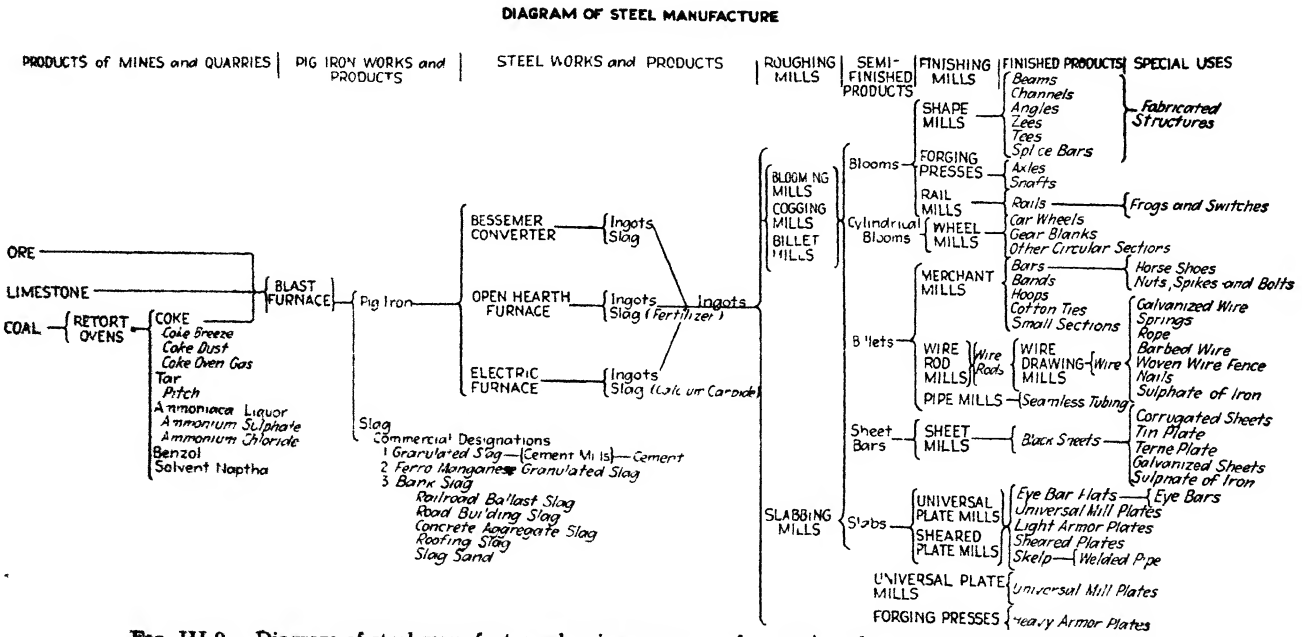


FIG. III-9.—Diagram of steel manufacture showing sequence of operations from ore to the finished product.

have been favorable to wrought iron in a case of sea water and alkaline water and to steel in the case of dilute acids and acidulated waters. These scientific tests are not entirely conclusive as a basis of commercial comparison. Also they have not always taken sufficiently into account the localized—*i.e.*, "pitting"—corrosion to which badly made material is especially subject. It is obvious that a badly pitted pipe or sheet will lose its usefulness even though the average corrosion over the whole surface is not great. This pitting is caused by irregularities in composition, such as carbon streaks in wrought iron or blowholes and segregation in steel.

Diagram of Steel Manufacture.—Another type of diagram often used to give a general view of the industry is shown in Fig. III-9.[1] This shows only steel manufacture but gives a picture of the many different operations required to bring steel to a marketable form.

References

HENRY M. HOWE: "The Metallurgy of Steel," vol. I, New York, 1890. This is the recognized standard authority on the metallurgy of the Bessemer and crucible steel processes and upon the properties of steel as far as they were known and understood at the time when this book was written. It will long remain a classic. There have been many editions of different dates, but no change in text since 1890.

F. W. HARBORD: "The Metallurgy of Steel," 6th ed., London, 1918. With a section on Mechanical Treatment by J. W. Hall.

DAVID CARNEGIE, assisted by SIDNEY C. GLADWYN: "Liquid Steel, Its Manufacture and Cost," 2d ed., New York, 1918. This is the best reference for labor and costs of manufacture.

WALTER LISTER: "Practical Steelmaking," Pittsburgh, 1929.

GEORGE H. MANLOVE: "Scrap Metals," Cleveland, 1918.

[1] From "The A.B.C. of Iron and Steel," 4th ed., Cleveland, 1921.

CHAPTER IV

IRON-ORE SMELTING IN THE TWENTIETH CENTURY

An iron-ore smelting industry requires an abundant supply of iron ore, fuel, flux, air, and water. Since the gangue of most iron ores consists largely of silica, the suitable flux is limestone, because it makes a silica-lime slag. There are a great many parts of the surface of the earth where iron ore and limestone occur within a reasonable distance of each other, but fuel and water are sometimes lacking. For fuel we commonly use coke, which is made from bituminous coal, but, unfortunately, not all bituminous coals will make a good coke. Water is essential for cooling parts of the furnace in order to prevent melting of the lining. The first, and most important, item of smelting expense is the cost of assembling the raw materials in one center. Water transportation of ore is cheap, even over very long distances, but coke is bulky and breaks up in handling, whereby it loses some value as a fuel.

IRON ORES

The iron ores used for smelting consist of chemical compounds of iron and oxygen containing more or less water, either in the form of moisture or chemically combined as water of crystallization.

Hematite, Fe_2O_3.—The best known of these ores is hematite, containing when pure 70 per cent of iron. The red hematites are the richer varieties, while the hydrated hematites, or limonites, usually contain a good deal of moisture, as well as water of crystallization, and are consequently poorer in iron, not often yielding more than 50 per cent iron. They are called *brown hematites.*

Oolitic hematite is a variety that exists in the form of spherical grains or nodules. It is important because it sometimes contains limestone and is, therefore, valuable not only for the iron but for the fluxing quality of the lime. The minette ore of France, especially Alsace-Lorraine, and of Luxembourg is an enormous deposit of this oolitic hematite, running from 30 to 40 per cent of iron and giving a pig iron containing from 1 to 2 per cent of phosphorus.

Magnetite Fe_3O_4.—Magnetite contains, when pure, enough iron (72.4 per cent) to attract the magnet. In the United States and Canada it often occurs mixed with impurities, such as silica, titanium, and phosphorus, in large percentages. But other magnetite ores—notably those of Sweden—are the purest ones that exist in large quantities anywhere and form one of the sources of the Swedish iron and steel, which is famous all over the world for its purity, *i.e.*, for its freedom from the objectionable elements sulphur and phosphorus.

Siderite, $FeCO_3$.—Another variety of iron ore is the so-called *spathic* iron ore, or siderite, which is, however, without any importance in the United States. This forms the famous "clay ironstone" of the Cleveland district in England. It is poor in iron and is therefore no longer smelted in any quantity in the United States in competition with the rich hematites. This ore is almost always calcined before smelting to expel the carbonic acid, in order to save the blast furnace the extra work of this expulsion in its upper levels.

Pyrite, FeS_2.—Enormous deposits of pyrite occur in many parts of the world, but the sulphur must be almost completely roasted from such ores before smelting, lest the sulphur in the ore plus the sulphur in the coke should together be too much for the slag to carry away as calcium sulphide. The sulphur remaining in the pig iron should be below 0.05 per cent, if possible, and preferably below 0.02 per cent, because sulphur is costly to separate from the metal once it is contained therein and is harmful to the physical properties of both cast iron and steel—with, however, certain infrequent exceptions to be mentioned later. Therefore, notwithstanding its abundance, pyrite is usually a costly raw material for the blast furnace. But mention should be made of pyrite ores containing copper, which, after removal of sulphur to make sulphuric acid and leaching out of copper for its metallic value, can be sold to iron smelters at a competitive price.

Occurrence of Iron Ore in the World.—There is no continent, and scarcely any country, which does not contain some deposits of iron ore. These ores are smelted on more than a trifling scale in Europe, Asia, Africa, North America, and Australia. South

America has enormous deposits on its west coast, from which ore is transported to other countries for smelting, and deposits in Brazil, which in size and purity are said to equal the famous ores of Sweden. But there have not yet been developed in South America extensive deposits of coal suitable for coke manufacture to supply blast furnaces with fuel. Considering the world in its entirety, four iron-ore producing districts stand out as most important through having influenced its industrial history—and even to some extent its civil history. They are located in Great Britain, northern Scandinavia, Central Europe, and the Lake Superior region. Today almost all these ores, with the exception of those in Central Europe, require some form of treatment to prepare them for blast-furnace smelting. A few words as to the treatments commonly used will therefore precede a brief discussion of the regions.

Presmelting Treatment of Iron Ores.—Reference has already been made to calcining siderite in England in order to remove its carbon dioxide constituent and to roasting and leaching cupriferous pyrite in order to secure its sulphur and copper values. Some ores also require driving off of moisture; *e.g.*, ores in northern Cuba contain as much as 27 per cent of water. Recent years have also seen a great increase in the mechanical concentration, or enrichment, of iron ores, by washing with water in specially designed machines which wash away clay and other gangue material and raise the purity and/or the grade of the material. Crushing followed by magnetic concentration also raises the grade and lowers the proportion of objectionable impurities, such as phosphorus. Ores in a state of very fine particles are also sometimes agglomerated or "sintered" into lumps, which are readily treated in the blast furnaces because of their porous character. The sintering operation likewise has the beneficial effect of further reducing the content of sulphur, if present. All these processes for presmelting treatment will be found described in detail in textbooks on mining or on subjects intermediate between mining and metallurgy.

Great Britain.—For at least two centuries England stood out as a leader in iron and steel production. The industry was based on several sizable deposits of ore in the British Isles, some of which were high grade, or rich, by which is usually meant high in iron content. Others were rather impure, meaning that they contained a good deal of phosphorus, but this produced a pig iron which melted easily and flowed readily into thin castings. England also possesses bituminous coal which makes as good a coke as any in the world. When her competitors began to make iron and steel on a very large scale, England lost her predominant position because of lack of progressiveness in two respects: (1) Her ironmasters failed to secure and import ore from other countries on a large enough scale to enable her to keep pace with the United States and Germany; and (2) they failed to adopt early enough new means and blast-furnace devices promoting fuel efficiency, tonnage production, and better chemical control of the operation and product.

This conservatism has both its strong and its weak points: It kept manufacturers away from experiments and developments which proved in some cases to be very costly; on the other hand, it caused the English industry, which had been a leader both in tonnage production and in technical skill, to drop to fourth place in pig-iron production. The general trends of production for the last sixty-seven years are shown in Fig. IV-1, in which we see that English production remained almost stationary while that of her competitors increased rapidly. As an opposite policy, Germany, when deprived of the Lorraine mines in 1918, began importing extensively from Sweden, until her production came back almost to normal. Likewise the iron manufacturers near the eastern United States seaboard secured ore deposits in Cuba and South America, when hard pressed by competition of blast furnaces located nearer than they to the Lake Superior deposits.

Lorraine-France-Luxembourg District.—This is the famous iron-ore district of Central Europe often referred to as the *minette district* and opened less than one hundred years ago. One outstanding characteristic of the district is a high content of phosphorus in the ore, so that the phosphorus in the pig iron produced is usually too high for an economical basic open-hearth process, because it is costly to remove a good deal of phosphorus in the basic open-hearth furnace. Therefore, the pig iron is especially suitable for a basic Bessemer converter, since all the impurities are removed rapidly in a Bessemer "blow." The ores are low in grade, averaging usually between 30 and 40 per cent of iron. But this is largely compensated by the fact that many of the ores have limestone as a gangue. It is, therefore, possible to mix ores having siliceous gangue with those having limestone gangue in proportions to give the desired silica-lime slag and, therefore, obviate the necessity of using a limestone flux. Consequently, the ore burden is as rich using this "self-fluxing" mixture as if richer ores were used and limestone added to them. This iron-ore district is the basis of extensive industry in Central Europe. It has twice been taken as the spoils of war, because

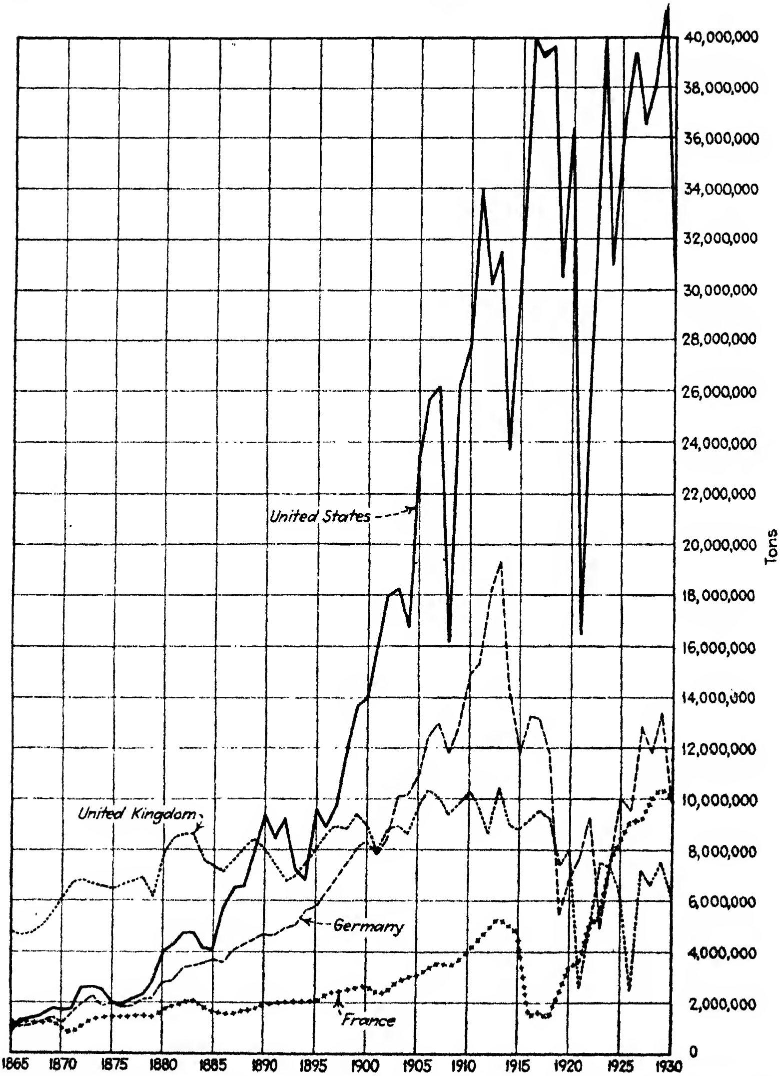


FIG. IV-1.—Annual pig-iron production in the four principal siderurgical countries of the world.

the Germans took it from the French in 1871 and the latter got it back in 1918. The influence of a great iron-ore district on the production of a country is illustrated in Fig. IV-1: Germany rapidly drew ahead of France in pig-iron production after 1870, when the minette ores were owned and mined by her on a large scale. It will, furthermore, be noticed that the German pig-iron production dropped 50 per cent in 1919 owing to the loss of the province of Lorraine. After that, Germany began importing iron ores extensively from Sweden and hence production rose again. It will be noted, however, that the French production rose significantly in tonnage, beginning about 1920. The fact that France passed Germany in 1930 is due, however, not entirely to the recovery of Lorraine but also to the depression's not being so great in France as it was in Germany.

Norway, Sweden, and Finland.—These Scandinavian deposits have been worked perhaps for a longer period of time than any other large iron-ore resources in the world. They represent also one of the most extensive deposits in the world, containing between 1,500,000,000 and 2,000,000,000 tons of ore. Their most outstanding characteristic is that they are magnetic in character. Some of them are extremely pure, meaning that they are low in phosphorus; others give a phosphorus iron suitable for a basic open-hearth process; and some have so much phosphorus that the pig iron is most suitable for the basic Bessemer. Some of the ores are naturally of very high grade, meaning high in iron content, and all of them are high grade after a water concentration. About 80 per cent of all these iron ores mined are exported. This is because coke has to be imported into Sweden at an extremely high price. Charcoal has been used for smelting there for centuries, but the forests are becoming exhausted and the charcoal more costly, so that an electric process of iron-ore smelting has been developed and brought to a high state of technical excellence in Sweden, although the tonnage is not large.

Lake Superior Region.—The discovery and development of the Lake Superior iron-ore deposits well illustrate the effect of large iron-ore resources on industrial development of a country. The deposits on the south side of Lake Superior were opened between the years 1854 and 1884, inclusive. The two larger ranges on the north side, Vermillion and the great Mesabi, were opened in 1884 and in 1892, respectively. From Fig. IV-1

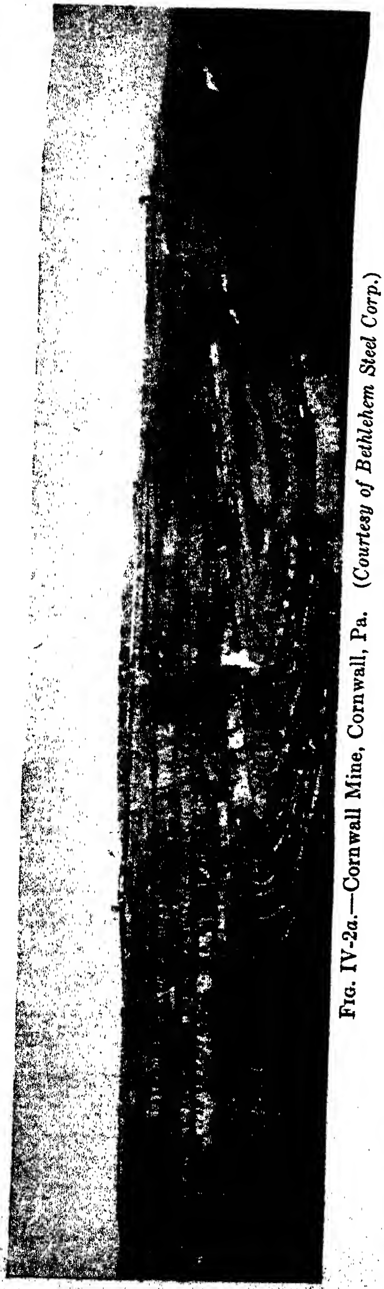


Fig. IV-2*a*.—Cornwall Mine, Cornwall, Pa. (*Courtesy of Bethlehem Steel Corp.*)

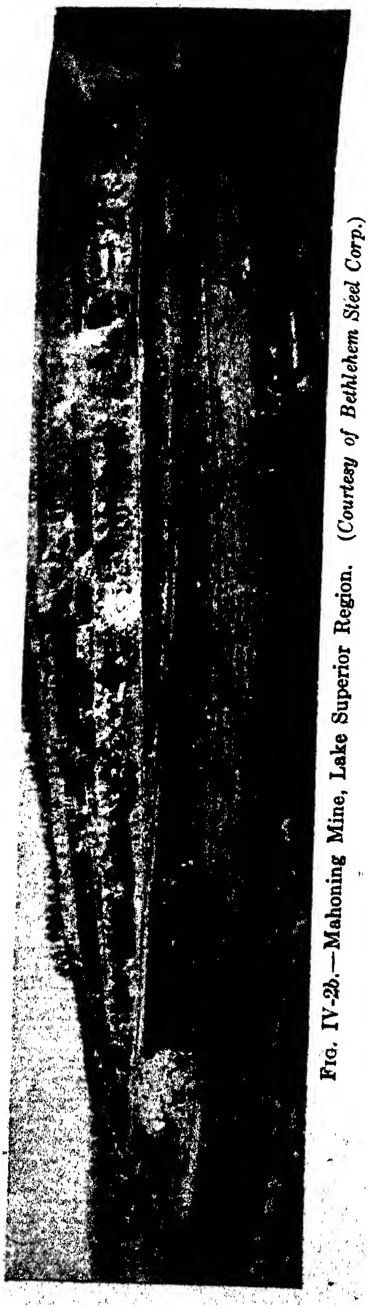


Fig. IV-2*b*.—Mahoning Mine, Lake Superior Region. (*Courtesy of Bethlehem Steel Corp.*)

it will be noticed that the United States passed Great Britain in production in the year 1890 and took first place as a pig-iron producer. She has been increasing her predominance ever since. Nearly 90 per cent of all the pig iron made in the United States now comes from Lake Superior ores. When first mined, these ores were rich in character but they now require water concentration in some cases. The amount of phosphorus in the ore usually makes them of basic open-hearth grade, although selected ores make pig iron low enough to produce Bessemer steel of the standard requirement of less than 0.100 per cent of phosphorus. It is probable that the industry of the United States would not have developed on such a large scale if it were not for the abundance of the Lake Superior ores, coupled with the cheapness with which they can be mined on account of the earthy character of some of them and the fact that they lie relatively near to the surface. An added advantage is their extremely cheap transportation to smelting districts on account of the presence of the Great Lakes. The character of the ores also makes it possible to handle them in great quantities by cheap methods.

FIG IV-3.—Steam shovel loading soft ore. (*Courtesy of Bethlehem Steel Corp.*)

Mining Methods at Lake Superior.—Some of the Lake Superior deposits lie near the surface and are therefore cheaply mined.

This is especially true of the soft, earthy deposits of the Mesabi range, which are sometimes worked in great open cuts, the ore being loaded upon cars by mammoth steam shovels or sometimes by the caving method, the ore falling by gravity into cars situated in underground tunnels. The massive, or rock, ores are more costly to extract, and the utmost skill of American blast-furnace men has been exercised to employ as large a portion of the earthy ores as possible without choking up the furnace. The practice of agglomerating or sintering fine ores into lump form is becoming more prevalent.

Ore Transportation.—A peculiarity of the Lake Superior deposits is that most of the ore is transported a distance of 800 miles or more in order to bring it to the coke. Thus, western Pennsylvania, Ohio, and South Chicago receive much of the ore shipped from the Lake Superior mines. Since the weight of coke used in the blast furnaces is only about one-half the weight of the ore, it might seem uneconomical to carry the latter to the former. But coke is bulky in proportion to its weight; furthermore, it suffers a good deal of waste in transportation in consequence of its friability and of the fact that so much of it is broken down into pieces less than 1 in. in diameter (technically known as *breeze*) which are not suitable for charging into the blast furnace. The ore, on the other hand, may be handled by the cheapest and most rapid labor-saving devices. Indeed, in many cases, the ore is never touched by shovels in the hands of man but is mined, charged, and discharged in units of several tons each by gravity or by specially designed machinery. The mining and transportation of this great amount of material is in itself a mighty industry, every advance in which has contributed in no small share to the increasing volume and importance of the iron, steel, and other industries of the United States. The steam shovel loads the ore into railroad cars, which run almost by gravity out on to long docks alongside of which are brought the boats capable of taking a load of 10,000 to 20,000 tons of ore each. The hatches of these boats are placed such a distance apart that the hinged ore chutes of the bins may be swung down and, when the gates are opened, the ore allowed to flow directly into the hold of the vessel. In a few minutes the vessel receives her full cargo. The unloading of the boats is accomplished with almost as great celerity as the loading, and by means of modern machinery a steamer containing as much as 15,000 tons of ore has been completely discharged in about 4 hr. at the other end of her journey. Nor is any time lost in coaling the vessel for another

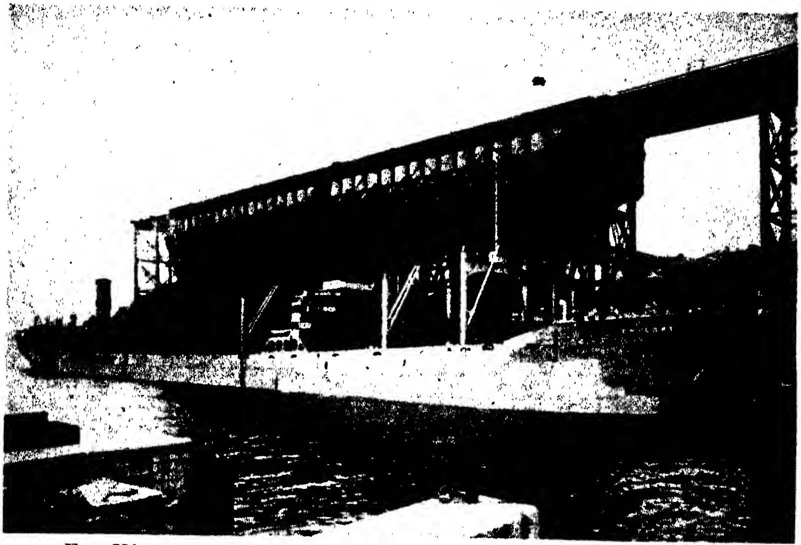


FIG. IV-4.—Loading an ore boat. (*Courtesy of Bethlehem Steel Corp.*)

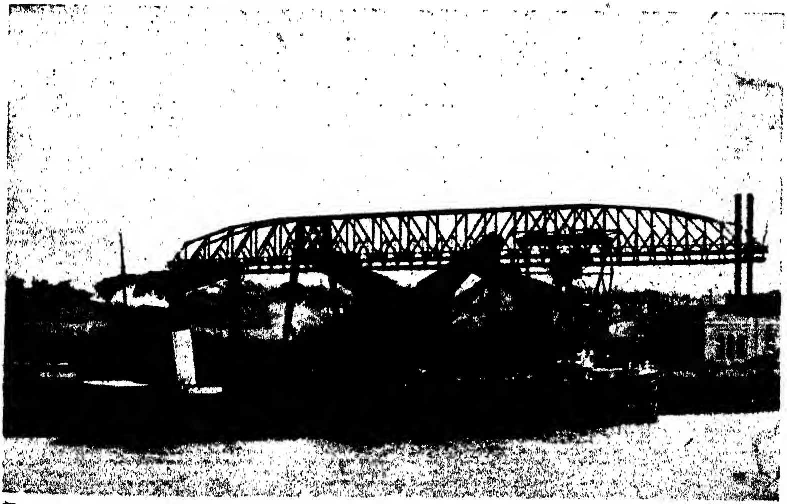


FIG. IV-5.—Unloading an ore boat with Hulett electric unloaders. (*Courtesy of The Wellman Company.*)

journey up the lakes and back. Great machines pick up whole railroad cars of fuel and empty them bodily into the chute which connects with the bunkers of the vessel, many of the ore steamers being so constructed that this wholesale loading of coal can go on at the same time as ore is being discharged.

Bessemer and "Non-Bessemer" Ores.—American iron ores are divided into two great classes known as Bessemer and non-Bessemer ores. The Bessemer ores contain somewhat more than one thousand times as much iron as they do phosphorus. They will, therefore, smelt to a pig iron containing less than 0.09 per cent phosphorus, which can be blown in an acid Bessemer converter to a steel having not more than 0.100 per cent phosphorus. This is the normal maximum for steel. These Bessemer ores command a premium of about 75 cts. per ton above the non-Bessemer ores, which, of course, are those higher in phosphorus.

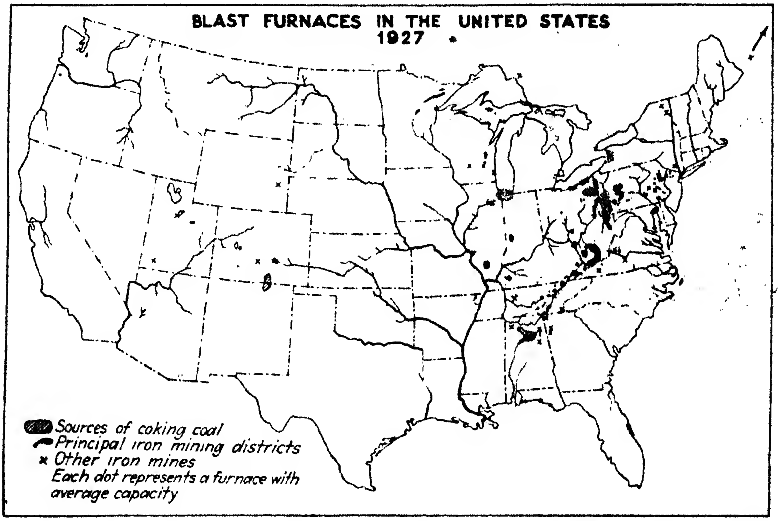


Fig. IV-6.—Iron-ore deposits in the United States. Also sources of coke and location of blast furnaces. (*From Richard Hartshorne, Journal of Geography, vol. 28, April, 1929.*)

Other United States Deposits (see Fig. IV-6).—In the district surrounding Birmingham, Ala., are found deposits of iron ore with limestone and coal so close together that none of it requires more than 50 miles' transportation to bring all three to a common smelting center. It is believed that the assembly cost of raw materials is cheaper in Alabama than at any other place in the world. The ores are rich in iron but higher in phosphorus than most American ores. They make a pig iron often containing as much as 0.50 per cent phosphorus, but the production costs are low. Other important iron-ore districts in the United States are the Adirondack region in New York State and the Cornwall district in Pennsylvania. Districts in Wyoming, Colorado, and Utah are important because they can be smelted close to markets for pig iron, which are a long distance from the eastern smelting centers.

Spain and Russia.—From the tonnage standpoint the deposits of Spain and Russia are important, although they have not as yet greatly affected the world's industrial evolution. Most of the Spanish iron ores are exported to England and other countries for reduction purposes. The Russian deposits are just now undergoing development and may have an important influence in the future.

Accessory Raw Materials

We have already discussed[1] the reasons why charcoal is used in a few instances for blast-furnace smelting, but we shall confine ourselves to discussing coke as a fuel in modern practice, because of its great predominance. Limestone requires no special discussion here, and the use of air in blast furnaces resolves itself merely into a discussion of the best apparatus for blowing the required quantity at the necessary pressure.

Coke.—All modern progressive plants make coke by the so-called *by-product process*, in which bituminous coal is subjected for about 17 hr. to distillation in a refractory fire-brick retort whereby almost all of its volatile constituents are driven from it, leaving a spongy mass containing 85 to 93 per cent of carbon, 7 to 15 per cent of ash, 0.5 to 1.25 per cent of sulphur, and 0.5 to 3 per cent of residual volatile matter. One ton of representative bituminous coal will yield approximately 70 per cent of coke, 10,000 to 12,000 cu. ft. of gas, 8.5 gal. of tar, 3 gal. of light oil, and 22.7 lb. of ammonia, calculated as ammonium sulphate. The gas has a calorific power in the neighborhood of 650 B.t.u. per cubic foot and is one of the most important fuels for steel manufacture and treatment. This is one of the reasons why a by-product coking plant is now customarily placed within, or adjacent to, the blast furnace and steel plant. Almost all of the coke-oven gas is today made available for steel heating and melting furnaces, and the gas which comes from the top of the blast furnace, which has a calorific value of only

---

[1] See p. 16.

about 90 to 110 B.t.u. per cubic foot, can be utilized for heating the coke retorts. Another advantage of having the by-product plants adjacent to the blast furnaces is because coal can be transported to them with relative economy, whereas coke is more friable and partly breaks into small pieces, technically known as "breeze," which cannot be used in blast-furnace smelting. The tar obtained from by-product coal distillation is also sometimes used as a fuel in open-hearth and other furnaces. The requirements of a good iron blast-furnace coke is that the pieces shall be neither too large nor too small. It is now customary when smelting fine ores to crush coke to a maximum size of 4 in. and to screen out from the mass all the breeze, the name applied to coke particles less than $\frac{3}{4}$ in. in diameter. This breeze can be used for firing on special grates, but it chokes up the blast furnace and should not be permitted to go into the stack. Another important characteristic of coke is that it shall be tough enough not to break into small pieces when handled and crushed. At the present time it is customary at some blast furnaces to dump the coke into bins situated directly over the bottom of the skipway (see Fig. IV-12), so

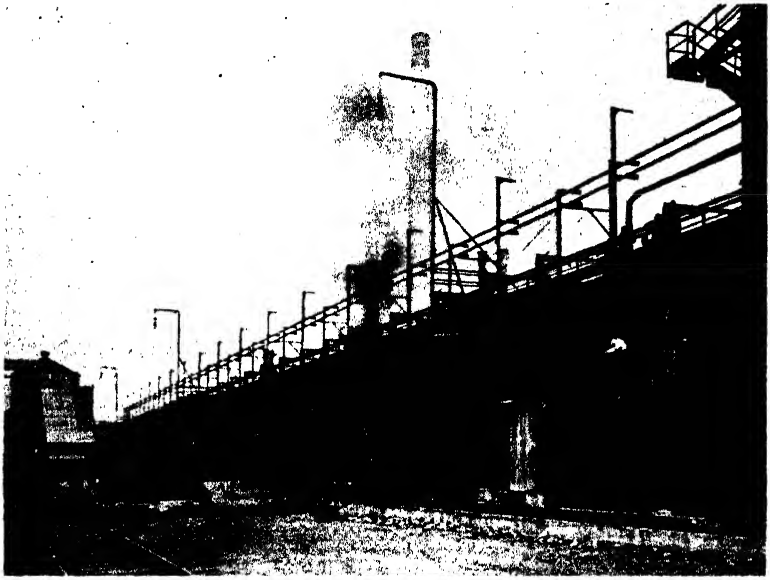


FIG. IV-7.—Battery of by-product coke ovens. (*Courtesy of Bethlehem Steel Corp.*)

that a gateway may open and coke may be allowed to flow by gravity directly into the skip, thus avoiding handling and breakage. A coke grizzly situated under this bin affords a last screening out of small pieces. Good coke should have a maximum of 12 per cent of ash, and preferably not more than 10 per cent. Likewise, a maximum of 1.25 per cent of sulphur, and preferably not more than 1 per cent.

Air.—Iron blast-furnace blowing apparatus is of either the reciprocating or turboblower type. Turboblowers began to be used about the beginning of this century, because of lower first cost, greater flexibility, less attention required, less weight and less space occupied (see Fig. IV-9). Turboblowers also lend themselves readily to automatic regulation in respect of uniform pressure or uniform volume delivered. Many mechanical-engineering authorities still advise reciprocating cylinder-blowing engines, however, because of complications in superheat and partial vacuum required for turbine operation, and because they believe the reciprocating engine is more uniform, more adaptable, and more economical in operation under service variations (see Fig. IV-10). Comparisons are still a matter of controversy and both types are installed on occasion.

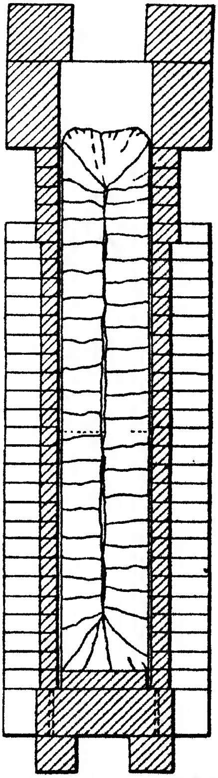


Fig. IV-8.—Cross section of retort. Structure of by-product coke.

A Modern Blast Furnace

A modern blast-furnace plant must include not only the stack itself and at least three stoves for preheating the blast but also an enormous battery of storage bins for the storage of solid raw materials, a coke-oven plant for producing fuel, blowing apparatus for air, pumping apparatus for water, ladles for taking away the pig iron and the slag, a casting machine for putting the iron in the form of pigs when necessary, and a slag dump for disposing of the cinder. Usually included in the blast-furnace plant is also a considerable battery of gas engines in which some of the top gas is converted into power and thence

FIG. IV-9.—Turboblower for iron blast furnace. Centrifugal compressor type, driven by condensing steam turbine. 110,000 cu. ft. air per minute. 20 to 30 lb. pressure. (*Courtesy of General Electric Co.*)

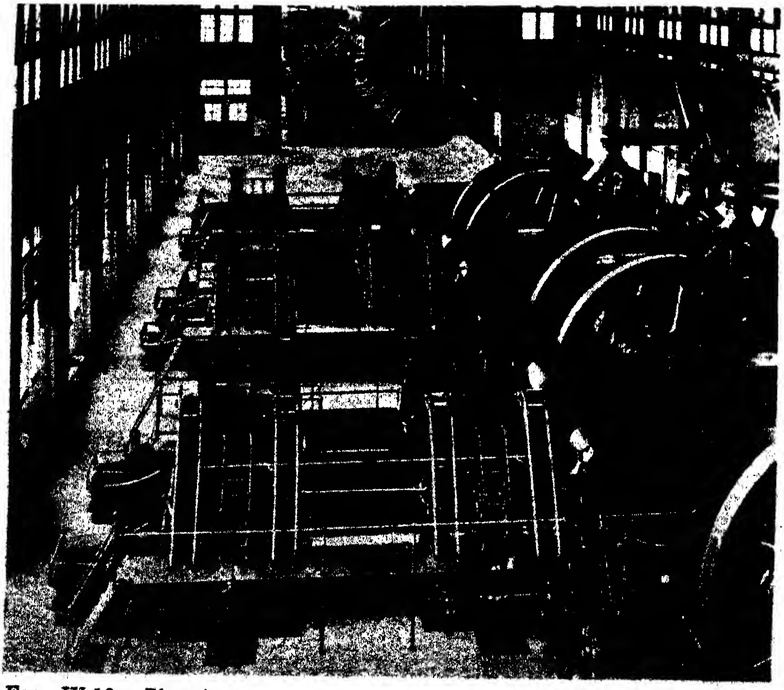


FIG. IV-10.—Blast-furnace blowing engines operated by blast-furnace gas engines. (*Courtesy of Bethlehem Steel Corp.*)

into electricity, as well as boilers for steam production. Such a plant will cost in the neighborhood of $3,000,000 to $4,000,000 per furnace. Obviously, to cover this subject adequately, a whole book would be necessary, and we can here only touch on the points of maximum importance.

Storage at Blast Furnace in Piles and in Bins.—Since most of the Lake Superior ores have to pass through the Sault Sainte Marie Canal in order to reach the smelting centers, and since this canal is icebound for three to five months each year, it is necessary to have large stock piles at all the blast-furnace plants to carry over the ore supply during the winter season. During the shipping season, the ore is unloaded by gravity from the bottom-dumping railroad cars which bring it from the ships to the plant directly into bins arranged in low rows near the blast furnace. An elevation of such bins is shown in Fig. IV-12. During the off season, the railroad cars are loaded from the stock piles and thence into the bins.

FIG. IV-11.—Storage pile at smelting plant (*Courtesy of Bethlehem Steel Corp.*)

Handling Solid Raw Materials.—One sectional view of a modern American blast furnace and handling apparatus is shown in Fig. IV-12, to which reference is made as follows:[1]

---

[1] Taken from WILLIAM A. HAVEN, Recent Developments in American Blast Furnace Design and Practice, *Journal Iron and Steel Institute*, No. 1, 1933.

Coke is loaded from a car or conveyor directly into two bins which will drop it, when desired, directly into the blast-furnace skip car, thus avoiding handling with consequent breakage. Ore and limestone are contained in two long parallel rows of bins situated adjacent to the furnace. Underneath these bins runs an electric larry, which receives a charge of one or both of these materials and transports it to the foot of the blast-furnace stack. The larries are fitted with weighing apparatus which weigh the material in transit. From the larry the material is dumped into the skip car shown, by which it is hoisted to the top of the furnace and dumped into the upper hopper. The bottom of this hopper is closed by a bell, which can be lowered at intervals and discharges the contents of the hopper into the lower hopper. In a great majority of our American blast furnaces, a McKee revolving distributor (see Fig. IV-13) distributes the raw materials evenly in the lower hopper, thus insuring a better distribution of the charge when it is dropped into the

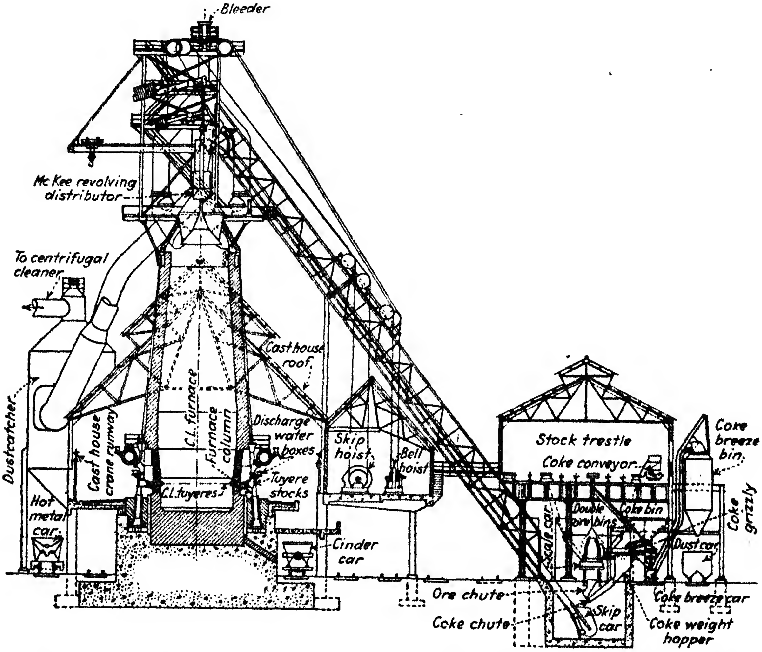


FIG. IV-12.—Sectional view of modern American blast-furnace and charging equipment. (*From William A. Haven, Recent Developments in American Blast Furnace Design and Practice, Journal of Iron and Steel Institute, May,* 1933.)

furnace. After the lower hopper has received many charges from above, this bell is lowered and the material allowed to fall in an annular stream into the furnace. Obviously, this is one of the times when fine dust is liable to be carried by the gases out of the furnace and into the gas-cleaning apparatus.

Fig. IV-13.—McKee rotating blast-furnace top hopper. The skip dumps a load of material into the upper hopper, the bottom of which is the small bell. This load of material, together with the upper hopper and the small bell, is then revolved through a predetermined angle. The small bell is then lowered, depositing the material into the large hopper. This process is repeated for every skip load until enough skip loads have been deposited to make one "round," as it is called, on the lower bell. Then this bell deposits its load into the furnace. Now the cycle is repeated, except that, for the next round, the angle of rotation of the upper hopper is changed. This gives a better distribution of coarse and fine material in the furnace, in order to prevent channeling of the gases, with consequent faster or slower working in different sections of the horizontal area of the furnace stack.

The hoisting of the skip and the lowering of both bells are under the direction of a man in the hoist house. The regularity with which the man operating the larry and the man in charge of the hoist house perform their functions has an exceedingly important influence on the regularity of the working of the blast furnace and, therefore, its uniformity and economy. An apparatus to record constantly the exact position of the stock line

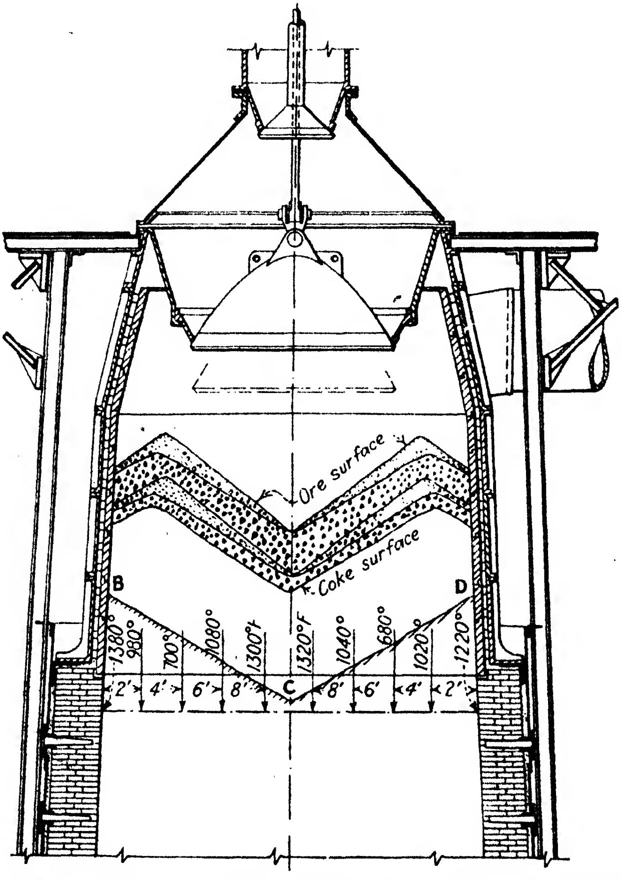


FIG. IV-14.—Solid raw materials at the stock line. The upper stock line shows how coarse and fine materials distribute themselves when the middle point of the stock line is about 9 ft. below the bottom line of the closed bell. The lower line *BCD* shows how the materials arrange themselves when the middle point is 17 ft. 3 in. below the bell. It is evident here that the coarse materials will tend to run downhill and accumulate around the central core of the furnace, thereby offering less resistance to the passage of the hot ascending gases of the furnace. This is further shown by the higher temperatures indicated at the central core of the furnace. It will also be noted that the temperatures near the periphery are also higher, showing that here too the gases ascend with greater velocity and consequently there is less absorption of their sensible heat by the solid charge.

in the furnace connects to an index in the hoisting house and advises the hoist man of the level of the stock line. It will be obvious from Fig. IV-14 that, since some material is in lumps and other in small size, there will be selective running down hill whereby lumps will tend to run toward the center, provided the stock line is too far below the bottom of the hopper (see line *BCD*), whereas there will be a double-cone arrangement when the stock line is close to the hopper. It is exceedingly important that the stock line be maintained at a constant point by charging raw materials as fast as the column descends in the furnace, in order to maintain as even as possible a distribution of large and small particles so that the ascending gases may travel evenly through the column of solids instead of finding points of least resistance. This is the reason why (when using earthy Mesabi ores) coke is sized from 4 to 1 in. in diameter and why even some of the lumpy ores are crushed to about 2-in. diameter when they are used together with earthy ores. However, it has been shown that the use of two or three sizes of raw materials gives a better contact between solids and gases than where only one size is used, provided the differences in sizes are not too great, and provided the distribution in the furnace is fairly uniform, so that small particles will partially fill up the interstices between the larger particles. The ideal is to get as perfect a contact between gases and solids as possible and to maintain the contact over as long a period of time as possible.

✓ **Furnace Lines and Their Development.**—The first blast furnace had a hearth which was very narrow in comparison with the diameter of the bosh and stack.[1] The object was to deliver the blast near the center of the furnace in order that a disproportionate amount might not seek the path of least resistance up along the furnace walls. A further advantage of this narrow hearth was the support offered to the charge in the furnace, as may be readily understood by reference to Fig. I-3. But there is today a better understanding of driving air so that a part of it penetrates by its own velocity to the very center of the furnace. Furthermore, modern coke is strong enough to support the entire weight of the superincumbent charge in the furnace, if necessary. And, finally, it is known that the blast itself affords a considerable degree of support to the weight of the solid material in the furnace. Indeed, the pressure of the blast is due solely to the resistance which the descending column of solids offers to the ascending gases. On account of these prevailing conditions,

---

[1] See Fig. I-4a.

hearth diameters are now made almost as large as the diameter at the top of the bosh. This gives greater hearth volume for combustion of coke and decreases the abrasion of the bosh inwalls due to the descent of the coke column when it is burned away near the base. A modern American furnace (Fig. IV-15) will have a hearth diameter of about 25 ft., because it is believed that this gives a greater speed of combustion than hearths either smaller or larger. It should be noted, however, that investigations in Germany on a somewhat extensive scale seem to indicate that no additional speed was obtained when the hearth diameter exceeded 18 ft. The problem in Germany is, however, different in two respects from that in America, because, first, the Germans do not have to get their blast-furnace temperature so high or their slags so limey, since a great deal of their iron is used in the basic Bessemer process and can therefore contain more sulphur than is acceptable for use in America in the basic open hearth; and, second, the Germans are not under the same necessity of using fine ores, which tend to reduce the ease with which the ascending column of gases will pass through the descending column of solids in the furnace Therefore, German blast pressures can be, and are, lower than they are in American practice. The maximum diameter of the American furnace at the top of the bosh is 28 ft., and it is customary to have a section about 10 ft. high with vertical walls at this point. The diameter at the stock line should be from 20 to 22 ft. Some recommend a throat-line diameter even equal to the hearth diameter. The object of a large stock-line diameter is to get a good distribution of raw materials in the furnace, as discussed more fully later. The total height of the furnace will be 75 to 105 ft. These general dimensions and lines are illustrated in Fig. IV-15.

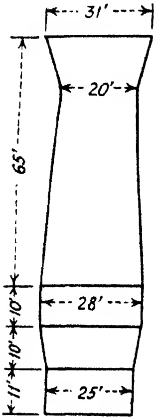


Fig. IV-15.—Lines and dimensions of a modern American iron blast furnace.

Limiting Dimensions.—When the preheated blast strikes the surface of the coke and combustion occurs, a temperature estimated to be in the neighborhood of 3150°F. is produced, by the reaction $C + O_2 = CO_2$. This temperature is somewhat reduced by the secondary reaction $2CO_2 + O_2 = 4CO$. The resulting white-hot nitrogen and carbon monoxide ascend through the bosh and begin very rapidly to melt the solid materials at a level approximately 18 to 20 ft. above the tuyères. This level marks the top of the bosh and therefore fixes the bosh height at about 20 ft. This again determines approximately the optimum diameter of the furnace at the top of the bosh, which also must be the maximum diameter of the stack, because, as the charge begins to undergo chemical reaction when it descends from the stock line, it tends to swell slightly. Therefore, the stack diameter must increase slightly from the throat to the top of the bosh. The diameter of the furnace at the throat is determined by conditions of good distribution of furnace stock from the bell. This again limits the height of the stack. Different types of ores will obviously produce different conditions. The modern American furnace using a considerable portion of cheap, earthy Lake Superior ores will be limited to approximately the dimensions shown in Fig. IV-15.

Tuyères.—The total area of the nozzles of all the tuyères in relation to the volume of blast will, of course, determine the velocity of the blast at the nozzles, provided the area of the conduits leading to the nozzles is always greater than the sum of the areas of nozzles involved. The number of tuyères around the periphery of the hearth will be determined by the optimum distance between tuyères and therefore the uniform distribution of blast. Finally, the diameter of each tuyère nozzle will, obviously, depend on the number and the total area desired. Many pages could be written on a discussion of the factors mentioned, but we may summarize here by saying that the modern furnace usually has between 10 and 12 tuyères, with a diameter between 6 and 9 in. each.

Furnace Lining.—Siliceous brick is used for lining the furnace from the hearth to the throat, because it is cheap and strong and resists both abrasion and melting. Since the slag is predominantly lime, we should expect that this acid lining would be attacked wherever the slag is molten—*i.e.*, in the bosh and smelting zone. Two factors tend to prevent this attack: first, the lining is cooled by water coolers, described in the next paragraph and, second, the normal blast-furnace reactions[1] cause a deposition of carbon in the charge. In time, this carbon bakes on to the inner surface of the brick, forming a hard scale which is not

---

[1] See Fig. IV-20.

easily abraded or dissolved in the liquid slag. The thickness of the lining in the stack will be roughly 2 to 3 ft.; in the bosh, 15 to 27 in.; and in the hearth, 2 to 4 ft. At various times linings only 9 in. thick have been used in the stacks of furnaces with the object of keeping this part of the furnace cool by radiation.

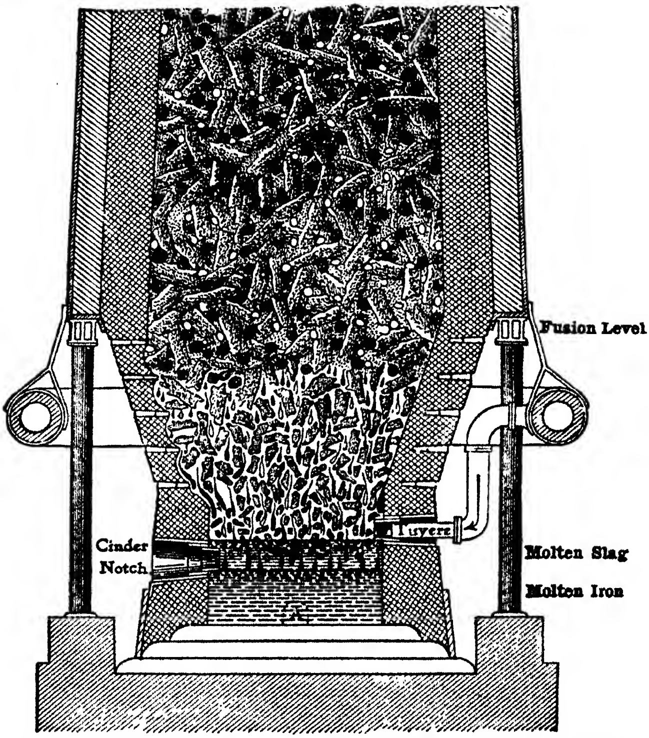


Fig. IV-16.—Section of blast-furnace smelting zone. (*From Howe, "Iron, Steel, and Other Alloys."*)

Lumps of coke	▬	Drops of iron	/
Lumps of spongy iron	●	Layer of molten slag	▤
Lumps of lime	○	Layer of molten iron	▦
Drops of slag	ò		

Cooling the Lining.—The bosh walls are always cooled by wedge-shaped steel castings placed in the brick work in circles, somewhat as indicated in Fig. IV-16. Sometimes bronze or copper castings are used instead of steel, because of the better heat conductivity of the metal. The lining of the stack is sometimes also cooled by water coolers spaced a greater distance apart than the coolers in the bosh. Sometimes the coolers in the stack are dispensed with altogether. The hearth bricks are cooled on the outside by water which flows continuously over the steel plates.

Water.—The amount of water used for blast-furnace cooling will depend on the size of furnace and conditions of operation, so that no general figures can be given, but a modern furnace will require about 5,000,000 to 7,000,000 gal. per day, of which about half is used for cooling the tuyères.

Life of Furnace.—Furnace linings must be torn down and rebuilt when the lining gets badly worn, so that the furnace does not work properly. An American furnace will last about three years for one campaign, during which 1,000,000 tons of pig will be produced. But records exist of American furnaces having made as much as 1,600,000 tons of iron before having to be torn down.

PRELIMINARY DISCUSSION OF THE SMELTING OPERATION

Cost of Making Pig Iron.—Costs of production are confidential in nature. The cost figures, shown in Table IV-I, are very general in nature and do not represent any individual furnace. They are only approximate as representative figures. It is probable that no one knows exactly what representative cost figures would be. Nevertheless, the figures in Table IV-I illustrate the important principle that the cost of pig iron is chiefly due to the cost of raw materials and the operating costs are of minor relative amount. Nevertheless, a very few cents per ton will make a considerable difference in the competitive

TABLE IV-I.—APPROXIMATE COSTS PER LONG TON OF PIG-IRON PRODUCTION[1]

District	Ore	Coke	Limestone	Labor	Supplies, repairs, etc.	Total
Northern United States	$8.00 to $12.00	$3.00 to $7.50	$0.20 to $0.75	$0.60 to $1.25	$1.30 to $2.00	$15.00 to $24.00
Southern United States	$2.00 to $ 5.00	$2.00 to $6.00	$0.25 to $1.00	$0.50 to $2.50	$1.20 to $2.00	$ 8.00 to $15.00
Europe	$5.00 to $ 6.00	$3.00 to $5.00	$0.10 to $0.40	$0.35 to $1.00	$0.50 to $1.50	$ 8.00 to $12.00
England	$3.75 to $ 6.00	$2.50 to $5.00	$0.20 to $0.40	$0.30 to $0.75	$0.50 to $1.60	$ 7.00 to $11.00

[1] These figures are only for illustration of principles. They should not be used for any estimates or calculations.

position of a producer in any market. The principal factors of operation which can reduce the cost of the product is in the efficiency of the use of fuel and labor. Tonnage is the principal factor in labor costs, because a furnace can make 1,500 tons of pig iron per day with almost the same labor that will be necessary to make 1,000 tons.

The Smelting Operation.—The blast furnace is a huge chemical vessel in which the materials are first heated to the point where some reducing chemical reactions will occur, then melted, and then still further heated until additional chemical reactions take place. In general, the principal chemical reaction is the reducing effect of hot carbon monoxide gas on the various oxides, notably the oxides of iron and of silicon, manganese, and phosphorus. H. H. Campbell[1] has given us the best summarized illustration of these reactions, as shown in Fig. IV-17. This is shown in connection with the small furnaces in use fifty years ago, but the principles remain the same today. It will be noted that an ascending column of hot gases passes through the furnace from the tuyères to the throat. The most voluminous gas is nitrogen, which takes no part in the chemical reactions. The most impor-

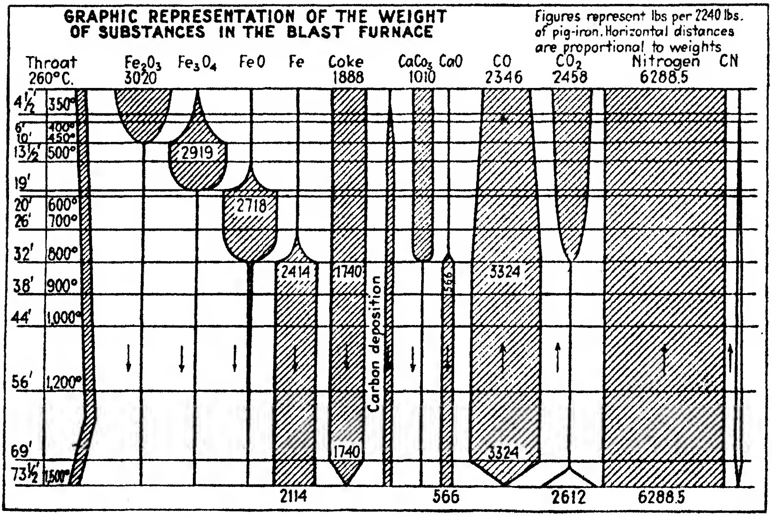


FIG. IV-17.—Graphic representation of the weights of solid materials descending in the blast furnace and of gaseous materials ascending, showing effect of reactions between gases and solids. (*From Campbell, "The Manufacture and Properties of Iron and Steel," New York,* 1907.)

---

[1] See reference, p. 20.

tant is carbon monoxide. It will be noted that this gas takes oxygen very rapidly away from hematite. Complete reduction occurs by the time the ore has descended 32 ft. down the stack. This reduction converts carbon monoxide to carbon dioxide, and the ratio of carbon monoxide to carbon dioxide in the top gases has long been considered the index of efficiency of blast-furnace reduction. Top gases which contain only twice as much carbon monoxide by volume as they do carbon dioxide have been considered to indicate good practice. But recently improved methods of combustion and better and longer contact between solid materials and gases have brought the ratio down to almost as low as 1.5 to 1. This is illustrated in Table IV-IA. A more detailed exemplification of blast-furnace reactions is given in Fig. IV-20, from which we can understand the column marked Carbon Deposition in Fig. IV-17. It is important that carbon be deposited on the bosh walls and on the solid materials in the stack of the furnace, notably on the surfaces of the spongy reduced iron, which puts it in a position to dissolve carbon when it is red hot and still more rapidly after melting.

The Different Zones of Iron and Silicon Reduction.—Iron oxide should be reduced in the upper part of the furnace stack. It has long been considered that even FeO should not be permitted to descend below the top of the bosh, but recent investigations indicate that, in the central core of the furnace, some FeO may be reduced by solid carbon even in the smelting zone itself. As to the oxides which are above iron in their heats of formation, we know that they cannot be reduced to metallic form until we get to the very high temperature of the smelting zone itself. They are probably not even then reduced by carbon monoxide but by solid carbon. Phosphorus is so near iron in the heat of formation of its oxide that all of it will be reduced and dissolved in the iron at any temperature which is feasible in blast-furnace operation, because we must have a temperature at least high enough to deliver the product in liquid form. Therefore, all the phosphorus existing in the iron ores will be reduced and pass into the iron. Ordinarily, all the manganese will also be reduced and dissolved, although it is possible, by using not too high a temperature and a slag relatively high in silica, to carry some of the manganese in the slag instead of in the iron. Silica is abundantly present in the charge, because coke ash is rich in silica and most iron ores contain it. The amount of silicon in the iron will, therefore, depend on the amount reduced from its oxides which will in turn depend upon the temperature of the furnace. A "hot" furnace will produce an iron relatively rich in silicon (say 2 to 3 per cent), and we may make a special product known as ferrosilicon containing as much as 10 per cent silicon. On the other hand, a relatively "cold" furnace will produce an iron low in silicon.

TABLE IV-1A.—ANALYSIS OF TOP-GAS SAMPLES[1]

Ore sizing	Number of samples	Per cent by volume				CO to CO_2 ratio
		CO_2	CO	H_2	N_2[2]	
No sizing	3	9.2	30.6	...	61.2	
	18	10.7	29.4	1.5	58.4	
	13	11.5	28.6	2.5	57.4	
	12	9.8	29.6	2.3	58.2	
	7	10.2	28.7	...	61.1	
Average[3]	53	10.5	28.1	2.0	59.4	2.68
Two sizes	2	10.9	28.4	...	60.7	2.60
Two sizes mixed	5	13.1	26.6	1.8	58.5	
	2	10.1	27.3	2.9	59.1	
Average[3]	7	12.2	26.8	2.1	58.9	2.20
Three sizes	1	13.4	26.5	...	60.1	
	4	13.2	23.7	2.5	60.4	
	8	15.2	24.5	2.4	58.0	
	2	13.2	28.1	...	58.7	
	5	13.4	26.9	1.6	58.1	
	54	17.2	25.4	.8	56.6	
Average	74	16.3	25.4	1.1	57.2	1.54

[1] From S P Kinney, Effect of Sized Ore on Blast Furnace Operation, U S. Bureau of Mines, *Technical Paper* 459, 1930

[2] By difference

[3] Weighted average

Optimum Operation Depends on Uniformity.—For the best operation of a blast furnace it is important that we obtain the greatest possible uniformity. This refers to chemical reactions uniformly taking place at the same level in the furnace and also uniformity of the passage of the ascending gases through all parts of the descending column of solids. By these two processes, uniformity in quality, in chemical composition, in temperature of the pig iron, in the economy of fuel combustion, and in furnace upkeep is maintained. The ascending gases will have a temperature of about 2750°F. at the level of the tuyères and about 350°F. at the throat. This drop in temperature obviously occurs by contact between the gases and solids. Where the gases find columns of least resistance between the solids, they will carry their temperature to a higher point in the furnace and *vice versa.* A study of a blast furnace to show velocity of the ascending gases at different points in the stack is shown in Fig. IV-18, which is taken from Fig. 4 of Flow of Gas in the Blast Furnace Shaft, by S. P. Kinney.[1] It probably does not represent extreme conditions, but it illustrates how parts of the column may be more permeable because of running down hill of larger particles and how the furnace walls make paths of low resistance. Of course, uniformity also depends upon uniform combustion at the tuyères, which is secured by constancy in volume, temperature, and pressure of blast. The two most important factors in furthering uniformity are, therefore, (1) uniformity in sizing and distributing of raw materials at the throat and (2) uniformity in combustion at the tuyères.

Blast Temperatures, Pressures, and Volumes.—A furnace producing 1,200 tons of iron per day (equivalent to 1,867 lb. per minute) must be supplied with about 75,000 cu. ft. of air (equivalent to 5,625 lb. of air) per minute. This air will be heated to a temperature of 1200 to 1400°F. The higher temperatures will be used where a large amount of earthy ores are not smelted, for the following reason: Earthy ores offer more resistance to ascending gases; therefore, they require a larger proportion of the porous coke in the charge to help keep the column permeable. But the higher the blast temperature, the less fuel will be needed to produce the requisite heat, and therefore the less permeable the charge. The speed of the operation depends upon the rapidity with which coke can be burned, because the charge can descend only as fast as coke is converted to gas. Therefore, the greater the blast volume, the greater the speed, provided the hearth is large enough to afford sufficient combustion space and provided the velocity of blast will drive it between the interstices of coke and uniformly distribute it from

---

[1] R.I. 2978, U. S. Bureau of Mines, December, 1929.

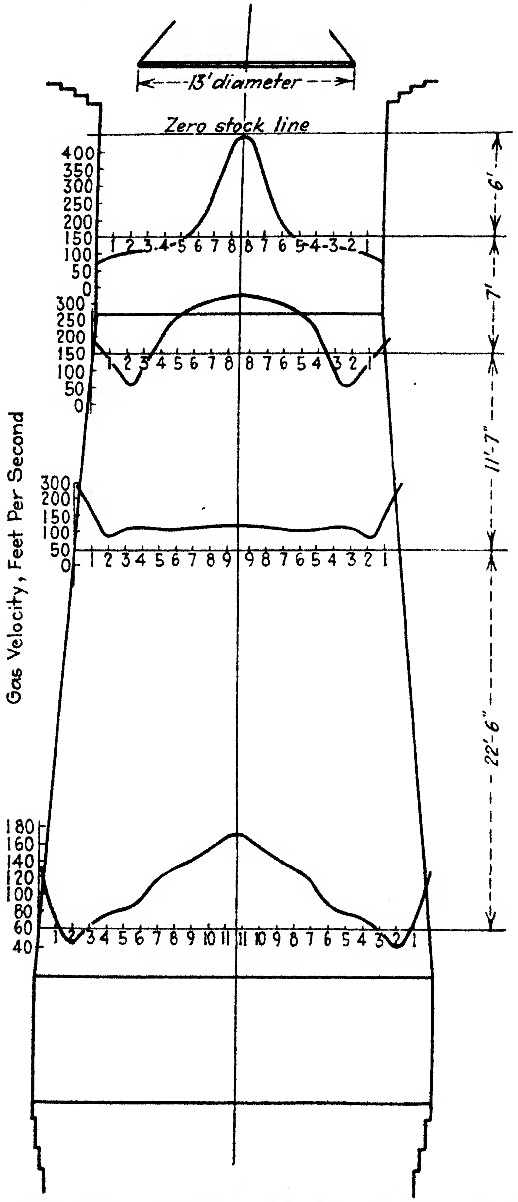


Fig. IV-18.—Gas velocity at various planes in an iron blast furnace. (*From Kinney, "Flow of Gas in the Blast Furnace Shaft," U. S. Bureau of Mines, December, 1929.*)

the mouths of the tuyères around the periphery to the center core of the furnace. The temperature of the blast also has a bearing in this connection, since the hotter the blast, the greater the speed of combustion. The blast pressure is a factor solely of the resistance which the charge affords to the ascending gases. If there should be any jamming in the furnace stack, the blast pressure would rise and the volume would tend to fall. The modern furnace is therefore equipped with devices which measure and automatically maintain at a constant point the volume of blast delivered to the furnace under a wide variation in pressures. Modern furnaces are also equipped to maintain the temperature of the blast at a constant point (see Fig. IV-19).

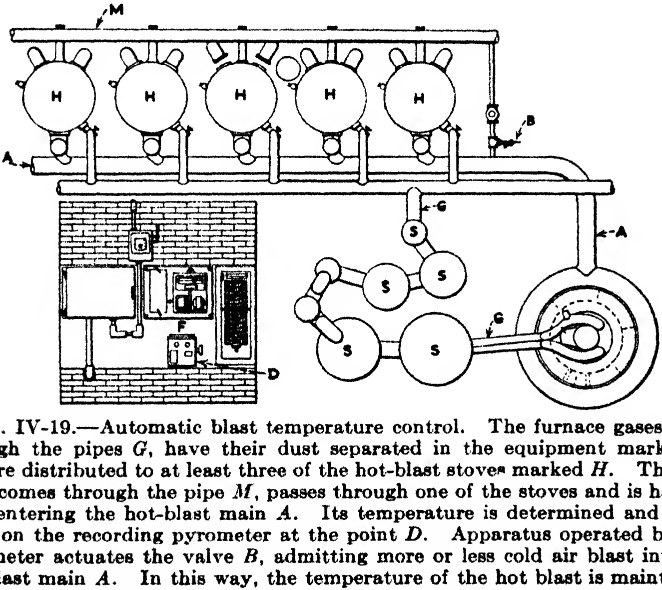


FIG. IV-19.—Automatic blast temperature control. The furnace gases come through the pipes *G*, have their dust separated in the equipment marked *S*, and are distributed to at least three of the hot-blast stoves marked *H*. The cold blast comes through the pipe *M*, passes through one of the stoves and is heated, then entering the hot-blast main *A*. Its temperature is determined and registered on the recording pyrometer at the point *D*. Apparatus operated by this pyrometer actuates the valve *B*, admitting more or less cold air blast into the hot-blast main *A*. In this way, the temperature of the hot blast is maintained at a constant predetermined figure. (*From The Iron Age, Apr.* 30, 1931.)

The Ascending and Descending Columns.—It takes approximately 8 to 14 hr. for solid materials to descend from the throat to the hearth, and it takes approximately 20 sec. average for the gases to ascend from the hearth to the throat. As the solid materials descend, they become heated and begin to be acted on by the ascending gases. The approximate temperatures attained, shown in Fig. IV-20, correspond approximately to the reactions which occur.

Chemical Reactions in the Upper Levels.—As soon as the iron ore enters the top of the furnace, two reactions begin to take place between it and the gases:

$$2Fe_2O_3 + 8CO = 7CO_2 + 4Fe + C; \qquad (1)$$
$$2Fe_2O_3 + CO = 2FeO + Fe_2O_3 + CO_2; \qquad (2)$$

and this continues with increasing rapidity as the material becomes hotter. The carbon formed by reaction (1) deposits in a form similar to that of lampblack on the outside and in the interstices of the ore. This reaction, however, is opposed by two reactions with carbon dioxide gas:

$$Fe + CO_2 = FeO + CO; \qquad (3)$$
$$C + CO_2 = 2CO. \qquad (4)$$

Reaction (3) begins at a temperature of about 300°C. (575°F.), which is met with about 6 or 7 ft. below the top level of the stock; and (4) begins at about 535°C. (1000°F.), or 20 ft. below the stock line. Reaction 4 is so rapid that the deposition of carbon ceases at a temperature of 590°C. (1100°F.). All the way down the ore is constantly losing a proportion of its oxygen to the gases. At higher temperatures than 590°C., FeO is stable and practically all of the hematite has been reduced.

$$Fe_3O_4 + CO = 3FeO + CO_2. \qquad (5)$$

The reaction between iron oxide and solid carbon begins at 400°C. (750°F.):

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

At 700°C. (1300°F.) solid carbon begins to reduce even FeO

$$FeO + C = Fe + CO. \qquad (7)$$

Practically all the iron is reduced to a spongy metallic form by the time the temperature of 800°C. (1475°F.) is reached. This is about 45 ft. from the stock line and less than 30 ft. above the tuyères. At 800°C. the limestone begins to be decomposed by the heat, and only CaO comes to the smelting zone:

$$CaCO_3 = CaO + CO_2. \qquad (8)$$

The foregoing facts are summarized in Fig. IV-20, which is adapted from H. H. Campbell, with certain changes. It is not to be supposed that these figures are exactly correct for the different levels, and it is probable that they change from day to day and from furnace to furnace, but a general idea may be obtained from this sketch. It will be seen that the upper 15 or 20 ft. of stock is a region of hematite and magnetite, gradually being converted to FeO by carbon monoxide gas and forming quantities of carbon dioxide gas. If these reactions were the only ones, the top gases would contain no carbon monoxide and would have no calorific power, but reaction (1) produces both metallic iron and carbon, both of which reduce carbon dioxide and thus waste much energy, as far as the blast furnace is concerned: Reaction (3) absorbs 2,340 but wastes 68,040 calories. Reaction (4) absorbs 38,880 calories. From 20 to 35 ft. below the stock line is the region of FeO, grad-

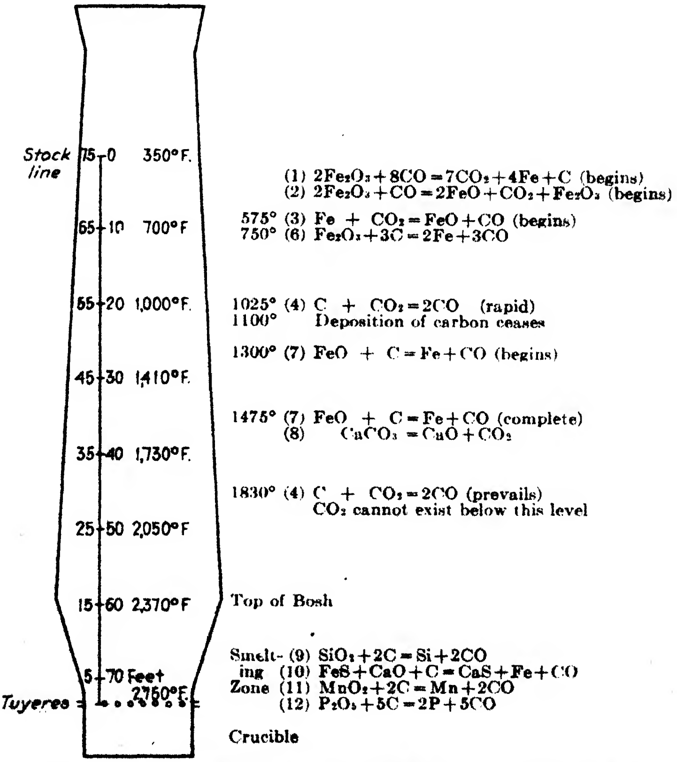


FIG. IV-20.—Diagram showing chemical action in blast furnace.

ually being converted to metallic iron sponge by carbon. At the lower level of this zone the limestone loses its carbon dioxide, which joins the other furnace gases. From 35 ft. down to the smelting zone is the region of metallic iron. This spongy iron is impregnated with deposited carbon, much of which soaks into it and dissolves.[1] This carburization of the spongy iron reduces its melting point and causes it to become liquid at a higher point in the furnace than it otherwise would.

On reaching the smelting zone, the iron melts and trickles quickly down over the column of coke, from which it completes its saturation with carbon, dissolving about 5 per cent of carbon at a temperature of 2750°F. At a corresponding point the lime unites with the coke ash and impurities in the iron ore, forming a fusible slag which also trickles down and collects in the hearth.[2] It is during this transit that the different impurities are reduced by the carbon, and the extent of this reduction determines the characteristics of the pig iron, for in this operation, as in all smelting, reduced elements are dissolved by the metal, while those in the oxidized form are dissolved by the slag. Only one exception occurs, namely, that iron will dissolve its own sulphide (FeS) and, to a less extent, that of manganese (MnS), but not that of other metals, as, for instance, CaS.

Chemical Reactions in the Smelting Zone.—There is always a large amount of silica present in the coke ash, and some of this is reduced according to the reaction:

$$SiO_2 + 2C = Si + 2CO. \tag{9}$$

The extent of this reaction will depend on the length of time the slag takes to drop through the smelting zone, the relative intensity of the reducing influence, and the avidity with which the slag takes up silica. A slag with a high melting point will trickle sluggishly through the smelting zone[2] and cause the iron to do the same, to some extent, thus giving it more chance to take up heat. A higher temperature in the smelting zone, which increases disproportionately the avidity of carbon for oxygen, will promote reaction (9).

Sulphur comes to the furnace chiefly in the coke. It is present as dissolved sulphur and as iron sulphide, FeS, which

---

[1] It is to be understood that this is a chemical reaction between two solids. No liquid is formed either before or after this carburization.

[2] See Fig. IV-16.

will dissolve in the iron unless converted into calcium sulphide, CaS. This conversion is brought about by the following reaction:

$$FeS + CaO + C = CaS + Fe + CO. \tag{10}$$

Calcium sulphide passes into the slag, and the odor of sulphur is very strong when the slag is running from the furnace. It is evident from reaction (10) that intense reduction, which increases the silicon in the iron, has the contrary effect on the sulphur, and this explains the common observation that iron high in silicon is liable to be low in sulphur. Indeed, this relation is so constant that it is almost a rule. The term *hot iron* has come to be synonymous in the minds of blast-furnace foremen with iron high in silicon and low in sulphur.

Manganese is reduced by the following reaction:

$$MnO_2 + 2C = Mn + 2CO. \tag{11}$$

The amount of manganese in the iron is dependent, to a certain extent, upon the character of the ores charged, but it may be controlled somewhat by the character of slag made, because an acid slag will carry a large amount of manganese away in the form of silicate of manganese, $MnSiO_3$.

With a certain unimportant qualification, the amount of phosphorus in the iron is controlled by the character of raw materials charged, and districts or countries having high-phosphorus ores must make high-phosphorus irons. This is not an insuperable objection, because the presence of phosphorus, even up to 1.5 per cent, is desired in certain irons for foundry use, and the basic processes for making steel can remove this element.

The chemical influence of the blast furnace is a strongly reducing one, and this is produced in order, first, to reduce the iron from the ore; second, to get rid of the sulphur; and, third, to saturate the iron with carbon.

Amount of Coke Used.—Obviously, the more coke that is used in proportion to the other solid materials, the greater the amount of heat generated in the furnace. This relation is called the *coke burden*. It is more usual, however, to speak of the amount of coke used per ton of iron produced, and this is commonly from 1,750 to 2,240 lb. of coke per long ton of pig iron produced.

Furnace-temperature Control.—While the total amount of heat generated in the furnace depends on the amount of coke used, nevertheless, the intensity of heat, or temperature, of the smelting operation does not depend primarily on the coke but rather upon the melting point of the slag. Slags are on the limey side of maximum fusibility. That is to say, if silica be added to a slag, its melting point will be lowered; whereas if lime be added to it, its melting point will be raised. In the melting of slags they change from solid bodies to pasty, viscous, and then fluid masses. The actual melting temperature extends over a somewhat long interval, and it is more common to speak of "free-flowing" temperature of a slag rather than its melting point. The lower the temperature at which a slag will flow freely, the lower in general will be the temperature in the smelting zone of the furnace, and *vice versa.* Therefore, the blast-furnace manager adds more limestone to his burden in order to get a hotter furnace by having a more limey slag and, therefore, one whose free-flowing temperature is higher. Of course, the more limey the slags, the more coke must be used in the burden, but the actual control and regulation are by means of the slag composition rather than the fuel burden. Less coke with higher blast temperature will give the same amount of heat as more coke with lower blast temperature. In the last analysis, however, it is not the proportion of coke or the temperature of blast which determines the temperature of the furnace but the temperature at which the slag will flow freely.

Opening and Closing the Tap Hole.—It is customary to open the tap hole and drain the furnace of iron at regular intervals, every 4, 5, or 6 hr. It is customary to drill through with a sledge and bar, unless the hole reaches in as far as frozen metal on the inside of the hearth. This is burned out with a jet of oxygen. When the last of the iron is going out of the furnace, a good deal of the slag accompanies it and this is skimmed off at the dam and skimmer (see Fig. IV-21). Since the slag floats on the metal, it is easily deflected to one side and allowed to run into a slag buggy. After the furnace is drained, the blast pressure is cut off and the hole closed by means of a mud gun which projects balls of clay into the opening. A recent innovation is a mud gun which can stop the hole without cutting the blast off the furnace.

Opening the Cinder Notch.—The cinder notch is opened at regular intervals. It is some time after an iron tap before an accumulation in the hearth permits of slag's being drawn from the cinder notch. Thereafter the slag must be drawn out at frequent enough intervals to prevent cinder rising above the level of the tuyère notches.

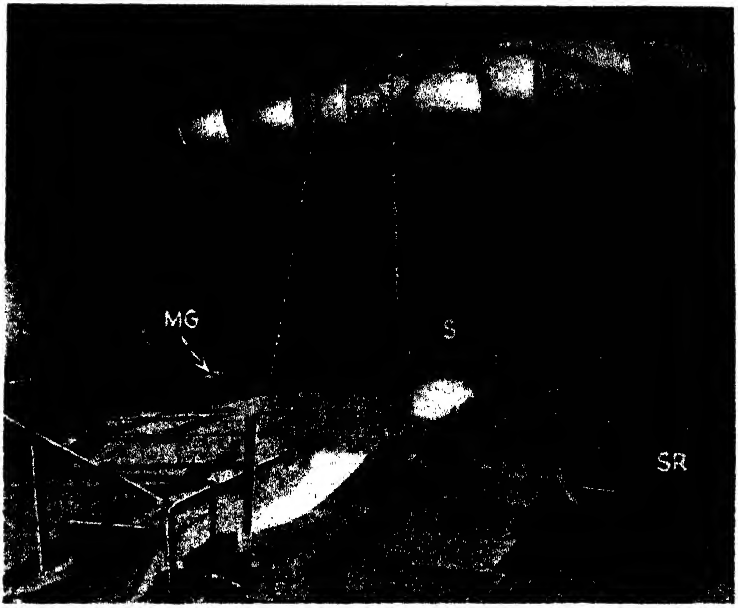


FIG. IV-21.—Liquid iron running from blast furnace into prepared molding floor. *MG*, mud gun to close tap hole; *S*, support for mud gun; *D*, dam or "skimmer."

CALCULATING A BLAST-FURNACE CHARGE

This subject is of prime importance to young metallurgists, because the ability to calculate a charge is sometimes a cause of advancement, and the knowledge of the way to do so is not always obtainable from one's superior.

Assumptions.—Let us assume that we desire to produce a slag containing 55 per cent lime, 15 per cent alumina, and 30 per cent silica, these proportions being determined by the experience of the manager, and that the materials from which the charge is to be made analyze according to Table IV-II. Assume furthermore that the coke ash is equal to 10 per cent of the coke, and that the iron we are going to make will contain about 1 per cent silicon.

TABLE IV-II.—ANALYSES OF MATERIALS USED

Material	CaO, per cent	MgO, per cent	Al_2O_3, per cent	SiO_2, per cent	Fe_2O_3, per cent	Fe, per cent
Ore A..........	5	4	2	11	..	60
Ore B..........	2	..	12	16	..	50
Coke ash........	20		18	50	..	10
Limestone	46	4	2	4	..	2

Silicon in the Iron.—This last assumption necessitates our allowing a corresponding amount of silica, because the silica reduced and absorbed by the iron will not be available for slag-making purposes. One per cent of silicon is roughly equal to 2 per cent of silica; we may therefore make the requisite allowance by subtracting from the silica in each material an amount equivalent to 2 per cent of its iron content. Thus we begin to make up Table IV-III.

Magnesia.—In considering slags, magnesia is classified under the head of lime, thus obtaining column 2 in Table IV-III.

TABLE IV-III.—ANALYSES AFTER ALLOWING FOR SILICON IN PIG

Material	CaO, per cent	Al_2O_3, per cent	SiO_2, per cent
Ore A	9	2	10
Ore B..........................	2	12	15
Coke ash..	20	18	50
Limestone......................	50	2	4

Self-fluxing of Materials.—It is evident that, in so far as each of the materials in Table IV-III contains all the components of the slag, they will partially flux themselves. For example, the 2 per cent of alumina in ore A will theoretically combine with 4 per cent of the silica (2 per cent $\times \frac{30}{15}$ = 4 per cent) and 7 per cent of the lime (2 per cent $\times \frac{55}{15}$ = 7.3 per cent) to make a slag of the desired proportions, leaving unfluxed percentages as per the first line of Table IV-IV. In the same manner we may use up all of the lime in ore B by uniting it with weights of alumina and silica in proportion to the percentages of these components in the slag. Similar simplifications in the analyses of coke ash and limestone may then be calculated, and Table IV-IV will be completed.

TABLE IV-IV.—ANALYSES AFTER SELF-FLUXING

Material	CaO, per cent	Al_2O_2, per cent	SiO_2, per cent
Ore A	2	....	6
Ore B	..	11.5	14
Coke ash	..	13.0	39
Limestone	43		

Weight of Charge.—Let us assume that we are going to make 1 ton of pig iron for every ton of coke used in the charge, and that the coke will be put in in charges weighing 11,000 lb. each. This weight includes about 10 per cent of moisture, dust, etc.,[1] so we calculate with it as if it weighed only 10,000 lb. Now let us determine how much ore will be put in each charge: The ores average 55 per cent of iron; therefore, $\frac{10{,}000 \text{ lb.}}{55 \text{ per cent}} = 18{,}000$ lb., the amount of ore that must be in each charge, according to the assumption of this paragraph.

Adjusting the Alumina and Silica.—Next adjust the different materials so that the weight of alumina shall be $^{15}/_{30}$ of the weight of silica. In the first rough approximation of this we may neglect the coke ash, because the weight of this ash is so small in relation to the other materials. Therefore only the two ores need be apportioned, and we quickly find by trying a few mixtures at random that 60 per cent of ore A mixed with 40 per cent of ore B will give the desired relation:[2] 60 per cent × 6 +

---

[1] This assumes that the breeze (or "braize") is removed after weighing the coke. If it is removed before, allow only 3 per cent excess, which makes coke charges equal 10,300 lb.

[2] Try first 50 per cent of each, and we see that there is too much alumina; therefore try less than 50 per cent of the ore having the most alumina and correspondingly more of the other, and we have it.

40 × 14 per cent = 920 parts of silica; 60 per cent × 0 + 40 per cent × 11.5 = 460 parts alumina; $^{460}/_{920} = {}^{15}/_{30}$. Now draw Table IV-V, and enter 10,800 lb. of ore A (= 60 per cent of 18,000), 7,200 lb. of ore B, 1,000 lb. of coke ash (= 10 per cent of 10,000), and the percentages from Table IV-IV. All the weights in this table may then be filled in except those of the limestone and total calcium oxide.

To obtain the total number of pounds of lime:

$$Al_2O_3{:}958 \times {}^{55}/_{15} = 3{,}513 \text{ lb.}$$
$$SiO_2{:}2{,}046 \times {}^{55}/_{30} = 3{,}751 \text{ lb.}$$

Average of 3,513 and 3,751 is 3,632.

TABLE IV-V.—ESTIMATED WEIGHTS OF MATERIALS USED

Material	Weight	CaO		Al_2O_3		SiO_2	
		Per cent	Pounds	Per cent	Pounds	Per cent	Pounds
Ore A	10,800	2	216			6	648
Ore B	7,200			11.5	828	14	1,008
Coke ash	1,000			13.0	130	39	390
Limestone	*C* 7,940	43	*B* 3,416				
Total, pounds			*A* 3,632		958		2,046

Adjusting for Lime.—It is now only necessary to determine the amount of total lime that shall bear the correct relation to the alumina and silica calculated. This we do by means of the method shown in the figures above Table IV-V. We enter this in the square *A* of Table IV-V. The figures at the square *B* are then obtained (3,632 − 216 = 3,416), and thence the weight of limestone to be used (3,416 ÷ 43 per cent = 7,940).[1]

---

[1] In practice this is often much simplified by taking the Al_2O_3 simply as fixed, within wide limits, and figuring merely the ratio of CaO and MgO to SiO_2; disregard Al_2O_3, unless it is abnormally high and therefore bad for physical reasons. If a constant limestone is used, all such calculations are much simplified by figuring the net CaO and MgO in the stone after the SiO_2 in the stone is satisfied.

If a given ratio of CaO + MgO to SiO_2 be desired, it is only necessary to add up the SiO_2 in ore and fuel, multiply by the desired ratio and divide

TABLE IV-VI. FINAL ESTIMATE OF CHARGE

Material	Weight	$CaO + MgO$		Al_2O_3		SiO_2		Fe	
		Per cent	Pounds	Per cent	Pounds	Per cent	Pounds	Per cent	Pounds
Ore A	10,400	9	936	2	208	11	1,144	60	6,240
Ore B	7,600	2	152	12	912	16	1,216	50	3,800
Coke ash	1,000	20	200	18	180	50	500	10	100
Limestone	8,200	50	4,100	2	164	4	328	2	164
Total weights			5,388		1,464		3,188		10,304
							−206(2 per cent × 10,304)		
			(54.8 per cent)		(14.9 per cent)		2,982(30.3 per cent)		

Checking the Calculations.—We now check up all the calculations by making up Table IV-VI, in which we go back to the original percentages found by chemical analysis and given in Table IV-II. In making up this final table, however, we use our experience in making slag calculations and estimate slight changes; *e.g.*, Table IV-V shows us that the alumina comes a little low in relation to silica; therefore we increase ore B, say, by 400 lb. and decrease ore A correspondingly. But ore A is high in lime; therefore we use a little more limestone to offset this reduction.

These figures are much closer to those desired than the limit of accuracy in furnace operation. The chief difference is that we are making a little more iron with 10,000 lb. of coke than we intended. If any change seems necessary, it is then well to reduce the weight of ore A to 10,000, leaving everything else the same. This will lighten the burden and bring the calculated lime, alumina, and silica even closer to the desired figures.

Phosphorus and Manganese.—No account of the phosphorus has been taken in the calculation above. This is necessary sometimes. For example, if ore A happened to be very high in phosphorus, we could not use so large a proportion of it. It would then be necessary either to secure another ore low in both phosphorus and alumina or else to make a slag with less alumina.

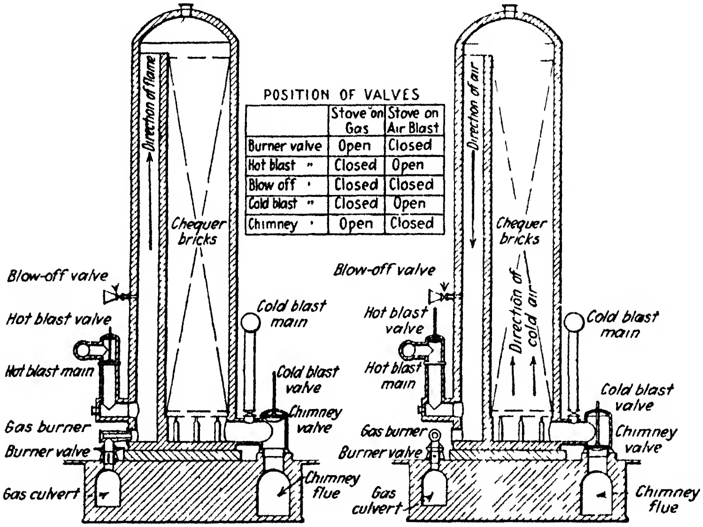
---

by the efficiency of the stone. The net SiO_2 in the ores should be taken; *i.e.*, the SiO_2 fluxed by the bases in the ore should be deducted.

The same line of reasoning applies to manganese but to less extent because the manganese in the iron can be controlled by the work of the furnace to a considerable extent, and in no event does more than two-thirds of that in the charge go into the iron.

AUXILIARY BLAST-FURNACE PLANT

Besides the operations of charging, operating, and tapping a furnace, there are many auxiliary operations to be performed, such as heating the blast, disposing of the pig and slag, cleaning the gas and converting it into heat or power, manufacturing coke, and sintering the flue dust.



POSITION OF VALVES

	Stove on Gas	Stove on Air Blast
Burner valve	Open	Closed
Hot blast "	Closed	Open
Blow off "	Closed	Closed
Cold blast "	Closed	Open
Chimney "	Open	Closed

Stove on Gas

Stove on Air Blast

FIG. IV-22.—The operation of a blast-furnace hot-blast stove. Figure on left shows stove burning gas from the blast furnace, figure on right shows stove heating blast which goes to blast furnace. (*From Fred Clements, "Blast Furnace Practice," vol.* II, 1929.)

Hot-blast Stoves.—The general principle of heating cold blast by means of stoves is illustrated in Fig. IV-22.[1] Each furnace has three stoves, of which one is always being used for heating the blast and the other two are being heated up by burning gas from the furnace, except for short intervals when it is necessary to clean the surfaces of the checker bricks. The ideal is to have the maximum heating surface exposed to the burning of the

---

[1] Taken from p. 330 of vol. II of Clements.

gases. In this way, the checkerwork is heated to a high temperature. The positions of valves, etc., when the stove is thus on gas, is shown on the left-hand side of Fig. IV-22. When the stove is heating the blast, the position of valves is shown in the right-hand figure. The cold blast is introduced underneath the checkerwork and passes in a direction opposite to the course of the flame in the previous phase. As the heat stored in the checkerwork is absorbed by the air, the temperature of the blast leaving the stove grows less. The temperature is, therefore, falling from a maximum to a minimum. Automatic arrangements, already described (see Fig. IV-19), arrange to introduce a varying amount of cold blast into the main with the heated blast so that the temperature of the air going into the furnace will be always at a predetermined constant figure. These automatic devices consist of a thermocouple pyrometer in connection with an electric motor. The thermocouple shows the temperature of the blast, which operates the motor in one direction and admits more cold air if the blast is too hot, or *vice versa* if the blast is too cold. After a stove ceases to give air at this minimum figure, it is changed over to gas and the blast is sent through an alternate stove.

FIG. IV-23.—150-ton mixer ladle. (*Courtesy of M. H. Treadwell Co., Inc.*)

Disposal of Pig.—The runner from the blast-furnace tap hole to a ladle is made as short as possible in order to lessen the labor of cleaning it after a tap. The liquid pig iron used to be received in a number of brick-lined ladles holding about 25 tons each. But now it is customary to use mixer ladles each having a capacity of 75 to 150 tons, or more (see Fig. IV-23). The advantage of these ladles is that they will hold the liquid metal molten for many hours, thus saving pig-iron "skulls" as well as ladle repairs, because one of these mixer-type ladles can handle a few hundred thousand tons of pig iron before they have to be relined. The mixer ladles are taken to either a foundry or a refining furnace, in both of which the metal is used without solidifying, or else to a mechanical pig-casting machine (see Fig. IV-24).

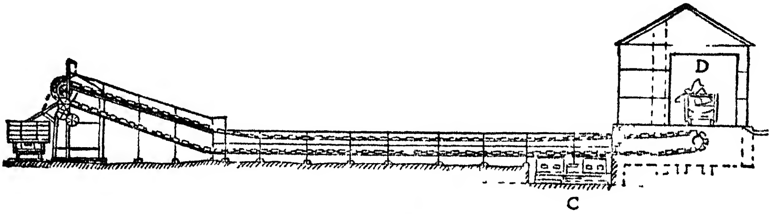


FIG. IV-24.—Heyl and Patterson pig-casting machine.

Mechanical Pig-molding Machine.—There are several types of molding machine, but a common form is illustrated in Fig. IV-24. It consists of a long continuous series of hollow metallic molds carried on an endless chain. *D* is the pig-iron ladle pouring metal into the spout, whence it overflows into the molds as they travel slowly past. The pig iron chills quickly against the metallic molds, and by the time it reaches the other end of the machine it consists of a solid pig of iron which drops into the waiting railroad car as the chain passes over the sheave. The pig iron is now in a form convenient for transportation or for storing until needed. The molds travel back toward the spout, underneath the machine and hollow side down. At the point *C* they are sprayed with whitewash, the water of which is quickly dried off by the heat of the mold, leaving a coating of lime to which the melted iron will not stick. This mechanical casting is a great improvement over the former method of cooling iron in front of the blast furnace, because of the severity of the work which the former method involved, which in hot weather was well-nigh intolerable to human beings. It also gives pigs which are cleaner, *i.e.*, freer from adhering sand. This siliceous sand is objectionable, especially in the basic open-hearth furnace.

Disposal of Slag.—Short runners lead from the monkey and also the dam to spouts permitting the molten slag to run into iron ladle cars.

Sintering.—The dust separated out from the top gases is extremely fine in size and cannot be returned to the furnace lest it should blow out again. It is sintered in a machine which agglomerates it into spongy lumps. These lumps work so efficiently in the blast furnace because of their extensive surface and contact with the ascending gases, and because they make a permeable column, that sometimes fine ores are sintered into lumps. This sintering consists in heating up the mass in a shallow bed on a grate until the fine particles are sintered and fused together at the edges, producing a spongy mass. In the case of flue dust, it is not necessary to add much, if any, fuel to the mass, because it contains small particles of coke blown over with the other dust. It is only necessary to ignite the mass by a flame and blow air through it to produce the necessary heat. In the case of fine ores, it is sometimes necessary to mix a little powdered fuel with the mass.

Power House.—The power house includes the boiler plant and the plant generating power from the top gases of the furnace. Some steam is always necessary around a blast-furnace plant and it used to be raised by the top gases of a furnace, but these are now so valuable for other purposes that it is more economical to raise the steam by using coke breeze or pulverized coal. When the amount of breeze separated from the coke in the ordinary operations of the coke plant and the coke-bin grisley is not sufficient to raise all the steam that may be necessary, this type of fuel, which is almost a waste by-product of coke production, can be supplemented with pulverized coal. When turboblowers are used for the production of blast, it is customary to drive them by steam. But by far the largest amount of power raised is by a type of gas engine specially adapted for burning the top gases of the furnace, which have a calorific power of only 90 to 110 B.t.u. per cubic foot. Some of the gas engines are used for blowing horizontal blowing engines (see Fig. IV-10), if that type of blowing mechanism is used, and others are used for driving electric generators from which electricity is supplied to the blast furnace and adjacent steel plant. It is customary to have one or two steam-blowing engines on hand to be used before top gas is available, or in the case of an emergency. Some power is also requisite for driving pumps for the cooling water.

FURTHER DISCUSSION OF THE SMELTING OPERATION

Autographic Records of Charging.—In order that the blast-furnace manager may have supervision over the regularity of charging operations at all times, the stock-line recorder makes a continuous autographic record of the level of the stock line in the furnace. Autographic records are also made of the times of hoisting each skip and of lowering each bell. These form invaluable checks on the performance of the operations most important for uniformity in stock distribution.

Autographic Records of Blast Temperature.—Autographic records are also made and kept of the blast temperature, pressure, and volume.

Slag or Cinder.—Slag consists principally of lime, silica, and alumina. In many cases a little magnesia is also present which is added to the lime for estimating the basicity of the slag. Some representative slag analyses with basicity ratio of lime + magnesia to silica are shown in Table IV-VII. The functions of the slag are to separate from the iron the gangue of an ore, the ash of the coke, and as much sulphur as possible, which means as much sulphur as has been converted into the compound calcium sulphide. The slag should not dissolve much more than 1 per cent of iron oxide. One of the important functions of the slag is to regulate and control the temperature of the smelting zone of the furnace, as already pointed out. Slag is a useful basis

TABLE IV-VII.—SLAG ANALYSES

Material	United States furnace	German furnace	English furnace
SiO_2	33	33	26
CaO	48	45	42
MgO	5	5	2
Al_2O_3	12	8	19
FeO	1+	3	1+
Others	1	6	10
Ratio: CaO + MgO to SiO_2	1.61	1.52	1.60

for cement manufacture because of its lime content. Many millions of bags of slag cement are made each year. It is also used for "slag wool," for railroad ballast, for road making, and, less commonly, for making bricks. In order that the furnace may work properly and that a good deal of sulphur may be kept out of the iron, it is necessary that the slag volume shall be at least 1,000 lb. per long ton of pig iron made. On the other hand, it is costly to have more than 1,500 lb. of slag per long ton of pig.

Weight of Slag.—The weight of slag may be calculated from the weight of lime, CaO, in the furnace, which may be calculated from the percentage of lime in the limestone and other materials charged into the furnace. Since all the lime charged goes into the slag, the amount of the latter will be equal to the weight of lime divided by the percentage of the lime in the slag. Thus, if we use per ton of iron 1,100 lb. of limestone, containing 50 per cent of lime, there will be 550 lb. of lime charged for every ton of iron made. If the slag made contains 40 per cent of lime, then the weight of slag will be $\frac{550}{0.40} = 1{,}375$ lb. per ton of iron made.

Drying the Blast.—The water vapor blown into the furnace (derived from the moisture of the air) is equivalent to from $\frac{1}{3}$ to 2 gal. of water per 10,000 cu. ft. of blast, or $2\frac{1}{2}$ to 15 gal. per minute, depending on the humidity of the atmosphere. This is equal to about from 20 to 125 lb. of water per minute. Though this steam is as hot as the blast, it materially cools the smelting zone of the furnace by dissociating there:

$$H_2O + C = 2H + CO \text{ (absorbs 28,900 gram calories);}$$

or 1 lb. of steam absorbs 722,500 calories. The hydrogen and oxygen reunite in a cooler part of the furnace and return the same amount of heat, but this does not compensate for that taken away from the smelting zone, where it is most needed. For this reason several American and European plants adopted James Gayley's process of drying the air by refrigeration before it is drawn into the blowing engine. This results in valuable saving in fuel and greater regularity of furnace working. In fact, so great is the improvement shown in this respect that there was a tendency at first to receive the results with skepticism.

The same condition prevailed upon the introduction of the hot blast, early in the last century, for the same reasons: that no explanation was forthcoming of the observation that the fuel saved in practice was so much greater in proportion than the heat saved or restored to the crucible. But it was pointed out by J. E. Johnson, Jr., in the discussion of Mr. Gayley's results, that certain functions of the smelting process can be carried out only above a certain "critical temperature," which was in fact the free-running temperature of the slag, and that the heat available above this temperature, and not the total heat developed in the furnace, is the measure of the economy that can be attained. Approximately speaking, the interval between the critical temperature and the theoretical combustion temperature is the measure of this available heat; and as the critical temperature is, roughly speaking, four-fifths of the theoretical combustion temperature, any change which increases or decreases the latter by a given proportion will increase or decrease the available heat by a proportion five times as great. This simple explanation enables us to calculate with accuracy the effect of any given change in known conditions.

Johnson also pointed out that the theoretical combustion temperature might be increased by enriching the air in oxygen, instead of reducing the moisture in it, since this enrichment would increase the calorific efficiency.

Labor at Blast Furnaces.—At an old-fashioned type of blast furnace, casting in sand, without mechanical devices to carry or break the pigs, as little as 200 to 250 tons of pig iron per 24 hr. would require about 15 men in front of the furnace, including a keeper, first helper, 5 assistant helpers, who open and close the tap hole, break the pigs from the sows, and do the general cast-house work, 5 men to carry iron, a "cinder snapper," a scrap man, and a stove man. This labor would be required for each shift. Back of the furnace there must be a scale man to weigh stock and 18 men on the ground besides 3 "top fillers" to handle material for burden, provided it is done in the old-fashioned manner.

On the other hand, at a furnace with mechanical devices for casting and for handling stock, more than four times as much pig iron can be made with 4½ to 6¼ men in front of the furnace, per shift, consisting of: 1 "blower" for each two to four furnaces, 1 keeper, 1 helper, 1 "cinder snapper," 1 "flue-dust man," 1 hot-blast stove man. Sometimes another man is required, called a "scrap man," or, perhaps, a laborer. With oxygen for burning out the red-hot iron in the tap hole, mud gun, short runners to slag and metal ladles, etc., one furnace is able to get along with 4 men and a fraction of a "blower" per shift. Back of the furnace a scale-car man is required, but, with mechanical handling to ore pockets and to the furnace top, about 5 to 6 men per shift per furnace can handle the stock to make 1,200 long tons of pig iron in 24 hr.

Irregularities in Blast-furnace Working.—Since the hollow castings surrounding the tuyères extend about 12 in. into the furnace, they are at a location of very high temperature where they may burn through if not kept constantly cooled by the water circulating inside them or if a piece of coke causes a hot flame to strike them in one point for a long time. The changing of tuyères on this account takes place at every blast furnace, sometimes once per month and sometimes oftener. Irregularities in blast-furnace working may also sometimes cause a spot on the side to become red hot, necessitating applying a stream of water upon it until the difficulty is corrected. Occasionally this has resulted in "break-outs." On the other hand, an error in burdening, or change in the weather causing damper air to be blown by the blowing engines, or a leaky tuyère causing water vapor to be blown into the furnace, etc., may result in cold working at the hearth, with hard taps (*i.e.*, difficulty in opening the tap hole to let the iron run out), low silicon and high sulphur in the pig iron, and accompanying difficulties. "Off iron," meaning pig iron different in analysis from that desired, may result from a furnace working either too cold or too hot. With better penetration of blast into the center of the furnace and good distribution of coarse and fine pieces at the throat, many of the former difficulties of furnace working have been greatly lessened, such as: pillaring, or cold charge in the core of the furnace; scaffolding, or building out of cold material from the walls inward until sometimes the charge "hangs" in the upper part of the stack and may have to be broken down by suddenly cutting off the blast pressure at the tuyères. Breaking down of a scaffold results in a "slip," like an explosion inside the furnace, which now seldom happens but formerly was not uncommon, especially when smelting the fine Mesabi ores.

Classification, Grades, and Uses of Pig Iron and Cast Iron (see Table IV-VIII).—Pig iron is graded according to the use for which it is intended, as follows: Basic pig iron, for use in the basic open-hearth furnace, must be low in silicon, which, being an acid-forming element, uses up limestone flux and may also attack the basic lining of the furnace. Bessemer pig iron must have enough silicon to provide heat, since the oxidation of silicon produces more useful heat in the process than does the oxidation of any other element; on the other hand, the pig must not contain too much silicon, because that would produce too much heat

TABLE IV-VIII.—ANALYSES OF SOME COMMON GRADES OF PIG IRON, ETC.

Trade name	Total C, per cent	Si, per cent	S, per cent	P, per cent	Mn, per cent
No. 1 soft ...	3.00 ±	2.75 to 3.25	0.05 and under	0.30 to 1.50	0.10 to 1.00
No. 1 foundry	3.25 ±	2.25 to 2.75	0.05 and under	0.30 to 1.50	0.10 to 1.00
No. 2 foundry	3.50 ±	1.75 to 2.25	0.06 and under	0.30 to 1.50	0.10 to 1.00
No. 3 foundry	3.75 ±	1.25 to 1.75	0.065 and under	0.30 to 1.50	0.10 to 1.00
Gray forge...	3.50 ±	0.75 to 1.75	0.07 and under	Under 1.00	0.10 to 1.00
Standard acid Bessemer pig	3.50 to 4.00	1.00 to 1.50	Under 0.08	Under 0.09	0.20 to 1.00
Basic pig	3.50 to 4.00	Under 1.25	Under 0.08	0.10 to 1.50	1.00 to 2.00
Malleable Bessemer	3.50 ±	0.75 to 2.00	Under 0.07	Under 0.20	0.50 ±
Ferrosilicon[1]..	0.50 to 2.00	10.00 to 50.00	Under 0.04	Under 0.10	0.20 ±
Silicospiegel...	1.00 ±	5.00 to 15.00	Under 0.02	Under 0.10	15.00 to 25.00
Ferromanganese	6.00 to 7.00	0.50 to 1.00	Under 0.03	....	40.00 to 80.00
Ferrophosphorus.....	1.00 ±	1.50 ±	Under 0.05	10.00 to 25.00	
Spiegeleisen...	4.50 to 6.00	1.00 ±	Under 0.04	....	15.00 to 35.00

[1] Ferrosilicon of 10 per cent grade, ferromanganese, silicospiegel, ferrophosphorus, and spiegeleisen are made in blast furnaces, by variations of the usual practice and by using special ores. Ferrosilicon of 20 to 50 per cent grades, and several other so-called *ferro-alloys*, are made in electric furnaces. These include ferrochrome, ferrotungsten, ferromolybdenum, ferrotitanium, ferrovanadium, etc. They are all practically pig irons with large amounts of the alloying metal. When these alloys are free from, or low in, carbon they are made by the thermit and other processes.

and also lengthen the time of blowing. The phosphorus in Bessemer pig must be low enough to give a steel containing not more than 0.100 per cent phosphorus. Pig iron for use in puddling furnaces is known as *forge iron.* That used to make malleable cast-iron castings is known as *malleable iron.* For making iron castings several grades of pig iron are used and mixed in order to give the exact analysis desired, as discussed in detail later. There are also made several cast-iron-like products known as *ferroalloys.* These are used chiefly to recarburize and/or make alloy steels.

CLEANING AND UTILIZATION OF BLAST-FURNACE GAS

For each long ton of pig iron made, there are produced from 125,000 to 150,000 cu. ft. of top gas (reduced to atmospheric temperature and pressure). Somewhat less than one-third of this is necessary for heating the hot blast stoves. A small proportion is needed for gas engines to drive the furnace blowing engines, provided a cylinder blowing engine is employed. The remainder is available for use in gas engines to generate electricity. In the last ten years, however, blast-furnace gas has become an exceedingly important fuel for the production of heat in open-hearth furnaces and in furnaces for heating for rolling or forging. Since the calorific power of the blast furnace gas is low for these purposes, it is mixed with coke-oven gas and/or producer gas for use in various furnaces. Blast-furnace gas is so very cheap that it is also used for heating the retorts in coke ovens and thus liberating a greater amount of coke-oven gas, which has a calorific power of about 650 B.t.u. per cubic foot. In America and Europe it is now customary to transport blast-furnace gas in large pipes from long distances to various localities in the plant and to maintain enormous reservoirs for its storage. The gases contain large amounts of dust which is detrimental to the gas and which would be useful as a raw material in the blast furnace. The first step for the utilization of the gas is, therefore, separating the dust from it. Progress in this connection has taken two directions, *viz.*, (1) holding the dust back in the furnace and (2) separating the finer dust from the gas after it leaves the furnace.

Holding the Dust in the Furnace.—The enlargement of the throat of a blast furnace beginning slightly below the stock line and following what have been called *venturi lines*, such as those shown in Fig. IV-15, results in lessening the velocity of the top gases and, therefore, the size of the dust particles they will carry. Using four offtakes from the furnace and allowing these offtakes to rise 20 or 30 ft. in the air, as shown in Fig. IV-12, still further reduces the dust content. Other devices include a set of chains hung in the throat of the furnace and a water spray blown in from several nozzles in a semitangential direction in the throat. The water is blown in by a compressed blast-furnace gas, since air should not be blown into this hot combustible gas for obvious reasons. By means of these various devices, the amount of dust carried out of the furnace by the top gases is reduced to one-fourth or one-fifth of the former weight per cubic foot of gas.

Separating the Dust After It Has Left the Furnace.—Gas is now led into a large dust catcher (see Fig. IV-12) in which the velocity is reduced, and it is given a whirling motion whereby the larger particles of dust settle out of it and are collected in a hopper from which they are drawn away. This should leave the gas with only the finest particles of dust, totaling less than 2 grains per cubic foot of gas. The gas is now passed through scrubbers, which it enters at the bottom and passes up through a fine spray of water. This reduces the dust content to a maximum of 0.153 grain of dust per cubic foot. It is now suitable for burning in the stoves and furnaces but not in gas engines. The gas for this last purpose must be further clarified by washing in centrifugal washers or disintegraters which beat the gas up by vanes into a spray of water and reduce the dust to a maximum of 0.03 grain per cubic foot. These methods of dust separation are costly and have the disadvantage of taking away the sensible heat of the gases and also saturating them with moisture. Already some European plants have been successfully separating the dust out of the gas in one operation using the electrostatic method first devised by F. G. Cottrell for nonferrous metallurgical plants in America. This method is said to leave the gas in better physical condition and to be slightly cheaper than the wet methods formerly employed.

References

Sir I. Lowthian Bell: "Chemical Phenomena of Iron Smelting," London, 1872. The classical treatise on the chemistry of the blast-furnace reactions.

J. E. Johnson, Jr.: "Blast Furnace Construction in America," New York, 1917. The best American book extant on this subject.

J. E. Johnson, Jr.: "The Principles, Operation and Products of the Blast Furnace," New York, 1918. The best recent American book on this subject.

Robert Forsythe: "The Blast Furnace and the Manufacture of Pig Iron," 2d ed., revised and enlarged by Carl A. Meissner and J. A. Mohr, New York, 1922. An elementary treatise of great usefulness for students and furnacemen.

Louis E. Gruner: "Studies of Blast Furnace Phenomena," translated by L. D. B. Gordon, Philadelphia, 1874. A standard treatise on the theory of blast-furnace smelting.

Fred Clements: "Blast Furnace Practice," vols. I, II, and III, London, 1929.

Frederick H. Wagner: "The Cleaning of Blast-furnace Gases," New

CHAPTER V

MODERN OPEN-HEARTH PRACTICE

SECTION A. BASIC

The cost of making basic open-hearth steel may be roughly estimated as follows:

Item	Cost
Metallic raw materials	$14 50
Fuel	0 70
Labor	0 92
Maintenance	0 66
Materials	0 66
Total	$17 44

These figures do not cover any particular furnace and are probably not representative of any special district. Each item would vary greatly depending upon location, conditions, efficiency, etc. The figures taken in relation to one another will, however, give a fairly accurate picture of the relative items of cost of steel making by this process. The item marked maintenance will include materials in repairs and a fund usually set up as a cost per ton required for rebuilding the furnace at the end of its campaign. The materials for operating would include cost for making steam, for molds, tools, supplies, flux, etc. No labor costs are included in the last two items. These costs illustrate clearly the great predominance of the cost of raw materials in the price of the finished steel. The expense of the process may be divided into what is often called (1) *cost of net metal,* and (2) *conversion costs,* or *costs above net metal.* The cost above net metal would include operation costs and metallic losses in the process. For example, the weight of the finished steel might be from 92 to 97 per cent of the total weight of pig iron, steel scrap, and recarburizing alloys. This corresponds to a metallic loss of 8 to 3 per cent, which would be included in the cost above net metal. The loss or shrinkage in weight will vary greatly and will be discussed in detail later. The metallurgist, by his expertness in conducting the chemical procedure during the conversion operation, has an important function in limiting the metallic loss during the process. It should be emphasized, however, that the highest function of the metallurgist is to improve the quality of the product. In this respect the record of the metallurgist in basic open-hearth plants during the past few years is one of which the profession may well be proud. The quality of basic open-hearth steel made today is greatly superior to that of a very few years ago. However, the metallurgist or steel operator can have a beneficial effect on the cost of the process in two ways: (1) by efficiency in conversion and (2) by utilizing cheap raw materials. Efficiency in conversion may be promoted by (1) layout of the plant to avoid interferences of one operation with another and to avoid delays; (2) saving of labor, fuel, and time; (3) lessening losses and scrap production; (4) lessening wear and tear on apparatus; (5) increasing the speed of operation, which saves in cost for labor, fuel, wear and tear, and overhead expenses per unit of steel produced.

Plant Arrangement.—The different open-hearth operations are as follows:

1. Getting the stock to, and in, the furnace.
2. Supplying the furnace with fuel and air and preheating these.
3. Working the charge, repairing the furnace, etc.
4. Recarburizing.
5. Disposing of the steel and slag.
6. Repairing and preparing ladles, ingot molds, etc.

Plant arrangement now conforms usually to a standard form which will be discussed in detail at the end of this section. It has been evolved by cooperation between the designing engineer, mechanical engineer, and metallurgical engineer. The principles of ample space in which to perform the operations listed above, minimum handling of materials and "back tracking" in transportation, and avoidance of interference of one operation with another govern the plant layout.

Saving of Labor, Fuel, and Time.—Obviously the greater the speed of the operation, the greater will be the amount of steel produced per men employed and per fuel burned. In Europe the tendency is to use relatively small charges in the furnace with consequently shallow baths and much quicker heats. In America

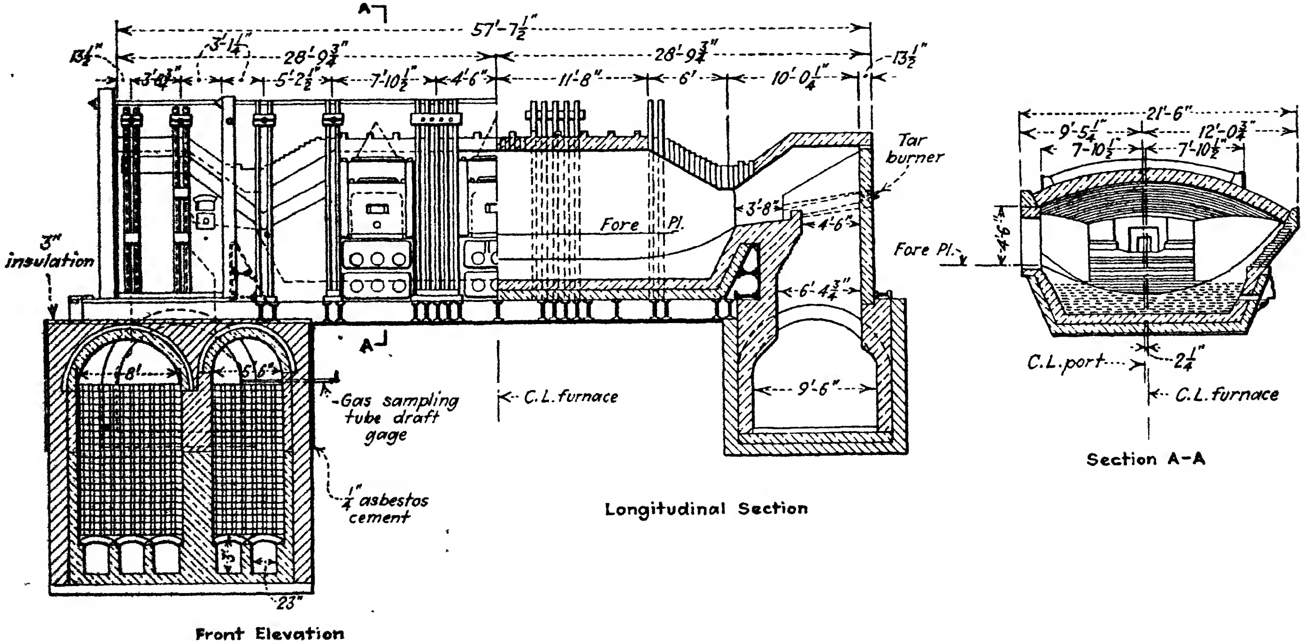


FIG. V-1.—Stationary open-hearth furnace. (*From Yearbook of the American Iron and Steel Institute*, 1931.)

it is common to use a furnace charge even greater than the rated capacity of the furnace. For example, a furnace of 100 tons rated capacity will habitually produce 110 tons of steel per heat. The result is that the time of the heat will be longer but its weight greater per furnace and possibly per furnace per hour. It is customary, therefore, to speak of the production of the furnace per 100 sq. ft. of hearth area per hour. On this basis a furnace will produce from 2 to 3.5 tons of steel per hour per 100 sq. ft. of hearth. We may illustrate this by a concrete example of a hearth 47 ft. long by 16 ft. wide with a rated capacity of 250 tons' charge. This is equivalent to a hearth area of about 750 sq. ft. If this furnace produces 360 tons of steel per day or 15 tons per hour, it will have an output of $15 \times 100 \div 750 = 2.0$ tons per hour per 100 sq. ft. of hearth

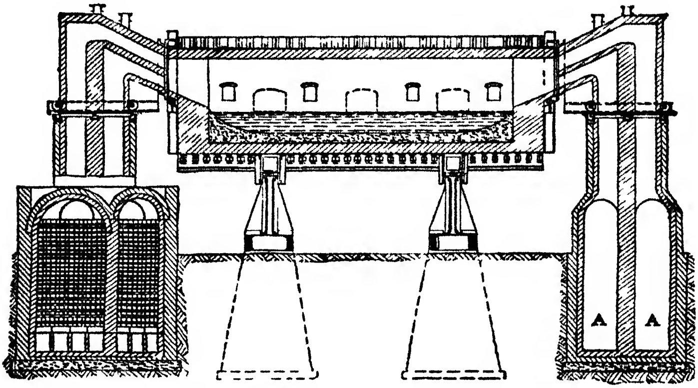


FIG. V-2.—Longitudinal section of rolling open-hearth furnace.

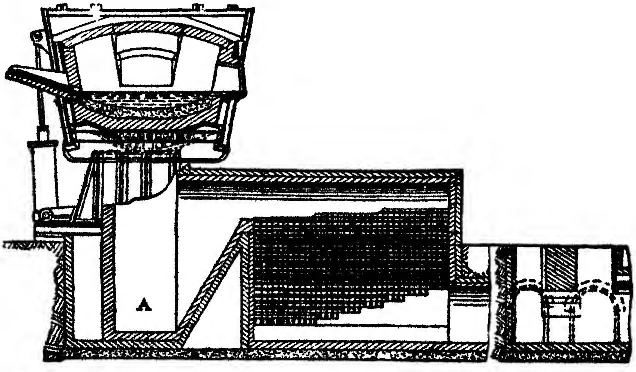


FIG. V-3.—Cross section of rolling open-hearth furnace.

area. This hearth area will be approximately 3 sq. ft. per ton of furnace capacity. The speed of the operation will depend upon the rapidity of melting, purifying, bringing to the desired tapping temperature, then tapping. In addition, time may be saved by efficient operation of repairing a furnace between heats and then getting the material in for the next charge. This is exemplified in Table V-I, in which the short time of heats in furnace C is accompanied by a lower number of British thermal units required per ton of steel produced. In addition to the element of time, labor may be saved by efficient management and fuel may be saved in two ways: (1) by using cheaper fuel and (2) by efficiency of fuel combustion.

Fuels.—When natural gas is available, it is the best and cheapest open-hearth fuel to use, but it is now somewhat rare. Blast-furnace gas is the cheapest fuel available, but its calorific power is too low for open-hearth melting. Great improvements have been made, both in America and in Europe, in recent years by mixing blast-furnace gas with other fuels such as coke-oven gas and sometimes producer gas or oil. Fuel oil is a common fuel, as is also tar from by-product ovens. Pulverized coal is a cheap fuel and has been successfully used at one American plant for many years but has not been adopted generally. Producer gas is the standard fuel and is commonly manufactured in producers immediately adjacent to the furnace building. In recent years it has been replaced by mixed gas for reasons of economy. Natural gas, by-product gas, oil, and tar are of sufficiently high calorific power to be used in the furnace without preheating. Moreover, they would decompose if heated for combustion. Producer gas has the disadvantage of being somewhat high in sulphur absorbed from the bituminous coal, and this sometimes introduces the sulphur into the steel bath. If oil contains more than about 0.06 per cent sulphur, it will also contribute sulphur to the steel.

It is now customary to report the fuel charge against a ton of steel in terms of the number of British thermal units represented by the fuel used. In this way comparative figures are obtained irrespective of whether producer gas, tar, natural gas, mixed gas, or oil is used. For example, we may say roughly that 4,500,000 B.t.u. will approximately represent either 550 lb. of coal or 4,500 cu. ft. of natural gas or 28 to 29 gal. of oil or tar, etc. Table V-II shows some characteristics and analyses of the principal open-hearth gaseous fuels. The use of mixed gases is still undergoing evolution, the object being to use as much of the cheap blast-furnace gas as possible and to mix with it varying proportions of other fuels to maintain a mixture having a uniform and predetermined calorific value. Sometimes two or three gases are mixed and automatic mixers, similar to that illustrated in Fig. V-5, have proved to be essential for best results in uniformity and furnace regularity. A claim for fuel economy when burning oil is that of using superheated steam for atomizing purposes: one operator superheats to 1000°F. and another to 1250°F. The first claims that he can cut down the use of oil per ton of steel made from 29 gal. to 28, and the second operator claims a saving of 2 gal. per ton of steel. Others insist that, if perfectly dry steam is used, no advantage can be had by superheating.

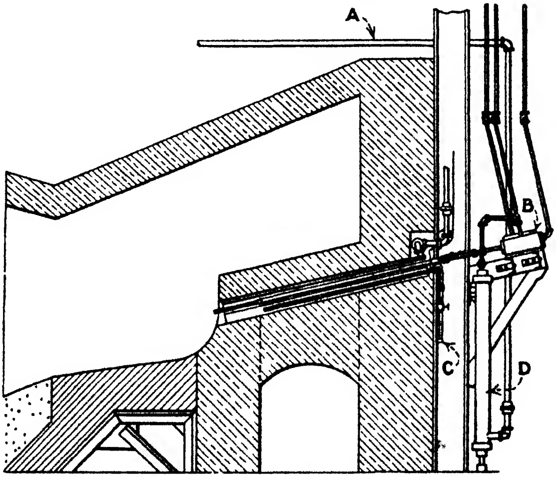


FIG. V-4.—Burner for liquid-fuel firing. (*From Hermann, "Modern Open-hearth Steel Works,"* 1924.)

Fuel Burners.—Where tar or oil is used for fuel, it is necessary to have some type of atomizer whereby the liquid is broken up into as small drops as possible in order to be more intimately mixed with air for combustion. In the case of tar or heavy oil, the liquid must be warmed in order that it will flow and in order that it will atomize more readily. The application of a tar burner is shown in Figs. V-1 and V-4. It is customary to have the burners mounted on mechanism which permits them to be withdrawn from the furnace on the side used for exit for products of combustion. The liquid is customarily atomized with dry steam.

TABLE V-I.[1]—OPERATING DATA OF VARIOUS OPEN-HEARTH FURNACES

Furnace	Fuel used	Number of heats reported	Average time of heats tap to tap		Average ingots per heat, tons	B.t.u. fired per gross ton
			Hr.	Min.		
A	Producer gas	Over 50	12	0	150.0	5,393,300
B	Fuel oil	318	12	35	119.8	4,947,000
C	Fuel oil	. . .	9	0	110 0	4,000,000
D	Coke oven gas	600	12	58	113.8	5,250,000
E	Fuel oil	210	13	59	154.0	5,112,000
G	Mixed gas (cold)	704	11	25	132 0	4,500,000
H	Fuel oil	547	12	18	123.0	5,147,000
I	Fuel oil	600	11	0	180 0	4,500,000
J	Producer gas	Over 100	12	10	155.0	4,839,800
K	Producer gas	Over 100	12	0	158.0	4,537,300
L	Mixed gas (preheated)	. . .	11	30	150.0	4,700,000
M	Coke oven gas	550	16	53	215 6	4,881,000
N	Producer gas	Over 50	15	30	250.0	5,049,000
O	Producer gas	Over 50	16	30	300.0	4,876,900
P	Coke oven gas	115	17	12	220.0	5,014,000

[1] W C. BUELL, JR., Improving Open Hearth Furnace Design, *Steel*, Apr. 8, 1933.

TABLE V-II.[1]—OUTSTANDING PHYSICAL AND THERMAL CHARACTERISTICS O THE PRINCIPAL METALLURGICAL GASEOUS FUELS

Gas at 62°F.	B.t.u. per cubic foot	Athermic flame temperature, °F.	Specific gravity	Combustible			Inerts		
				H_2	CO	Hydrocarbons	N_2	CO_2	H_2O
Blast furnace	90	2550	1.01	2.73	24.80	0.11	57.48	13.16	1.72
Coke oven	540	3580	0.335	52.5	5.8	36.1	3.9	1.4	0.3
Producer	145	2920	0.884	12.2	22.7	3.2	55.9	5.8	0.2
Natural	1138	3560	0.640	0	0	98.5	1.45	0.05	0.0

[1] G. B. THORNE, Blast Furnace Gas in the Steel Plant, *Blast Furnace and Steel Plant*, June, 1931.

Better Fuel Efficiency.—Besides use of cheaper fuels, the fuel cost per ton of ingots may be decreased by increasing the fuel efficiency of the furnace. This has been accomplished to such a degree that, whereas a basic open-hearth furnace had a fuel efficiency of 18 per cent a few years ago, claims are now made for furnaces having 24 per cent efficiency. Fuel efficiency can be obtained by (1) lessening the radiation from the furnace while at the same time not letting it get so hot inside that the refractory linings will melt; (2) a more intimate mixing of fuel and air. This is best accomplished by automatic mixing independent of manual control and by arrangement of the furnace ports, which are the openings through which the fuel and air enter the furnace chamber; (3) prevention of infiltration of air into the chamber to interfere with the combustion control; (4) constantly watching the analysis of the gas, especially the percentage of free oxygen, if present, and the percentage of carbon dioxide and carbon monoxide; this is now sometimes done by automatic carbon dioxide recorders; (5) uniformity of pressure of atmosphere within the furnace coupled with automatic regulation of the velocity of the fuel and gas entering and the products of combustion leaving and passing up the stack; (6) automatic regulation of temperature in the furnace to the desired point. Most of these arrangements will be discussed in more detail later.

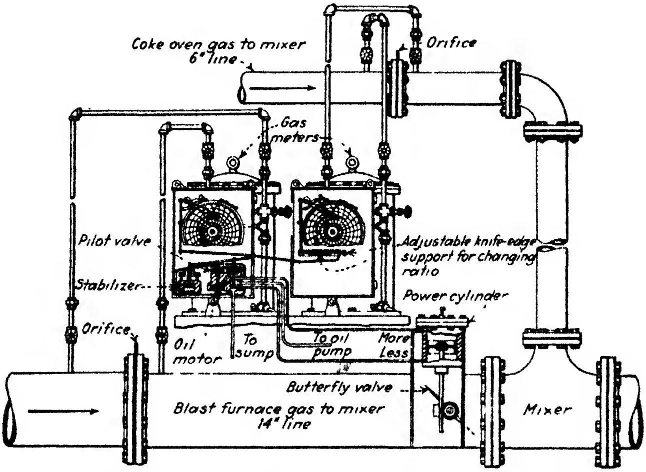


FIG. V-5.—Operating installation of ratio control for mixing gases for combustion. The layout of an installation in a West Virginia steel plant to permit proper mixing of coke-oven gas with blast-furnace gas is shown in the line drawing above. (*The Iron Age*, *Jan.* 22, 1931.)

Increasing Speed of Operation. High temperature during the melting period, skillful calculation of charge to promote rapid and early chemical action in the furnace, expertness in fluxing, etc., and speed in repairing the furnace lining between heats and in charging the materials in the furnace, all promote rapidity of operation and economy in cost. Very modern American open-hearth furnaces now use a machine for projecting dolomite to patch the lining between every two heats (see Fig. V-8). It is obvious that, where liquid pig iron direct from the blast furnace is used in the open hearth in place of solid pig, it will make the operation shorter. The same is true when liquid steel is used after blowing in the Bessemer furnace, instead of solid steel scrap. This is the so-called *duplex* process.

Lessening Losses and Scrap Production.—The loss of metal during conversion comes largely from oxidation of scrap during the melting period and its absorption by the slag in the form of iron oxide. In some cases, the very fine condition of the scrap with consequent large sections exposed to flame makes a large loss inevitable. The best safeguard is to melt as rapidly as possible. It is also possible and common to reduce iron oxide out of the slag. This phase of the subject will be better understood in connection with the physical chemistry of steel making. In addition to the metal lost in the slag, the amount of steel production in the form of scrap as ladle skulls, ingot butts too short to roll, spilling, etc., will obviously decrease the production of steel salable and will consequently increase the unit cost of the operation. Of course, the loss in weight between the total mass of metallic raw materials and that of the good steel ingots produced and shipped to the rolling mill will depend also on the weight of impurities oxidized out of the bath during the heat. We may illustrate this as follows: If a charge consists of 50 per cent pig iron and 50 per cent steel scrap, it may contain an average of 2 per cent carbon, 1 per cent manganese, 1 per cent silicon, and 0.25 per cent phosphorus, or a total of more than 4 per cent of impurities which will be removed from it during the conversion process. These items will appear in the open-hearth cost figures as loss during the conversion process.

Standard Plant Layout.—Now that the different parts of the furnace have been described, we can discuss in more detail the standard plant layout which conforms roughly to Figs. V-6 and V-7. The position of the gas producers is not shown, but, when

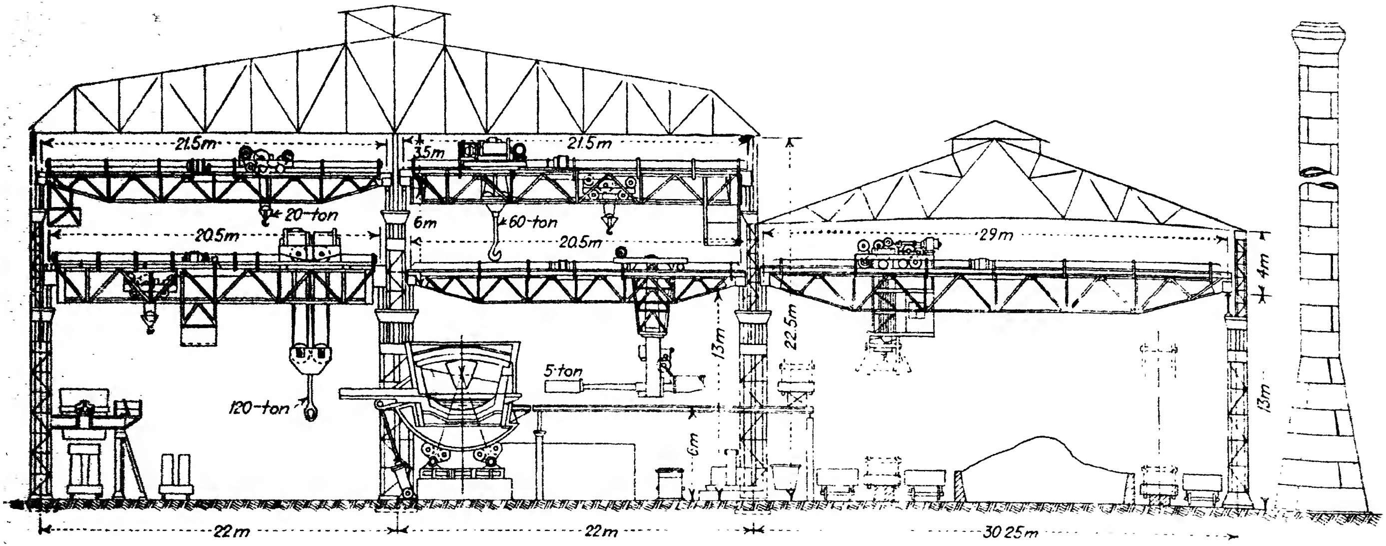


Fig. V-6.—Cross section through a steel plant, 1930. (*From Wood, Journal Iron and Steel Institute, No. II, vol. 122, 1930.*)

present, they would be located at a point at the extreme right of Fig. V-6. Next will come the stock yard containing the steel scrap and pig iron. This yard is spanned by electric cranes and contains tracks on the right for the receipt of the raw materials in railroad cars, and on the left there may or may not be tracks for the buggies upon which are placed the charging boxes which carry the raw materials from the stock yard to the furnace. Sometimes these buggies are taken by a switching locomotive from the tracks in the stock yard to tracks on the charging platform of the furnace, where their position is indicated more clearly in Fig V-7 at the point marked *CC*. Sometimes the stock-yard crane loads raw materials directly from the stock yards into charging boxes on an extension of the open-hearth furnace charging platform at the point indicated in Fig. V-6. Details of charging machines will be given in a later section. The furnace platform, sometimes also called charging platform or melting platform, is on the same level as the hearth. The materials for repairing furnace bottom, for fluxes, and for recar-

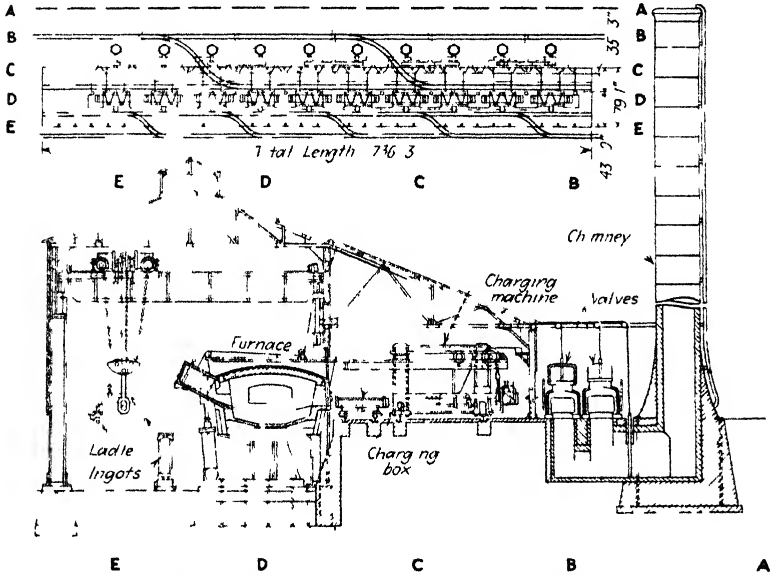


FIG. V-7 Horizontal and vertical sections through open-hearth plant (In horizontal or vertical section the letters have the same significance) AA, stock yards, BB, reversing valves, CC charging mechanism on its tracks, DD, 10 open-hearth furnaces EE, teeming mechanism The regenerators are located under the charging platform burizing are usually weighed out and spread on this platform. The space above is spanned by one or more electric cranes. The front of the furnace, which contains five doors, faces the platform, but there is usually an extension of the platform around the back of the furnace to afford access to the back wall and the ladle into which the steel is poured, and for putting the recarburizer into the casting ladle when the steel is tapped. On the melting platform are also located the levers for reversing valves and the automatic-control apparatus and recording apparatus which regulate and/or control the procedure of the furnace operations. The regenerative chambers are located under the melting platform. At the back of the furnace is the casting pit with permanent stands for the casting, or teeming, ladles where they are supported on trunnions when the metal is tapped into them. After tapping, the ladles are carried by the teeming cranes over to the pouring platform (Fig. V-6) where the liquid metal is poured into ingots. The casting pit contains tracks for the ingot cars on which are the ingot molds and for standard gondola cars into which refuse and scrap can be placed.

THE BASIC OPEN-HEARTH FURNACE

The furnace is a fire-brick structure entirely enclosed in steel plates and bound together with structural beams and tie-rods (see Fig. V-1). Even the regenerators are now enclosed in steel plates on the sides and heavily insulated all over. Furnaces are built either with the hearth stationary, as shown in Fig. V-1, or else with a tilting or rolling hearth, as shown in Figs. V-2 and V-3.

Stationary Furnace.—The stationary furnace is now standard here in America for all sizes up to at least 150 tons' capacity, because they are less expensive to install (see Table V-III, page 137) and require no repairs to machinery and no power to operate them. They also avoid the very great difficulty which the tilting furnace has in making connection between the uptakes or ports and the furnace chamber proper so that the fuel and air for combustion may enter without leakage of outside air in the crevices. The back wall of the stationary furnace is difficult to repair between heats, because there is severe scorification along that line on the hearth wall where the slag and metal surfaces meet. This makes a long crevice to be filled up with repair material after the heat is ended and this is difficult on a steep wall. The situation has been met by the so-called *sloping back wall,* which is now standard practice in American plants (see Fig. V-1). The hearth is supported solidly on I beams but usually arranged to allow for circulation underneath in order that the lining may be somewhat cooled by radiation (see Figs. V-1 and V-2).

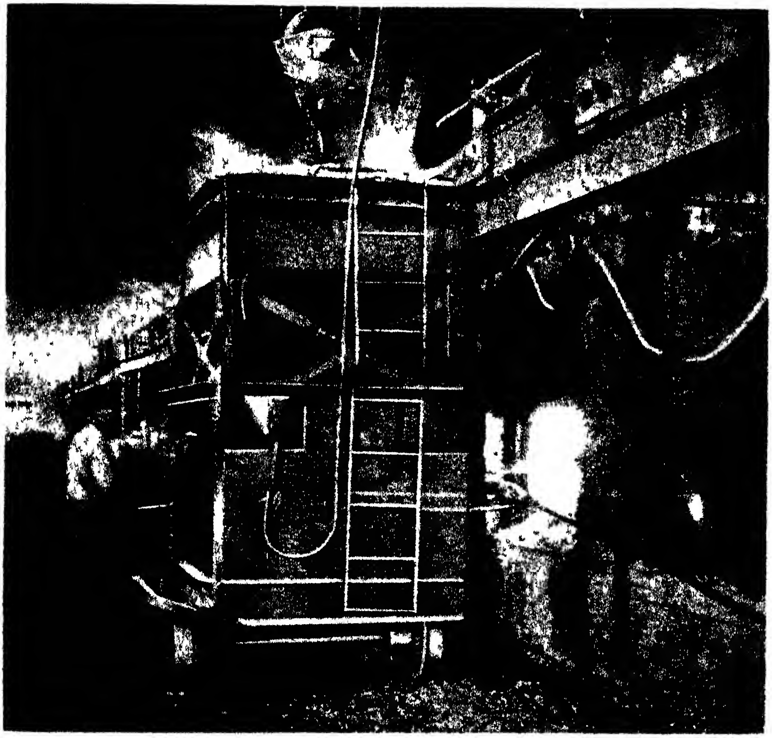


FIG. V-8.—Present-day practice in repairing hearths. The dolomite, which is a calcium-magnesium carbonate from which the CO has been driven by roasting, falls from the hopper shown on to a belt which travels rapidly, impelled by a electric motor. The inclination and horizontal direction of the belt are under the control of the operator, who thereby "shoots" the dolomite to any location desired on the wall of the furnace. (*From L. R. Reinartz, Modern Trends in Open-hearth Operations, Blast Furnace and Steel Plant, January,* 1932.)

Tilting Furnace.—All furnaces taking a charge of much over 150 tons of liquid steel are built with a tilting or rolling hearth, because that enables a part of the steel to be poured out at intervals and relieves the casting cranes from carrying a ladle with more than 150 tons of steel (see Fig. V-9). Attempts to get around this by dividing a stream from a stationary furnace into two spouts and thence into two ladles have not been generally acceptable. Tilting furnaces also have the advantage of being able to pour off a foul slag and then use a clean slag for the finishing stage of the purification process. This practice is more common in Europe, where pig iron is often very high in phosphorus and first slags can be made so rich in phosphate as to be salable for an agricultural fertilizer. In America we do not encounter high phosphorus in pig iron except in Alabama and Nova Scotia, so that the American furnaces are usually of the stationary type unless built in very large sizes. The tilting furnace also makes more rapid working possible because the hearth can be tilted toward the front to make boiling very rapid, which gets rid of carbon and carbon monoxide gas more quickly, without causing the bath or slag to boil out of the doors of the furnace. Tilting furnaces are a little easier to repair by hand, but they are also harder on the refractories because the lining may suffer strain. They are also more difficult to control in respect to the infiltration of air into the furnace chamber, on account of the joint required for tilting (see Fig. V-2). Tilting furnaces also get rid of tapping-hole difficulties sometimes encountered in stationary furnaces, although this is not so much

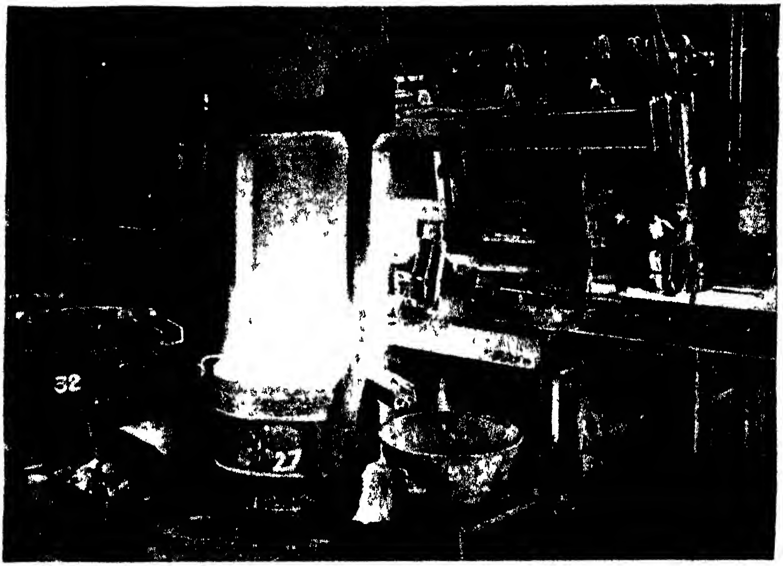


Fig. V-9.—Tapping steel into ladle from tilting open-hearth furnace.

of a factor since the use of a blast of oxygen for burning out any iron obstructing tapping of the furnace has become general practice. In that special type of practice known as the *Talbot process*, which will be discussed shortly, a rolling furnace is essential because a part of the charge must be poured out of the furnace without removing all. Except for foundry work, it is now unusual to install tilting or rolling furnaces. Foundry furnaces are generally small in size; 15 to 30 tons' capacity is a common limit, and individual furnaces run as low as 5 or even 3 tons. These furnaces are most often charged by hand, and the rolling type facilitates this operation somewhat. The ease of tapping is an especial advantage where castings are being made, because delays may cool the metal to the point where castings will not run readily, or the carbon may be burned out excessively and the metal lack fluidity on this account.

There are two types of tilting furnaces, known respectively as the Campbell and the Wellman. In the Campbell type the hearth of the furnace is arranged so that the center of tilting is coincident with the center of the ports, and therefore the furnace can be oscillated without shutting off the supply of gas and air. In order to facilitate this, there is a little clearance between the uptake and the furnace proper, and these parts are surrounded by water-cooled castings. In the Wellman type the gas and air supply must be cut off when the furnace is tilted. In tipping the Wellman furnace the ports move with the hearth, and they are therefore seated in a water tank, which makes an air-tight connection with the downtakes when the furnace is in a horizontal position but breaks it when it is tipped forward.

The Wellman type is not so expensive to build as the Campbell and probably requires less repairs. The Campbell type has the advantage that the bottom can be repaired along the slag line without interrupting the operation and that the lining can be sintered into place by the heat of the flame when the hearth is in any position. This is more important in the acid furnace than in the basic, where a mixture of dolomite and tar can be set by the heat contained in the furnace walls themselves. In the Wellman type, when the furnace is tipped for pouring, cold air can enter it through the ports. Finally, a great advantage of the Campbell type is the fact that a great deal of ore can be used during the operation, and, although the boiling of the charge is violent on this account, metal does not flow out of the furnace doors, because the hearth can be tipped in the opposite direction. The slag which runs off during this period is allowed to pass through a hole in the bottom of the port opening, at the joint between the fixed and the rotating portion, where it is continually exposed to the flame and therefore not liable to chill up.

Parts of Furnace.—The furnace *hearth*, or *bottom*, is the shallow dish which contains the liquid metal. It is indicated in Fig. V-1 and clearly shown in Figs. V-2 and V-3. Above the hearth are the *side walls* extending to the skewback of the roof and pierced

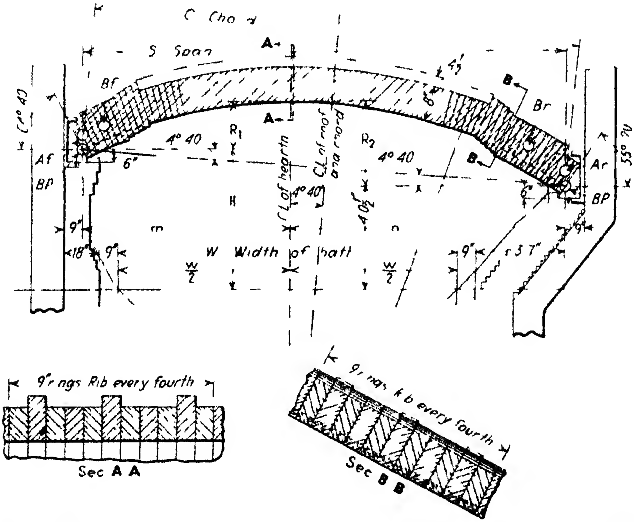


FIG. V-10 —Basic open-hearth furnace roof (*From W. C. Buell, Jr., Improving Open Hearth Furnace Design, Steel, Jan. 23, 1933.*)

on the front side by five water-cooled doors. The *tap hole* in the stationary furnace is so placed that it will drain all the metal and slag out of the furnace when open (see Fig. V-21). During the heat it is, of course, plugged with clay or hearth material which is pierced with an iron bar when the metal is ready to tap. If any steel has solidified in this hole during the heat, it may be pierced with a jet of oxygen, since it is red hot and burns readily. The *roof* is a shallow arch springing from skewbacks on both sides and supported by I beams and tie rods. It is made of bricks set in lengthwise; they are 12 to 18 in. long with ribs 3 to 4 in. longer every fourth row (see Fig. V-10). The roof is badly burned out by the flame and the spattering of slag. It is made of silica brick, because this is most durable at high temperatures, but this has the disadvantage of being eaten away more readily by basic slag. The furnace *ports* are the openings through which the gas and air enter and by which the products of combustion pass out of the furnace into the downtakes. It is obvious that each set of ports is used alternately for entrance and exit, when the furnace reverses regenerators. This part of the furnace is so important that it will be discussed subsequently under a special side heading. The *slag pockets,* shown at *AAA* in Figs. V-2 and V-3, are intended to catch dirt which may be carried over from the furnace through the ports and into the downtakes. The object is to keep as much of the dirt out of the regenerators as possible. It is obvious that the downtakes will serve as such when the products of combustion are going to the regenerators on one side, whereas the corresponding passage on the other side of the furnace will then be serving as *uptakes* from the slag pockets to the ports.

Sizes and Dimensions of Furnace.—The standard modern American basic open-hearth furnace will have a capacity of 100 to 150 tons of liquid steel per heat. It will have a length of bath of 35 to 47 ft. and a bath width of 14 to 18 ft. The longer the furnace hearth, the more nearly will combustion be completed before the products of combustion enter the outgoing ports. This promotes fuel economy and port life. On the other hand, the bath must not be too long or it will be colder at one end than at the other. The width of the hearth will be dependent upon the possibility of repairing it between heats, because this repairing has to be done through the doors which are all on the front side of the furnace. Hearths can be wider now, when a dolomite gun is used for repairs, than when all repair materials had to be thrown through the doors with a shovel. The area of the upper surface of the steel bath will vary between 460 and 675 sq. ft. This represents roughly from 3 to 4.20 sq. ft. of surface per ton of steel. This surface is the actual area of contact between the slag and the metal; therefore, it is the working surface of the principal chemical reactions of the furnace. The depth of the American furnace bath will be between 26 and 45 in. Greater depth increases the weight of metal in the furnace but decreases the speed of chemical action between metal and slag. Heats having bath depths of over 30 in. will usually require 10 to 15 hr. per heat, *i.e.,* time from tap to tap, which includes repairing the furnace for the next heat, charging, melting, purifying, and tapping. It is a common claim in America that deeper baths produce greater tonnages of steel per hour with lower oxidation of iron and less damage to the hearth lining. The effective productivity of a furnace is represented by the tons of steel which will be produced per 100 sq. ft. of upper surface of the bath per hour, and this figure will average in America between 2 and 3 tons. In Europe it will be no larger than this, except at Terni, Italy. However, in Europe and England the time of the heats will be shorter, and the weight less, owing to the fact that the baths are usually much shallower. Some metallurgists maintain that baths deeper than 40 in. produce steel of lower quality. The reasons given are twofold: First, so-called *inclusions* do not rise fast enough entirely to clarify a deep bath. Inclusions are solid, oxidized particles which are entangled, or occluded, in liquid steel during the operation, and especially during the recarburizing period. The second reason offered is that there is insufficient circulation in a deep bath to insure uniformity in chemical composition and temperature. An extensive investigation carried on by the Verein deutsche Eisenhüttenleute[1] into the composition of an open-hearth bath at different depths in a furnace of 65 to 70 tons' capacity with a bath depth of 24 to 28 in. indicates that the carbon in the bath is in general higher near the surface. In one case it was as much as 22 per cent above the average, and 4 per cent below the average at the bottom. The manganese seems to be 13 to 15 per cent above the average at the bottom of the bath and 3 per cent below the average at the top. The phosphorus is very irregular with uncertain trends as to top and bottom, while the sulphur is generally higher at the top, where it is about 17 per cent above the average and 12 per cent below the average near the bottom. A discussion of possible reasons for these differences in composition will be found on page 152.

Construction of Hearth, or Bottom.—A steel pan supported on I beams gives the structural strength to the bottom. To build the bottom a tapered plug the size of the finished tap hole and extending to the center is first inserted in the tap-hole arch. Around the plug is rammed ganister. The plug is withdrawn and the hole filled with anthracite coal and clay. The hearth lining can then be constructed around this tap hole. Next to the pan are laid one or two layers of second-quality brick, then a

---

[1] S. Schleicher, *Stahl und Eisen*, vol. 50, pp. 1049–1060, July 24, 1930.

course of chrome brick, and after that three or more courses of magnesia brick. At the ends and sides, the layers are laid up to form a rough basin. This brick basin is the foundation for the real basic hearth, which should be of high-quality calcined magnesia. The magnesia lining is intimately mixed with about 10 per cent of tar, or 5 to 20 per cent of basic slag, or part of each, to serve as a binder. It is then shoveled on to the hearth and spread evenly to form a layer ½ in. thick, which is set in place at the full heat of the furnace for about 10 min. The lining material becomes pasty in the heat of the furnace and is shaped with a rabble around the bottom, sides, and ends. Further layers are then set in on top of the first layer until a thickness of hearth of 19 to 35 in. has been built up. It is obvious that the building up of a hearth will require some days' time at the full heat of the furnace. After the hearth is constructed, it is customary to melt a bath of slag in the furnace and spread it to all parts inside the refractory basin to give it a strong surface.

Repairing Bottoms.—Between the heats, bottoms are repaired by filling up holes with dolomite.[1] After each heat there is a crevice all along the slag line which requires to be filled up. While magnesia is used for the bottom (except sometimes the top layer or two which may be made of dolomite because it sets more easily), dolomite is, nevertheless, used for repairing. If all the holes and crevices are filled in the bottom between each heat, the metal having been carefully drained or puddled out of every hole before the repair material is put in, bottoms will last almost indefinitely. If a hole is left, however, the charge may work its way down and force up whole sections of the bottom lining. Sometimes the metal even works it way out through the bottom of the furnace. A sticky or viscous slag is also liable to bring up parts of the bottom by sticking to it. Bottoms last better when the furnaces are kept heated at all times, even over the week-ends, because the refractory material shrinks on cooling and is liable to form cracks.

Construction of Side Walls.—The side walls of the furnace are customarily constructed of silica brick, and it is usual practice to put a layer of neutral chrome brick between the basic hearth

---

[1] Dolomite is a magnesia limestone, and after calçining consists of a mixture of lime and magnesite, CaO, MgO, with a little silica and other impurities.

and acid walls. In the case of sloping back walls, the hearth material is spread over the brickwork to near the level of the roof.

Roof.—The roof is made thin and of the most refractory bricks that can be obtained, *i.e.*, almost pure silica, with only enough lime to hold it together in a compact mass. The side walls are also thin, and the radiation from the furnace chamber is great. This is intentional, because thicker walls and roof produce endless roof trouble by melting of the brick. Formerly roofs were built even thinner than at present, but improved port design and maintenance, with a definite "boost" of the combustibles into the furnace chamber, resulting in effective flame control and direction so that the flame does not impinge so disastrously on the roof refractories, enables roofs to be built thicker, with consequently less heat loss through them. Roofs are suspended from beams independent of the side walls. The most durable roof is that having ribs every fourth course of brick, as indicated in Fig. V-10. A strong roof is one in which special bricks are made to hang from overhead supports, called a *suspended roof.* Basic slag spattering against the silica roof during a violent furnace boil eats it away rapidly. After the first hundred heats or so, the roof gets noticeably thinner every heat, and they usually are so thin before three hundred heats have been made that it is considered desirable to renew them, although roof campaigns of well over three hundred heats are not uncommon. If a small part of the roof falls into the furnace, it may be possible to absorb and neutralize the acid bricks in the slag, then repair the hole, and finish the heat. The roof knuckle, indicated in Fig. V-11, is especially exposed to intense heat. Some furnaces have been built without this knuckle, but the roof's sloping at this point drives the heat down toward the bath. Low roofs tend to burn out more rapidly, whereas high roofs tend toward slow heats and greater fuel consumption.

Furnace Ports.—The function of ports is to cause an intimate mixture of fuel and air, which is a large factor in fuel economy. They must also direct the travel of the flame so that it shall not impinge on the bath, roof, or side walls. Perfection in this respect cannot be attained, but it is obvious that the flame will have a disastrous effect in decreasing the life of the furnace lining in any part which it strikes and that it may oxidize the bath excessively if it comes too much in contact with it. New ports are much better than those which have suffered loss of effective shape through eating away or distortion. Another important factor in flame direction is the velocity with which the flame enters the furnace. Tall regenerators, which give a chimney effect and a "boost" to the incoming air, are efficacious. But the best results are obtained when a fan gives an automatically controlled, uniform velocity to the air coming through the ports. The gas should be spread out all over the width of the hearth beneath the air, and the two should mix intimately just before they enter the laboratory, or work chamber. The air especially must be kept from direct contact with the bath, and for this reason the gas is introduced below the air. This arrangement has the further advantage of promoting the better mixture of the two, since the gas is lighter in specific gravity. It is obvious that the ports are also exit openings one-half of the time. They are, therefore, subject to intense heat from the products of combustion and liable to burning out. There are many different types of ports, all of which are good,

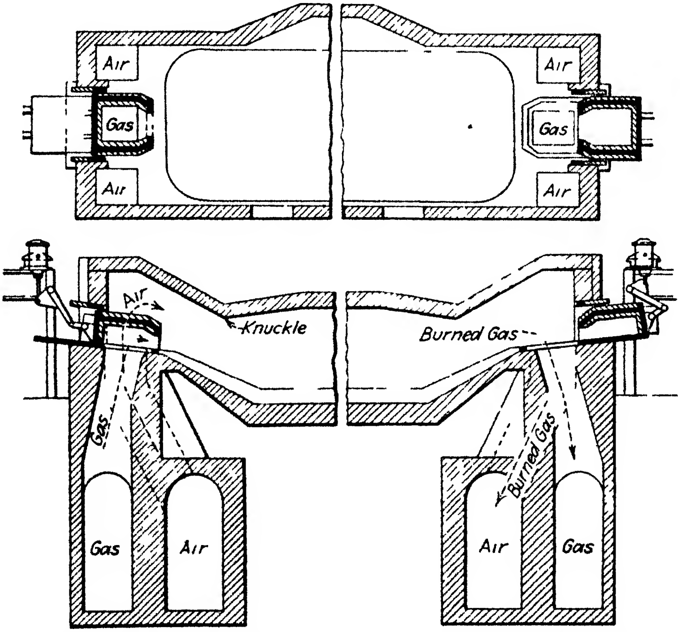


FIG. V-11—Diagrammatic sketch of furnace showing operation of Rose movable ports. (*From George E Rose and F M Washburn, Mixed Gases in Open-hearth Furnaces, Blast Furnaces and Steel Plant, September*, 1930.)

but only three types will be mentioned here, as illustrating different principles:

Rose Port.—The Rose type of port has a movable chamber lined with brick which fits over the opening from the gas uptake, as shown at the left in Fig. V-11. But when the gas uptake is used as downtake, the movable box is withdrawn from the furnace, as shown on the right in Fig. V-11. This protects the box from heat of the products of combustion and allows extra space for the exit of the gases, which is advantageous in furnace operation.

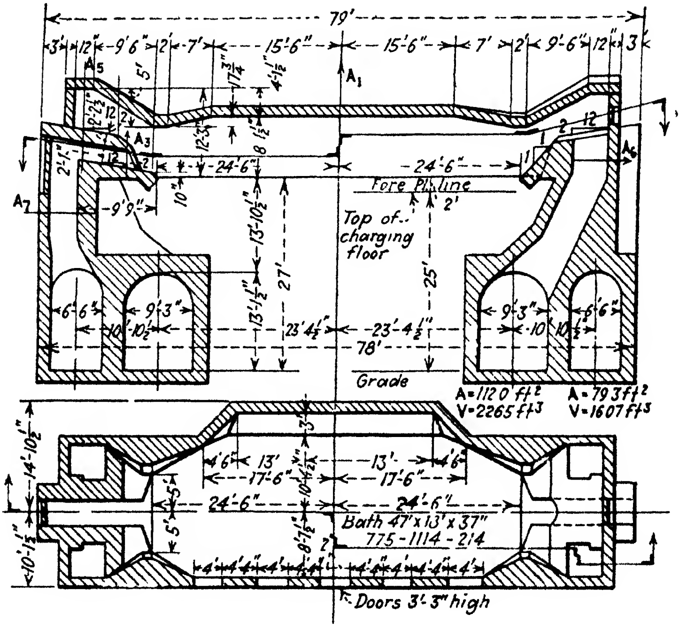


FIG. V-12 – Second largest stationary furnace in this country. It uses the Venturi port (*From W. C. Buell, Improving Open-hearth Furnace Design, Steel, Apr.* 3, 1933.)

Venturi Port.—According to the Venturi principle, the uptakes enter a sort of mixing chamber, and the area of the entrance from the mixing chamber into the furnace is less than the combined area of the three uptakes. This is illustrated in Fig. V-12. The principle insures an excellent mixing of fuel and air and is said to promote fuel economy efficiently. A similar principle is used in the Terni port illustrated in Fig. V-13, which, however, has parallel sides to the mixing chamber. The

Terni furnaces in Italy, which first used this principle, have a very high record for rapidity of working and fuel economy. It would seem that a definite mixing chamber, or combustion chamber, as an adjunct at both ends of the furnace chamber, for the intimate mixing of combustibles before they enter the work chamber, or "laboratory," of the furnace effectively promotes good combustion and fuel economy.

Removable Ports.—A type of port which has many advocates, especially in England and Europe, is one in which that part of the brickwork most subject to destructive action by the products of combustion can be bodily removed from the furnace and replaced with a fresh block, as shown in Fig. V-14. In this way new ports can be substituted for old almost without delay to the furnace operation.

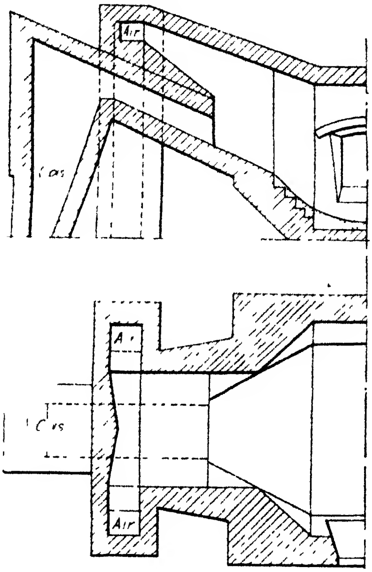


Fig. V-13.—The Terni port. (*From Wood, Iron and Steel Institute (London), July,* 1930.)

Port Floors.—The port construction, even of basic open-hearth furnaces, is commonly of silica bricks, since these are both cheaper and more durable. The floors of the ports are liable, however, to severe corrosion by spattering of basic slag from the bath. In some cases, the floors of the ports are protected by a layer of some neutral material, such as chromite, $Cr_2O_3.FeO$, which is attacked by neither acids nor bases, and which melts at a temperature of about 2175°C.

Insulation of Furnace.—Many furnaces are now insulated all over. This practice began by insulating the regenerators and then the slag pockets and uptakes. This has the obvious advantage of preventing infiltration of air at those points where there might be an internal vacuum instead of pressure. When the furnace chamber is insulated above the floor line, it is obvious that pyrometric control must be constantly employed, because there is a narrow margin between the temperature necessary inside the furnace and the point of initial fusion of the brick. Entwisle[1] says that the total amount of heat radiated from the surface of a 100-ton open-hearth furnace above the floor lining is 9,000,000 B.t.u. per hour and that by insulation this loss can be reduced to 4,000,000 B.t.u. per hour, which is 8 to 10 per cent of the fuel input. Of this saving nearly 50 per cent is from the furnace above the floor line. The radiation from a roof which is worn thin may be reduced by 75 per cent through insulation. I am advised by C. F. W. Rys[2] that regenerator chamber walls are insulated to a thickness of ½ to 1 in. and the roofs with a

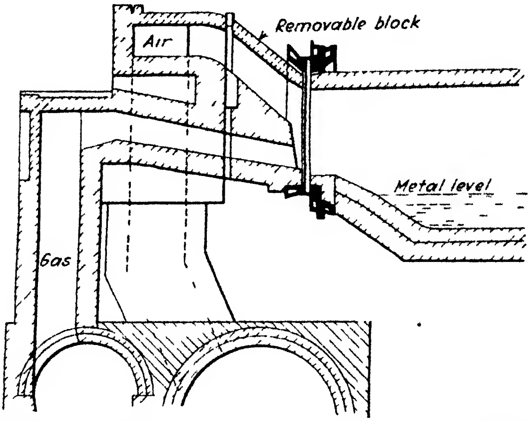


FIG. V-14.—The Friedrich port. (From Wood, Iron and Steel Institute (London), July 1930.)

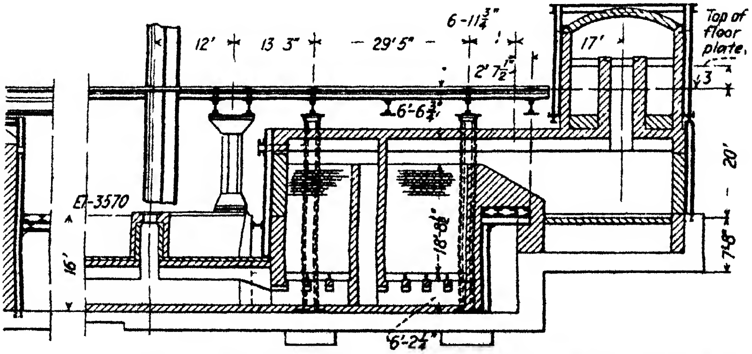


FIG. V-15.—Two-pass regenerators of Magnitogorsk furnaces. (From Thorne, *Blast Furnaces and Steel Plant*, June, 1931.)

---

[1] "Year Book of the American Iron and Steel Institute," N. Y., 1933.

[2] Private communication, July 21, 1933.

thickness of 4 to 5 in. The furnace above the floor level is insulated on the side walls, bulkheads, etc., with a thickness of 1 to 2 in. of insulation. Furnace roofs are insulated with slag wool for a thickness of 2 to 5 in.

Water Cooling.—Open-hearth doors are now always water cooled, because this prevents warping and makes the melting platform more comfortable. It is also very common to have parts of the brickwork of the port water cooled and occasionally even other parts, such as the skewbacks of the roof and places in the walls of the downtakes and furnace proper. A 110-ton furnace may use as much as 1,000,000 gal. of water every 24 hr. for cooling the furnace proper and the reversing valves. It is claimed that the heat carried away by the water is no greater than would be radiated from the furnace in any event, so that fuel economy is not lowered.

Regenerators.—With the furnace are connected two pair of regenerators which preheat the gas and air for combustion as described in Fig. III-4. The internal volume of each of these chambers is equal to three-fifth to nine-tenth of that of the working chamber itself. The larger the regenerators, the greater will be the amount of heat intercepted in them, and therefore the lower the temperature of the gases that go to the stack. The amount of space actually occupied by the bricks, or checkerwork, is the important consideration, however, and this should be from 120 to 350 cu. ft., total, for all four regenerators per ton of furnace capacity, the volume of the two gas regenerators usually being about 30 to 40 per cent less than that of the air regenerators, because the volume of gas used is less than that of the air, and also because the gas does not require to be preheated so much, since it is already somewhat warm from the gas producer. Gas of high calorific value, or which will break down if heated, such as natural gas and coke-oven gas, is not passed through regenerators. But producer gas, mixed gas, etc., will give improved fuel economy and higher temperatures if preheated. Tar, oil, etc., may be warmed by steam in their storage tanks and the pipes leading to the furnace. During the operation of the furnace more or less slag, dirt, and dust are carried over with the outgoing gases. To intercept this the slag pockets or dirt pockets *AA* are provided; but in spite of them the spaces between the bricks of the checkerwork become partially choked, and for this reason, as well as because the deposit of dust makes the surface of the bricks rough, the total area between the bricks must be much larger than the area of the ports, so that the velocity of the gas will not be lessened. The furnace must be laid off for repairs when the passages between the bricks are choked by dirt, but, on the other hand, the interstitial space is limited, because the bricks must be laid in such a way that the maximum amount of surface shall be exposed and the gases forced to the greatest possible contact with them. Recently special types of regenerator bricks have been devised to afford large surface for heat absorption and small horizontal surfaces for deposition of solids.

The modern construction makes the regenerators as tall as possible in order that incoming gas and air may be forced into the furnace by the draught, and also because this chimney effect causes the incoming gas and air naturally to seek the hottest places and the outgoing gas the coolest places, in this way equalizing the temperature in the different parts of the regenerators. They should be not less than 15 to 20 ft. high. In order to get the height, it is now customary at some plants to use two-pass and three-pass regenerators, as indicated in Fig. V-15. This involves a number of changes of direction in the products of combustion but each change in direction insures a better separation of solid materials carried over from the bath. A further advantage of these multiple-pass regenerators is that the bricks at the top of the first pass from the furnace are the ones which suffer most from burning out. If these bricks are changed at intervals, the chambers may last a long time and thus save considerable expense in tearing down and rebuilding. There must be suitable open space both below and above the regenerator bricks themselves to distribute the gas flow evenly, but it will be obvious from Fig. V-3 that there will be portions of the checkerwork in every chamber which will be practically valueless. This will be more in evidence the longer the chamber in relation to its height.

Reversing Valves.—The function of reversing valves will be clear from Fig. III-4. The old type of mushroom valve is obsolete in America. Water-cooled valves are standard, as is also mechanical operation as distinguished from hand operation, because the additional cost of interest on higher first cost and power to move is more than saved by lessened leakage and furnace delays. There are several types of valves in use, but the Forter and the Blaw-Knox valves are now very commonly employed. These are illustrated and described in Figs. V-16, V-17, and V-18.

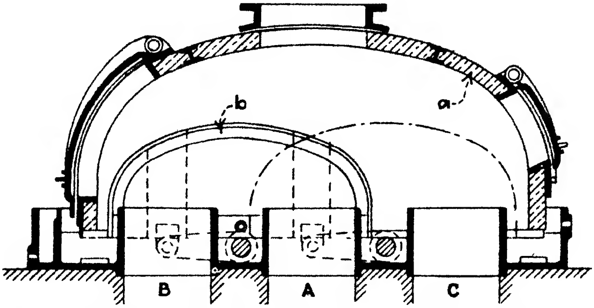


FIG. V-16.—Simple Forter valve. Both outer and inner hoods of this valve are seated in water to form a seal. When the inner hood is in the position marked *b*, it is obvious that passages *A* and *B* are connected, whereas, when the inner hood is in position *a*, passages *A* and *C* are connected. The inner hood is raised by suitable mechanism and transferred from one position to the other. (*From Hermann, "Modern Open Hearth Steel Works."*)

Isley Furnace.—An ingenious method of solving the problem of reversing valves is the Isley furnace shown schematically in

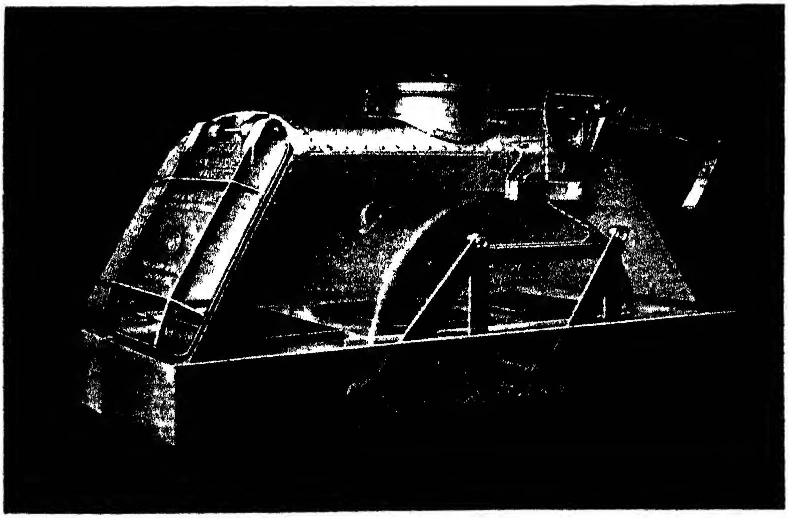


FIG. V-17.—Phantom view showing general design and construction of W-S-M gas reversing valve. (*Courtesy of The Wellman Engineering Co.*)

Fig. V-19. This furnace is fitted with two stacks with an aspirator in each stack, so that an exact draft can be obtained in either direction. Results with this furnace seem to indicate that very good control of combustion and furnace work-chamber conditions is obtained thereby.

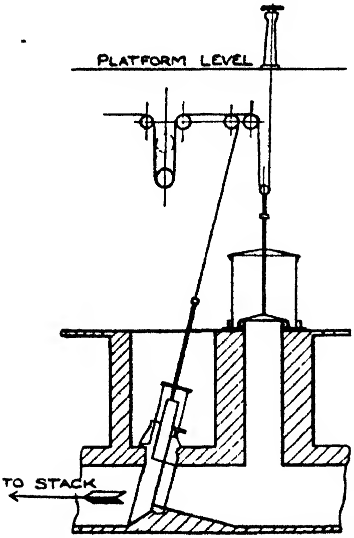


FIG. V-18.—Blaw-Knox valve (*From Jour. Iron Steel Inst., No.* II, 1930.)

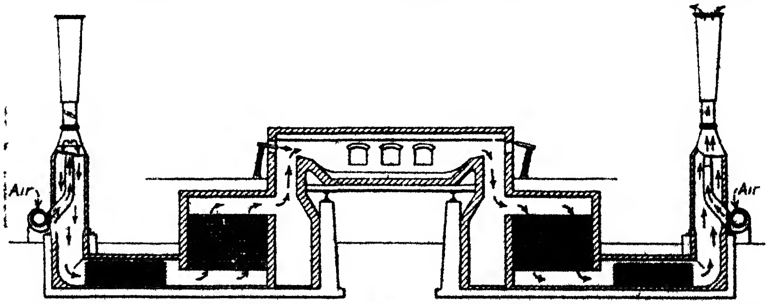


FIG. V-19.—Conventional view of Isley furnace-control apparatus applied to an open-hearth furnace. (*From Merkt, The Yale Scientific Magazine, November,* 1931.)

Life of the Furnace.—The "life" of an open-hearth furnace means the number of heats that it can make continuously without stopping for any more extensive repairs than can be made without allowing it to cool down. No figure can be given for this except in the most general way. The life of the furnace will be ended usually in one of three ways: (1) the falling in or abandonment of the roof, (2) the eating away of the ports, so that the flame can no longer be maintained properly, or (3) the failure of the regenerators, which may occur either through the choking of the checkerwork or through a crevice formed by the contraction and expansion of the bricks, so that there is a serious leak between the gas chamber and the air chamber, and premature combustion takes place. If the roof of a basic furnace lasts 350 heats, it is considered good work. The other parts of water-cooled furnaces and furnaces having greater length —40 ft. and over—will last nearly twice as long. Three hundred and fifty heats would mean about 18 to 24 weeks' work in

America. Foundry furnaces will last only about one-half as many heats as given above in many instances. The reasons for this are (1) the higher temperatures usually attained when making steel for castings and (2) the longer heats. Another important factor in the life of the furnace is its continuous firing, as contrasted with shutting down each week-end. Continuous firing is now the standard practice, because it saves repairs, heat, and labor charges. Many ingot-steel foundries take only two heats per day from their open-hearth furnaces, and most of them shut down for Sunday, although the firing continues.

Cost of Open-hearth Furnaces.—Stewart J. Cort[1] gave the following figures of costs for a single open-hearth furnace which are given herewith as Table V-III. These costs do not include cranes or other auxiliary equipment mentioned in the next section of this book, with the exception of waste-heat boilers. These figures are based on stationary furnaces built six or more in a line, and tilting furnaces three or more in a line.

TABLE V-III.—COMPARATIVE COSTS FOR ONE FURNACE

Type of furnace		Furnace with foundation	Waste-heat boilers	Building	Total
Stationary	Tilting				
60-T		$116,000	$25,000	$120,000	$261,000
75-T		145,000	30,000	130,000	305,000
100-T		193,500	35,000	155,000	383,500
	100-T	270,000	35,000	170,000	475,000
	200-T	360,000	40,000	200,000	600,000
	250-T	400,000	40,000	220,000	660,000

AUXILIARY EQUIPMENT

The auxiliary open-hearth furnace equipment will include cranes over the melting platform and over the casting pit, tracks, cars, charging boxes, charging machines, ladles, etc., for charging both solid and liquid raw materials, as well as fluxes and slag-making materials, recarburizers, etc. It will also include ladles for receiving liquid steel and slag from the furnace, tracks and gondola cars for taking care of refuse, teeming platforms where the operator stands to teem liquid steel from ladle into ingots,

---

[1] "Year Book of the American Iron and Steel Institute," p. 161, New York, 1926.

tracks, cars, stools and ingot molds for forming and taking care of the ingots, stripping machines for removing the mold from the ingot when the latter is solid, and, finally, waste-heat boilers to take advantage of sensible heat in the gases after they leave the regenerators

FIG V-20 —Melting platform and low-type' charging machine (*From 'The Open Hearth Furnace Catalogue of The Wellman-Seaver-Morgan Co*)

Charging Solid Materials. The steel scrap and pig iron, which go to make up the bulk of the metallic charge, as well as iron ore and limestone flux, and other solid materials, if any, which are used in bulk, are brought to the furnace in charging boxes having

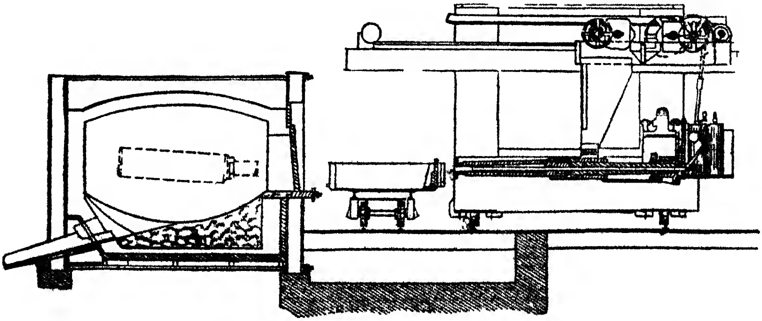


FIG V-21 —"High-type" charging machine and position of charging box when ready to dump This shows also arrangement of tap hole and spout in stationary furnace the general appearance shown in Fig. V-21. Each box holds the equivalent of 2 to $2\frac{1}{2}$ tons of pig iron and three or four boxes are carried together on small, flat cars. In American practice these cars run on tracks immediately in front of the furnace, as shown in Fig. V-20 This has the disadvantage of their interfering with access to this and neighboring furnaces but enables them to be more rapidly put into the furnace and emptied (see Fig V-21). In English and Continental practice it is common to have the tracks for charging box cars situated outside the melting platform, as indicated in Fig. V-6, but this increases the time of charging. Charging machines are rarely of the crane type in America (see Fig. V-6). But more often of the so-called *low type* shown in Fig. V–22. An older form of high-type machine is shown in Figs. V-7 and V-21. The charging machine moves the charging boxes on their cars back and forth, as desired, after the locomotive has delivered them in front of the furnace. The head of the bar on the charging machine locks into a socket on the box and enables it to be introduced into the furnace and turned over to empty any part or all of its contents. Each of the five front doors of the furnace is used on occasion. A machine can charge at the rate of about one box per minute, if there are no delays.

Fig. V-22.—Low-type charging machines on melting platform of open-hearth furnaces. (*Courtesy of The Wellman Engineering Co*)

Size of Steel Scrap.—Steel scrap in small sizes, such as trimmings from plates and loosely bundled wire, is low in price and disadvantageous in two respects: (1) It occupies too much space in the furnace; and (2) it oxidizes very readily before melting. Herty says that small steel scrap will produce approximately 8.3 lb. of iron oxide during melting for every 100 lb. of

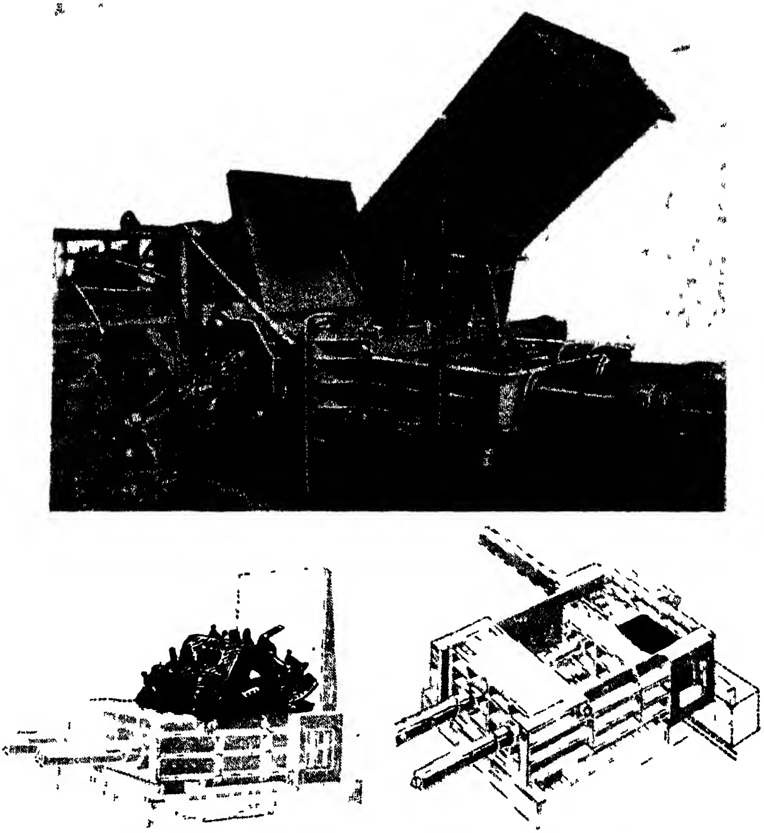


FIG. V-23.—Bundling scrap for open-hearth furnaces.

scrap, whereas "heavy melting scrap," such as ends of ingots, will produce only about 1.7 lb. of iron oxide per 100 lb. Many types of small scrap are now bundled in hydraulic machines as diagrammatically indicated in Fig. V-23. The Ford Motor Company has recently installed bundling presses large enough to compress a full-sized discarded automobile. The compressed cars are put in open-hearth melting furnaces of 400 tons' capacity and melted down, after which the metal is refined in other open-hearth furnaces.

Handling Liquid Metal.—Mixers of varying capacities from 500 to 1,500 tons each are used as reservoirs for the storage of liquid pig iron when and as wanted (see Fig. VI-2). In more recent practice mixer ladles, already mentioned, are used for receiving the pig iron at the blast furnaces and bringing it to the open-hearth plant, where the ladle serves as a reservoir. In either case, the liquid pig is poured from the reservoir into a ladle containing 25 tons or so. This ladle is brought to the open-hearth house, picked up by a crane, and poured into the open-hearth furnace through a movable runner. When liquid steel

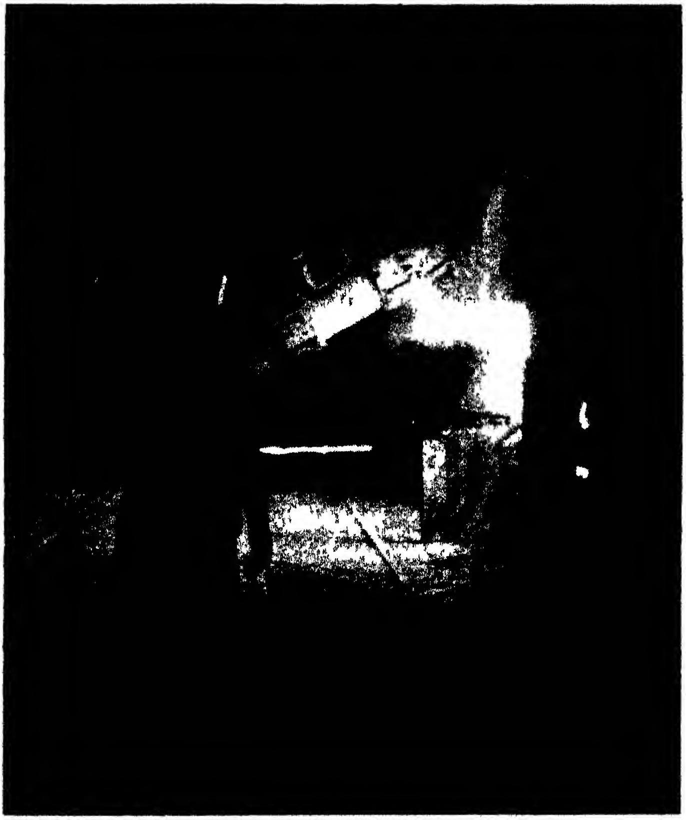


Fig. V-24.—Charging liquid metal into basic open hearth. *(Courtesy of Bethlehem Steel Corp.)*

is also used in the open-hearth furnace, *i.e.*, when pig iron is blown in a Bessemer converter and the blown metal transferred still liquid to the open-hearth furnace for dephosphorization, a similar method of charging the liquid metal is employed, as indicated in Fig V-24 We need hardly add that both solid and liquid metal passes over scales in transit, so that its weight is recorded and charged against the furnace.

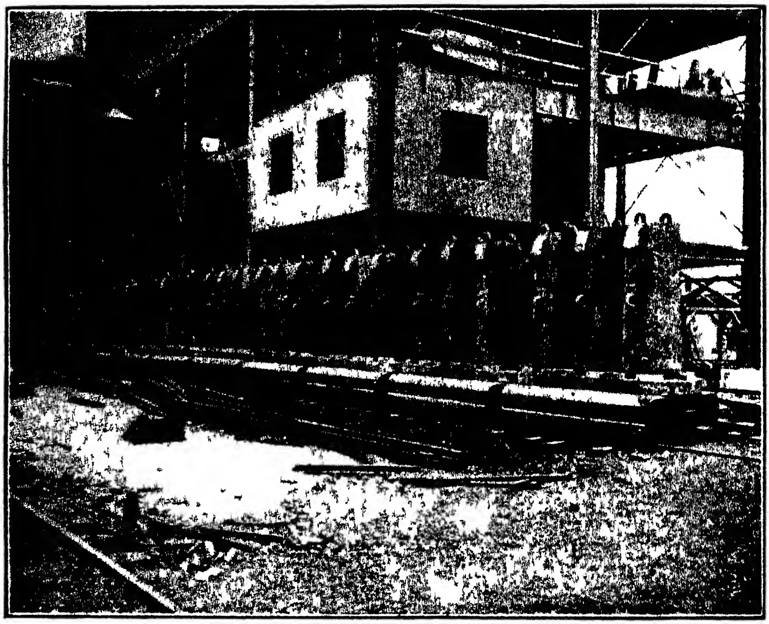


Fig. V-25 —Line of cooling ingot molds outside steel mill.

Ingot Cars, Stools, and Molds.—Cast-iron stools rest on ingot cars and cast-iron ingot molds rest on the stools in turn, as indicated in Fig. V-25. The ingot molds are brought alongside of the teeming platform in the steel mill by a small locomotive (see Fig. V-26). After the finish of the steel operation, the liquid metal is tapped or poured into the teeming ladle, which usually has a capacity of about 125 tons. The ladle may rest on permanent trunnions in back of the furnace or may be held in position by one of the cranes which span the casting pit. In either event it is so held that its overflow spout, shown in Fig. V-9, will lead the slag, which floats on top of the metal, into an adjacent slag ladle, leaving only a thin layer of slag to protect the steel from oxidation and freezing during the teeming operation (Fig. V-26*a*). The teeming ladle is fitted with a nozzle, which in turn is closed by a stopper on the end of a long rod (Fig. V-27). This stopper can be raised out of the nozzle by means of a lever, as shown in Fig. V-28. The stopper is raised entirely clear from the nozzle to avoid any spattering. The inner diameter of the nozzle, therefore, determines the size of the stream of metal, which in turn determines the rate at which the ingot molds are filled, the total time required to empty a ladle of steel, etc. This nozzle size is of prime importance in affecting the surface and character of the steel ingots. Ingot molds are carefully painted inside with clay wash or tar. Sometimes they are even dipped bodily in hot tar in order to insure a good coating. Good molds should

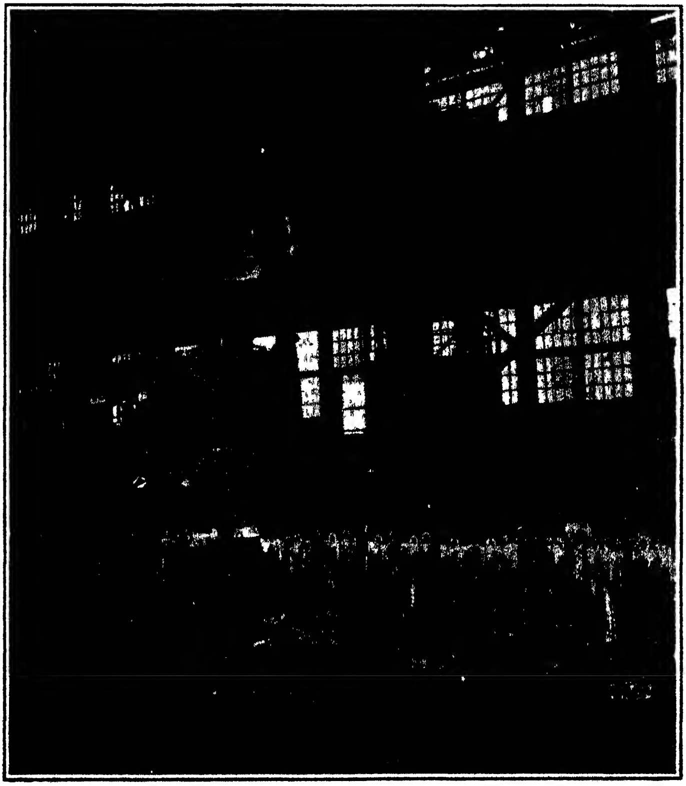


FIG. V-26.—**Teeming a 100-ton open-hearth heat into ingot molds.** (*Courtesy of United States Steel Corp.*)

last long enough to make one hundred ingots. Claims are made for as many as three hundred ingots per mold, but this is practice of doubtful economy, because the molds form cracks inside into which the liquid steel runs. When the molds are stripped from the ingots, these projections tend to tear the skin of the ingot, leaving a mark which is not eradicated by any amount of rolling.

FIG. V-26a.—Disposal of open-hearth slag when tapping. (*From Blast Furnace and Steel Plant, January,* 1932.)

Stripping.—After the ingots are teemed, or cast, they are allowed to stand for at least half an hour in order to solidify, and they are then transferred to the stripping house, shown in Fig. V-29. Here the ingot molds are removed from the ingots and placed on a new stool ready to go back to the steel mill for another teeming. This leaves the ingots on their cars, on which they are transferred to the rolling mill for further operations.

AUTOMATIC CONTROL OF OPEN-HEARTH FURNACES

There are four respects in which the operation of the open-hearth furnace should particularly be controlled, *viz.*, (1) conditions of combustion, (2) analyses of gas within the furnace chamber, (3) gas velocities and pressures within the furnace chamber, and (4) temperatures. In some cases all of these conditions are continuously indicated to the operator and recorded. The operator adjusts the controls in order to maintain the conditions as he desires them. In other cases some or all of these conditions are not only indicated and recorded but automatically regulated so as to be independent of manual control, except as the automatic apparatus is changed to maintain somewhat different conditions.

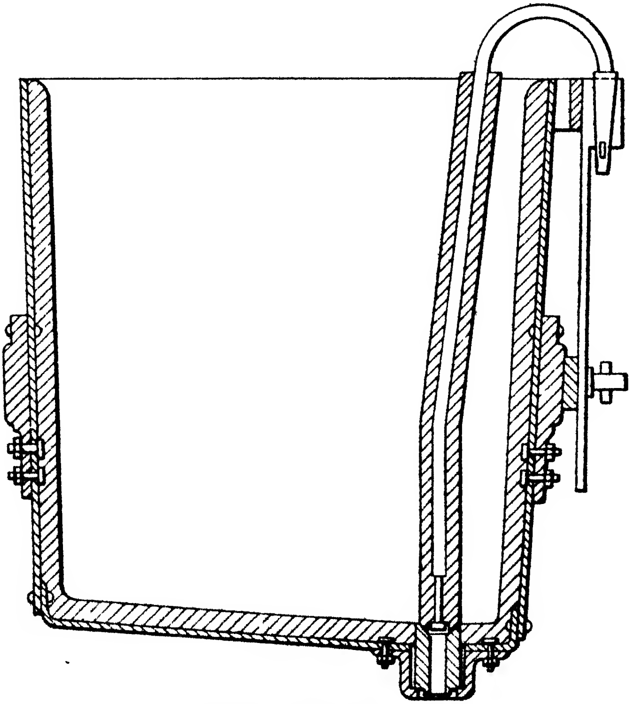


FIG. V-27.—Steel teeming ladle

Automatic Control of Combustion.—We have already indicated how blast-furnace gas is intimately mixed with coke-oven gas in order to maintain a uniform calorific power of mixed gas supplied to the open-hearth furnace. In addition to this, it is necessary, whether gas or oil is used for fuel, so to regulate the relative volumes of air and combustible that the most desirable combustion conditions shall be maintained. This does not always mean perfect combustion, because, during the melting-down period when the temperature must be as high as possible, it may be desirable to use air in excess of that necessary for perfect combustion in order that we may get the maximum production of carbon dioxide. In some cases, it is, therefore, habitual to have the combustion regulated so that the furnace gases will contain about 1 per cent of free oxygen during the melting-down period. At a later period the ratio may be changed to obtain as near perfect combustion as possible. Other operators prefer to use the same ratio throughout and get the highest possible temperature available with the amount of fuel used. A form of combustion regulator is shown in Fig. V-30. It will be noted that a Venturi principle volume indicator is used in both the air and the gas lines. Each side of the Venturi orifice in these lines

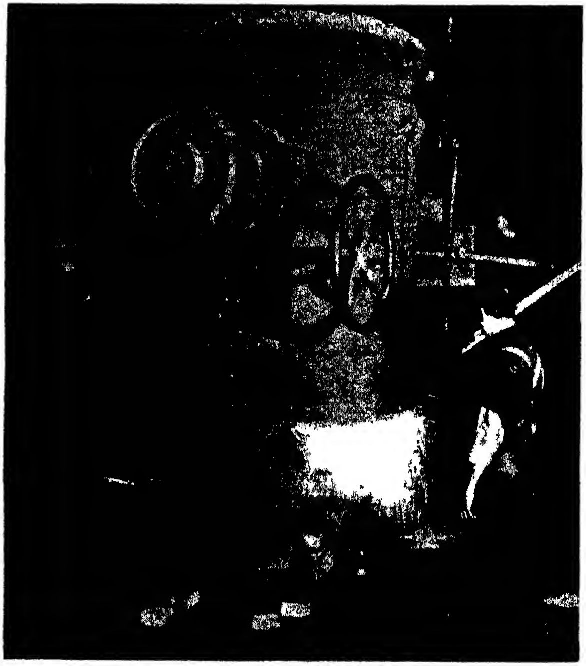


FIG. V-28.—Teeming steel into molds.

and pipe leads to a diaphragm and this, in turn, by means of a lever, opens or closes a valve in the air line. The levers can be adjusted to maintain automatically a wide range of air and gas ratios. If the operator requires more heat in this furnace and turns on a larger amount of gas, a corresponding increase is automatically made in the air volume. Corresponding control can be had when oil or tar is used for fuel in place of gas.

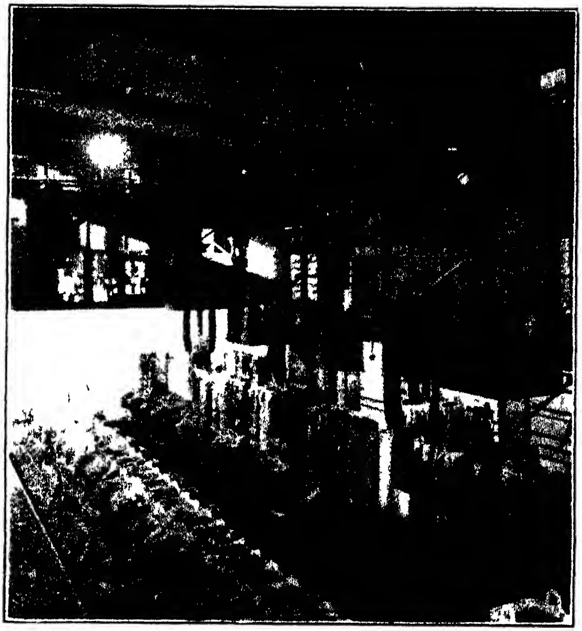


FIG. V-29 Electric strippers in operation. (*Courtesy of U. S. Steel Corp.*)

Analyses of Furnace Gases.—Apparatus is on the market which will continuously indicate the amount of carbon dioxide present in any gases. This is installed at some open-hearth furnaces as a check on the combustion conditions. It may be used there with or without automatic regulation of combustion. In some cases continuous recording of carbon dioxide is not practiced, but complete gas analyses are made every 24 hr. More

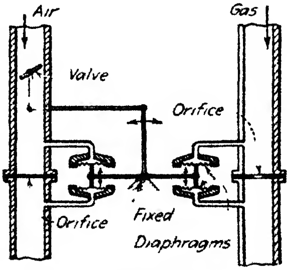


FIG. V-30.—Regulator for relative volumes of air and gas. (*From Blast Furnace and Steel Plant, February, 1932.*)

recently apparatus has been devised for the continuous recording of oxygen in gases, but this is not as yet extensively employed.

Gas Velocities and Furnace Pressures.—In order that combustion conditions may be adequately controlled, it is necessary that the working chamber of the furnace should be at all times under a slight pressure so that there is no opportunity for infiltration of air through open doors, cracks, etc. An indicator placed in the middle of the roof, or in the front wall just over the middle door, should show about ½-in. water pressure at all times. Sometimes this indicator is automatically connected with a fan forcing air into the regenerator on the one side and another fan drawing the gases from the waste-heat boiler into the stack on the other side. In this way the furnace is much more accurately controlled than if dependent on chimney draft. In connection with combustion conditions, it should be mentioned that the insulation of regenerators, uptakes, etc., has been incidentally very beneficial because of preventing infiltration of air in parts of the apparatus where inner pressure is impossible.

Temperatures.—Furnace temperature is controlled by increasing or decreasing the amount of fuel used and also by the frequency with which reversals in direction of gas and air are made. It is obvious that if incoming gas and air are using one pair of regenerators too long, their preheat will decrease by a serious amount. On the other hand, if they are reversed too frequently, there will be a constant building up of temperatures which may endanger the life of the brickwork. To maintain the desired temperature with the least necessary amount of fuel, and to maintain uniformity of temperature at all times, is the optimum practice. Where this was judged by eye and reversals made at the judgment of the operator, very ununiform results were obtained. Where reversals are made by time, such as every 15 or 20 min. or longer, results have also been far from uniform. The best results have been achieved by reversing the valves when the difference in temperature between the air entering its regenerator on one side is about 200°F. less than the temperature of the products of combustion leaving the regenerator on the other side. This is diagrammatically indicated in Fig. V-31. If the flame is passing through this furnace from right to left of the diagram and the thermocouple at *C* on the right indicates a temperature 200° lower than the thermocouple at *C* on the left, then an electric device automatically sets in motion the apparatus which reverses the valves and changes the direction of the current of gas and air. In some cases the apparatus is rigged to ring a bell and/or give other signals, so that the valves are reversed by the operator when this much difference in temperature is shown.

THE OPERATION IN BRIEF

Formerly the so-called *pig-and-ore process* was practiced; *viz.*, 100 per cent of the charge consisted of pig iron and enough iron ore was used to oxidize all the impurities therein. This naturally was practiced where pig iron was cheap, as, for example, in Pittsburgh and in Germany. But this is necessarily very slow, and almost all American furnaces now use at least 40 to 60 per cent of steel scrap, because this makes a smaller amount of impurities to be oxidized off. In some cases as much as 100 per cent of steel scrap is used, but this is also special practice requiring special methods. We shall first consider a charge using only steel scrap and pig iron.

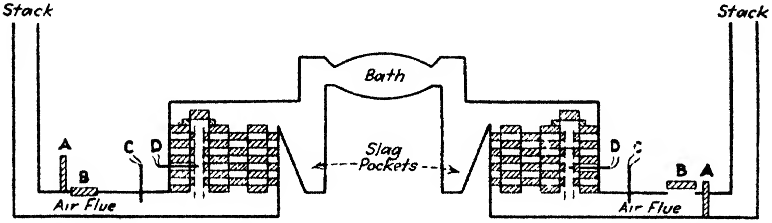


FIG. V-31.—Diagrammatic drawing showing the location of the thermocouples on both sides of the furnace. *A* indicates stack dampers and *B* indicates air lids; *C* indicates the recommended location of the control (and recorder) couples in the air flues; *D* indicates the alternate location of the thermocouples in a well in the checker chambers. (*From Leeds & Northrup Co., Bull.* 841, 1931.)

Mixers.—Mixers have the great advantage of providing pig in quantities of 25 tons or so at frequent intervals. Mixer ladles are more economical, and, since experience has taught operators a method of partially reducing sulphur in them, they have become active competitors of large mixers. In some cases the mixer is used as a preliminary refiner, about 4 to 5 per cent of ore and 5 to 6 per cent of lime being added to it. In the mixer, manganese, silicon, phosphorus, and sulphur are thus removed in amounts worthy of consideration. Purifying in the mixer increases the output of the open-hearth furnace; moreover, the costs for repairs, labor, and fluxes in the mixer are comparatively small.

Order of Charging.—For simplicity we shall consider a charge of 50 per cent of steel scrap and 50 per cent of pig iron. About 10 per cent of the steel scrap is spread evenly over the bottom, preference being given to plate scrap and small-size scrap because of its greater covering power. It is placed here for the purpose of protecting the bottom. On top of this is placed about 6 to 10 tons of limestone for slag-making purposes and about 4 tons of iron ore or roll scale. Then follows about as much scrap as can be crowded into the furnace with a few tons of pig iron on top of it. The object is to have the easily melting pig iron placed on top, so that it will trickle over the partly melted steel and tend to reduce oxidized scrap that has been formed in the flame. As soon as the charge has softened and sunk down in the furnace, there is room for the rest of the scrap and 30 or 40 tons of liquid pig iron. As the metal melts down, it forms a pool in the bottom of the furnace. The impurities in this react with iron ore and other iron oxide, so that all of the phosphorus, most of the silicon, and all but about 0.25 per cent of the manganese will be oxidized and pass into the slag. Some of the carbon will also be eliminated.

Lime Boil.—During the melting of the scrap it is oxidized, and chemical reactions take place between its oxide and the impurities it contains. The iron ore in the bottom of the furnace may also enter into the action. At the same time the limestone in the bottom of the furnace is being calcined:

$$CaCO_3 \rightleftarrows CaO + CO_2.$$

As this gas bubbles up through the liquid metal, it forms what is known as a *lime boil.* The gas also oxidizes some iron:

$$CO_2 + Fe \rightleftarrows FeO + CO.$$

Melting.—When the charge is fully melted, the "lime comes up," as it is said. This lime is not yet fully melted and a period ensues in which a fully liquid slag is formed. If necessary, some fluorspar, CaF_2, is added to assist in making this liquid. The basic slag should contain at all times more than 50 per cent and preferably at least 55 per cent of $CaO + MgO$. It is desired that the bath should hold at least 0.20 per cent of manganese until the end of the heat, because this lessens the tendency of iron oxide to dissolve in the steel. The more manganese put in with the charge, the more sulphur is removed during the operation. And for this reason basic pig iron should contain at least 1.75 per cent of manganese. Basic pig iron should also contain not more than 1 per cent of silicon, because this forms silicon dioxide, which requires calcium oxide to neutralize it, because the silicon dioxide should never be in excess of 10 to 15 per cent in the slag. The slag on the newly melted bath will also contain a certain amount of FeO and Fe_2O_3. The latter is used for the further oxidation of impurities. After melting it will be necessary to put in an additional charging box or so of iron ore if the carbon still requires considerable reduction. It is imperative, however, that no iron ore should be added to the furnace within an hour of the time the charge is tapped, because the oxidizing character of the slag and therefore the oxygen in the bath should be as low as possible during the final stages, as will be explained later under the head of the physical chemistry of steel making. It will require 4 to 8 hr. between charging and the time when the lime comes up.

Functions of the Slag.—The slag is the agent through which the chemical reactions of the operation are effected. Its oxidizing action is obtained chiefly from iron ore, but also by oxidation through oxygen and carbon dioxide in the furnace gases. It must always be basic enough to hold all the phosphorus which has been oxidized and, if possible, all the sulphur which can be converted to calcium sulphide. This is somewhat uncertain, especially if sulphur is brought in from the fuel through the furnace gases, but there is usually some reduction of sulphur from the average analysis of the raw materials to that of the finished steel. The slag also serves as a blanket between bath and furnace gases to lessen oxidation of and sulphurization of the steel. Nevertheless, some exposure occurs, because there is always a boil during the later period of the heat in which escape of carbon monoxide gas from the steel causes liquid metal to be thrown up into the furnace atmosphere.

The variations in bath analysis at different depths, shown on page 126, afford an opportunity to illustrate the removal of some of the metalloids: Carbon bubbles out of the steel in the form of carbon monoxide gas. This gas will rise at all times and also will be more likely to form near the top where the oxidizing slag reacts with the carbon in the metal. The manganese will obviously be lower at the top, since its conversion to manganese oxide takes place where the slag reacts with the metal.

The behavior of phosphorus is irregular and greatly dependent on temperature, because phosphorus will oxidize in preference to carbon at relatively low temperatures and *vice versa* at temperatures of a higher level. Sulphur is eliminated from the steel mainly through the formation of manganese sulphide, which slowly separates from solution in the liquid bath and slowly rises to the surface, so that we should expect to find a greater concentration in the upper levels.

Finishing the Heat.—After the charge is fully melted, it only remains to bring the steel to the desired purity, to raise the temperature to the point where it is sufficiently fluid for tapping, and to recarburize in part. Usually only carbon remains to be oxidized after the lime comes up. A sample of the bath taken at this time will give the first representative chemical analysis of the heat and, if the carbon is right, it only remains to get the temperature to the desired point, to recarburize in part, and tap. If by any chance the phosphorus has not been entirely eliminated, then it will be necessary to lower the temperature of the furnace and add some pig iron. At low temperatures, phosphorus will oxidize instead of carbon and *vice versa.* Carbon must be the last element to leave the steel, because it has a strong influence in keeping iron oxide out of the bath. The addition of cold pig iron increases the carbon in the metal, lowers the temperature of the bath, and usually enables the phosphorus to be reduced to the desired point. This "pigging up," as it is called, is, however, to be avoided when possible. Sometimes pig iron is added for the purpose of creating a "pig boil" in order to stir the bath and/or to raise its temperature.

If, after the lime comes up, the carbon in the bath is high, it may be necessary to add one or two boxes of ore. The finish of the heat usually requires 4 hr. or more. During most of this time, the bath should boil actively, the temperature should rise, and the carbon drop. Since carbon will inevitably be oxidized as long as the steel remains in the furnace, it is obvious that there must be more carbon in the bath just after melting than we expect to have in the finished steel, but the excess should not be too great. Test samples are taken at intervals with a spoon and are analyzed to show the progress of the reactions. In most cases it is customary to reduce the final carbon slightly below that desired in the finished steel, because, when the recarburizer is added, a little carbon comes in with the silicon and manganese, and this makes the final steel slightly higher in carbon than the final bath. In some cases it is customary to reduce the carbon very much below the point desired in the finished steel and then add considerable carbon with the recarburizer. This causes a violent stirring of the metal and is believed by many to assist in removing dissolved oxygen from the steel.

Slag.—Final basic slags will contain:

10 to 15 per cent SiO_2
45 to 55 per cent $CaO + MgO$
10 to 18 per cent FeO
5 to 15 per cent P_2O_5.

The slag is the crux of the open-hearth operation, and it must be kept slightly oxidizing at all times except just at the end.

Recarburizing.—The original purpose of recarburizing was to bring up the steel to the desired content of carbon; hence the name. At present, the most important purpose is to rid the bath of oxygen as fully as possible. Both silicon and manganese contribute to this end. Manganese is a more powerful deoxidizer than silicon, but silicon has also the function of lessening the gas bubbles or blowholes in the solid steel. Aluminum and vanadium are both more powerful deoxidizers than manganese. Aluminum is not always used because of a danger mentioned hereafter, and vanadium is not always used on account of its cost. One of the most important recent improvements in the manufacture of basic open-hearth steel is the possibility of performing a part of the recarburizing in the furnace. The recarburizer contains manganese, silicon, and carbon. It often consists of ferromanganese containing about 80 per cent of manganese, and ferrosilicon containing 50 per cent of silicon. Where a good deal of carbon is also to be added to the steel, alloys containing less silicon and manganese than these may be used, together with pig iron or bags of anthracite coal in small sizes. Even when making medium or high-carbon steel, some operators prefer to reduce the carbon in the bath to a low point and then add liquid pig iron in the furnace, because this gives a boil to the bath, which stirs it and rids it of oxygen. The chemistry of the recarburizing operation is important. The recarburizer is added both to give certain elements to the steel and to take certain impurities out of it. The importance of this second function will be appreciated on recalling that the makers of Bessemer steel were not able to produce a marketable product until they learned to take oxygen out of the liquid bath by means of manganese added with the recarburizer. Finally, the chemistry of the recarburizing operation is complicated by the circumstance that some reactions occur between the recarburizer and the slag of the process. It is on this account that recarburizing is difficult, and was formerly hazardous, in the basic open-hearth furnace. Especially if silicon is added in the basic open-hearth furnace and reacts with the metal and slag, it may form enough silicon dioxide to decrease the effective basicity of the slag, so that phosphorus will be reduced. If reduced, it will, of course, return to the bath. This occurrence is known as *rephosphorization.* We have already noted that silicon dioxide is a stronger acid than phosphoric anhydride and will drive the phosphorus out of combination unless a large excess of calcium oxide is present to hold both. Recent experience has taught operators so to manipulate the heat as to be able to add a part of the ferromanganese directly in the furnace. This has the advantage of performing the reaction when the metal is hotter, which means that it will be more nearly complete. It also forms the solid manganese oxide in a relatively thin basin, so that the oxide does not have so far to rise in order to clarify the steel. In the ladle it might have a depth of 10 ft. through which to rise to reach the surface. Finally, the putting of ferromanganese in the furnace causes it to be again stirred into the metal by the action during tapping. One of the most important of all the improvements in open-hearth practice has been the development by Doctor Herty and his associates of a recarburizing alloy rich in both silicon and manganese, known as *silicon-manganese.* This is now beginning to be extensively used in America. It is especially efficacious in producing oxides of silicon and manganese which will coalesce and separate more easily from the steel, thus ridding it of the so-called *oxidized inclusions* before it freezes. In some cases an alloy containing silicon, manganese, and aluminum has also been used. If a basic heat is tapped within 10 or 15 min. after adding the recarburizer, the amount of inclusions is less than if the steel waits in the furnace long enough for a secondary reaction to occur which produces more oxides in the metal. In the ladle it is customary to add the silicon and also aluminum, if the addition of aluminum is permitted. This practice is somewhat hazardous because aluminum oxide forms extremely fine particles which separate with difficulty from liquid metal. If carbon is added, it is often added in the ladle. After a pool of liquid metal has accumulated in the ladle from the furnace, the carbon is thrown in, in the form of anthracite coal in bags. This creates a violent boiling of the metal in the ladle, due to the escape of carbon monoxide gas, and it is believed that this action helps to decrease the oxygen left in the steel.

Deoxidizing the Bath.—The carbon, manganese and silicon contained in the recarburizer will all deoxidize iron according to the following type reactions:

$$Mn + FeO = MnO + Fe. \tag{1}$$

$$3C + Fe_2O_3 = 3CO + 2Fe. \tag{2}$$

$$Si + 5FeO = FeO_2.SiO_3 + 4Fe. \tag{3}$$

Of these, manganese is the most powerful deoxidizer and will come nearest to ridding the bath of oxide. The carbon monoxide has the disadvantage of being somewhat soluble in the molten metal; consequently, although large volumes of carbon monoxide gas escape from the steel during recarburizing, there is, under normal conditions, a constant evolution up to the time when the metal becomes solid, and there is probably even a small amount of carbon monoxide retained in solution, as well as gas bubbles (called *blowholes*) inclosed in the solid metal. Silicon not only reduces iron oxide but also is a prime factor in preventing these blowholes, as will also be described in Chap. VIII. The oxides of manganese and silicon tend to separate themselves from the liquid bath, and it is thus that they remove the oxygen, whereas the oxides of iron are much more readily retained by the steel. Nevertheless, the removal of oxygen by manganese and silicon is not complete; because, first, the deoxidation of the FeO and Fe_3O_3 is not complete and, second, the oxides of manganese and silicon do not completely separate from the steel but, on account of lack of fluidity, remain in tiny particles entangled in the solidified mass. Unless there be an excess of manganese and silicon above that necessary to fulfill reactions (1) and (3), their deoxidizing effect is far from complete, and it is partly on this account that the recarburizer is so calculated as to leave about 0.50 per cent of manganese and 0.10 per cent of silicon in open-hearth steel.

Reactions between Recarburizer and Slag.—The slag being an oxidized product and the recarburizer being essentially a reducing agent, there is always a certain interchange of elements between the two, the slag giving up some of its oxygen to the carbon and manganese of the recarburizer, and the latter contributing manganese to the slag, both by virtue of reaction (1) and of the following:

$$FeO(SiO_2)_2 + Mn = MnO(SiO_2)_2 + Fe. \qquad (4)$$

The slag is decreased in iron oxides and increased in manganese oxide as a consequence of the recarburizing operation. There is more iron oxide reduced from the slag than manganese oxide contributed, and this effect is produced by direct reduction of iron, by means of carbon monoxide, in accordance with the following reaction:

$$2FeO.SiO_2 + CO = FeO(SiO_2)_2 + CO_2 + Fe. \qquad (5)$$

It is always difficult to recarburize steel in the presence of a basic slag, lest the carbon, silicon, and manganese of the recarburizer reduce phosphorus from the slag and cause it to pass back into the metal:

$$2(3CaO.P_2O_5) + 5C = 6CaO.P_2O_5 + 5CO + 2P;$$
$$4(3CaO.P_2O_5) + 5Si = 2(6CaO.P_2O_5) + 5SiO_2 + 4P.$$

Therefore in basic practice most of the recarburizer is added to the stream of metal while it is pouring from the furnace into the ladle, and special arrangements are made for allowing the slag which floats on top of the metal to overflow at the top of the ladle and thus be largely separated. In careful practice "rephosphorization" need not exceed 0.01 to 0.02 per cent of the steel, although a much larger increase may take place through accident. But, as the steel and slag remain in the acid-lined ladle which is always used for teeming purposes, some silicon in the steel oxidizes and passes into the slag and some ladle-lining material is fluxed off by the slag, especially if the temperature is high. Thus, phosphorus and a little sulphur may be reduced out of the slag and absorbed by the metal during teeming, especially if the teeming operation is a long one. The high temperatures and long teeming periods of foundry work tend to produce this rephosphorization.

The recarburizer usually consists of ferromanganese and ferrosilicon together with anthracite coal, charcoal, or coke which is broken into small pieces and loaded into paper bags. Anthracite is the commonest. When phosphorus is desired, which it is for tin-plate steel, ferrophosphorus is added in the ladle. In some cases, stick sulphur is added in the ladle. In making high-carbon steel for rails, etc., we may use liquid spiegeleisen, as in the Bessemer process. This requires cupolas to melt the spiegel and a mixer in which it is stored in molten condition until wanted. When part of the ferromanganese is added in the furnace, it results in some 50 per cent of its manganese being oxidized and lost in the slag. Of the other elements, there is absorbed by the steel in the ladle: 45 per cent of the carbon in anthracite, 85 per cent of the manganese in ferromanganese, 80 per cent of the manganese in spiegel, 65 per cent of the silicon in ferrosilicon, 75 per cent of the phosphorus in ferrophosphorus, and 67 per cent of the sulphur in stick sulphur. From 67 to 75 per cent of the carbon in the ferromanganese, spiegel, and ferrosilicon is absorbed by the steel.

Temperatures.—The temperature in the furnace chamber will depend largely on the steel made, because obviously a high-carbon steel will be fluid at a temperature where low-carbon steel will be scarcely molten. With wide variations we may say that the temperature of the furnace chamber will average somewhere between 2800 and 3100°F. Producer gas will enter the gas regenerators at approximately 1000°F., having absorbed some heat from the flues through which the flame has just been passing toward the waste-heat boilers. The air will also absorb heat from the flues and come to the air regenerator at 1500 to 1700°F. After passing through the regenerators, the air will come to the uptake at a temperature between 2100 and 2300°F. Of course, it will be lower the longer the furnace has been on this phase since reversing. The products of combustion, after passing through the regenerators, will leave them at about 1900°F. They will be at a temperature of about 1100 to 1400°F. at the waste-heat boilers and about 450 to 600°F. at the stack. As previously mentioned, the difference in temperature between the air entering its regenerator and the products of combustion leaving their pair of regenerators will not exceed 200°F. when the furnace is automatically controlled as to temperature and reversal.

Weight of Slag.—The weight of slag will depend upon silicon, phosphorus, and dirt in the metal and will average in America between 10 and 20 per cent of the weight of the steel. Its weight can be calculated with sufficient accuracy by dividing the total lime put into the furnace (plus 30 per cent of itself to allow for wear of the lining) by the percentage of lime in the slag. Thus, if 15,000 lb. of lime are charged into a 100-ton furnace, the weight of the slag will be: 15,000 × 1.3 ÷ 0.55 = (roughly) 35,000 lb.

Metallic Loss in Process.—The shrinkage in weight between total metallic charge and finished steel will be very variable, as mentioned at the beginning of this chapter. An analysis of what it may be in some cases, to illustrate the principles involved, is given in Table V-IV.

TABLE V-IV.—LOSS IN BASIC OPEN-HEARTH PROCESS
(50 per cent pig; 50 per cent scrap)

Charge	Pig iron	Scrap	Average	Loss
Carbon, per cent	3.75	0.25	2.00	2.00
Silicon, per cent	0.70	0.06	0.38	0.38
Manganese, per cent	1.75	0.50	1.15	0.95
Phosphorus, per cent	1.30	0.04	0.67	0.67
Sulphur, per cent	0.037	0.03	0.03	
20 per cent slag at 15 per cent iron	.....	....	....	3.00
				7.00
Iron reduced from ore	.....	...	....	1.50 gain
Net loss	....	....	....	5.50

When large proportions of ore which is reduced by the carbon in the bath are used, the production may exceed 100 per cent.

Pig-and-ore Process.—Where pig iron is cheaper than scrap, the charge may consist entirely of pig and ore, and it is then customary to hasten the operations by some of the special processes, such as the Talbot and the Monel. The original pig-and-ore process is abandoned very largely in America, because of the length of time required to burn off the impurities unless they are diluted by steel, and because steel scrap is more abundant than it is in Europe. The use of scrap also gives a thinner blanket of slag and therefore quicker heat penetration and a quicker operation. It is difficult for a beginner to understand why the reactions are not more rapid in the open-hearth furnace, when the entire purification of pig iron in the puddling furnace is accomplished in an hour and a half, including melting; but the difference is due to the very shallow bath in the puddling operation and its extensive contact with the fettling. If we should attempt to purify under such strong oxidizing conditions in the open-hearth furnace, the molten metal would boil violently, because of the high temperature, and for the same reason would also become so charged with oxygen as to be worthless. Even at the low temperature of the puddling furnace, the boiling is so violent as to increase the height of the bath, and this action would be proportionately increased at the temperature of the open-hearth furnace, which, at the end of an operation producing dead-soft steel, will be about 1650 to 1700°C. (3002 to 3092°F.).

Talbot Process.—The Talbot process has a basic-lined furnace and a charge above 200 tons in some cases. The tilting furnace is used in order that any desired quantity of metal or slag may be poured out at will. The operation is continuous, and the furnace is drained of metal only once a week. After the first charge has been worked down to the desired percentage of carbon, the great part of the slag is poured off, and then about one-third of the steel is poured into the ladle, recarburized, and teemed into the ingot molds in the usual way. To the charge of metal left in the bath are now added iron ore and limestone to produce a basic and highly oxidized slag, and through this slag is then poured an amount of pig iron equal to the steel removed. The reaction between the impurities in the pig iron and the iron oxide in the slag is very vigorous but does not cause a frothing or foaming, because all the materials are in the liquid form and the gas bubbles through them without great difficulty; however, much of the slag runs out of the furnace.

The oxidation is so rapid that the silicon and manganese are said to be oxidized almost immediately, together with most of the phosphorus; then the carbon is worked off in the usual way, with more ore and limestone used if necessary. The temperature is low at first, in order that the phosphorus may be more readily burned. At the end of 3 to 6 hr., the bath has again become purified, and another cast removed, the whole operation being then repeated. The yield of steel is 106 to 108 per cent of the weight of the pig iron charged, because of the large amount of iron reduced from the ore by the impurities in the pig iron.

$3C + Fe_2O_3 = 2Fe + 3CO$ (absorbs 104,120 calories).

$6P + 5Fe_2O_3 = 10Fe + 3P_2O_5$ (evolves 141,700 calories).

The advantages of the process are: Three or four heats of 75 tons each are obtained in 24 hr. without the use of steel scrap. The yield is large (though this advantage is somewhat neutralized by the cost of the iron ore used). The temperature of the final metal can be more easily controlled. The disadvantages of the process are: The very large cost of furnaces and the slightly higher cost for repairs.

Monel Process.—Upon a basic hearth limestone and ore, or other form of iron oxide, are heated until they become pasty, and then molten pig iron, equivalent to the capacity of the furnace, is poured upon it. When steel scrap is plentiful, a part of the metal charge may be composed of this material, charged with the limestone and ore. Oxide up to 25 per cent of the weight of the pig iron charge is used. The temperature of the bath is necessarily low, since pig iron direct from a blast furnace or from a mixer will not be more than 200 or 300°C. above its melting point, and therefore the phosphorus will be oxidized very rapidly. The slag foams up and pours out of a special slag notch; in 1 hr. the bath is free from 90 per cent of the phosphorus, most of the silicon and manganese, and all but about 2 per cent of carbon. The operation is then continued in the usual way to eliminate the carbon, and the metal is tapped when this has been reduced to the desired point. The total time is the same as in an ordinary pig-and-scrap process. The apparent disadvantages of the process are excessive cutting of the hearth and a heavy loss of iron in the rich slag which flows off at the beginning of the operation.

Duplex Process.—In several large American plants the combined Bessemer and basic open-hearth process is in operation, an acid converter being used to oxidize the silicon, manganese, and most of the carbon, while the phosphorus and the remainder of the carbon are eliminated in a basic open-hearth furnace. In the different localities there are different ways of carrying out this combination, but these divide themselves into two general methods: In one method, the metal is blown in the converter until it is purified to the point where it is practically equivalent to so much high-phosphorus, molten steel scrap, which is then mixed with either liquid or solid pig iron in the open-hearth furnace and worked as any ordinary pig-and-scrap heat after melting. In another, and more common, method, the pig iron is blown in the converter until it contains about 1 per cent or so of carbon, and this product, with little or no additional pig iron, is then dephosphorized and decarbonized in the open-hearth furnace. The advantages of the combined process are: It shortens the open-hearth purification by sometimes much more than half the usual period. It relieves the basic hearth of the presence of silica which tends to scorify it. Both of these improvements have a secondary advantage in increasing the life of the hearth. An advantage from the Bessemer standpoint is that a poorer grade of iron can be converted and yet a higher grade of steel produced. Open-hearth railroad rails, which are frequently made by the duplex process in America, bring a higher price than Bessemer rails. Finally, the duplex process makes the steel maker independent of the variable price of so-called *melting steel scrap.*

In carrying out the process, large mixers are used as a reservoir for the liquid pig iron. Sometimes a little purification is carried on in these furnaces. They supply pig iron to the converters and to basic furnaces as well, if desired. The blown metal is also frequently poured into a mixer of its own, which serves as a source of supply to the open-hearth furnaces, and again a little purification may be effected in this mixer. The use of these mixers not only makes each part of the process somewhat independent of delays in the other part but also corrects slight irregularities in analysis of pig iron or blown metal, thus providing more uniform conditions in each furnace, which greatly facilitates the operation therein. Under proper conditions, an open-hearth furnace with auxiliary converter and mixers, may make as many as 40 to 50 heats per week, as compared with 18 heats by the ordinary method.

Duplex Talbot.—Instead of working down the carbon, silicon, and manganese in the Talbot furnace, it is now common practice to pour into the bath purified metal from the Bessemer converter. As this passes through the oxidized basic slag, the phosphorus is washed out of it; finally, pig iron is poured into the bath, resulting in a violent boil and evolution of heat, with deoxidization of the metal and slag, after which the steel should be ready to tap, following perhaps a half hour's adjustment and raising of temperature.

Processes in Two Open-hearth Furnaces.—At a low temperature phosphorus is very easily oxidized and absorbed by a basic slag, even in the presence of carbon, but when the heat is high the oxidation of phosphorus is hindered by the carbon, for the reason already explained—that the affinity of carbon for oxygen increases more rapidly with the temperature than the affinity of the other elements in the bath. We could obtain the desired conditions in the open-hearth process, but the operation would be extremely slow at this low heat, and the carbon would pass away slowly. These difficulties have been met by the Campbell No. 2 and Bertrand-Thiel processes, the former of which was developed at Steelton, Pa., and the latter at Kladno, Czechoslovakia.

Campbell No. 2 Process.—A charge, consisting of all pig iron or of pig iron and scrap, is placed in a basic open-hearth furnace and the purification carried on at a low temperature until almost all the silicon and phosphorus and part of the sulphur and carbon are eliminated. The bath is then tapped from the basic furnace and poured into an acid-lined furnace, care being taken that none of the basic slag goes with it. The process is now continued at a higher temperature, in the usual way to make acid open-hearth steel. The disadvantage of this process is that the transferring of molten metal from one furnace to another is not an easy matter, nor, in fact, is it possible with the arrangements in many plants.

Bertrand-Thiel Process. Hoesch Modification.—The Hoesch process is now in use in some of the German plants, where it is said to give very satisfactory results. Instead of using two furnaces, as in the original Bertrand-Thiel process, and pouring from one to the other, it uses one furnace but pours the bath into a ladle after the first period of purification; the purpose of this is to separate it from the highly phosphorized slag. When this is effected, the metal is poured back into the same furnace and the purification completed. In the first period, all the silicon and manganese, most of the phosphorus, and about one-half of the carbon are removed; in the second period, the remaining phosphorus, carbon, and some additional sulphur are eliminated. The slag separated after the first period contains 20 to 25 per cent of phosphoric anhydride; therefore it finds a ready sale as agricultural fertilizer.

All-scrap Process.—In certain localities in America, steel scrap is cheaper than pig iron, but its use is open to the objection that it is severely oxidized and wasted during the melting period unless there be some pig iron with it to give a reducing influence. Instead of using pig iron, however, some plants now replace it with coke or with a carbonaceous material. The proportions are usually not less than 20 per cent of coke and the balance steel scrap.

PHYSICAL CHEMISTRY OF STEEL MAKING

It has long been known that speed in purifying in the open-hearth furnace required a rapid diffusion of iron oxide from the slag into the bath. This is especially employed in the oxidation of carbon during the later period of the heat. It has also been known that the liquid steel should be as free as possible of oxygen at the end of the heat in order that its quality may be high, because the deoxidizers added only imperfectly perform their work. It has also been known in a general way that four factors especially increase the tendency of the bath to absorb and retain dissolved oxygen, *viz.*, (1) only small amounts of carbon in the steel, (2) large amounts of oxygen in the slag, (3) high temperature of the bath, and (4) fluid slag.

It has also been known that the presence of manganese in the liquid steel lessened the tendency of oxygen to dissolve therein. For several years it has been the universal practice to maintain at least 0.20 per cent of manganese in the bath at all times. But now these basic facts have been investigated in a thorough manner under the direction of Dr. Charles H. Herty, Jr., with the result that the operation has been placed on a very much more scientific basis and enormous improvements have been made in the conduct of the heat and especially in the quality of the finished metal.

Equilibrium between Metal and Slag.—Herty has established the fact that certain principles prevail when there is chemical equilibrium between the metal and the slag, but this equilibrium may be disturbed if the operation proceeds too rapidly, with the result that the bath may contain more than the equilibrium amount of dissolved oxygen at the end. Or the bath may be so deep that equilibrium may not be established between all parts of the liquid steel and the slag lying upon it.

Temperature and Iron Oxide Solubility.—If liquid steel is covered by a slag which can freely give up oxygen to the metal, then the amount of iron oxide dissolved in the metal will be a function of the temperature. This is indicated in Fig. V-32. It is also indicated in Fig. V-33, in which it is seen that there is greater proportion of iron oxide in the metal as compared with that in the slag the higher the temperature of the bath.

Available Oxygen in Slag.—But Herty has also shown that the amount of iron oxide in the slag does not represent the amount available for diffusion to the bath, because that united in the slag in the form of a singulosilicate, $2FeO.SiO_2$, known as *fayalite*, will not leave the slag. Another very important observation, however, is that fayalite decomposes at higher temperatures and its iron oxide, therefore, becomes available for oxidizing the bath. This is another reason why high temperature increases the tendency for the bath to retain oxygen in its final stage. So powerful is the effect of oxygen in the slag producing oxygen in the metal that it is now universal practice to forbid the adding of iron ore to the slag within one or two hours of the time of tapping. This permits the available oxygen in the slag to be exhausted by diffusion to the metal until equilibrium conditions be established. For this reason it is better not to carry on the operation too fast, and it is also better to reduce the carbon in the metal below

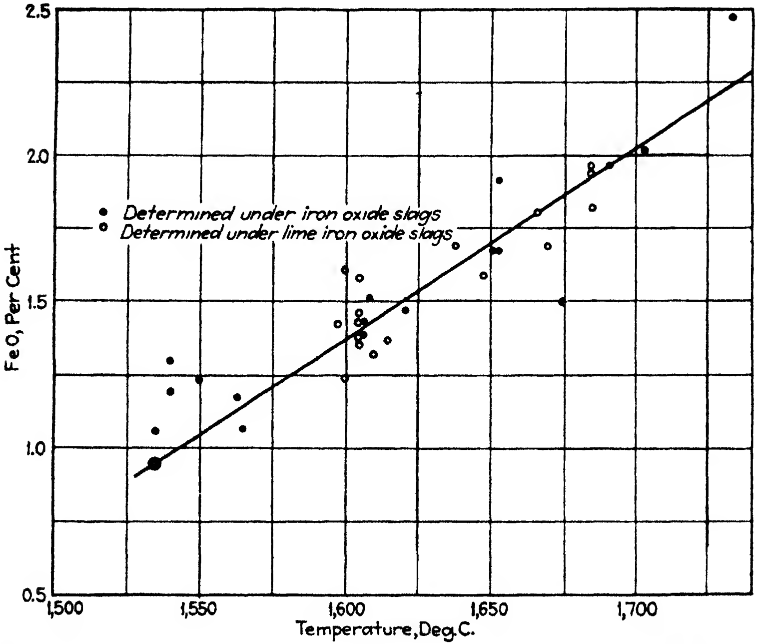


FIG. V-32.—Effect of temperature on solubility of FeO in iron. (*From Herty, Mining and Metallurgical Investigations*, *Bull.* 34, 1927.)

the desired finishing point and then bring it back during recarburizing, because this action greatly helps to establish equilibrium conditions.

Carbon and Oxygen Solubility.—As the bath gets lower and lower in carbon, it gets higher in dissolved iron oxide. This is clearly shown in Fig. V-34, which confirms the observation that the higher the temperature, the more the dissolved oxygen, everything else being equal. However, low carbon is doubtless the most potent factor in effecting high-dissolved oxygen. Since 1860, or before, it has been known that low-carbon steel was the most subject to oxygenation and its accompanying phenomena of numerous blowholes and entangled particles, or inclusions.

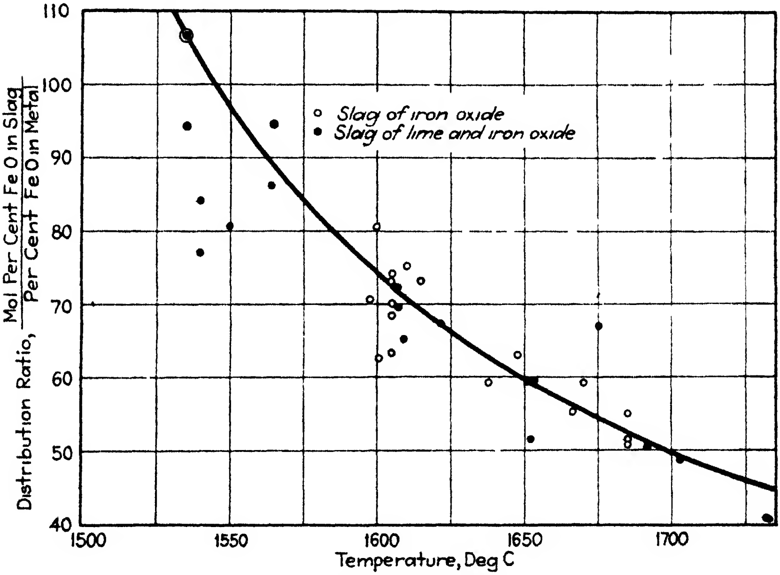


FIG. V-33.—Effect of temperature on the distribution of iron oxide between slag and metal (*From Mining and Metallurgical Investigations*, *Bull.* 34, 1927.)

Viscous Slag.—A viscous slag will not give up its oxygen to the metal as readily as will a fluid slag. This is one of the reasons why it is desirable to thicken up the slag with lime at the end of the heat. A double influence exists in this respect since the higher the temperature, the more liquid the slag, everything else being equal, and also the more readily will oxygen dissolve in the steel.

Summary.—We may summarize the conditions tending to lessen the amount of oxygen in the final bath somewhat as follows:

1. Maintain at least 0.20 per cent of manganese in the liquid steel at all times.
2. Do not have the temperature any higher than necessary to produce steel of the desired fluidity, especially at the end of the process and especially when making low-carbon steel.
3. Have the available oxygen in the slag as low as possible at the end.
4. Thicken up the slag at the end of the operation.
5. Recarburize; do not "catch carbon on the way down."
6. Add ferromanganese in the furnace and tap within 10 or 15 min. thereafter.

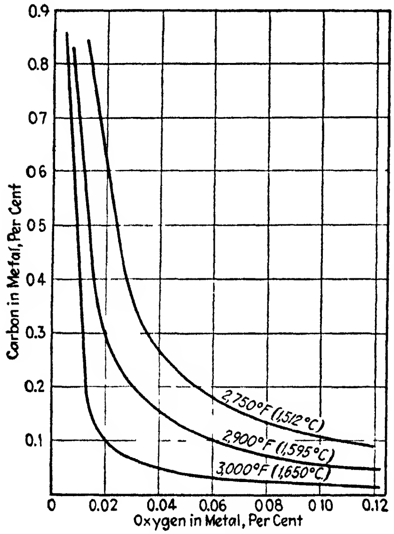


FIG. V-34.—Equilibrium concentrations of carbon and oxygen in the metal at various temperatures. (*From Mining and Metallurgical Investigations, Bull.* 34, 1927.)

References

ALPHONSE BARBEROT: "*Fabrication de l'acier au Four Martin*," Paris, 1923.

KARL DICHMAN: "The Basic Open Hearth Steel Process," translated by Alleyne Reynolds, New York, 1911. This book is now interesting only historically.

V. WINDETT: "The Open Hearth," New York, 1920.

HUBERT HERMANNS: "The Planning, Erection, and Operation of Modern Open Hearth Steel Works," London, 1924.

WILLIAM C. BUELL, JR.: Improving Open Hearth Furnace Design, a series of articles running in *Steel* from Oct. 3, 1932, until October, 1933, or perhaps later. These contain a wealth of information on furnace construction and design and presumably will be published in Cleveland, Ohio, on completion of the serial in book form.

SECTION B. ACID OPEN HEARTH

The acid open-hearth furnace and process differ from the corresponding basic furnace and process in several respects. The outstanding economic differences are two: (1) The acid process requires more costly raw materials; therefore the product is more expensive, for we have seen that the chief cost of the open-hearth process is the cost for raw materials. (2) The quality of the acid steel is, in some respects, superior. Let us discuss these a little more fully:

Acid Raw Materials Are More Costly.—The basic process can remove from the raw materials all elements above iron in the electropotential series, notably silicon, manganese, phosphorus, and carbon. It can also remove some sulphur. The acid process can remove silicon, manganese, and carbon, but the acid slag will not retain phosphorus and keep it away from the metal. Therefore we are limited in our choice of raw materials—steel scrap and pig iron—for the acid process and must pay more for it in consequence.

Acid Steel Is, in Some Respects, Superior to Basic Steel.—The normal product of the basic furnace is below 0.03 per cent of phosphorus and below 0.03 per cent of sulphur, while the normal product of the acid furnace is above these maxima. Therefore, the improved, modern basic steel is liable to be tougher and slightly more ductile than acid steel. But basic steel is liable to be higher in other objectionable impurities, notably dissolved oxygen (probably as iron oxide in solid solution in the steel) and associated defects of oxygenated steel, *viz.*, blowholes and entangled solid oxidized particles, often called *inclusions* and consisting of silicon dioxide, manganese oxide, silicates of iron oxide and manganese oxide, etc. Dissolved oxygen tends, like phosphorus, to make steel brittle. Therefore there is a balance between the effect of lesser phosphorus and greater dissolved oxygen in basic steel, depending on the relative proportions of each. Unfortunately, basic steel is somewhat uncertain as to the proportion of dissolved oxygen it may contain, but the industry is gradually reaching the position where chemical determinations of dissolved oxygen will become a part of all standard procedure and be included in purchase specifications. Basic steel will then rise one step upward in the confidence of engineers, if, and when, its dissolved oxygen is proved to be low. This practice has not yet come, because of the difficulty of oxygen determinations and the length of time required to make them. As to blowholes, they are more prevalent in basic steel, especially when the carbon is below 0.30 per cent, because basic steel contains more oxygen than acid steel when the heat is finished, and therefore there are more gases in liquid solution which come out as gas bubbles when the metal solidifies, especially carbon monoxide gas. Blowholes are most objectionable in steel castings, because the metal is not subjected to mechanical work which may weld them up. Therefore, acid steel finds an important field of usefulness in steel-casting manufacture. Basic steel is predominant in tonnage in the steel-casting field in America, but acid open-hearth steel is very important in tonnage in this industry, whereas it has, with one exception, very little influence on the economics of the markets in rolled and forged products, such as structural steel, machinery steel, and even automobile steel. This exception occurs when steel is to be subject to vibrations; or stresses of a varying character, like alternations of tension and compression, or frequent and/or rapid changes in the amount of the stress. This type of stress is called *dynamic stress*, as distinguished from static stress, and metal subjected to this dynamic stress is liable to failure or breakage through what is called *fatigue*. Steel may be broken in time by a fatigue stress which is only 40 per cent of its ultimate static tensile strength, and it may be broken by a combination of corrosive influences and a fatigue stress when the latter is only 25 per cent of its ultimate strength. Therefore, steel subject to dynamic stresses and/or corrosive atmospheres must be low in inclusions, because inclusions sometimes act as what are called *stress raisers* in fatigue service and cause premature failure. Manufacturers of automobiles and other machinery now often limit the amount of inclusions permitted in acceptable steel, by prescribing a microscopic test to disclose them. Some engineers insist on acid steel for service where dynamic stresses are to be suffered.

These differences in the economic position of the acid process are dependent on the metallurgical features, which will be discussed in turn:

Acid Open-hearth Slag.—The slag in the acid open-hearth process is predominantly acid, containing usually in the neighbourhood of 50 per cent of silicon dioxide, while the sum of the two bases, FeO + MnO, is always a few per cent less than this except shortly after iron ore has been added as an oxidizing flux and before it has been reduced by impurities in the bath. Most of the silica comes from oxidation of silicon in the raw charge, with a little scorification of the acid furnace lining. Therefore, the silicon in the acid pig should be below 1 per cent, because it determines the weight of slag formed. If the pig contains also about 1.75 per cent of manganese, this helps to keep oxygen out of the bath and to reduce the loss of iron in the slag as iron oxide. If the slag is a black color when the metal charge is thoroughly melted, it indicates too much iron oxide in it. A few hundred pounds of lime are then added to it. The exact amount cannot be stated for all cases but is judged by the experience of the melter. Lime will make the slag more fluid, reduce iron oxide from it, and bring it to a light brown or light greenish-yellow color. The slag must be brought to this condition and the metal heated to a fluid state before ore is added to the slag for oxidizing purposes. Ore is then added in such amounts and at such rates as will cause a constant reduction of carbon in the steel, approaching the predetermined tapping analysis. It is obvious that the charge must melt with considerably more carbon in it than is expected at tapping time. In no case may any iron oxide be added to the slag within 1 hr., and preferably within 2 hr., of tapping time, because these final hours should see the carbon in the steel continually reducing the oxide in the slag to the point where both are low in oxide. Of course, the furnace gases inevitably oxide the slag continuously, but a good boil in the metal should keep metal and slag in equilibrium.

"Conditioning" the Bath.—As the heat approaches the end, the bath must be brought from a state of violent boiling to a condition of being flat and quiet, with only a few bubbles of carbon monoxide gas breaking through at intervals. The success of the acid process—and the quality of the steel—depends on the uniformity with which the "condition" is achieved. Its appearance will differ slightly with baths of varying analysis but should be uniform with baths of the same carbon content. The proper condition is also indicated when silicon begins to be reduced from the slag into the metal. This increase of silicon in the steel is, in itself, an indication that the metal is very low in iron oxide.

Low Oxygen in Final Slag.—The impurities in the bath are oxidized by the "available" oxygen in the slag. The mechanism by which this is accomplished is doubtless a migration of iron oxide from slag to bath. But all the iron oxide in the slag is not free to leave it. Herty has shown that the mineral fayalite, $2FeO.SiO_2$, exists in solution in the slag, and that the iron oxide in this fayalite is not free to go to the metal. This is one of the important reasons why a slag in the acid furnace is not so oxidizing as one in the basic furnace, because much more of the iron oxide is held in fayalite. An increase in temperature tends to decompose fayalite and set free its iron oxide, and therefore an increase of temperature must be avoided at the end of both acid and basic heats. An oxidizing slag is dark in color, while a whitish slag contains little available iron oxide. To finish with a light-colored slag and to finish with slag and metal in chemical equilibrium means to finish with a steel bath relatively low in dissolved oxygen, which is, of course, the principal claim for superiority of acid over basic open-hearth steel.

Recarburizing an Acid Bath.—Test samples taken from the bath are broken and examined by the melter to estimate the carbon in the steel. At intervals, especially when the desired analysis is approached, samples are sent to the chemical laboratory for analysis. When this is right, ferrosilicon is charged into the furnace. The silicon in this alloy reduces some of the iron oxide dissolved in the steel and also stops any further oxidation of carbon. It is at this point that the acid furnace shows another point of advantage over the basic, in respect to quality of the product, because recarburizing with silicon before manganese has these advantages: Silicon does not reduce iron oxide as fully as does manganese, but the silicon dioxide formed tends to flux the iron oxide in the bath, and the two together form larger particles than either one alone, and the larger the particle, the easier it will rise from the steel. Furthermore, iron silicate remains melted longer than does silicon dioxide, and this is another reason why particles agglomerate and rise better. After the ferrosilicon has been added, the bath is allowed to remain quiet for a time, and then ferromanganese is added. Manganese oxide does not flux iron oxide, but silicon has already partially freed the bath from iron oxide, so there are not so many manganese oxide particles formed. All recarburizing is done in the furnace in acid practice, because the temperature is higher there, and because this gives less distance through which the oxides have to rise in order to clarify the steel before it becomes solid. It is customary to tap an acid heat within 10 to 20 min. after adding the ferromanganese, in order to avoid the "secondary reaction" already mentioned in connection with basic practice, which adds "inclusions" to the liquid steel.

Holding Metal in Ladle.—There is not so much danger in superheating acid steel before tapping as there is in the case of basic steel, because "rephosphorization" cannot occur. So sometimes acid steel is tapped very hot and allowed to stand for 20 to 45 min. in the ladle before teeming, for the purpose of allowing inclusions to rise.

Loss.—The loss in the acid process will not be so large as in the basic, because the pig iron and scrap charged are not so impure, and because the amount of slag made and the amount of iron oxidized and retained by the slag are not so large. The loss will vary on an average from 3 to 5 per cent, so that the final metal will weigh 95 to 97 per cent of the weight of the charge. The analysis of this difference is shown in Table V-V.

Table V-V.—Analysis of Acid-furnace Charge
(30 per cent pig; 70 per cent scrap)

Charge	Pig iron, per cent	Scrap, per cent	Average, per cent	Loss, per cent
Carbon	3.75	0.25	1.30	1.30
Silicon	0.90	0.10	0.34	0.34
Manganese	0.60	0.40	0 46	0.46
Phosphorus	0.035	0.045	0.04	0 00
Sulphur	0.03	0.03	0.03	0.00
8 per cent slag at 15 per cent iron	.....		...	1.20
Net loss	.....	. .	.	3.30

Furnace Lining.—The acid furnace has, of course, a silica lining, or it would be fluxed and destroyed by the slag. Silica is stronger at high temperatures, less costly, easier to maintain, and more durable than magnesite. The lining is made according to the same procedure as already described for the basic furnace, with corresponding changes in materials used. Clay bricks come next the steel hearth pan, then silica bricks, and then almost pure silica sand with which is mixed a very small amount of lime to make it frit together into a strong mass at the heat of the furnace. The sand is "set" in thin layers, as already described, and the finished hearth is "washed" with an acid slag to give it a surface glaze. A piece of hearth material, cut out, or dynamited out, of a hearth, will ring like a bell when suspended and struck with a hammer.

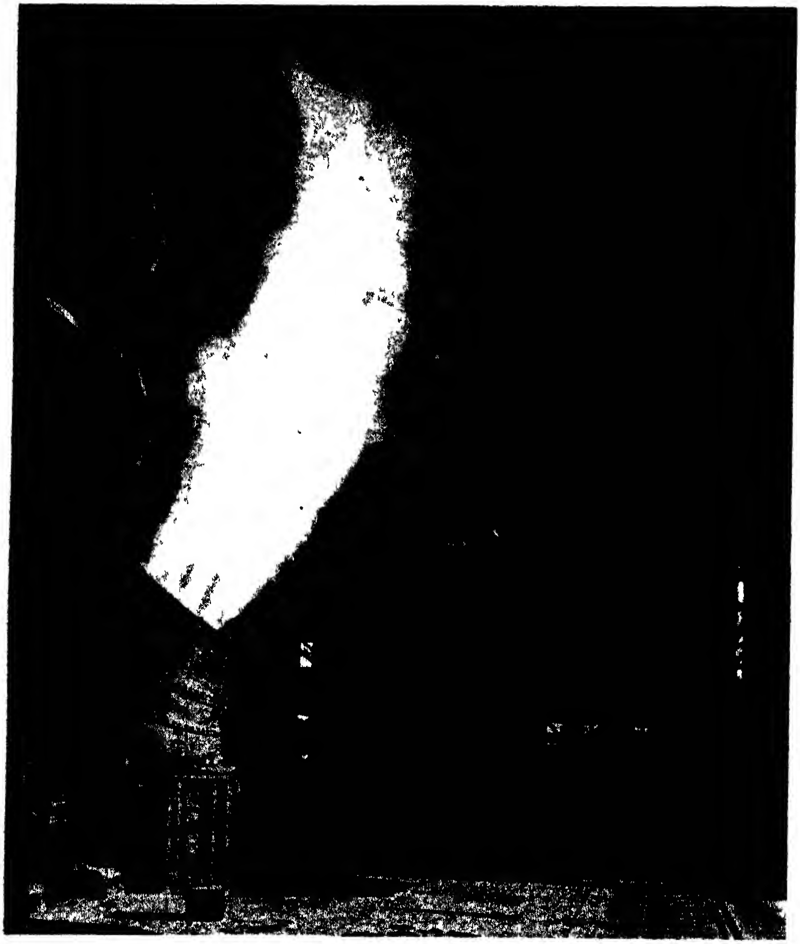


FIG. VI-1.—A Bessemer blow. (*Courtesy of Lackawanna Steel Co.*)

CHAPTER VI

THE BESSEMER PROCESS

Pig Iron Used.—Pig iron for the acid Bessemer process has, preferably, about 1.5 per cent of silicon.[1] Silicon is the chief slag producer and also the chief heat producer.

$$Si + O_2 = SiO_2 \text{ (generates 201,000 gram cal.).}$$

To keep it at a low figure limits the amount of slag made, which limits one of the sources of iron loss. Furthermore, the lower the silicon, the shorter will be the time of blow; but it is usually risky to allow it to fall below 1 per cent, or the blow will be cold. and it is only by very rapid working and permitting the least possible delay between operations, so that the converter and ladles are kept very hot, that we are able to get along with as little as this. The manganese is about 0.7 per cent. This also furnishes heat.[2]

$$Mn + O = MnO \text{ (generates 87,000 gram cal.).}$$

But it is now an expensive ingredient of pig iron and also has the effect of making very liquid slags, which cause a good deal of slopping or "spitting" from the converter (*i.e.*, ejection of the material by the blast) and also makes the steel ingots dirty and spotted with oxide spots, owing to slag carried over with the steel. Pig iron containing manganese 1.50 per cent and silicon 1.00 to 0.90 per cent gives a very "wet" slag, which follows the metal into the ladle and boils up through it, oxidizing the manganese in the steel.

$$FeO + Mn = MnO + Fe \text{ (generates 22,900 gram cal.).}$$

The phosphorus and sulphur is usually below 0.09 and 0.03 per cent, respectively, in order that the steel may be salable, as neither of these elements is reduced in the acid Bessemer process, but increase by 10 per cent of themselves.

---

[1] "Silica remains in the slag with the heat which it has absorbed during the reaction, CO and CO_2, on the contrary, leave the bath and carry their sensible heat with them. $C + O = CO$ (generates 26,320 gram cal.). $C + O_2 = CO_2$ (generates 94,390 gram cal.). The carbon in the pig iron is about 3.50 per cent. In "Textbook of Metallurgical Problems," by Allison Butts, will be found estimates of heats formed, radiated, and otherwise carried away from the Bessemer converter.

[2] Indeed, formerly, in the Swedish Bessemer practice, the pig iron contained 2 per cent of manganese, and this element was relied upon as the chief source of heat, because silicon was necessarily low in the Swedish charcoal pig iron.

Mixer.—It takes about two blast furnaces to supply one converter with metal, so that a modern plant of two to four converters will be operated in conjunction with a large blast-furnace plant. The product of each of these furnaces, if not too different from the desired analysis, will be poured into a huge reservoir, or "mixer," capable of holding 150 to 1,500 tons, which is then used as a source of supply for the converters.

The mixer serves several very useful purposes:

1. It equalizes the irregularities of pig-iron composition by mixing the product of several furnaces and also brings the composition somewhat under the control of the metallurgist of the Bessemer plant, because he not only can pick and choose from the different furnaces but has a few large cupolas under his dominion in which he can melt iron of any desired analysis to pour into the mixer and help regulate its contents.

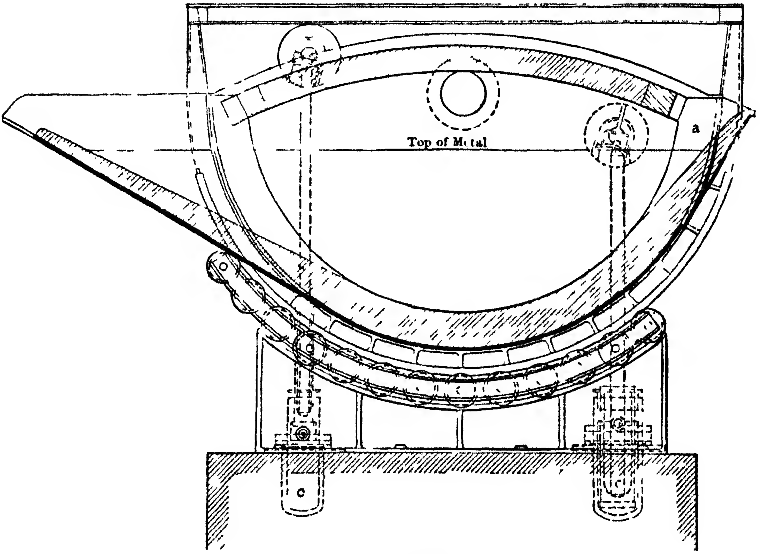


Fig. VI-2 —Mixer.

2. Because of its large size, and the fact that it is continually in receipt of new fresh metal, the mixer can keep its contents molten for an indefinite length of time, whereas a ladle containing 25 tons of pig iron would chill in a few hours. Mixers are supplied with oil blowpipes which can contribute a small amount of heat to the charge, but it is not often necessary to use them. Sometimes they are heated by gas and the regenerative process.

3. The capacity of the mixer is so large that a delay either at the blast furnace or at the steel works will not discommode it greatly, and thus each operation is independent of the other.

4. Pig iron in the mixer suffers a slight loss in sulphur, because manganese sulphide forms and, not being very soluble in iron, slowly rises into the slag.

Industrial Situation.—Only the acid Bessemer process is in use in America, because a sufficient supply of pig iron suitable for the basic Bessemer is not available to establish a competitive basis which alone can guarantee success, and because basic Bessemer steel is the poorest in quality and lowest in price. At one time the process was started but failed through lack of suitable pig iron at a low enough price to make commercial success; a second reason for failure was inability to sell the high-phosphorus slag produced, because American farmers were not familiar with its advantages as a fertilizer, and the necessary educational campaign was not completed in time to save the industry. Unless this slag can be sold as a by-product, the returns are not sufficient for commercial success.

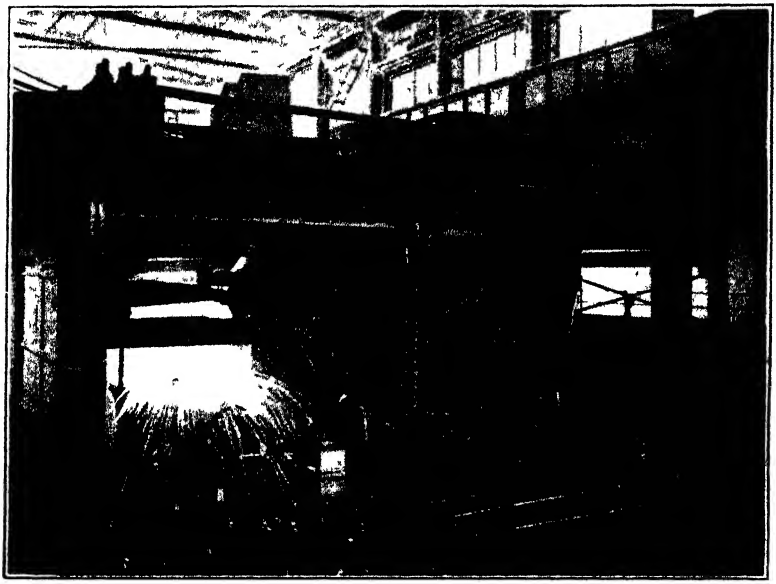


FIG. VI-3.—Pouring pig iron out of 1,300-ton mixer. (*Courtesy of United States Steel Corp.*)

In order to make acid Bessemer steel of satisfactory quality, we must start with a pig iron below 0.09 per cent in phosphorus, and this entails charging into the blast furnace ore mixtures averaging one thousand times as much iron as phosphorus. Such ores have been growing scarcer every year, and consequently the tonnage of Bessemer steel has been decreasing not only in actual amount but even more so in relation to the tonnage of basic open-hearth steel. But this has brought about the use of the duplex process, by which the silicon, manganese, and most of the carbon are blown out the steel in an acid-lined converter, after which the liquid metal is transferred to a basic open-hearth furnace in which its phosphorus is removed. This is, in effect, the commercial equivalent of using liquid steel scrap in a basic open-hearth furnace. The silicon is removed in a furnace in which it will do no harm to the lining; the carbon is removed with greater rapidity; and the product sells as basic open-hearth steel.

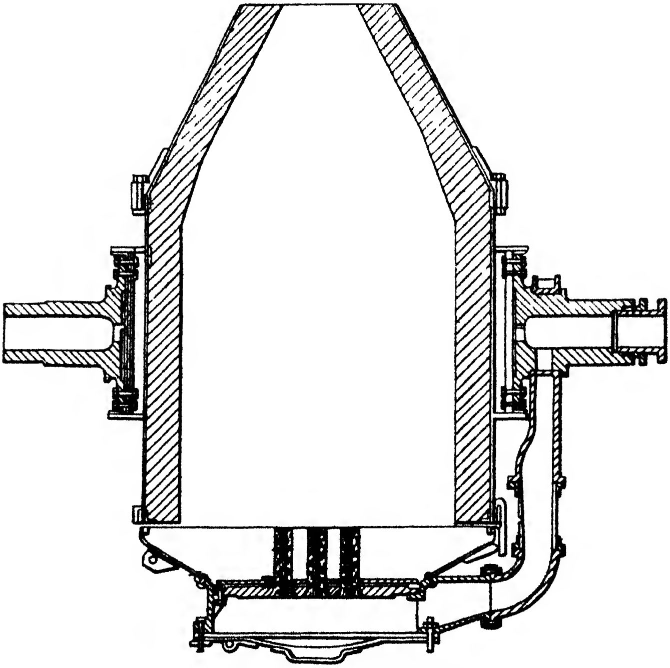


FIG. VI-4.—Section of converter.

Construction of the Converter.—The converter consists of a steel shell, riveted together and supported by two trunnions upon which it can be made to rotate. One of these trunnions is hollow and serves as a windpipe to connect the blast from the blowing engine with the wind box at the bottom of the vessel. On the other trunnion is fastened a pinion, by which the converter can be rotated through an angle of at least 270 deg. The lining of the bottom is pierced with about 250 half-inch holes, which connect the wind box with the inside of the converter and serve for the passage of the blast. The shape of the converter is such that, when it is lying on its side, the metal will not cover any of these tuyère holes (see Fig. VI-6). This is necessary, or the blast could never be turned off without having molten metal run down into the wind box. The advantage of the eccentric shape is that less heat can escape from the nose.

Lining.—The lining is made of highly refractory acid material composed principally of silica. In England a ganister rock is used, or sometimes the lining is rammed up around a pattern and is composed of siliceous material held together by a small amount of fire clay. In America it consists usually of blocks of ganister or of mica schist (a siliceous rock consisting of pseudostrata, or laminae, formed by tiny plates of mica) laid with a thin layer of refractory fire clay between, and in such a manner that the edges of the laminae will be exposed to the wear to which it is subjected.[1] After a new lining is put in, it is carefully dried, and every Sunday afternoon, before the converter begins its operation for the week, a fire is kept in it for several hours in order to heat the lining to a red heat. Between the heats the lining is repaired, if necessary, with balls of siliceous material and clay. On Sundays, and with an occasional lay-off for which one extra shell is provided, more extensive repairs are made, and in this way the lining is made to last several months—say 10,000 to 20,000 heats. The converter slags are always high in silica and corrode the lining only slightly. If, however, any uncombined oxide of iron comes in contact with it, it is attacked very rapidly. For this reason the mouths of the tuyères are rapidly eaten away, and this part of the converter lasts only about 25 to 30 blows (see Fig. VI-5). The bottom is therefore fastened to the body with links and keys, so that it may be readily detached and replaced by a new one. Indeed, in some works bottoms are changed with

---

[1] If we represent the blocks of mica schist by big books and lay these books in a horizontal position with the edges of the leaves exposed, they will illustrate the method employed.

an average delay to the operation of only about 20 min. for each replacement.

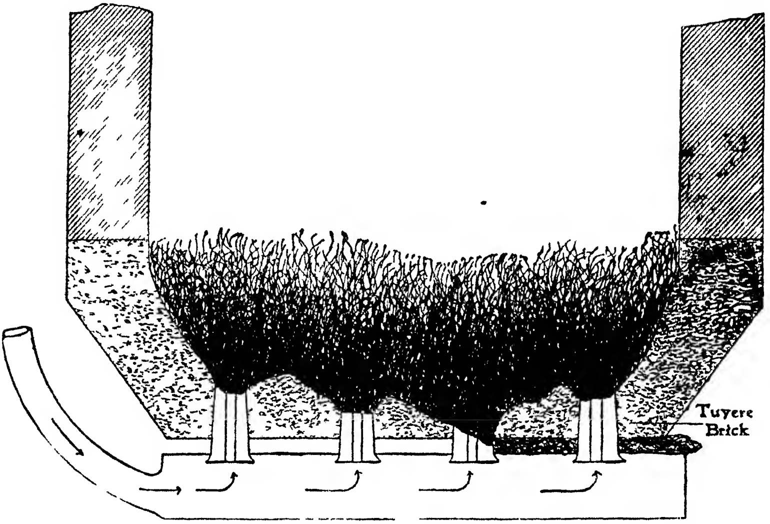


Fig. VI-5.—Corrosion of the bottom lining of Bessemer converter.

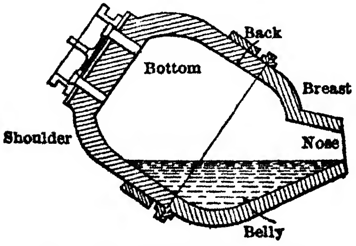


Fig. VI-6.—Converter parts.

Bottoms.—The lining of the bottom is made by placing the tuyère bricks (see Fig. VI-5) in position and then filling in around them with refractory material consisting of damp siliceous material held together with clay and containing usually some coke breeze, which seems to lessen the chemical activity of the corrosion. The details of lining vary so greatly that no general rules can be given. The number of tuyères is from 18 to 30, the number of holes in each from 12 to 18, and the size of the holes $\frac{3}{8}$ in. (England) or $\frac{3}{8}$ to $\frac{5}{8}$ in. (America). The correct lining is of the greatest importance and is the most influential factor in determining the life of the bottom, which furthermore depends upon the care in drying, the temperature of blowing, the pressure of blast, and the composition of pig iron. A bottom should dry 36 hr. or more. Its life is shortened by (1) hotter blows, (2) longer blows, (3) lower blast pressure, because the blast holds the metal away from the mouths of the tuyères, and (4) more manganese in the pig iron, because a wet slag is more corrosive. Between heats, when the vessel is on its side receiving the recarburizer, pouring into a ladle, or receiving a new charge, the lining of the bottom can be repaired. For instance, if one tuyère eats away faster than its fellows, the excessive corrosion can be prevented by stopping it up with mud, because, if no air passes through the holes, no oxide of iron is formed at their mouths. Or a worn tuyère brick may be replaced by a new one, etc. These repairs are chiefly made through the wind box, the back plate of which is removable.

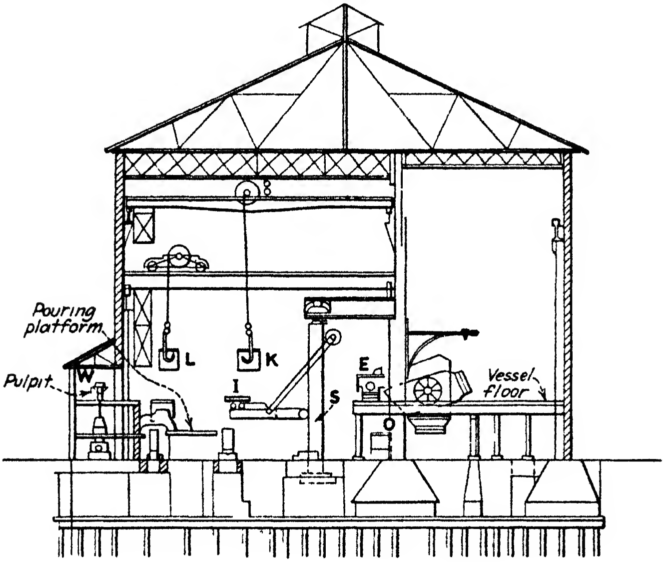


FIG. VI-7 —Section through converter house.

When a bottom is worn out, it is taken away and a new one brought on a car and placed under the converter, which is in the vertical position. Around the top is piled a ring of thick wet mud, and, as the bottom is forced up against the body by hydraulic pressure, the mud is squeezed into a firm joint. Lack of space prevents an account of some of the interesting expedients that are resorted to to stop an occasional leak in this joint without delaying the first heat, which must be avoided if possible, as the first heat, on a new bottom is already too liable to be a cold one.

Bessemer Plant and Its Arrangement (see Figs. VI-7 and VI-8).—The plant consists of a mixer *A*, already mentioned, some cupolas in which pig iron is melted for the purpose of adding it to the mixer to counteract any irregularities in chemical composition which may exist there because the blast furnaces are temporarily "off grade" in their product, and means for making this transfer of metal. There are from two to four Bessemer converters, or vessels, as they are sometimes called. Facing these is the "pulpit" on which the "blower" stands to direct and control operations, especially the "blow" itself. There are also two or more cupolas *F* in which alloys can be melted for recarburizing, together with tracks, ladles *H*, etc., for bringing these melted alloys to the vessels and charging it in them *E*. In the converter house itself are tracks and arrangements for ingot-mold cars, teeming platform, and teeming facilities for putting the liquid steel into molds. Adjacent to the converter is the blower house from which air blast is obtained.

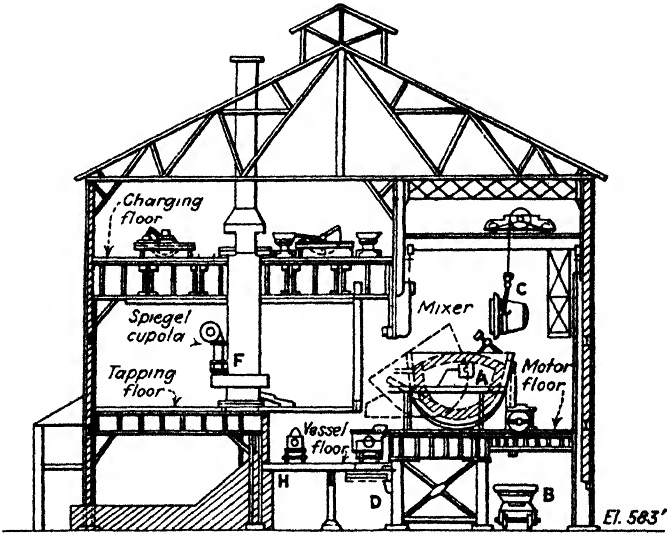


FIG. VI-8 —Section through cupola and mixer house.

Uniformity in Operation.—Uniformity in operation is now the keynote of the improved acid Bessemer process. This has been described in detail by Richard S. McCaffery.[1] Uniformity includes uniformity in analysis and temperature of pig iron, in temperature of blow, in volume and/or pressure of blast, and in

---

[1] The Bessemer Process and Its Product, "Yearbook of the American Iron and Steel Institute," New York, 1931.

times of operation, of waiting for recarburizer, and other conditions affecting the temperature and/or quality of the product. Since slight variations are inevitable, the blower now has improved means at his command for controlling each of the five first-mentioned factors. Among the most important of these are means for exactly controlling the blast to each individual converter and knowing by means of instruments situated on the pulpit what are the pressure and volume of blast and the speed of the blowing engines. Recent installations include the use of a turboblower, because of the possibility of exactly controlling this.

Fig. VI-9.—Pouring metal into the converter. (*a*) Converter, (*b*) cupola, (*c*) ladle, (*d*) runner

Conduct of Operation.—With the converter lying on its side, somewhat as in Fig. VI-6, the liquid metal is poured into it. The blast is then turned on and the converter turned to an upright position, and then the blower orders a cold-metal addition to be made to the vessel. If this is cold steel scrap, it is merely for reducing the temperature of the bath to exactly the desired point. If it is pig iron, it will lower the temperature and also increase the metalloids to be oxidized. If it is ferrosilicon, it will increase especially the silicon, the chief source of heat in the process. The amount of this cold-metal addition is determined by the temperature and silicon content of the mixer metal. By this addition the factors which chiefly affect the temperature of the blow are brought always to the same point, irrespective of irregularities in the raw material. For the next 4 to 10 min. of blowing, the silicon and manganese are oxidized, forming a slag of silica with oxides of iron and manganese. The iron and its impurities rapidly absorb most of the oxygen in the air blast, but iron is deoxidized in large part by the other elements.

$$\begin{aligned} FeO + Mn &= Fe + MnO. \\ FeO + C &= Fe + CO. \\ 2FeO + Si &= 2Fe + SiO_2. \end{aligned}$$

In the first part of the blow, when the temperature is relatively low, silicon and manganese will also take oxygen away from any carbon which has been oxidized.

$$\begin{aligned} 2CO + Si &= SiO_2 + 2C. \\ CO_2 + Si &= SiO_2 + C. \\ CO + Mn &= MnO + C. \end{aligned}$$

At a later period, this condition is reversed. The weight of molten material in the converter increases during the slag-making period. Therefore, if the blast pressure remains constant, its volume will drop, as indicated in Fig. VI-11. On the other hand, if the volume is maintained constant by the blower, the pressure will rise as indicated in Fig. VI-12. The pressure must always be above 15 to 20 lb. per square inch, because then the blast will break into a fine spray of bubbles when it strikes the metal.

Critical Temperature.—As the temperature rises, chiefly owing to the oxidation of silicon, the chemical affinity of carbon for oxygen increases relatively more than that of the other impurities, and the reaction $2CO + Si = SiO_2 + 2C$ ceases and then reverses:

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

What is the exact temperature at which this reversal occurs has never been determined, but we may estimate it as being somewhere between 1450 and 1550°C. (2642 to 2822°F.); and unless the silicon is all oxidized before this temperature is reached, we shall have "residual silicon" in the steel. In English Bessemer practice, where silicon is often above 2 per cent of the pig iron, this is not rare, because the high silicon takes longer to go and also increases the temperature:

$$Si + O_2 = SiO_2 \text{ (generates 201,000 cal.)}.$$

There is also a critical temperature for manganese oxidation, above which its oxidation by iron oxide is reversed and residual manganese is left in the steel; but this happens only when the manganese in the pig iron is very high. No warning is given that the temperature is approaching these critical points, because no flame—nothing but sparks—comes from the mouth of the converter until carbon begins to burn, and therefore no indication is given to the operator of the degree of heat.

Second Period.—The second period begins when the carbon commences to burn, which happens in America only after the silicon and manganese have been almost eliminated. During this period the reactions consist principally of the oxidation of carbon, although a little silicon passes off at the same time. It is interesting to note that the phosphorus and sulphur in the metal are not eliminated, because the acid slag will not dissolve them even if they become oxidized. For this reason the percentage of these impurities increases slightly during the blow, because their actual weight remains the same, while the weight of the bath decreases. When the carbon begins to burn, the same volume of blast will need less pressure passing through the vessel, and conversely, as indicated in Figs. VI-11 and VI-12. There is a tendency for a large number of pellets of slag, and even metal, to be thrown out of the mouth of the converter during this period. This is known as *spitting*. If, however, the operator maintains a constant volume, with consequently decreasing pressure in this later period, spitting may be wholly or chiefly eliminated.

The second period lasts another 4 to 6 min. During this period there is a considerable flame issuing from the mouth of the converter resulting from the combustion of carbon monoxide gas as it meets the outer air. Flames at different stages in this period are shown in Fig. VI-10.

Uses of Bessemer Steel.—McCaffery[1] says that the largest uses of Bessemer steel in America are for skelp for welded tubes, sheet steel and tin plate, screw stock, wire, hoop, and automotive forging stock. Most of these uses call for low-carbon steel with not very high requirements for strength, toughness, and ductility. This is the type of steel which the Bessemer process can produce most effectively in competition with the basic open hearth. Some typical analyses of these types are given in Table VI-I.

---

[1] *Op. cit.*

Finishing the Heat.—When the carbon has been reduced to about 0.03 per cent, the flame drops and the operator knows that the blow is ended. He instantly turns the converter down and then cuts off the blast. The metal is next recarburized right in the vessel by the addition of alloys containing silicon, manganese, and carbon. A few minutes may be allowed for the recarburizer to act, and the charge is then poured into a ladle and afterwards teemed into molds to form ingots. All of these operations are similar in principle to those already described in connection with the basic open-hearth process. In making dead-soft steel for wire, material to be welded, etc., we add ferromanganese as high in manganese as possible. This material will contain about 7 per cent of carbon, 80 per cent of manganese, and 13 per cent of iron. It is only necessary to add about 500 lb. to a 15-ton bath, and therefore it will dissolve without being melted, although it is customary to heat it to a red heat in order to lessen the chilling of the metal. This dead-soft material will then have the requisite amount of manganese but will be low in carbon and frequently less than 0.01 per cent in silicon. But, if we are making steel of 0.50 to 0.80 per cent carbon, such as rails, we add an alloy with less manganese in proportion to its carbon, such as spiegeleisen, for example. This requires a

TABLE VI-I.—ANALYSES OF VARIOUS BESSEMER STEEL PRODUCTS
Soft Bessemer Steel Grades

Product	C	Mn	P	S
Skelp	0.06 to 0.08	0.35 to 0.45	0.090	0.045
Soft wire	0.06	0.30 max.	0.10 max.	0.05 max.
Medium wire	0.07 to 0 10	0.30 to 0.45	0.110 max.	0.08 max.
Hard wire	0.12 to 0.16	0.80 to 0.90	0.110 max.	0.08 max.
Sheet and tin bar	0.08	0.40	0.100	0.040
Screw stock				
Ordinary	0.08 to 0.12	0.70 to 0.90	0.08 to 0.12	0.10 min.
Screw stock:				
Special grades:				
High carbon	0.25 to 0.35	0.70 to 1.00	0.115	0.075 min.
Special	0.08 to 0.16	0.75 to 1.10	0.08 to 0.12	0.20 to 0.30
A. S. T. M	0.08 to 0.16	0.60 to 0.90	0.09 to 0.13	0.10 to 0.18
G. M. C	0.08 to 0.16	0.70 to 0.90	0.09 to 0.13	0.10 to 0.15
S. A. E. 1112	0.08 to 0.16	0.60 to 0.80	0.09 to 0.13	0.075 to 0.15
S. A. E. 1120	0.15 to 0.25	0.60 to 0.90	Max. 0.06	0.075 to 0.15

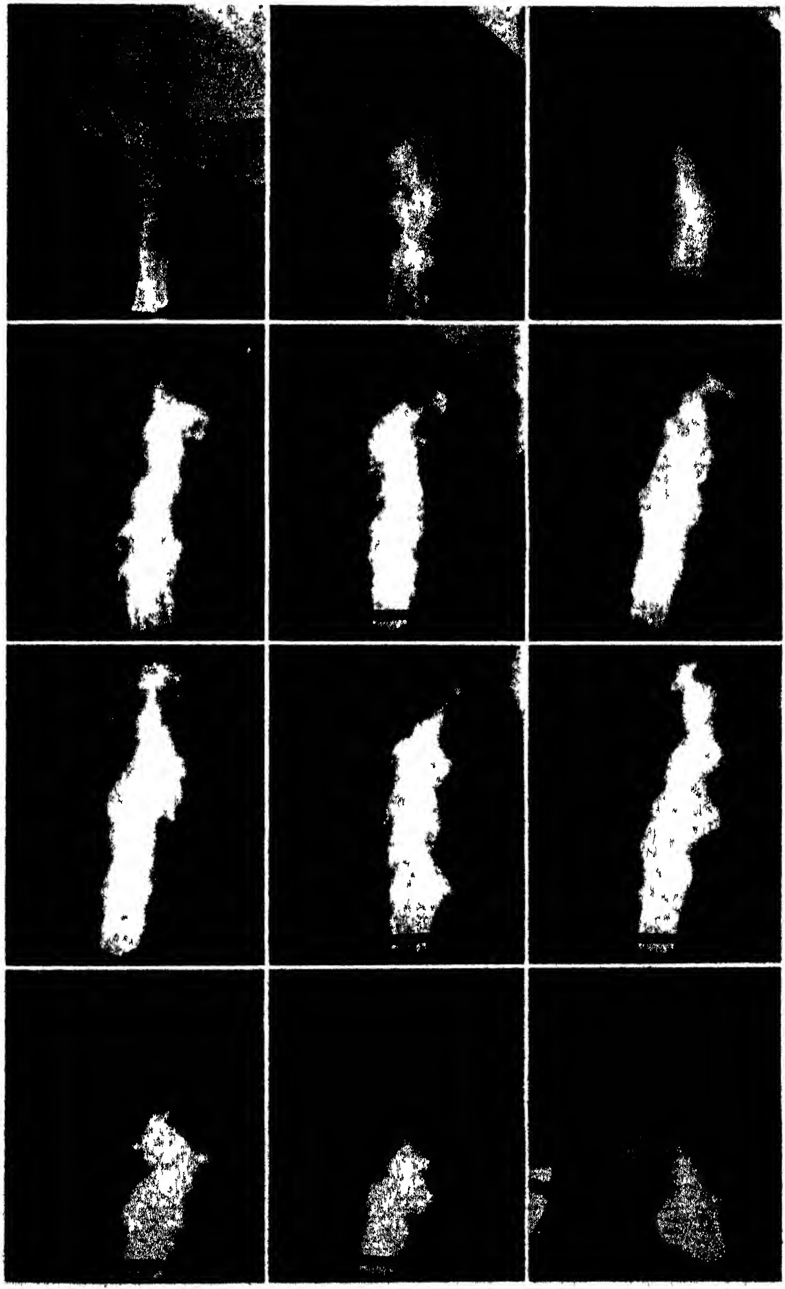


Fig. VI-10.—Flames during the second period of an acid Bessemer blow.

relatively large weight of spiegeleisen in order to bring the manganese to the desired point, and this necessitates melting the spiegeleisen so that it will not chill the bath and so that it will react readily. It is for this purpose that spiegel cupolas are provided.

It might be thought that a more economical method could be found than that of burning up all of the carbon in the pig iron and then adding the desired amount, and in fact such a method was employed in Sweden, where the carbon was burned down to the desired point, as estimated by the appearance of the sparks issuing from the converter, the vessel being then turned down and the charge held until a hammer test confirms this estimate. Such a complicated procedure, however, requires a hotter bath and very slow working, and it is much cheaper to burn the carbon until the drop of the flame and then add the requisite amount.

Slag.—In Table VI-II the lime and magnesia in the slag come from a small amount of blast-furnace slag which finds its way to the converter through the mixer, in spite of efforts made to hold it back at all points when pouring. Because the blast-furnace slag is basic, it has the effect in the converter of making the slags wet and sloppy, and therefore increasing the loss. Although the iron as shot is shown in only one case, this is not because it is absent in the other cases but merely because it was not determined. At all times the slag carries a great many pellets of iron, which should be added to the combined iron, since they represent a loss in the process. It is interesting to note how closely the amount of iron in the slag, after the spiegel addition, approximates 15 per cent,[1] and there seems to be a chemical balance which fixes this amount as a condition of equilibrium. When the silicon in the pig iron is higher, and therefore the amount of slag made is larger, there is a slightly lower percentage of iron oxide in it. The practice of "side blowing for heat," described below, has the effect of increasing the amount of iron oxide in the slag by increasing the oxidizing influences in the interior of the converter. The rise in manganous oxide in the slag during recarburizing is, of course, due to the formation of manganese oxide by the action of the manganese on the oxygen of the bath, while the iron oxide in the slag is reduced at the same time by the action of manganese and carbon.

---

[1] Not including pellets, which average 6 to 8 per cent more.

TABLE VI-II.—REMOVAL OF IMPURITIES IN THE BESSEMER CONVERTER, WITH ACCOMPANYING SLAG ANALYSES

Time after commencement of blow		Removal of metalloids per cent					Authority	Analysis of corresponding slags per cent										
		C	Si	Mn	P	S		SiO_2	Al_2O_3	FeO	Fe_2O_3	Iron as shots	MnO	CaO	MgO	P	S	Alkalies
Min	Sec																	
Pig iron		2.98	0.94	1.43	0.100	0.06												
2	0	2.94	0.63	0.09	0.104	0.06	Howe America	42.40	5.63	40.29	4.36		6.54	1.22	0.36	0.008	0.009	
3	20	2.71	0.33	0.04	0.106	0.06		50.26	5.13	34.24	0.96		7.90	0.91	0.34	0.008	0.009	
6	3	1.72	0.03	0.03	0.106	0.06		62.54	4.06	21.26	1.93		8.79	0.88	0.34	0.010	0.014	
8	8	0.53	0.03	0.01	0.107	0.06		63.56	3.01	21.39	2.63		8.88	0.90	0.36	0.014	0.008	
9	10	0.04	0.02	0.01	0.108	0.06												
Steel																		
9	20	0.45	0.038	1.15	0.109	0.059		62.20	0.276	17.44	2.90		13.72	0.87	0.29	0.010	0.011	
									Al_2O_3 & P_2O_5									
Pig iron		3.55	2.39	0.49	0.09													
8	0	3.21	1.08	0.15			King America	62.65	7.98	1.93		10.52	15.78	0.65	0.52			
15	0	1.25	0.11	0.13	0.09			73.24	4.51	0.00		8.72	11.83	1.11	0.64			
17	0	0.207	0.06	0.13	0.08			75.63	5.19	0.00		7.70	10.92	0.96	0.38			
18	0	0.034	0.04	0.10				61.30	4.24	13.47		9.12	10.82	0.75	0.29			
Steel		0.370	0.06	1.17	0.09			64.15	5.71	13.95		2.39	12.81	0.75	0.24			
									Al_2O_3									
Pig iron		3.93	1.96	3.46	0.040	0.018	Bell England	40.95	8.70	0.60			2.18	30.25	16.31	0.01	0.34	0.32
After slagging		2.465	0.443	1.645	0.040	Trace		46.78	4.65	6.78			37.00	2.98	1.53	0.03	0.04	Trace
End of boil		0.949	0.112	0.429	0.045	Trace		51.75	2.98	5.50			37.90	1.76	0.45	0.02	Trace	Trace
End of blow		0.087	0.028	0.113	0.045	Trace		46.75	2.80	16.86			32.23	1.19	0.52	0.01	Trace	Trace
Pig iron		4.00	1.02	1.83			Bangbro Sweden	50.20	3.86	1.80			5.44	27.22	10.88			
3	0	4.30	0.03	0.22				55.26	2.86	14.20			26.31	0.62	0.22			
4	45	0.90	0.03	0.12				47.20	2.70	18.52			31.01	0.38	0.14			
5	45	0.10	0.03	0.09				40.50	2.24	31.19			25.43	0.32	0.11			

The weight of slag at different periods of the Bessemer process has been calculated by H. H. Campbell from its analyses, with the following average results:

TABLE VI-III.—SLAG WEIGHTS IN BESSEMER PROCESS

Percentage of blow finished	Period	Pounds of slag	Percentage of charge
20	Silicon flame	1,035	4.5
36	Brightening	1,146	5.1
66	Carbon flame	1,255	5.5
89	Full carbon flame	1,385	6.1

The final amount of slag made will probably average about 7.5 to 8 per cent of the weight of the metal produced or, roughly, 7 per cent of the weight of the pig iron charged.

History of Removal of Elements.—The progress in purification during some Bessemer operations is shown in Table VI-II. It will be noted that the manganese goes most rapidly; this is partly because it has a slag into which it can readily dissolve. Usually the carbon has not been reduced much until all the silicon is oxidized. Phosphorus and sulphur are not removed; indeed, they both increase slightly in percentage, because their weight remains the same whereas the weight of the steel in which they are contained decreases by oxidation during the blow and by loss of carbon, etc.

Control during the Blow.—For many years it has been customary for the steel blower to have means of reducing or increasing the temperature of the Bessemer blow at will. At first the means of reduction was the addition of cold steel scrap to the charge. Later, means were provided for introducing a jet of steam into the blast, which cooled the bath very rapidly by the heat absorbed in decomposing water. On the other hand, if the temperature required raising, a limited means of doing this was by turning the converter partly over on its trunnions, whereby some of the tuyères blew air into the bath near its surface and some actually above it. This is called "side blowing for heat." In this way a certain amount of carbon dioxide was formed instead of carbon monoxide. We have seen that recent Bessemer practice provides for control over both the analysis and the temperature of the initial pig iron, so that correspondingly little adjustment of temperature is required during the blow. The very important control by the blower of the volume and pressure of blast and the speed of the blowing engine has also been mentioned. The blower turns the blast on and off, rotates the converter when desired, and judges by eye, from the appearance of the flame, the temperature of the bath and the exact point when the carbon has been burned out and the operation should be stopped. He gives orders for bringing in the pig iron, the recarburizer, etc., and is responsible for such a conduct of the different operations that they do not interfere with one another and cause delay of the mill.

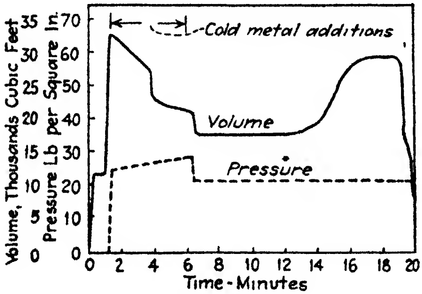


FIG. VI-11.

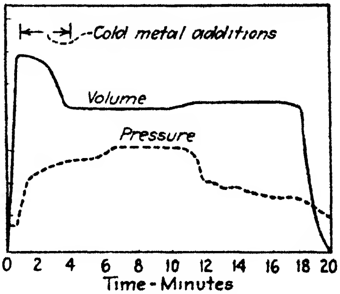


FIG. VI-12.

FIG. VI-11.—Blast records of a Bessemer blow during which the pressure was maintained constant and the volume allowed to fluctuate as it would.

FIG. VI-12.—Blast records of a Bessemer blow during which the volume was maintained almost constant and the pressure allowed to fluctuate as it would. (*From McCaffery, Yearbook, American Iron and Steel Institute*, 1931.)

Gases.—Some gases collected during the course of a Bessemer blow are shown in Table VI-IV. The lesson learned from these analyses is that nitrogen is the chief constituent of the converter-flame gases at all times, but especially before the carbon begins to burn. After this action begins, however, the carbon burns chiefly to carbon monoxide, until the gases leave the vessel, when the carbon monoxide burns with brilliant flame to carbon dioxide. The oxidation of carbon to carbon monoxide generates 29,160 gram cal. per gram atomic weight of carbon, whereas the oxidation to carbon dioxide generates 97,200 gram cal. for the same weight of carbon.

Loss.—The difference in weight between the pig iron charged into the converter and the steel ingots made will be 8 per cent in

Table VI-IV.—Analyses of Bottom-blown Converter Gases

Time after starting blow, minutes	CO, per cent	CO_2, per cent	O, per cent	H, per cent	N, per cent	Reference
2	......	10.71	0.92	.....	88.37	Sir Lothian Bell
4	3.95	8.59	....	0.88	86.58	
6	4.52	8.20	....	2.00	85.28	
10	19.59	3.58	....	2.00	74.83	
12	29.30	2.30	.....	2.16	66.24	
14	31.11	1.34	.....	2.00	65.55	
18	End of blow					
3 to 5	......	9.127	4.762	.....	86.111	
9 to 10	17.555	5.998	1.699	0.908	73.840	
21 to 23	19.322	4.856	0.967	1.120	73.735	
26 to 27	14.311	1.853	0.550	1.699	81.587	
2 to 3	......	6.608	7.256	...	86.137	
8 to 10	15.579	5.613	1.296	1.112	76.400	
12 to 15	25.580	4.144	0.980	1.040	68.256	
17 to 19	25.606	2.995	1.318	1.120	68.961	

good practice, although running above that (say to 10 per cent) in some mills. This is distributed approximately as follows:

	Percentage
Carbon burned	3.5
Silicon burned	1.0
Manganese burned	0.5
7 per cent slag at 15 per cent iron	1.0
7 per cent slag at 7 per cent iron pellets	0.5
Volatilized and ejected	1.5
	8.0

The Basic Bessemer Process

While the basic Bessemer process is not in use in America, it is of importance in Germany and France and is used in England. The reason it failed twice in an American installation was because, first, pig iron with 2 to 2.5 per cent of phosphorus was not available at a competitive price in America and, second, the farmers had not been educated to use the basic slag as a fertilizer. A market for this slag is essential for the steel to compete in price. The ores of the minette region in Central Europe and some of those in England make a pig iron especially suitable for the basic Bessemer process, where phosphorus is essential as the principal heat-producing element.

$$2P + 5O = P_2O_5 \text{ (366,900 gram cal.)}$$

The basic Bessemer process has the advantage over the basic open hearth in lower costs for labor, installation of equipment, and fuel. Its disadvantages are greater loss of weight of metallic charge and lower quality of product. The basic Bessemer converters in Germany have capacities up to 45 tons each. The lower quality has been due to more oxygen retained in the metal after blowing large volumes of air through it for 15 min. and lack of control in respect to temperature and composition. The basic converter is lined with calcined dolomite, and about 14 to 20 per cent of lime is added with the charge to form a basic slag.

Basic Bessemer Pig Iron.—Basic Bessemer pig iron contains a maximum of 1 per cent of silicon, and preferably about 0.50 per cent, because this oxidizes to silicon dioxide, which wears the lining of the converter and uses up lime flux. Manganese will be over 2 per cent, and sulphur maximum 0.20 per cent. Sulphur is reduced slightly during the same period of the blow as phosphorus and, therefore, can be higher than in the acid process. The phosphorus must be in the neighborhood of 2 to 2.50 per cent in order to give the necessary temperature.

Chemistry of the Blow.—The first two periods of the blow are very similar to those of the acid Bessemer process except that the silicon goes very rapidly, on account of the basic slag, and the manganese more slowly for the same reason. There is, in fact, residual manganese usually left in the steel until the end of this blow, and this is an advantage because it deters oxygen from dissolving in the metal and also reduces the amount of manganese necessary to add with the recarburizer. We have already pointed out that phosphorus will be oxidized in preference to carbon at relatively low temperatures, and *vice versa.* Indeed, phosphorus will rob carbon of its oxygen when the temperature is low and carbon will rob the phosphate when the temperature is high. However, it has been impracticable to blow cold air through pig iron at a low enough temperature to oxidize phosphorus in preference to carbon and the other elements, and therefore the oxidation of this element must wait until all the silicon, manganese, and carbon have been removed. Phosphorus will oxidize before iron, but it is not far enough above iron in the electropotential series to serve as a great protection. For this reason, there is a good deal of iron oxidized at the same time as the phosphorus.

Slag.—The proportion of basic slag made will naturally be greater than that of acid slag and will usually total about 25 per cent of the weight of the metal. It is important so to control the blow that a slag shall be produced containing 15 per cent or so of phosphoric acid, as this makes it salable as an agricultural fertilizer. The amount of iron in the slag in oxidized form should not be above 10 per cent, although there will be also a small percentage of pellets.

Loss.—The loss of metal will be much higher than in the acid process, averaging perhaps 13 to 17 per cent, a part of which is due to the fact that the pig iron used contains a larger amount of impurities to be oxidized:

	Percentage
Carbon	3.7
Silicon	0.5
Manganese	1.5
Phosphorus	2.5
25 per cent of slag at 9 per cent iron	2.3
Pellets	1.0
Fume and ejected	1.5
	13.0

Comparison of Acid and Basic Bessemer.—The basic Bessemer process finds its chief field in localities where the ores produce a pig iron very high in phosphorus, as, for instance, the minette ores smelted in Germany and elsewhere. The great skill of the Germans enables them to produce by this means a high grade of structural steel by a process which is not intrinsically so well adapted to produce as high quality of steel as any of the others, because of the greater oxidation of the bath, the danger of rephosphorization, and the liabilities to error in the *afterblow*. England too is a user of this process, but it is no longer in use in America because this country does not produce the desired grade of pig iron in sufficiently large quantities. The operating costs are higher than those of the acid Bessemer process for several reasons: (1) The blows are long. (2) The basic lining is more costly than silica and wears out faster. (3) Fluxes must be added to form the slag. (4) The mechanical handling is more complicated, owing to the extra pouring off of slag, etc.

Afterblow.—The final, dephosphorization, period of the basic blow is known as the *afterblow*, because it follows what corresponds roughly to the ordinary blow of the acid process. During this afterblow phosphorus is rapidly eliminated and absorbed by the slag. We have no means of knowing by the appearance of the flame how this chemical reaction proceeds, and therefore the afterblow is continued on the basis of experience, by blowing for a certain number of minutes or else a certain number of revolutions of the blowing engine. Phosphorus goes into the slag in the form of a lean phosphate of lime perhaps having the formula $(CaO)_4P_2O_5$, which corresponds to about 60 per cent of lime and 17 per cent of phosphorus. A variable amount of sulphur is also eliminated during the afterblow and goes into the slag in the form of calcium sulphide. Some also may be volatilized as oxides of sulphur. A fluid slag and the presence of manganese both assist in the removal of sulphur, sometimes to the extent of 75 per cent of that present. The addition of a certain amount of oxide of iron as a flux with the lime aids in producing a fluid slag and also gives a slightly higher yield of steel. In recent years improvement in the control of the operation during afterblow has greatly improved the quality of basic Bessemer steel and it now sells in European markets in competition with other steels for a great many uses, chiefly because it brings a lower price.

Recarburization.—The bath must not be recarburized in the presence of a basic slag because the latter gives up phosphorus by reduction and the metal is "rephosphorized." What the chemical action is that produces this rephosphorization is not clearly known, but it is probable that manganese is an important factor; hence an additional reason for adding as little manganese after the blow as possible, although this cannot be well controlled, as the metal is more oxidized in the basic than in the acid blow and therefore requires a larger addition of manganese to render it free from "red-shortness" and "rottenness." The difficulty is avoided in great part by pouring off all the basic slag possible and then holding more back in the vessel when the metal is poured into a ladle. The recarburization then takes place in the ladle instead of in the vessel. The other chemical reactions of the recarburizing operation are similar to those given under the acid process.

Reference

HERMANN WEDDING: "The Basic Bessemer or Thomas Process," translated by William B Phillips and Ernet Prochaska, New York, 1891

CHAPTER VII

ELECTRIC PROCESSES FOR PRODUCING HIGH TEMPERATURE

The twentieth century saw the advent into the steel industry of furnaces heated by electric current instead of by the combustion of fuel. This type of furnace is now of great importance, especially in the production of steel castings, alloy steels, tool steels, and grades of high-quality carbon steels. It deserves a treatment many times longer than we have space for it in this book, where it is imperative to devote much space to other processes in which a larger number of those who use the book in colleges will probably be interested because of their extensive tonnage productions. The use of electric furnaces has permitted three very important metallurgical advances to be made, *viz.*,

1. Production of high temperatures.
2. Production of red-heat temperatures which can be very accurately and automatically controlled, for tempering steel, etc. This phase of the subject is not discussed here. It will be found in Chap. XIII.
3. Electrolysis, which is, in brief, the separation of a compound into its ions, as, for example, $FeCl_3$ into Fe and Cl_3, whereby the Fe appears at the cathode and the Cl_3 at the anode.

We do not, at present, have much practical use for electrolysis in iron and steel metallurgy, unless we include under this category, nickel plating, chromium plating, electrogalvanizing, etc. A process of producing pure iron by the electrolysis of ferric chloride was used and is still in vogue but is not now of industrial importance. We shall confine this chapter to a discussion of the production of high temperature from electric energy. This high temperature is used in ferrous metallurgy for the two following processes:

1. Melting.
2. Smelting, which is defined as melting with some accompanying chemical change, such as reducing, or else refining.

There are two important reasons why heat from electricity is used in preference to heat from the combustion of fuel for melting and smelting. They are:

1. We can get higher temperatures.
2. We can get furnace atmospheres which will not contaminate the metal—or they may even be vacuums. Fuel cannot be burned to a high temperature without a considerable amount of carbon dioxide, and even free oxygen, being present in the products of combustion. Furthermore, these products of combustion must be in the same chamber with the charge being heated if high temperature in the charge is to be secured. The oxidizing character thus given to the atmosphere in the furnace unavoidably results in oxygen's being transferred to the slag and thence to the metal, or even directly to the metal when it is exposed to the furnace atmosphere.

There is a third reason for the use of electric heat, but it applies in only very exceptional localities on the earth: That is the rare country or district where electricity can be made with exceptional cheapness and where fuels are extraordinarily costly. These places are so few that we shall not confuse the main issues by including this as a general reason for using electricity for heat, although we shall discuss the practice in its appropriate place. Finally, we note that the high temperature is obtained only when electricity is converted into heat by the resistance which some medium offers to the passage of the electric current, and this is exemplified in three different ways:

1. Resistance of a solid.
2. Resistance of a liquid.
3. Resistance of the air, *i.e.*, the so-called electric *arc*.

The resistance of a solid is exemplified when we have some type of ore mixed with coke or charcoal, and an electric current of very high amperage is caused to pass through it. The resistance of the carbonaceous fuel, together with usually some tiny arcs where pieces of the fuel do not make good contact, produces a high temperature which brings about a reaction between the carbon and the ore, which reduces metal. This is illustrated in furnaces where chrome and iron ore is mixed with finely ground anthracite coal and a current passed through. The mass is melted and ferrochrome is produced, which is an alloy of iron, chromium, and carbon and is used for making alloy steels.

Ferrosilicon is made by a similar process in which silicon dioxide and iron ore are mixed with charcoal. Pure silica is reduced by carbon only when a temperature of 1485°C. (2700°F.) is reached, and therefore this reaction only partially prevails in the blast furnace, but much higher temperatures than this can easily be maintained in the electric furnace, and ferrosilicons of 50 per cent or more of silicon are produced. Another illustration of electric heating by the resistance of solid matter is shown in Fig. VII-1, which is a furnace for heating steel for hardening or tempering. Inside the furnace are "heating elements," or "resistors," connected in series and heated red hot by an electric current, but of a material which will not be melted or oxidized at high temperatures. Their temperature can be automatically controlled with accuracy, and they radiate their heat to the steel tools.

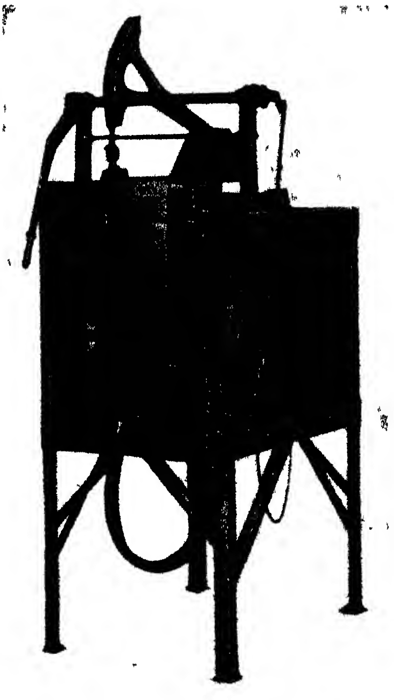


FIG. VII-1.—"Hevi-duty" electric heating furnace using "resistors." (NOTE.—This type of furnace is not discussed here, but in Chap. XIII.)

The resistance of a liquid is used in many melting and refining furnaces for steel, brass, and other alloys, in which the liquid bath itself is heated by the passage of an electric current. The difficulty first met in this type of furnace was the problem of making electrical connections to the liquid bath without either chilling off the bath or melting the connectors. This difficulty has been met by employing the principle of induction and inducing a secondary electrical current in a circular bath without connectors.

The resistance of the air will be considered in the discussion of arc furnaces. A summarized view of the uses of electricity in iron and steel metallurgy is shown in Fig. VII-2. This, of course, does not include the uses of electricity in machinery, such as dynamos, motors, and electromagnets. The subject of production of accurately controlled red-heat temperatures for hardening, tempering, etc., is discussed under the heat treatment of steel; that of chromium plating, etc., is briefly mentioned under corrosion or rusting. Therefore, Chap. VII will treat only of the production from electricity, and processes for utilization, of high temperatures for melting and smelting.

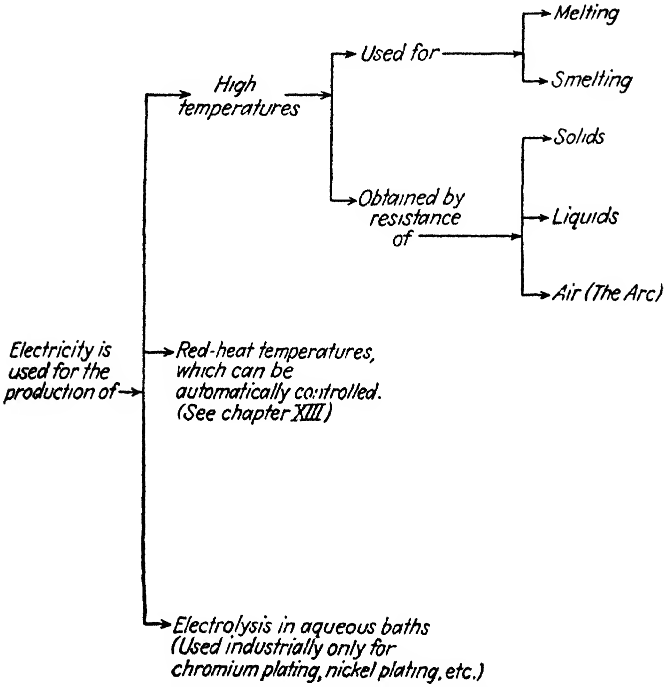


FIG. VII-2.—Summary of the metallurgical uses of electricity in iron and steel processes.

Melting and/or Smelting.—Smelting includes melting. It happens that most electric high-temperature furnaces in the iron and steel industry are used sometimes for melting and sometimes for smelting. In some cases the same furnace may be used for both purposes. For example, electric furnaces in gray cast-iron and malleable cast-iron foundries have melting as their chief purpose. Likewise, furnaces used for melting alloy-steel scrap, where the object frequently is to produce an alloy steel as near as possible the same analysis as the scrap used. But even these furnaces may be (and sometimes are) on occasion used for a slight purification of their contents. Therefore, we shall not try to differentiate between furnaces as to the purpose for which they are used but discuss them according to their method of producing heat, *i.e.*, solid resistors, liquid resistors, and arc furnaces.

HIGH-TEMPERATURE ELECTRIC FURNACES USING SOLID RESISTORS

The commonest furnaces of the solid-resistor type are those used for the production of ferroalloys, and especially ferrosilicon, ferrochrome, ferrovanadium, ferrotungsten, ferrophosphorus, ferrotitanium, and, sometimes, ferromanganese and many other alloys. All of these ferroalloys are used to add to a steel bath, usually at the end of the purification process, either for recarburizing or else to make an alloy steel. The reason for using an electric furnace for reduction to ferroalloys is because a very high temperature must be obtained before carbon will effectively reduce the oxides of most of the metals in question. This is not necessarily so in the case of manganese, chromium, phosphorus, tungsten, and molybdenum. Indeed, ferromanganese and ferrochrome are very often made in blast furnaces, but grades containing more than 80 per cent of manganese or more than 45 per cent of chromium are produced in the electric furnace. The same is true with ferrosilicon containing more than 20 per cent of silicon. Probably the two ferroalloys made most abundantly in the electric furnace are ferrosilicon and ferrochromium.

Ferroalloy Manufacture.—The manufacture of ferroalloys in the electric furnace is kept a close trade secret, and, while there are published accounts of the methods used both in patent applications and in technical literature, it is certain that details of practice at the present time differ from these published accounts. The general principle involves mixing iron ore with an oxidized ore of the metal which is to be produced, and with slightly more than the theoretical amount of carbon to reduce all the metals which are to be present in the alloy. For example,

$$\underset{160}{Fe_2O_3} + \underset{36}{3{:}C} = \underset{112}{2{:}Fe} + 3CO.$$

Thirty-six weights of carbon will be required with 160 weights of pure iron ore to produce 112 weights of iron. Likewise

$$\begin{array}{ccccc} SiO_2 + & 2C & = Si & + 2CO. \\ 59 & 24 & 27 & \end{array}$$

Twenty-four parts of carbon will reduce 59 parts of silica to produce 27 parts of silicon. If the alloy to be produced is to contain 50 per cent of iron and 50 per cent of silica, it will be comparatively simple to calculate the weights of ores and carbon to use, allowing a small percentage of carbon in excess for losses and also to be present as carbon in solution in the liquid alloy. All the constituents of the charge are thoroughly mixed together and shoveled into a furnace which is encased in steel plates on the outside, bound firmly together with steel tie-rods, and lined with some type of refractory. A common form of furnace is a rectangular box with open top (see Fig. VII-3). Electrical contact is sometimes made to the charge in the furnace by an inner lining of graphite blocks, or of powdered carbon put in in the form of a paste and dried. Suspended over the open-furnace top are one or more carbon or graphite rods. These serve as the second pole for electrical connection, or electrodes, so-called. After part of the charge has been shoveled into the furnace, the suspended electrode or electrodes are lowered until they touch the charge, and then more charge is shoveled in until the box is nearly full. In ferroalloy furnaces the reducing agent may be an impure form of carbon such as ground-up anthracite coal or coke or charcoal. Also the charge may differ in that steel scrap or turnings may be used instead of iron ore. These are matters of price. For example, scrap-

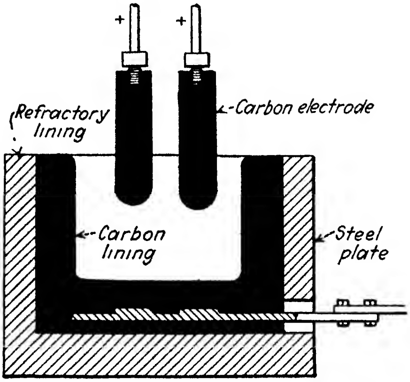


Fig. VII-3.—Type of furnace used for ferroalloy manufacture.

steel borings and turnings usually cost less per unit than iron in hematite and likewise save the cost of carbon for reduction purposes.

After the charge is in the furnace and the suspended electrodes immersed to the proper depth, a current of high amperage is turned on. The coal, coke, or charcoal, as the case may be, conducts the electric current, with the production through resistance of a great deal of heat energy. Electric arcs are also sometimes formed where there is imperfect contact between the solid conducting particles. When a high temperature is reached, carbon begins to attack the oxide; *e.g.*, $SiO_2 + 2C = Si + 2CO$. In many of the ferroalloy furnaces the carbon monoxide gas which is produced in this way also serves as a reducing agent, thereby being oxidized to carbon dioxide. Carbon dioxide gas, however, will attack carbon of the reducing agent, or the carbon electrodes, and be reduced again to carbon monoxide. The heat of the furnace not only produces the reactions cited above but also melts the reduced elements, which dissolve in each other to form a liquid alloy, which in turn dissolves carbon to its saturation point. The higher the temperature, the larger the proportion of carbon dissolved. The amount of carbon also depends upon the alloy. For example, ferrosilicon will be saturated at 1 per cent or less of carbon, whereas ferromanganese will dissolve 6 per cent or more. The temperature is so high that metals may be volatilized in the lower portion, but, by piling up solid charge and keeping the top relatively cool, the losses by volatilization may be greatly reduced.

Electric Pig-iron Manufacturing.—The electric production of pig iron is similar in principle to the production of ferroalloys, but we have much more complete data in print on the methods employed. The iron ore is mixed with charcoal or coke and the current is passed through as previously described. Sometimes an open-topped rectangular furnace is used, like that illustrated in Fig. VII-3. But the best known of the pig-iron electric furnaces is the so-called *electrometall* furnace at Domnarfvet, Sweden, shown in Fig. VII-4. This has a lower box in which the smelting takes place, but this is surmounted by a shaft through which the mixture of ore and reducing agent is fed and through which the waste gases from the furnace percolate for the purpose of preheating the charge before it reaches the smelting zone. Electricity is used for the production of heat in the smelting of pig iron in Sweden and Norway, because the cost of current production is extremely small and because coke and charcoal are there more costly to use for heat-producing purposes. There are only a few places in the world where these unusual conditions of cheap electricity and very costly solid fuel exist in association with iron-ore deposits, and where, therefore, an electric pig-iron smelting industry is carried on. The three localities are northern Scandinavia, northern Italy, and Japan. In the pig-iron furnace the electricity does not go to the lining of the furnace but is carried by three electrodes. One of these is shown in Fig. VII-4, and the two other electrodes are equally spaced around the hearth.

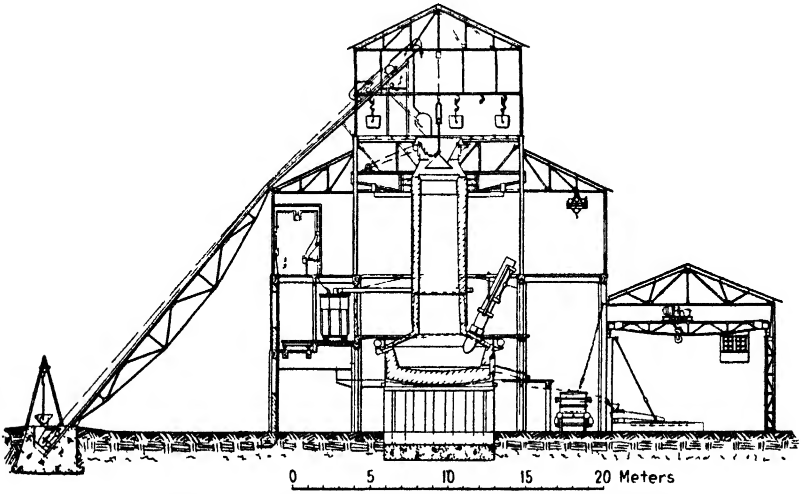
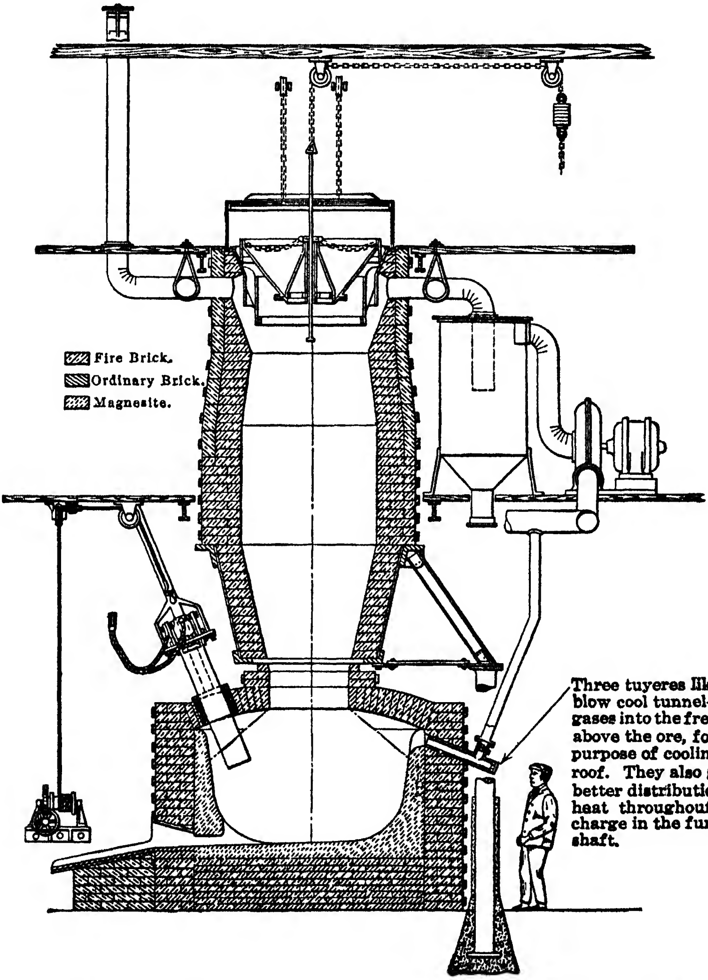


Fig. VII-4.—The Domnarfvet ore-smelting electric furnace.

General Description of the Domnarfvet Process.—The charge, consisting of ore, flux, and enough coke or charcoal for reduction purposes, is introduced at the top of the shaft in the usual way. The angle of rest of the charge permits it to lie in the crucible and shaft in such a way as to leave an annular free space just under the electrodes and tuyères (see Fig. VII-5). Into this space is blown a portion of the top gases, amounting to about 60 to 80 cu. meters per minute. A very important function of these gases is to distribute the heat, which is too much concentrated in the neighborhood of the electrodes, and to preheat the charge in the shaft. The circulation also has the effect of cooling the roof of the lower portion. It is extremely important to get a correct burden, *i.e.*, a correct adjustment especially of the ore and carbon for reduction. This carbon, in the form of charcoal or coke, has the double function of serving as conductor for the



Three tuyeres like this blow cool tunnel-head gases into the free space above the ore, for the purpose of cooling the roof. They also give a better distribution of heat throughout the charge in the furnace shaft.

FIG. VII-5.—An earlier form of Domnarfvet furnace, showing more clearly some of the details.

electric current, and so bringing heat to the ore, as well as effecting the chemical reduction and also furnishing carbon for solution in the metal. The oxygen in the charge is the only means of burning the carbon, and the adjustment must be correct, but this is now accomplished regularly and they no longer have cold iron, which results from either too much or too little carbon in the charge. The calculation depends on (1) the kind of ore used, which is magnetite at Domnarfvet, (2) the analysis of the top gases, which at the same place is as follows: carbon monoxide, 60 to 65 per cent; carbon dioxide, 20 to 25 per cent; hydrogen, 20 to 10 per cent, and (3) the amount of electrode consumed by oxygen of the ore, which is roughly 10 kg. per metric ton of pig produced, equivalent to 10 kg. per 1,650 kg. of 60 per cent magnetite ore. Charcoal has a higher electrical resistance than coke, thus increasing the temperature of the furnace but decreasing the power consumption per ton and the speed of production. Coke has a higher ash content than charcoal and tends to graphitize at arc temperatures and thus to react less readily for reduction purposes. At Domnarfvet they use one-third coke and two-thirds charcoal in the burden.

Charge.—Per metric ton of pig iron produced the charge is as follows: About 1,650 kg. of ore (magnetite containing 60 per cent of iron), 350 kg. of mixed charcoal and coke, 200 kg. of limestone.

Production.—The furnaces produce each about 60 metric tons of iron per day, equivalent to about 22,000 tons per year. When using 75 per cent of sintered ore in the burden, the production was increased to about 70 tons per day, and the current consumption dropped from 2,300 kw.-hr. per ton to 2,150 kw.-hr. The top gases are very small in comparison with the coke blast furnace, on account of containing no nitrogen from air. They amount to about 500 cu. meters per ton of pig, or 200 cu. meters per minute, plus the gas which is used for circulation, although this is almost a plus-and-minus item.

Electrical Data.—Each Domnarfvet furnace has a load of 10,000 kva., made up of two double transformers of 5,000 kva. each, and giving the same number of phases as there are electrodes, which, at present, is eight per furnace. The secondary circuit carries 60 to 100 volts, and the temperature may be controlled within limits by varying the voltage. Each electrode carries 22,000 to 25,000 amp.; the power input is 2,300 to 2,400 kw.-hr. per metric ton produced; the load on the furnace is 6,300 kw., which gives an output of 3.5 metric tons of pig per kilowatt-year.

Furnaces Using Liquid Resistances

In every furnace of this type the liquid resistance is the bath of metal itself, and it is heated by the resistance it offers to the passage of electric current. Pure iron has a resistance to the electric current six to seven times that of pure copper; cold steel has a resistance about eight times copper, and molten steel about one hundred ten times that of copper. There are two serious difficulties in operating such a furnace. The first is making electric connection to a liquid bath, and the second is the circumstance that the cross-sectional area of the bath must be small in order that the current of electricity through a unit area shall be very large. An outstanding advantage of the resistance furnace is that the electric current through the metal produces a stirring and circulation of the bath which are exceedingly important in producing uniformity and rapidity of reaction. The so-called *pinch effect*, discovered by Dr. Carl Hering, keeps the steel in motion, so that the metal heated to a high temperature in the part of the bath where the cross section is small circulates into the other parts and distributes its heat. A second important advantage is that the heat is generated within the metal itself where its effect is wanted. The difficulty of a small cross section of bath is met by generating the heat in channels of small cross section, connected with a larger pool of metal which serves as the principal furnace bath. This is illustrated in Fig. VII-7. The difficulty of making electrical connection with liquid bath is met by the so-called *induction principle*. It should be clearly borne in mind that the induction principle is a method of causing an electric current to travel within a circuit. It is in no sense a method of heating.

Induction Principle.—The simple induction furnace is based upon the principle of the ordinary static transformer, whereby alternating electric current is transformed to lower voltage and higher amperage. It was independently developed by E. A. Colby, of the United States, and F. A. Kjellin, of Sweden, whose American rights have been joined under one management. A sectional elevation of the furnace is shown in Fig. VII-6, in which *CCCC* is the core of an electromagnet, around one leg of which a coil of wire *AA* passes. When an alternating current goes through the coil *AA*, it sets up an alternating magnetic field in the core *CCCC* and this in turn sets up a secondary current in the circle *BB* parallel to the coil *AA*. In other words, an alternating current passing through the coil *AA* induces an alternating current in the coil *BB* without there being any metallic connection between the two. This is a well-recognized phenomenon in electrical engineering and requires no further comment here. In the furnace operation the circle *BB* is a hollow ring in the brickwork into which melted metal is poured.

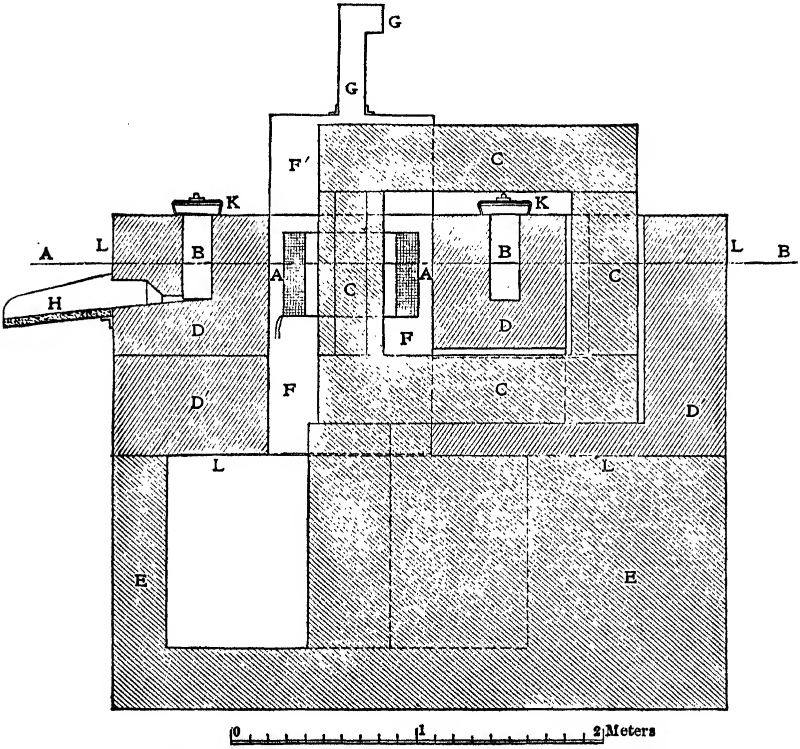


Fig. VII-6.—Vertical section of Kjellin induction furnace.

The resistance offered by this melted metal to the passage of the induced current generates heat which will maintain the temperature or raise it to any desired point. The slot *BB* is really an annular crucible into which pig iron, steel scrap, iron ore, and flux may be charged as if it were an open-hearth furnace, and the operation of steel making is practically the same in principle except that electric heat is employed instead of regenerated gas and air. We may charge solid metal if desired, but, in such a case, it is well to leave a shallow circle of metal in the bottom of the slot *BB* after each operation is ended, to serve to carry the induced current during the beginning of the next operation, until the solid charge is melted.

Roechling-Rodenhauser Furnace.—The combination induction furnace is shown in Fig. VII-7. This is in effect a combination of three simple induction furnaces, the coils of the metallic baths joining in a central pool. By means of this pool, a more effective refining may be employed, for the pool serves the purpose of a bath upon which slags may be charged, etc. It has also several steel terminal plates imbedded in the lining, which are connected to a few heavy turns of copper placed outside the primary coils, which collect and feed to the terminal plates the induced current in these turns, thus suppressing magnetic leakage.

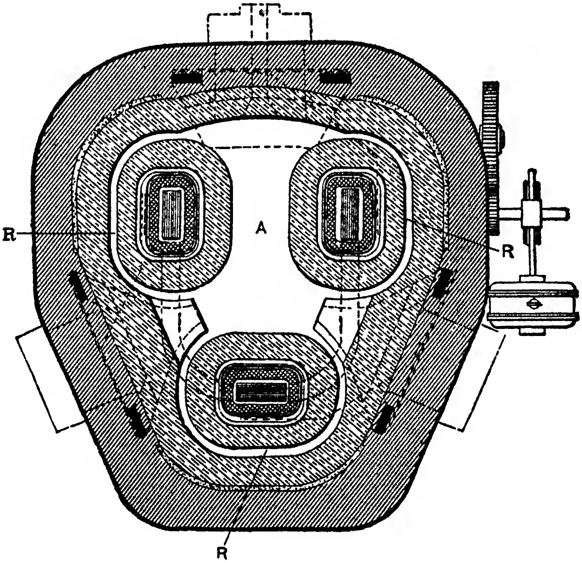


Fig. VII-7. - Horizontal section of Roechling-Rodenhauser furnace

The High-frequency Furnace.—If an alternating current of high voltage and very high frequency be caused to travel in a coil, such as the water-cooled copper inductor coil shown in Figs. VII-8 and 9, it will induce a current of high amperage in a near-by circuit, such as, for example, the graphite crucible indicated within the copper coil. If the crucible is not made of graphite but of some material which will not conduct the electricity and if it contains metal, then the current will be induced in a zone at and adjacent to the periphery of the metal. By varying the characteristics of the primary current, one not only may change

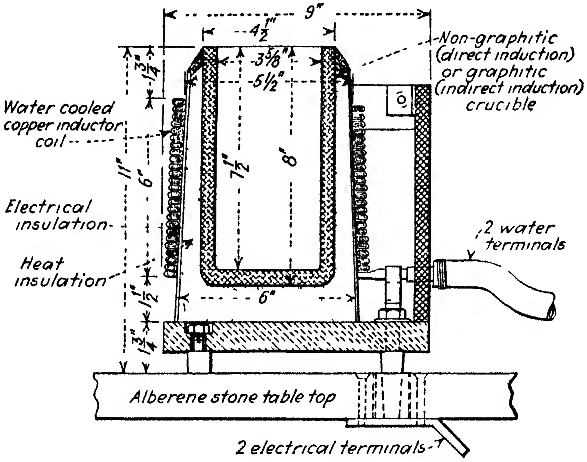


FIG. VII-8.—Cross section of high-frequency furnace.

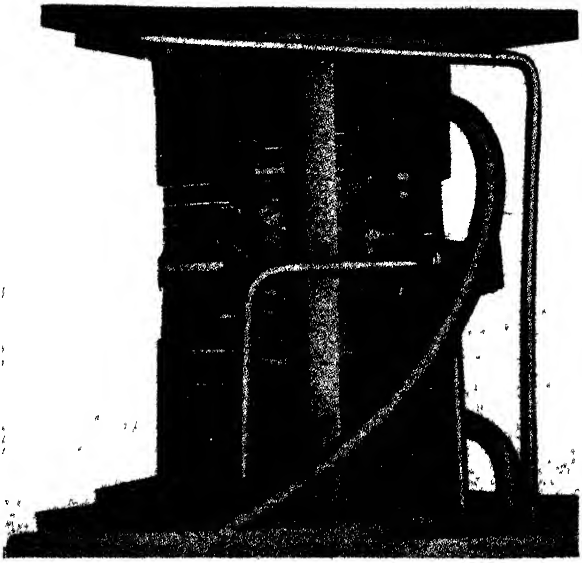


FIG. VII-9.—Inside view giving coil construction of the working model furnace. (*From E. F. Northrup, Iron Age, Jan. 15, 1931.*)

the intensity of the secondary (induced) current but may cause the secondary current to travel in a circuit extending from the periphery to a greater or less depth toward the central core of the metallic contents of the crucible. The heating effect of the secondary current is very rapid. A cold charge of steel within the crucible may be melted in only a few minutes. The coil which conducts the primary current is made of a hollow copper tube through which water is caused to circulate to protect it from being overheated by the heat radiated from within the furnace. In modern furnaces the coil is "graded," as indicated in Fig. VII-9, by having the number of turns at the central portion less than the number on each end. The copper coil is of an elliptical shape and is wound with its greatest length vertical in the central portion and its greatest length horizontal

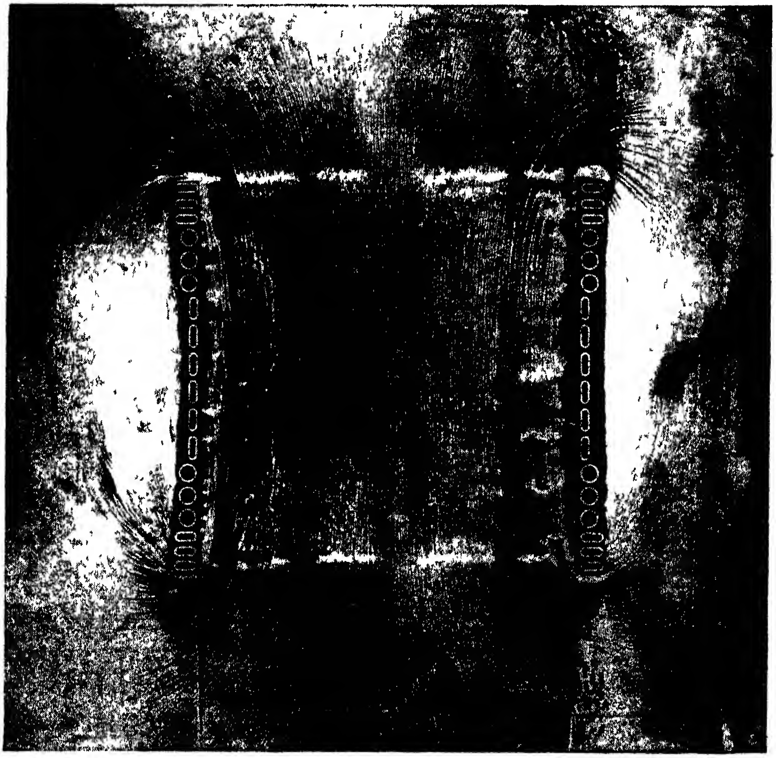


FIG. VII-10.—Graded coil of Ajax-Northrup furnace. (*Courtesy of Ajax Electrothermic Corp.*)

at each end, with a few turns between of round tubing. This is illustrated in Fig. VII-10. The object is to give a magnetic field within the coil which is more nearly uniform and parallel to the axis of the inductor throughout its length. This makes the field of force straighter and reduces the end losses at the top and bottom. The circuit in the inductor coil is anticlockwise from the center upward and clockwise from the center downward, as shown in Fig. VII-11.

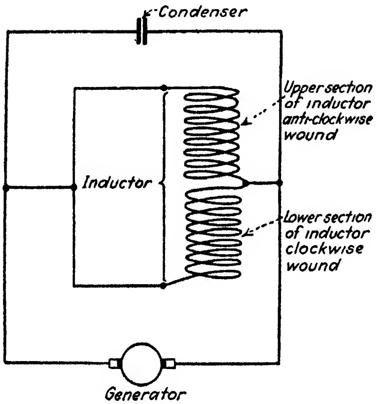


Fig. VII-11.

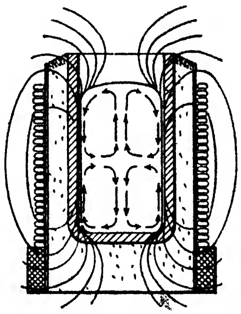


Fig. VII-12.

Fig. VII-11.—Diagrammatic connections of a parallel coil inductor. (*From Northrup, op. cit.*)

Fig. VII-12.—Hypothetical circulation in liquid bath in contrary-wound high-frequency furnace.

Stirring of the Bath.—One of the important characteristics of liquid baths heated by a current of electricity within them is the so-called *motor effect* through which the current causes a circulation or stirring of the bath. This causes the bath to rise in the center and to descend along the outer surface. When the coil is wound in opposite directions from the center toward each end, the theoretical stirring of the bath is roughly in accordance with Fig. VII-12. Circulation within the bath has the double advantage of producing greater uniformity in temperature and composition of the liquid metal and also in a very rapid reaction between the metal and the slag, which, because of its lower specific gravity, remains near the top of the crucible.

Efficiency of Induction Furnaces.—There will obviously be a loss of electrical energy in transforming a primary into a secondary current in any induction type of furnace. This has resulted in the arc furnace's being more efficient electrically than the induction furnace. On the other hand, the heat lost by radiation is much less in the induction type of furnace, especially of the high-frequency type now under consideration. The result is that the power input of the high-frequency furnace is very little, if any, greater per unit of work done.

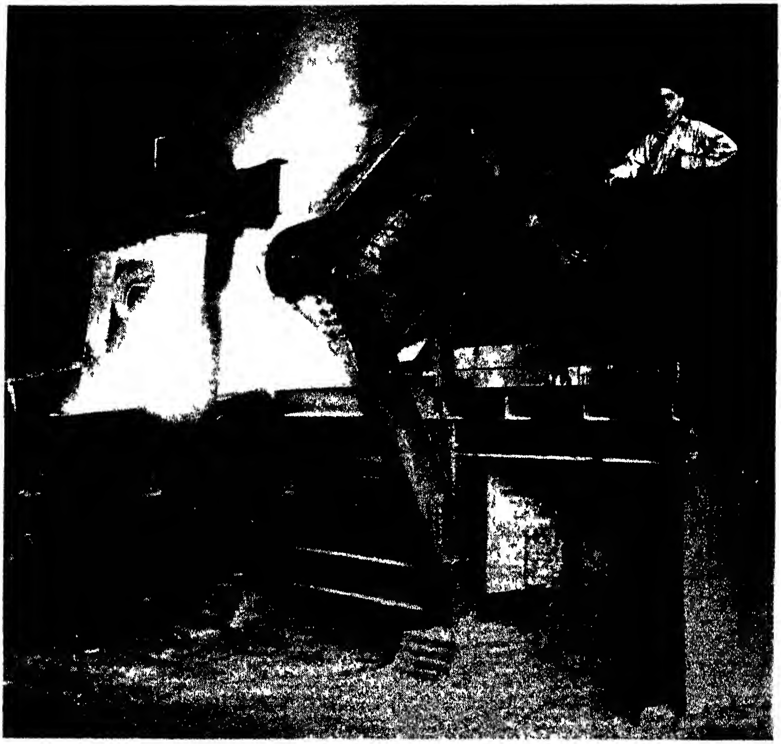


FIG VII-13.—Four-ton 1,200-kw., Ajax-Northrup high-frequency furnace pouring stainless steel. (*Courtesy of Ajax Electrothermic Corp.*)

History of High-frequency Furnace.—The electrical principles upon which the development of the high-frequency furnace depends were first studied in connection with this application by Dr. E. F. Northrup in the beginning of this century. The first types were only of laboratory size but, through a long course of laboratory experimentation, they have been developed until there are many industrial steel furnaces melting a ton of metal in one charge. The largest furnace to date is the 4-ton furnace shown in Fig. VII-13, which is in operation in the Chicago district.

Practice in High-frequency Furnaces. High-frequency furnaces are used very largely for melting alloy-steel scrap, because there is less oxidation of the costly alloy elements than in any other process. It is also used for the production of high-quality steel with very low carbon, because the arc electric furnace, with its carbon or graphite electrodes, does not lend itself to a complete removal of carbon from steel. The high-frequency furnace also has a greater control over the exact composition of the metal and an excellent control over the temperature. The power input into the high-frequency furnace is an exact regulation of the temperature of the metal. It is therefore possible not only to control but to learn the temperature of the metal from the electrical instruments which record the furnace operation. High-frequency furnaces are used in America for melting with only slight adjustments in composition. They are used in Europe, however, also for refining operations, which can be carried on very quickly because of the circulation of the bath.

Times of Operation.—In Europe it is common to operate high-frequency furnaces so as to produce a heat every hour. There are several 1-ton furnaces in France which produce 24 tons of steel per day. In America the speed of operation is usually somewhat slower than this. The difference is that in America the furnaces are not supplied with so large an energy input per unit weight of charge. This is the important factor in determining the speed of operation of the furnace.

Special Types of Practice.—The high-frequency furnace has been operated so that the steel is both made and poured out of the furnace in a vacuum, with the result that it is entirely protected from oxidation of the air. This is not practiced on an industrial scale, although a good deal of metal has been made in this way in Germany by Dr. Rohn and a great deal of electrolytic iron, 99.97 per cent pure, has been melted in a vacuum for special purposes, notably by Dr. Yensen of the Westinghouse Electric and Manufacturing Company. Another special type of practice using a high-frequency furnace is the centrifugal casting of steel. This has been employed during the past few years for making cannon tubes at the Watertown Arsenal, and a similar process has been described in the issue of *Steel* for Mar. 13, 1933, for rotary casting of rings to avoid the formation of dendrites and banding. The reason the high-frequency furnace serves so well with the centrifugal type of casting for steel is because it has good control and adjustment of the temperature of the liquid bath.

Furnaces Heated by Arcs

Furnaces heated by arcs have the obvious disadvantage that the temperature is excessive in the immediate neighborhood of the arc and decreases rapidly with distance so that the furnace temperature is nonuniform. Nevertheless, they have the advantage of high electrical efficiency and of lending themselves to a type of bath of wide adaptability as to length, width, and depth. The only serious difficulty in the mechanical handling of such a bath as far as charging, tapping, and working with the usual tools is concerned is the interference of the electrodes which project from the roof or sides, as indicated in Fig. VII-14. The arc type of furnace has received more development in steel works than the resistance type, so that it represents the greatest number of furnaces in industrial operation as well as a much greater tonnage of metal produced.

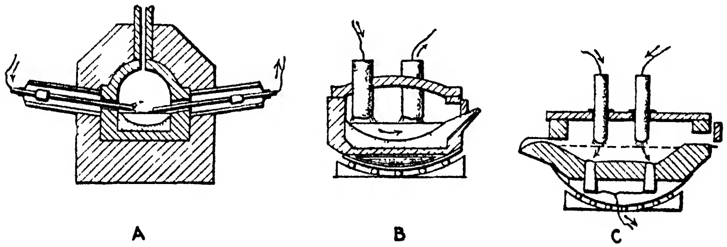


Fig. VII-14 Types of electric-arc furnace heating *A*, indirect arc; Stassano type. Heat radiates to bath. *B*, direct arc; electricity does not intentionally traverse hearth. *C*, direct arc; hearth serves as conductor of electricity.

Direct and Indirect Arcs.—The direct-arc furnace is that in which the arc travels between the electrodes and the liquid bath. This is made in two variations, *viz.*, that one in which there are electrodes both above and in the hearth, and the one in which all electrical connections are made with suspended electrodes (see Fig. VII-14). The direct-arc system of heating applies the heat right at the surface of the bath but does not distribute it uniformly over the area. The electrodes usually dip into the slag, but the slag does not "wet" the carbon surface, and a myriad of tiny arcs pass back and forth to and from the electrodes. A very common design for this type of furnace is three overhead

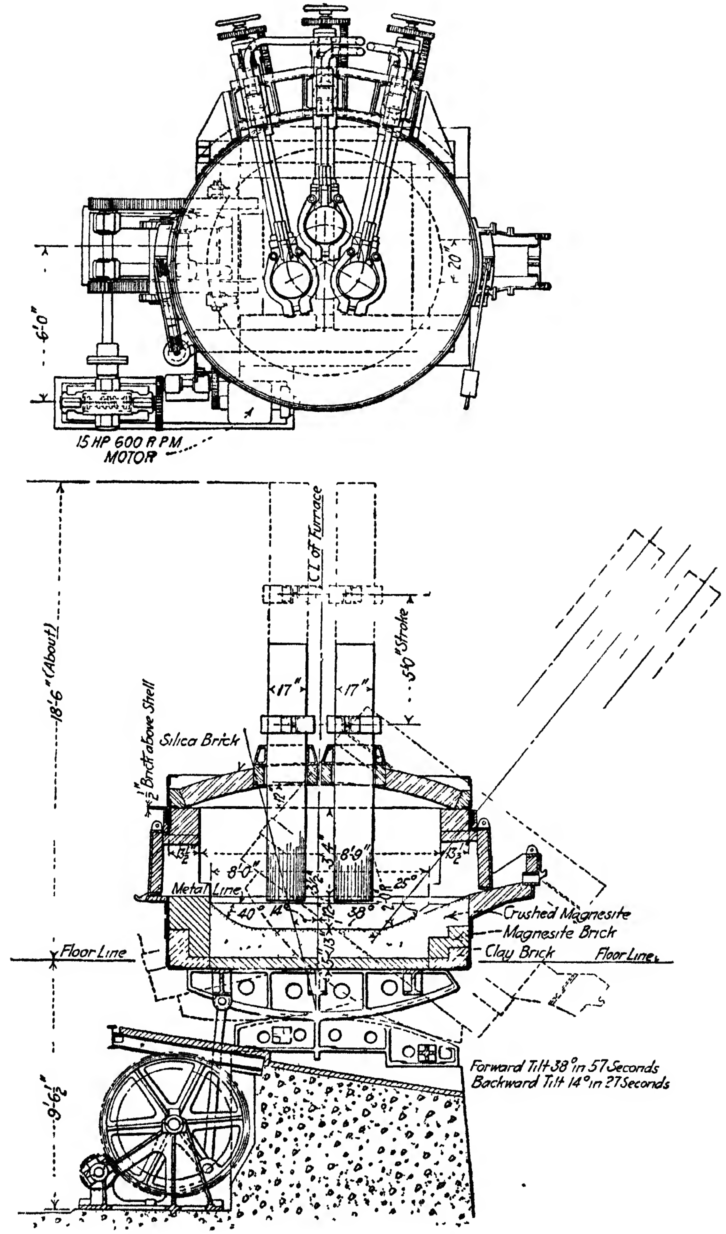


FIG. VII-15.—Forty-ton Héroult electric steel furnace. The electric leads to the three electrodes are hollow copper pipes through which water circulates. This cooling greatly decreases the losses due to "reactance." (*Courtesy of James H. Grau.*)

electrodes with a three-phase alternating current. The indirect arc heats by radiation. It is not so economical of heat as the direct arc and is hard on furnace refractories. Moreover, an important advantage of the direct arc is that calcium carbide may be formed in the arc between calcium oxide and carbon in the slag. The use for this calcium carbide will be discussed later.

Electrodes.—Electrodes are made either of graphite or of agglomerated amorphous carbon. The former are more durable and have a longer life, whereas the latter are cheaper to buy and are sometimes even made at the plant operating the furnace. Electrodes are threaded at both ends, so that, when burned down to a stump, a new electrode may be added to the old. Standard sizes of one type of electric-arc furnace, together with sizes of electrodes, are shown in Table VII-I.

TABLE VII-I.—STANDARD SIZES OF HÉROULT FURNACES[1]

Sizes of furnaces, tons	Size of carbon electrode, inches	Average charge, pounds	Standard sizes		
			Transformer capacity, kilovolt-amperes	Inside diameter shell	Inside diameter of lining
				feet inches	feet inches
½	4 (graph)	1,500	350	4 9	3 5
1	8	3,000	600	6 9	4 3
2	12	5,000	1,200	7 9¼	5 6¼
3	14	8,000	1,600	8 9¼	6 6¼
7	17	16,000	2,200	11 0	8 9
10	20	22,000	2,500	12 0	9 0
15	24	32,000	3,000	13 6	11 3
20*	24	43,000	2,250	14 6	11 6
30/40*	24	80,000	3,000	17 6	15 3

Foregoing average charges are conservative and are usually exceeded by furnace operators.

[1] From a catalogue of the builder, the American Bridge Company.

* 20-, 30-, and 40-ton furnaces are for refining molten metal only.

Carbon vs. Graphite Electrodes.—Graphite electrodes cost about twice as much as carbon per pound but have 3 to 3½ times the conductivity, so weigh less than one-half per unit of current carried. They are used in more than half the electric furnaces of the country. Their disadvantages are: lower strength per unit of cross section, lessened area of bath surface in which the arcs are active, higher heat conductivity, which means greater radiation loss through electrodes but also better cooling of the electrode in the holder. The advantages of their smaller size are: The holes through the roof are smaller, which is of much importance on account of its strength; the control mechanism is lighter; broken stumps are easier to remove from bath; the smaller electrodes are handled more easily, in general; and the smaller surface area radiates less heat from that part outside the furnace. The graphite electrode oxidizes less easily in the furnace.

Automatic Regulation of the Arc.—By means of electrical control devices the operator may set the furnace so that any determined length of arc may be automatically maintained. The higher the voltage, the longer the arc and the greater the heat input into the furnace. Special devices are used for very rapid adjustment of the arc during great fluctuations which occur during the melting of scrap, or other solid metal, which may suddenly melt away from close proximity to the electrode.

Tilting Furnaces.—All the furnaces used for steel refining and superheating for foundries are arranged to tilt, especially for the removal of slag. Most of them also have tap holes, so that the furnace may be tipped and the steel tapped from under the slag, thus getting it into the ladle without slag.

Power Charges.—The only economical manner in which to operate an electric furnace is to regularly use "off peak-load" power or else to maintain an almost uniform load. "Standby" charges from the power producer, when the furnaces are idle, quickly run into heavy expense, and it is often customary to base charges per unit of electricity on the maximum amperage used, so that short circuits during the melting period are very costly.

Thermal Efficiency.—The thermal efficiency of the direct-arc furnace is very high as compared with other metallurgical furnaces. This balances in part the high cost of heat obtained from electrical energy. Thus, Lyon, Keeney, and Cullen[1] give the thermal efficiency of the Héroult furnace as 70 per cent as compared with:

	Percentage
Iron blast furnace	60
Acid open hearth	18
Basic open hearth	20
Crucible furnace	4

---

[1] *Bull.* 77, U. S. Bureau of Mines, 1916.

The 30 per cent lost thermal efficiency of the Héroult furnace consisted chiefly of losses through electrodes, by conduction through roof and to the cooling water, by bad joints, and by electrode oxidation, as well as radiation losses through doors and a little through the lining and roof.

History of Electric-arc Furnaces in America.[1]—In the year 1910, there were 10 electric steel furnaces operating in the United States, producing 52,141 gross tons of steel during the year. Twenty years later there were more than 600 electric furnaces in operation, and the production was over 1,000,000 tons, of which about one-third was steel ingots and two-thirds were iron and steel castings. At that time (1930) about one-third of all steel castings in America was made in electric furnaces. Dr. Paul Héroult began in Europe his experiments on electric furnaces for iron and steel production in the latter part of the nineteenth century. He had previously had a very large part in the development of electric furnaces for aluminum production. Héroult patented his iron and steel furnaces, but he generously donated without patent the results of his very thorough knowledge and understanding of the metallurgical principles involved. His furnace was of the suspended-electrode type without conducting electrodes in the hearth. In 1910, F. T. Snyder brought out a furnace using a single suspended electrode and a water-cooled electrode built into the furnace bottom. It had the advantage of simplicity and lower consumption of electrodes by oxidation. He also had an ingenious roof design which permitted him to pull back the roof and allow the furnace to be charged through the top, whereas the Héroult furnace was charged through doors and the electrodes had to be raised out of the way during charging. The Girod furnace, developed in France, was introduced in the United States in 1908. It had several conductors in the bottom as shown in *C* (Fig. VII-14). Three types of indirect-arc furnaces have also been developed, but most of these have gone out of use, because radiation from the arc caused a short life of furnace linings and roof. An exception is the Detroit furnace shown in Fig. VII-16, which is very much used for melting cast iron. One great advantage of this type of furnace is that it is cylindrical and rocks, which agitates the bath and seems to have the effect of improving the structure and strength possessed

---

[1] Chiefly from Moore, *Transactions Electrochemical Society*, September, 1931.

by the liquid metal after it solidifies in molds in the form of castings. As far as we know, this is the only indirect-arc electric furnace now of industrial importance. A direct-arc furnace known as the *'Lectromelt furnace* was developed in 1916. Its principal novelty was that it tilted in two directions, so that the slag could be discharged from the back door and the metal poured out of the front door.

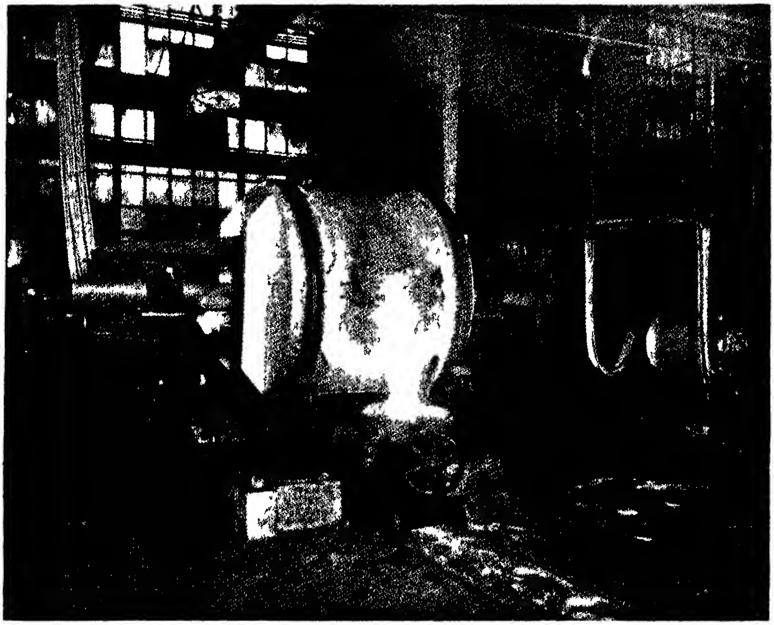


FIG. VII-16.—Detroit rocking electric furnace in pouring position. (*Courtesy of Detroit Electric Furnace Co.*)

Arc-furnace Sizes.—Electric furnaces for foundries are usually from 3 to 10 tons capacity each, whereas those for making steel for ingots have a capacity up to 30 to 75 tons each. One capable of holding 100 tons at a time has actually been in operation and is illustrated in Fig. VII-18. This furnace is supplied with a double set of three electrodes, however, in order to distribute the heat more uniformly.

EXAMPLES OF ARC ELECTRIC-FURNACE PRACTICE

Arc furnaces are used in America for superfining basic open-hearth steel, for the manufacture of steel castings, and for the manufacture of castings of gray, chilled, and malleable cast iron.

They are used for these purposes to a far greater extent than are resistance furnaces. Arc furnaces are also used for melting alloy-steel scrap to produce new alloy-steel ingots, but in this type of practice they share the field much more equally with the resistance furnace, especially the high-frequency type.

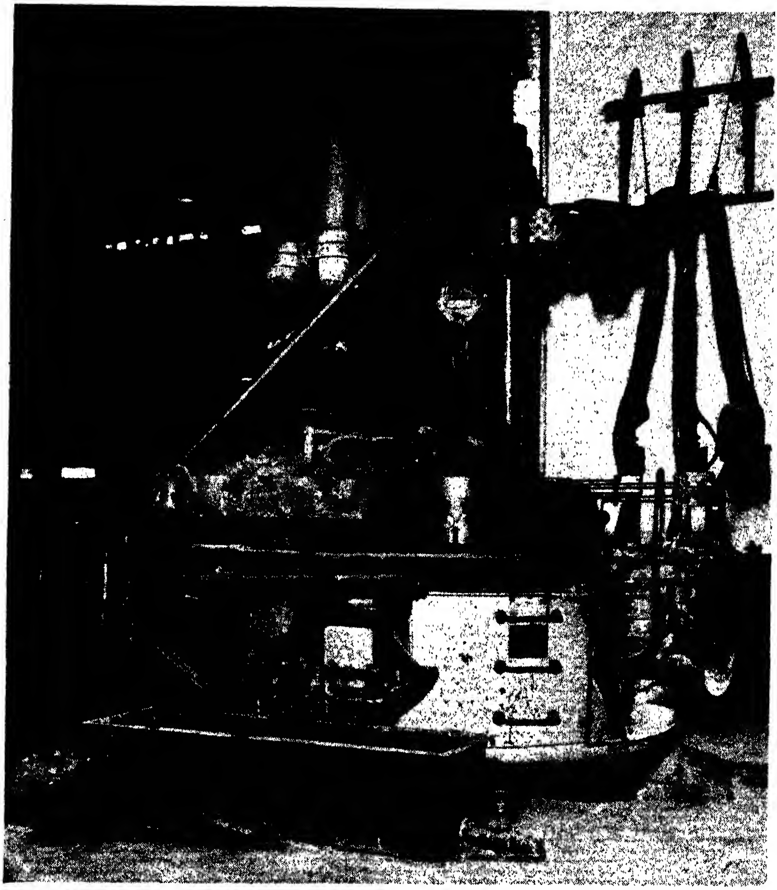


Fig. VII-17.—Charging an 'Lectromelt furnace. (*Courtesy of Pittsburgh Electric Furnace Corp.*)

Superrefining Liquid Steel in Basic Electric Furnaces.—Sulphur, occluded oxides (inclusions), and dissolved gases are not completely eliminated by the Bessemer or open-hearth processes. The crucible process has long produced a steel excelling these in quality, but its operation is costly and the product is made in small units, so that large ingots are made by pouring several crucibles into one mold, and the analysis is subject to nonuniformity. The electric furnace, when expertly operated, will produce a steel equal in properties to crucible steel and freed to any desired extent from impurities and occluded particles or gases. That it has not always accomplished this result is due to lack of care or expertness and has delayed its more general adoption. It is also more costly than the older "tonnage" processes, because of the greater cost of electric heat than of that obtained from fuel. Therefore, the cheapest way to make steel of this high quality is to perform all the purification possible in the open-hearth furnace and then pour the liquid steel into the electric furnace, where the sulphur is reduced to a harmless point and the inclusions and gases eliminated. The first essential is that only moderately impure metal shall reach the electric furnace, because sulphur above about 0.08 per cent is reduced with much expense and waste of time, and highly oxidized steel is never restored to high quality. Bessemer steel is no longer superrefined in America. Phosphorus may be eliminated in the basic electric furnace, but this is uneconomical, because the basic

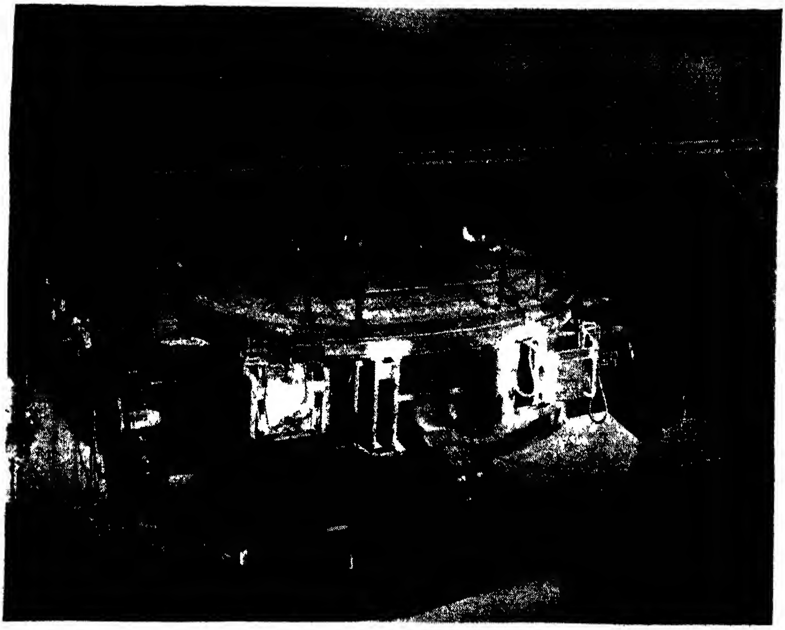


FIG. VII-18.—100-ton electric-arc furnace. Note the elliptical shape and the six electrodes. (*Courtesy of Timken Steel and Tube Co.*)

FIG. VII-19.—Superrefining liquid steel. Pouring basic open-hearth steel into a 40-ton basic electric-arc furnace. (*Courtesy of James H. Gray.*)

FIG. VII-20.—Three-ton Héroult electric furnace at Johnstown plant of the Lorain Steel Co. (*Courtesy of James H. Gray.*)

open-hearth elimination is cheaper; hence has arisen the so-called *triplex* process, in which the liquid metal goes from the Bessemer to the open hearth and thence to the electric furnace.

Furnaces Used.—More than 300,000 tons of steel are superrefined annually in electric furnaces in the United States, of which the greater part is treated in arc furnaces of the Héroult type.

Operation of Superrefining.—Liquid steel from the open-hearth furnace is poured into the electric furnace, great care being taken that no open-hearth slag gets into the electric furnace. The steel should have been carefully analyzed and should contain less than 0.08 per cent of sulphur; manganese of 0.15 to 0.40 per cent; phosphorus 0.02 per cent or less; and carbon 0.10 to 0.25 per cent (10 to 25 points) lower than that desired in the finished steel, in order to allow leeway for carbon to be increased by coke added for deoxidizing purposes, plus a little which goes in with the final additions of manganese, silicon, etc. The amount of steel poured into the furnace must be carefully estimated, in order that the additions can be adjusted correctly. While the steel is pouring in through one door, sufficient lime to make a slag covering for it is shoveled through another, mixed with about 20 per cent of its weight of fluorspar and 15 to 20 per cent of sand, to make a fluid slag. The slag will not exceed 2 per cent of the weight of the bath. If the carbon in the open-hearth metal is too low, some anthracite may be dissolved in it during the transfer or may be shoveled into the electric furnace while the steel is pouring in. Sometimes part or all of the slag is not introduced until the steel has been for some time in the furnace, and sometimes two slags are used.

The open-hearth steel usually chills over the top when it gets into the furnace, and the furnace is first set for high temperature, which should result in the charge's being melted in 30 min. to 1 hr. Cold metal at this point is, however, one of the difficulties and costly features of the process. When the metal and slag are melted, a sample is taken for analysis. The sample of slag will show a brown color, indicating that the steel is still oxidized. To a 20- or 25-ton heat about 100 lb. of coke dust are now added and the temperature kept up. In 15 to 30 min. the slag should begin to lighten in color, and within 1 hr. after adding the coke it should be light gray or white and should smell of acetylene when dipped in water. If necessary, more coke dust and, possibly, more slag mixture will have been added in the meantime. From now until the end of the heat a slag should be maintained that contains some calcium carbide, the purpose being to desulphurize and deoxidize the steel.

$$\left.\begin{matrix}\mathrm{3MnS}\\ \mathrm{3FeS}\end{matrix}\right\} + \mathrm{2CaO} + \mathrm{CaC_2} = \left.\begin{matrix}\mathrm{3Mn}\\ \mathrm{3Fe}\end{matrix}\right\} + \mathrm{3CaS} + \mathrm{2CO}.$$

$$\left.\begin{matrix}\mathrm{3MnO}\\ \mathrm{3FeO}\end{matrix}\right\} + \mathrm{CaC_2} = \left.\begin{matrix}\mathrm{3Mn}\\ \mathrm{3Fe}\end{matrix}\right\} + \mathrm{CaO} + \mathrm{2CO}.$$

The carbide is formed by the action of lime and carbon at the electric arc:

$$\mathrm{CaO} + \mathrm{3C} = \mathrm{CaC_2} + \mathrm{CO}.$$

In the case of large baths, the metal must be stirred frequently, because carbide may not be found near the doors.

The carbide slag is the best means of degasifying the steel, and steel that is degasified is assuredly desulphurized. It requires 1½ to 3 hr. to degasify under a carbide slag, and it must be maintained strongly basic and reducing, and fluid at all times. Coke must be added when necessary, and the doors must be kept closed and luted tight with clay as much of the time as possible. Dripping of the acid roof or scorifying the lining may spoil the slag and the operation.

After the steel is deoxidized, the ferrosilicon, ferromanganese, ferrochrome, ferrovanadium, etc., may be added. They should be added in small doses so as not to chill the metal, and all additions should be complete 45 min. before the heat is tapped, during which the bath should lie as quietly as possible in the furnace to allow all inclusions to escape. This corresponds to the "killing" period of the crucible process. Ferrosilicon should be added first, then ferromanganese and ferrochrome, and lastly ferrovanadium, to avoid inclusions. The bath must be kept liquid and as quiet as possible at all times and lies dead for the last 45 min. for the same reason. If the color of the slag shows that any of the elements, as manganese and chromium, are being oxidized, coke should be added and the conditions investigated. Elements, like nickel, which do not oxidize should have been added as soon as the bath was melted, in order to avoid chilling it during the later part. It must never be allowed to become viscous, lest it entangle solid particles, while an excessively high temperature must also be avoided.

The heat should be tapped at a temperature 200 to 250°C. above its melting point, held in the ladle while the temperature drops about 100°, and poured 100 to 125° above its melting point, which will, of course, depend on its analysis. The reasons for hot working and cool pouring are the same as those given under the acid open-hearth process. It is of paramount importance that the steel be tapped from underneath the slag. All the care, skill, and expense expended to eliminate "inclusions" may be thrown away if any slag or dirt is poured or tapped with the steel and mixed with it to again produce sonims. The total time of a heat, from charging liquid metal to tapping, will be roughly 4 to 5 hr. and the power used equals 100 to 200 kw.-hr. per ton of product.

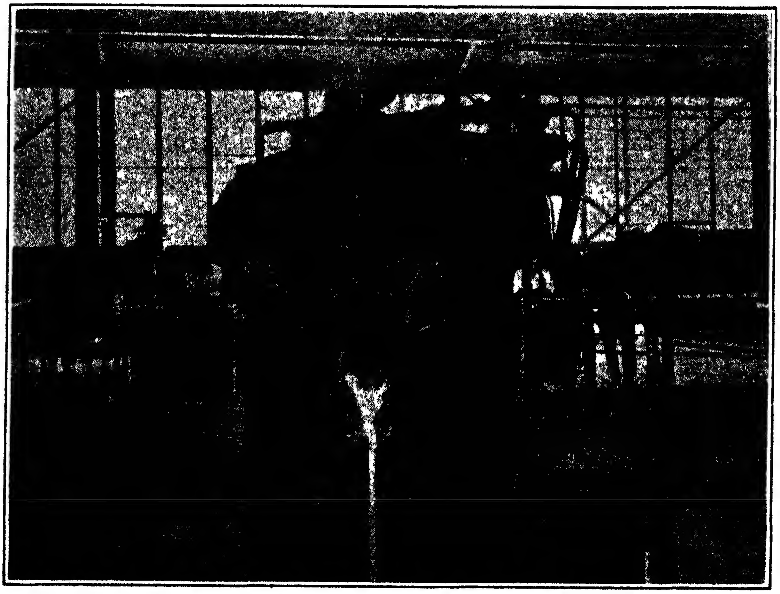


FIG. VII-21.—Seven-ton Héroult electric furnace pouring out the slag after tapping the steel. (For the prevention of inclusions it is imperative that all the slag be retained in the furnace when the steel is tapped into the ladle.) (*Courtesy of James H. Gray.*)

After the steel is tapped, the bottom is repaired with dolomite, about 500 lb. of dolomite being used for a 25-ton furnace. The roof and walls are carefully examined and precautions taken to avoid trouble in the next operation. As in the open-hearth process, the worst cutting is at the slag line. The bottom lasts

2,000 to 3,000 heats and the roof from 50 to 200 heats, depending on care and the make of furnace.

The final slags will contain about 20 per cent of silica, 70 per cent of lime plus magnesia, 0.30 to 1 per cent of calcium carbide, about 1 per cent of sulphur, and less than 1 per cent of iron.

Superrefining Bessemer Steel.—At one time it was proposed to superrefine Bessemer steel by removing its phosphorus, sulphur, oxygen, and inclusions in a basic electric furnace, but this proved to be impractical, because the removal of phosphorus required an oxidizing slag. It is an established fact, often denied and doubted but nevertheless generally recognized now, that electric steel which has been treated under an oxidizing slag is not of such good quality as steel of the same composition which has been treated under a reducing slag only, even though a reducing slag is used after the oxidizing slag has been used and removed. Therefore the best result is obtained by pouring Bessemer steel into an open-hearth furnace, to remove its phosphorus, and then superrefining. The use of an oxidizing slag in the open-hearth furnace does not lower the quality of the steel so much as when it is used in the electric furnace. This is perhaps due to the fact that the temperature is not so high in the open-hearth furnace. In one plant in Europe, Bessemer steel is superrefined, but this is special practice because it happens that the ores from which the pig iron used for Bessemer converting is obtained are very low in phosphorus; therefore the Bessemer steel is low in phosphorus and it is superrefined in the same way in which basic open-hearth steel is superrefined in this country, *i.e.*, without using an oxidizing slag.

Acid Open-hearth Steel Is Not Superrefined.—Acid open-hearth steel is not sufficiently improved by superrefining to command an increase in price commensurate with the expense of superrefining.

Steel Castings.—Both acid and basic electric furnaces are used for melting steel for making castings. The steel-casting field is practically the only one in America in which the acid electric furnace is used, and the reason it is used for castings is because its product can compete[1] in phosphorus and sulphur content and it has advantages in cost and in freedom from inclusions and gas bubbles which are more objectionable in castings than they are in ingots. Electric-furnace ingots are produced with a very small amount of both sulphur and phos-

---

[1] See page 232.

phorus, and, in this field, the acid furnace is practically unable to compete on account of the extremely high cost that would be necessary for raw materials. The process of melting for castings is virtually one of melting down steel scrap in the electric furnace, bringing it to the desired temperature and exact composition, and then tapping it. This operation requires only 1 to 1½ hr. in an acid furnace. It requires 1½ to 3 hr. in a basic furnace, depending on how much, if any, refining is done. Pure stock is sometimes melted in a basic furnace, but often advantage is taken of the basic slag to purchase cheaper material and refine it from phosphorus and sulphur. The melting of scrap in an arc furnace is greatly complicated by the "jumping" of the arc and irregularity of the power input, due to breaking of contact between the electrode and the scrap packed in the furnace. Pure stock is melted under reducing, instead of oxidizing, conditions. The common practice is to use a relatively high voltage during melting, with lower voltage during the later stage. In the basic furnace, lime is charged on the hearth to protect it when the scrap is introduced and to form the basis of a basic slag.

Acid vs. Basic.—Every acid furnace is cheaper to operate than the corresponding basic furnace. This applies to Bessemer, open-hearth, and electric processes. The raw material, however, is cheaper for the basic process. Except for phosphorus and sulphur, the product of the acid process excels in quality because of more oxidizing slag in the basic process, more difficult recarburizing (with consequent trouble from inclusions), and a great amount of impurities to be removed in the slag, with resulting hazard of reversions of impurities to the steel. The relative economy of the acid operation is due to its being shorter, requiring less repairs to lining, less fluxes, and less metalloids added in recarburizing.

When we come to melting pure stock in the electric furnace, it is evident that the basic process loses its chief advantage, *viz.*, the lower price of raw material. True, we may remove sulphur, but the cost of otherwise pure stock containing up to 0.08 per cent of sulphur is not much less than the cost of raw material which will make low-sulphur steel even in the acid electric furnace. It is claimed that a little sulphur is removed in the acid furnace, provided manganese is used freely. A slag containing calcium carbide is the most efficient desulphurizer known, and this cannot be used in an acid furnace, but many believe that manganese and low-sulphur stock is cheaper than the combined additional costs of the basic operation. Coke is used in an acid slag to give it a reducing character.

The relative brevity of the acid operation is due to:

1. The comparative ease with which acid slags may be maintained in a deoxidizing condition.

2. The briefer deoxidizing and degasifying period, because the steel itself is less oxidized, and is normally free from gases.

3. The freedom from melting of such large proportions of fluxes.

4. Less recarburizer additions to be melted.

These circumstances require for the acid process, less current, less labor, and less cost for overhead per ton of product.

Acid steel requires less manganese, and usually no ferrosilicon need be added, because it is reduced from the acid slag and acid lining:

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

This decreases the cost of additions. The lining is less corroded, and acid refractories cost less than magnesite, besides being more durable. Acid side walls and roof are normally used even in basic furnaces, on account of their strength and high melting point; if the acid roof drips, it does not damage an acid slag. Acid fluxes are also less costly than basic fluxes, and the slag does not accumulate impurities, so that the acid slags may be used several times.

Finally, well-made acid steel is uniformly of high quality and not subject to the dangers from which basic steel suffers. For example:

1. After the melting stage is complete, acid steel is less oxidized than is basic steel at the same period.

2. It normally contains less dissolved or occluded gases, because silicon is maintained in it almost automatically.

3. The danger from siliceous inclusions is absent, because silicon is being reduced into the steel and it cannot be both reduced and oxidized at the same time.

4. Other inclusions are avoided during the heat, because even manganese is not oxidized when added to the bath.

5. The slag is pure, which avoids danger of reversions to the metal in either the furnace or the ladle.

The basic furnace has the great advantage that we may, when market conditions make it desirable, melt and refine impure stock. And a very serious special hazard in the acid electric process is the tendency of the slag to become infusible and viscous, with consequent danger of formation of inclusions.

Melting Impure Scrap to Produce Electric Steel (Basic Furnace Only).—Scrap containing more than 0.08 per cent of sulphur and/or 0.02 per cent of phosphorus must pass through an oxidizing period before it can be deoxidized. This lengthens the process and lowers the quality, because oxidized steel is not always perfectly deoxidized—some say it never is. The raw material is cheaper and is easier to secure. In practice the operation differs in that, besides putting limestone (instead of lime) on the hearth, we use enough iron ore with the scrap to oxidize all the silicon and phosphorus but not any of the other elements. This requires low temperature until the oxidizing (black) slag is removed. If the temperature is too high, some manganese, chromium (if present), and carbon will be removed. Sometimes scrap pig or new pig iron is charged with the stock to melt down hard and allow more ore to be used. It is most desirable that the charge, when melted, shall be reduced to less than 0.02 per cent of phosphorus, except in the case of steel for castings, which may be higher. On account of the basic slag, the silicon goes before the phosphorus.

Charging.—Pig iron, if used, is put next the limestone on the hearth, in order to protect the latter from iron oxide. On top of this is put the large scrap, and then the interstices filled with small scrap as well as possible, to lessen "jumping" of the arc. Unoxidized scrap is used, as rusty steel adds an uncertain oxidizing influence. Scrap containing nickel must be avoided, as the nickel will not be removed.

Black Slag.—When the charge is melted and the "lime comes up," a sample of the bath is taken and analyzed. If phosphorus is removed, the black slag is poured off with the aid of rabbling. It must be completely removed, including any that adheres to the sides. If too thin to follow the rabble, it must be thickened with lime. If the phosphorus in the initial charge was above 0.07 to 0.09 per cent, we may require a second black slag for removing it. This is costly and usually uneconomical, because purer stock is normally less expense than a longer operation and additional fluxes.

White Slag.—When melted and purified, with the black slag removed, the bath is ready for the white slag. This is made up of lime, thinned with calcium fluoride or sand, or both. It is mixed before charging, and about one shovel of coke also is used for each three shovels of lime.

Use of Fluorspar or Sand for Thinning.—Sand is cheaper than fluorspar and it avoids corrosion of the side walls and roof caused by the volatility of the fluorspar. It thins the slag effectively but decreases its basicity and interferes with the permanency of the carbide in the slag. It also increases the danger of adding ferrosilicon early in the process, by decreasing the excess of bases. The commonest practice is to use part fluorspar and part sand, keeping the slag fluid but never allowing the silica content to exceed 18 to 20 per cent.

Recarburizing and Refining.—The temperature is raised as rapidly as possible and the analysis adjusted to give the steel about 10 to 25 points less carbon than is desired in the final analysis; manganese 0.15 to 0.40 per cent, and silicon 0.10 to 0.20 per cent. There will be no waste of metalloids later in the operation, because no subsequent oxidation of the bath. Carbon is added in the form of coke, charcoal, or ground electrode stumps. Sometimes pure pig iron is used, depending on market conditions, and sometimes washed metal, as in the crucible process. Carbon in coke enters the metal to the extent of about 60 per cent of its weight and usually causes a boiling of the bath, due to escape of carbon monoxide gas. If the bath is very wild, ferrosilicon may be added with carbon, but usually the order of charging is like that in the acid open-hearth recarburizing, so that carbon (the cheapest deoxidizer) will remove all the oxygen it can, then silicon, and then manganese. Some operators omit the ferromanganese, but others use it to deoxidize more thoroughly and remove any silica inclusions present. The need of manganese is greater the more extensive has been the oxidizing action previously. If impure stock was used, it is doubtful whether the white slag and calcium carbide will deoxidize the bath sufficiently.

When the white slag and recarburizers are charged, the doors are closed tightly and the heat increased and atmospheric oxidizing conditions decreased as much as possible. The amount of white slag is 3 to 7 per cent of the weight of the bath. It should be melted and have lost its brown color in about an hour after charging. If the color does not begin to go in 30 to 40 min., more coke should be added to it; its fluidity should be kept right by additions of lime, calcium fluoride, or sand as needed. Upon reaching this point we come to a condition similar to the superrefining operations already described. If ferromanganese was not added with the other recarburizers, it is added when the slag is white. This saves a little manganese. Some operators add ferrosilicon in small doses toward the end of the heat, but this is dangerous practice.

Superrefining.—We are now ready for the superrefining (*i.e.*, carbide) slag: Coke dust is mixed with about twice its volume of lime and thrown in near the arcs, where the carbide reaction will take place. More coke dust is also scattered over the slag. The practice is essentially the same as that described previously. The operation lasts about 2 to 3 hr. after the black slag is removed, and the total time will be 5½ to 7 hr. or longer, depending on the degree of purification and skill of the operator. On the other hand, too much hurry during the deoxidation and degasification period results in inferior steel.

The making of low-carbon steel in electric furnaces is more difficult, because overoxidized baths are almost impossible to deoxidize.

Melting Alloy-steel Scrap.—Ferroalloys which are used for the manufacture of alloy steels, such as nickel steel, chromium steel, stainless steel, high-speed steel, and tungston steel, are high in price. But there is now a regular market supply of alloy-steel scrap containing the costly alloying elements in a much less expensive form than if they were contained in the ferroalloys. Furthermore, it is possible to get some type of scrap, such as high-speed steel scrap or stainless-steel scrap, which is very close in analysis to the new steel desired and which can be melted in an electric furnace with so little oxidation of its components that the liquid bath requires very little adjustment in alloying elements before it is ready to pour into a new product. This requires melting under as reducing conditions as possible, because some of the elements, such as vanadium and tungsten, oxidize so easily that care must be taken to prevent losses. The high-frequency furnace has an advantage in this respect, because it can melt with less loss by oxidation than any of the other processes in vogue, and it is often used for this work, but the arc furnace is also employed in some plants.

Arc Furnace Making Cast-iron Castings.—The cupola is the cheapest furnace for melting cast iron, but it must be run with great skill and attention in order to give reasonable uniformity in composition and temperature; it involves a loss of silicon in the metal during melting, an increase in sulphur, and some uncertainty as to the final proportions of these elements in the metal. It also has a limit in temperature above which it cannot heat the iron. Finally, the cheapest form of scrap, *viz.*, fine turnings and borings, can be used in the cupola only to a limited extent, because they tend to clog the charge and make it impervious to the blast. The air furnace costs more for fuel and labor than the cupola and it too has an upper limit in temperature. Therefore the arc furnace has found a place in foundries producing gray cast iron, chilled cast iron, and malleable cast iron. Its high cost for heat is partly neutralized by its capacity to use cheap raw materials. For example, we may charge an electric furnace with the cheapest borings or turnings and these may be desulphurized if necessary and may be adjusted to exact composition by additions of suitable alloys. We may use steel scrap and carburize it at a high temperature with petroleum coke, thus making a "synthetic" cast iron if, and when, steel scrap can be purchased at a very low price as compared with cast iron. In the electric furnace the composition may be adjusted with as great exactness as in the air furnace, and it has the advantage over the latter that the furnace atmosphere may be deoxidizing instead of oxidizing and that the temperature may be higher if desired. The higher temperature is especially employed when alloy cast irons are made. It is also noted that cast iron, when heated to a temperature well above its melting point, has a grain structure after freezing of smaller flakes of graphite in more isolated particles, which gives greater strength to the metal. This is true of alloy cast irons, such as those containing nickel and chromium or those having molybdenum. It is also true—to some extent at least—of unalloyed carbon cast iron. In the electric furnace we may adjust the composition of the cast iron in any of its components, including the normal carbon content of about 3.50 per cent or carbon as low as 2 per cent. This can be accomplished in the air furnace also, but not in the cupola. The advantage of agitating the metal while liquid has already been mentioned.

Duplexing.—In some foundries the larger amount of heat necessary for melting is obtained in some cheap form of combustion, as a cupola, whereas the superheat required for special chemical adjustment, etc., is obtained by treating the cast iron in some electric furnace after it has been melted.

ADDITIONAL NOTE ON ACID ELECTRIC STEEL FOR CASTINGS.—Scrap sufficiently low in phosphorus and sulphur can be melted in an acid electric furnace at an actual cost for raw materials plus "cost above net metal," which is no greater than the total of the two corresponding costs for the basic electric furnace.

References

C. L. MANTELL: "Industrial Electrochemistry," New York, 1931. 2 vols., vol. I, New York, 1924. Vol. II, by Colin G. Fink.

W. G. McMILLAN and W. R. COOPER, "A Treatise on Electrometallurgy," London, 1910.

A. J. ALLMAND and H. J. T. ELLINGHAM: "The Principles of Applied Electrochemistry," 2d ed., London, 1924.

J. BRONN: "Der elektrische Ofen," Halle am See, 1910.

ROBERT M. KEENEY: Manufacture of Ferro-alloys in the Electric Furnace, *Trans. Am. Inst. Min. Met. Eng.*, vol. 42, pp. 28–82, 1920.

DORSEY A. LYON and ROBERT M. KEENEY: "Electric Furnaces for Making Iron and Steel," Washington, 1914. Contains some important theoretical data.

PAUL NICOU: "Le haut fourneau électrique," Paris, 1913.

WILLIAM RODENHAUSER, J. SCHOENAWA and C. H. VOM BAUR: "Electric Furnaces in the Iron and Steel Industry," translated by C. H. Vom Baur, 3d ed., New York, 1920.

COLIN C. GOW: "The Electrometallurgy of Steel," London, 1921.

JEAN G. ESCARD: "L'électrométallurgie du fer et de ses alliages," Paris, 1920. Especially good on ferroalloys.

ALFRED STANSFIELD: "Electric Furnace for Iron and Steel," New York, 1923.

BENJAMIN FREEMAN and FREDERICK G. HOPPE: "Electroplating with Chromium, Copper and Nickel," New York, 1930.

CHAPTER VIII

THE INGOT-MAKING STAGE OF MANUFACTURE

By whatever process steel is manufactured it leaves the steel mill in the form of an ingot or casting.

It might be thought that this ingot-forming stage of manufacture was of minor importance and that, if we could so control the steel-making process as to avoid excessive amounts of impurities, then the quality of the resulting ingots or castings would almost necessarily take care of itself. It is now well recognized that this is by no means true and that many injurious defects may appear during the ingot-making stage, although some of these may be caused by improper methods of manufacture, such as too high or too low temperature on leaving the furnace or insufficient deoxidizing of the bath. Other defects may originate during the ingot-making stage itself, such as teeming too soon after adding the recarburizer, teeming too fast or too slowly, too hot or too cold, improper shape or proportions of ingots, or the addition of too much aluminum or other deoxidizer to the metal in the ingot mold.

The defects which may appear during the ingot-making stage are:

1. The inclusion or entanglement in the solid steel of minute particles of slag or other oxidized substances. These occur often in so fine a form as to be like an emulsion, and it has been suggested that we might almost consider them colloids. They separate from the steel very slowly and their presence in the solid metal is a source of weakness or brittleness or both. Their source is largely the oxidation of silicon, manganese, aluminum, and other metals added to deoxidize the steel; also minute particles of slag, dirt from the ladle lining, manganese sulphide, etc. The general name *inclusions* has been given to these solid nonmetallic impurities.

2. Blowholes or gas bubbles entangled in the metal (see Fig. VIII-1).

3. A weak crystalline structure formed during the solidification of the steel and having such forms as very large crys-

tals, or "ingotism;" fir-tree crystals, or dendrites; columnar crystallization (see Figs. VIII-5 and VIII-8).

4. A pipe or shrinkage cavity extending so far down into the ingot that it is not removed when the ingot top is cut off during the rolling operation (see Figs. VIII-10 and VIII-11).

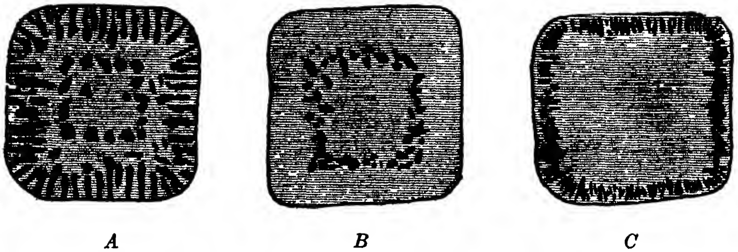


FIG. VIII-1.—Locations of blowholes in steel ingots. *A*, deep-seated and skin blowholes. *B*, deep-seated blowholes only. *C*, skin blowholes only (see also Fig. III-3, p. 43).

5. Segregation or the concentration of impurities in localities, thus forming points of weakness. This is almost invariably the result of oxidized or dirty steel, excessive impurities left from the furnace stage, or excessively slow cooling of the ingot allowing the liquation of more fusible compounds to the late-freezing portions of the ingot or casting.

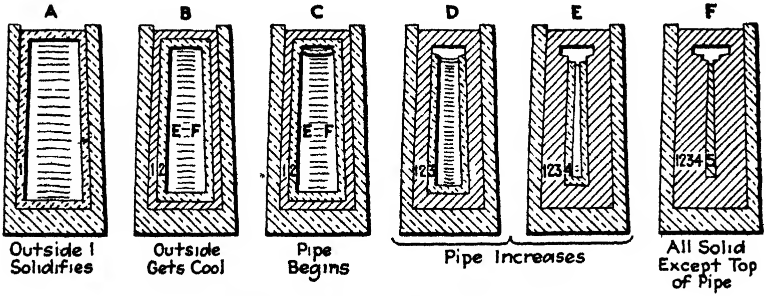


FIG. VIII-2.—Stages in the formation of a pipe.

6. External cracks due to straining the surface of the steel during solidification or when the ingot mold is removed in the stripping process.

7. Scabs on the outside surface of the ingot, caused by particles of slag or oxide of manganese.

8. Internal checks, or "flakes," *i.e.*, minute cracks in the interior of the steel which weaken the structure.

"Inclusions."—When large in size, these inclosures are commonly the result of accident, negligence, or ignorance and therefore could usually have been avoided by the exercise of due care, but, in microscopic particles aggregating as much as 0.25 to 0.30 per cent of the weight of the metal, they are often found in Bessemer and open-hearth steels not as a result of chance but as a regular occurrence. (Oxides, silicates, and sulphides of iron and manganese, oxide of silicon or aluminum, and tiny particles of slag are the commoner examples of these enclosures.) Entangled particles of slag seem to be due to their having become caught in the solidifying metal before they had an opportunity to rise to the surface. The bulk of the oxides of manganese and silicon and the silicates of iron oxide and manganese oxide originate through the recarburizing reactions in the bath, and the tiny particles thereof are retained because they cannot separate immediately. Like the cream in milk, time must be allowed for them to rise to the surface. The same necessity is felt to an even greater degree in the case of sulphide of manganese, which separates from a molten bath of iron or steel only upon long standing. The sulphide of iron appears to be actually soluble in the molten metal and not to separate until after solidification. Any of these occluded particles may be harmful to metal. It is now commonly believed that many previously unexplained failures of steel are due, in part at least, to such defects, and the "shelling" off of the surface of railroad rails and locomotive tires is often directly traceable to this cause. Sometimes the inclusions appear like a cloud or mist in the form of a plane within the body of the steel, forming a definite plane of weakness. This is especially the case with aluminum oxide. The proportion of entangled particles in the ingot will depend largely on the precautions taken during the final stages of the steel-making process, the opportunity allowed for inclusions to separate before and during teeming, and the care with which deoxidizers, such as aluminum, are added in the ingots to quiet the steel.

Finishing the Heat and Precautions in Recarburizing.—We have already discussed the importance of finishing the liquid-steel bath with as little dissolved oxygen as possible and adding deoxidizers in a shallow bath when possible to allow inclusions to rise to the surface better. Even holding in the ladle helps to clarify the steel, but there is a limit to the time permitted for this. The principle is clearly illustrated in Fig. VIII-3, in which is shown how the silicates present in the steel which is teemed from the nozzle of the ladle at its bottom are less in proportion after each period of holding the metal, whereas they increase as pouring proceeds. This is especially true when the ladle has been partly emptied and the liquid metal contains the inclusions which have been rising from the bottom all the time. This principle has led to the rule of acid open-hearth practice: "Tap hot and pour cold." Titanium has long been used for clarifying steel not only because it has a strong affinity for oxygen and assists in the deoxidation of the steel but because its oxide also helps to flux and tends to coalesce and cause to rise to the surface oxides of some of the other metals. The titanium must be added after all the other oxidizers and must be kept out of contact with the slag. Vanadium is a powerful deoxidizer and it has the effect, when added after all the other deoxidizers, of robbing some of the oxides of manganese, iron, etc., of their oxygen and so causing them to dissolve in the steel. In this way vanadium is one of the best scavengers that can be used and is a powerful deoxidizer but must not be left in the steel to the extent of over 0.30 per cent because its presence increases steel's brittleness.

✓**Separation of Inclusions.**—Three conditions help solid oxidized particles to separate by gravity from liquid steel:

1. Larger size: manganese oxide and silicon dioxide formed by reaction with dissolved iron oxide are extremely small in size when first formed. If they will react to form silicates and if they remain liquid, they will grow by coalescence. Reaction and coalescence are more likely if silicon is added first and then manganese, as already pointed out. A great advantage of adding silicon first is because it finds much iron oxide with which to unite and form silicates. Herty has shown that an inclusion with 78 per cent iron oxide and 22 per cent silicon dioxide has a freezing temperature of 1240°C.; it will coalesce easily and rise rapidly. While an inclusion with 45 per cent iron oxide and 55 per cent silicon dioxide has a freezing point of 1430°C. He says that a steel recarburized with ferrosilicon and ferromanganese both added in the ladle contained from 0.03 to 0.09 per cent of silicate inclusions; a similar steel with ferrosilicon added in the furnace and ferromanganese in the ladle contained 0.02 to 0.05

per cent of silicate inclusions; but when silicon-manganese alloy was added to a similar steel in the ladle, it contained only 0.015 to 0.04 per cent of silicates.

2. The more fluid the metal, the more rapidly the inclusions will rise.

3. A period of rest will allow the steel to clarify, as already said (see Fig. VIII-3).

Blowholes.—The chief cause of blowholes in steel is the presence of oxide of iron in the metal. This oxide of iron reacts with the carbon added in the recarburizer and forms carbon monoxide gas, which may be produced during the entire solidification period and thus cause many blowholes. That oxide of iron is one of the chief causes of blowholes is shown by many things; *e.g.*, (1) steel known to be highly oxidized is very liable to blowholes; (2) cast iron, which from its chemical composition can never be much oxidized, is not so subject to blowholes; and (3) the addition to steel of deoxidizers prevents the formation of blowholes. Blowholes are especially liable to occur in low-carbon steel. When the metal is in a molten state, it readily dissolves certain gases, such as hydrogen, nitrogen, oxygen. Upon solidification these gases come out of their state of solution but may become entangled in the steel and cause a gas bubble or cavity varying all the way in size from microscopic proportions up to 1 in. or more in length. The formation of these blowholes is precisely similar to the formation of air bubbles in ice; water dissolves a good deal of air while in the liquid state and, as we all know, it is well-nigh impossible to freeze the water without

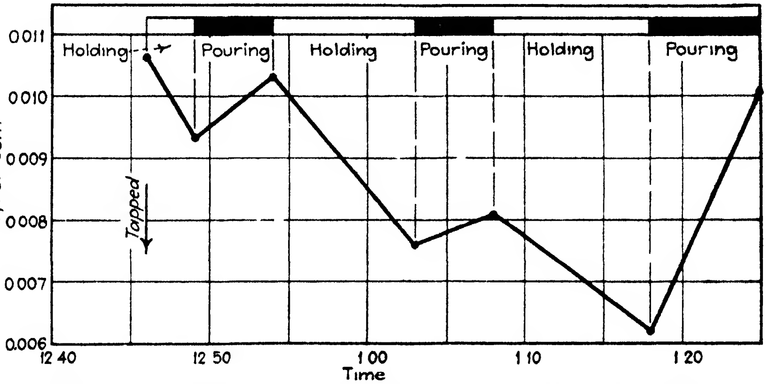


FIG VIII-3. —Elimination of silicates during pouring (*From Herty and Jacobs, Clean Steels from Acid Open Hearth, Metal Progress, February,* 1931.)

obtaining a great many air bubbles in the ice, due to the separation of this air during freezing. The occurrence in the case of steel is not so prevalent as in the case of ice, and it is by no means impossible to obtain steel absolutely free from this defect. Apparently the reason for this is that the gas separates from steel a short time before solidification is complete, and thus the bubbles have *some* opportunity to escape before they are enclosed in the solid.

Prevention of Blowholes.—Chief among the deoxidizing elements which are added for this purpose are manganese, silicon, and aluminum. These elements seem to act partly by deoxidizing the iron and carbon, in both ways reducing the formation of carbon monoxide, and partly by increasing the solvent power of the solid metal for gases, so that a less amount separates. The amount of these deoxidizing substances necessary to be added will depend largely upon the extent to which we desire to prevent the formation of blowholes. In the case of steel castings it is often necessary that blowholes be entirely prevented, but in the case of ingots which are to be subsequently forged or rolled it is not necessary that blowholes should be absent altogether, because they will be closed up under the pressure of the mechanical work and their sides welded together. Indeed, their presence is sometimes desired, because when they separate from the steel they occupy space, thereby counteracting to a certain extent the shrinkage of the metal during solidification and tending to reduce the volume of the shrinkage cavity, or pipe. For this reason a small number in some harmless locality is often intentionally allowed to form in steel ingots. Mr. Brinell found in his steel works that, if the percentage of manganese plus 5.2 times the percentage of silicon is equal to 2.05 or more, the steel will be entirely free from blowholes. In this case, however, the pipe will be large. If this sum is equal to 1.66, the steel will contain a harmless number of minute blowholes, but the pipe will be small. This figure is therefore about the correct amount for ingots under conditions similar to those of Mr. Brinell's experiments and not far different in any event. Mr. Brinell also found that the addition to the steel of 0.0184 per cent of aluminum will give approximately the same result as that given by the amount of manganese and silicon last mentioned, 1.66.

Desired and Undesired Blowholes.—But blowholes too near the skin of the ingot may break out into a crack, and once such a crack is formed no amount of mechanical work will eliminate or hide it. Such a crack requires cold chipping of the metal—the metal must be chiseled out of the piece down to the very root of the defect. After this rolling will produce a smooth surface.

Location of Blowholes.—The number and size of blowholes are no more important than the position they occupy in ingots in relation to the external surface. Even in castings, blowholes, if present, should be deep-seated, as they are then less liable to be exposed by machine work performed on the surface. In the case of ingots the deep seating is of still greater importance, because then the blowholes may be closed up before they have an opportunity to break through to the surface and thus become oxidized on their interior. The normal gases in blowholes are reducing in effect, and thus the interior surfaces of the holes are bright and silvery in appearance and readily weld together; but if they become oxidized they will never adhere firmly. For instance, a blowhole near the surface, as in Fig. VIII-1, is liable to break through to the exterior when the ingot is put under pressure. This not only causes a crack in the steel but allows the air to oxidize the interior of the hole and thus prevent the crack's being welded up by the rolling. It is not at all uncommon to see a number of these openings form during rolling.

As the percentage of manganese plus 5.2 times the percentage of silicon decreases from 1.66, the blowholes become correspondingly deeper seated. Finally, when this sum becomes as low as 0.28, the blowholes are harmlessly located in the interior. It is usually impracticable, however, to get the manganese and silicon as low as this in steel, because manganese is needed to counteract the bad effect of sulphur and oxygen.

The location of the blowholes is also very largely dependent upon the fluidity of the metal when first cast into the molds. The more fluid it is, other things being equal, the nearer will the blowholes be to the surface of the solid ingot. On the other hand, if the casting temperature is too low, there will be a dangerously large number of blowholes in the steel, because it solidifies so quickly that very little opportunity is afforded for any part of the dissolved gases to escape. The fluidity of the steel depends partly upon its temperature and partly upon the amount of impurities in it. Therefore every different kind of steel has a different correct casting temperature. It is to be observed that low-carbon steel suffers greatly from blowholes, because the less the carbon, the greater the liability to oxidation of the steel.

Effervescing and Killed Steel.—Effervescing steel is one in which the escape of gases goes on even in the ingot mold, producing a constant boil, with many resulting blowholes and a relatively small volume of pipe. But "dead-killed" steel is that which has been thoroughly deoxidized, so that it lies quiet in the molds and solidifies with few, if any, blowholes. A steel which effervesces in a very definite way and gives an almost uniform number of blowholes, none of which are in the ingot skin, is known as *rimming* steel. This steel boils over from the sides to the center, making a low-carbon skin with the center somewhat more segregated. Uniform conditions of deoxidizing and teeming temperature must be maintained in order to secure this regularity of rimming behavior. In this steel there is no pipe, but the volume of blowholes equals about 2 to 4 per cent of the volume of the ingot. It is impossible to have dead-killed steel unless the steel contains medium or high carbon, so this rimmed steel is much in demand for low-carbon analyses.

Crystallization of Steel in Ingot Molds.—When iron and steel freeze they crystallize, and these crystals grow with great rapidity, so that, if their passage through the solidification period is slow, they will attain a very large size. This formation of large crystals is known as *ingotism*. It is especially liable to occur if the metal is cast at too high a temperature or is allowed to cool through the solidification period at too slow a rate. In the case of steel, ingotism may be detected by breaking the casting; the large size of the crystal faces or facets will then be observed. As the cooling of ingots proceeds from the surface inward, the crystals join one another and grow somewhat like a fir-tree structure; with their long axes perpendicular to the wall of the ingot mold, as shown in horizontal section in Fig. VIII-4 and in vertical section in Fig. VIII-5. These long crystals are known as *dendrites*. The lines between the dendrites are lines of weakness in the body of the steel. One of the most important functions of rolling or forging of steel is to break up these lines of weakness in the steel and to convert the dendritic structure into a fine-grained, uniform mass, as indicated by sections (2) and (4) in Fig. VIII-6. In medium- and low-carbon steel, however, the crystal lines and junctions are always evident after mechanical work, as illustrated in Fig. VIII-7. In the crystallization (freezing) of steel in a cast-iron ingot mold there are three zones formed:

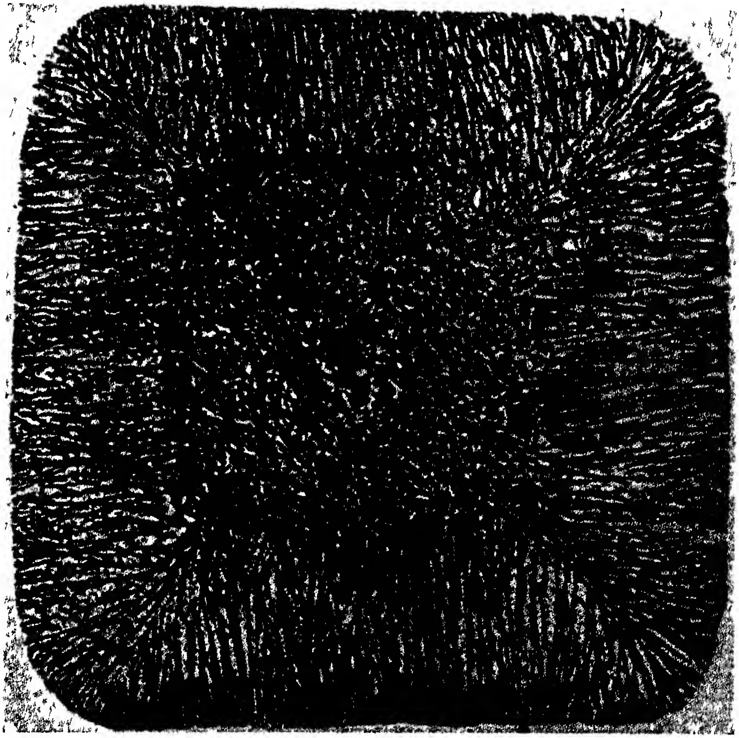


FIG. VIII-4.—Horizontal fracture of steel ingot showing dendritic structure. (*From Gathmann Engineering Co., "Ingot Contour and Its Relation to Sound Steel."*)

1. Immediately next the wall the metal is chilled by rapid radiation through the mold. The crystals here are small and equiaxed, lines of weakness between them thus being avoided (see Fig. VIII-8). This gives a relatively tough "skin" to the ingot which resists tearing when the mold is lifted off the ingot and also resists breaking when the steel is first worked in the rolls or forge. Every effort is made to get this skin as thick as possible, but the contact between ingot and mold wall is not very

long, since the hot ingot shrinks away from the mold. If the ingot is forced into the mold and contact maintained, the skin is thicker, as shown in Fig. VIII-5.

2. Next comes a zone of dendrites.
3. Finally, an inner core of roughly equiaxed crystals.

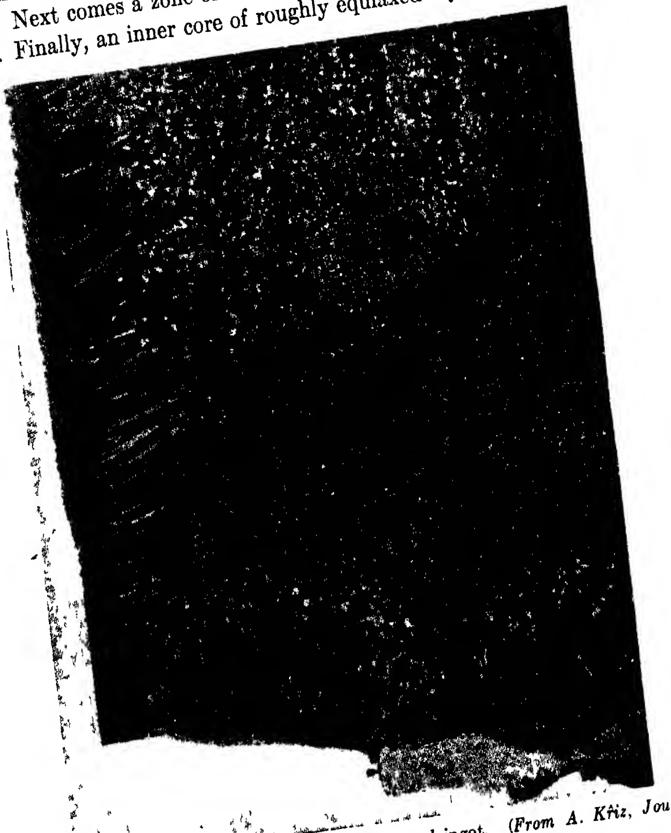


Fig. VIII-5.—Primary crystallization in a steel ingot. (*From A. Křiz, Jour Iron Steel Inst., No.* 1, 1932.)

Because of this ingot structure, ingots are "saddened" when first mechanically treated; *i.e.*, they are given light reductions in the rolling mill or forge in order to toughen them before they are subjected to much pressure.

Pipes.—When steel is poured into a mold, it forms almost immediately a thin skin of frozen metal against the cold surface of the sand or iron. The radiation of heat thereafter necessarily takes place through these surfaces, and therefore a casting will usually complete its solidification by the formation of thicker and thicker layers of solid metal around all the sides. The top surface, however, will usually remain molten longer than the rest because the hottest metal is usually at this point, having been the last to leave the ladle, and also because the heat is not conducted away by the air so fast as by the walls of the mold. This is especially true where the casting is poured into an iron

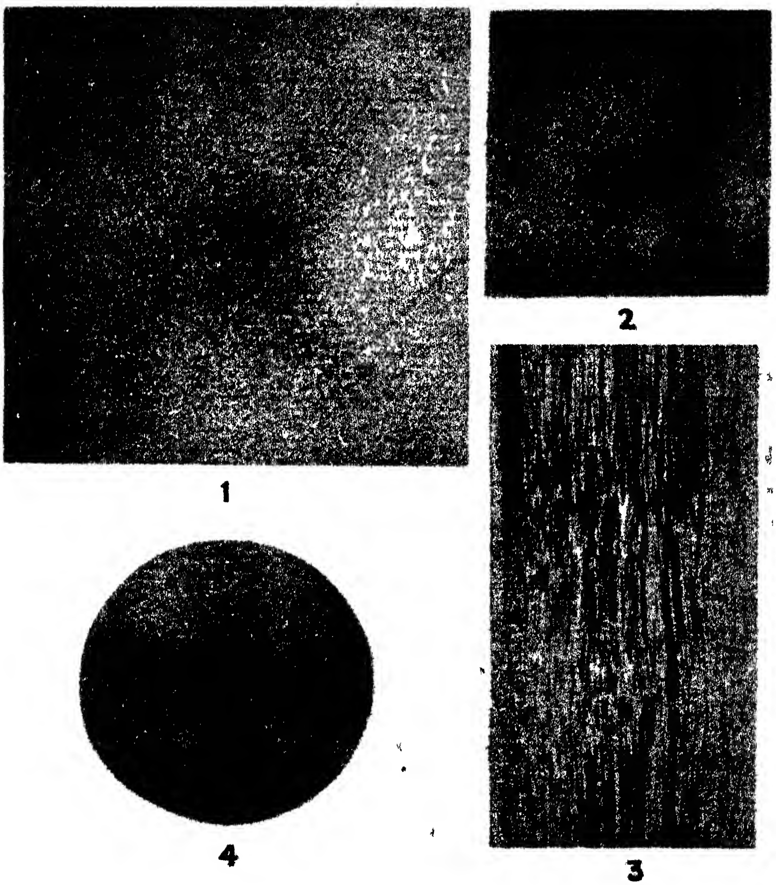


FIG. VIII-6.—Effect of reduction of area on the dendritic structure of high-carbon tool steel. (1) Bar hammered to 2.5 in. square. (2) Same hammered to 1.5 in. square. (3) Longitudinal section of 2. (4) No. 1 hammered to 1.5 in. diameter. Carbon 1.09 per cent, manganese 0.36 per cent. (*From Keshian, Trans. A. S. S. T., November*, 1927.)

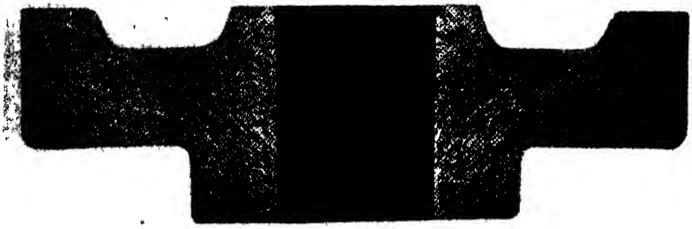


FIG. VIII-7.—Flow lines in a medium-carbon steel after the original ingot has been forged and punched hot. (*From Publication* 72 *of The National Machinery Co., Tiffin, Ohio.*)

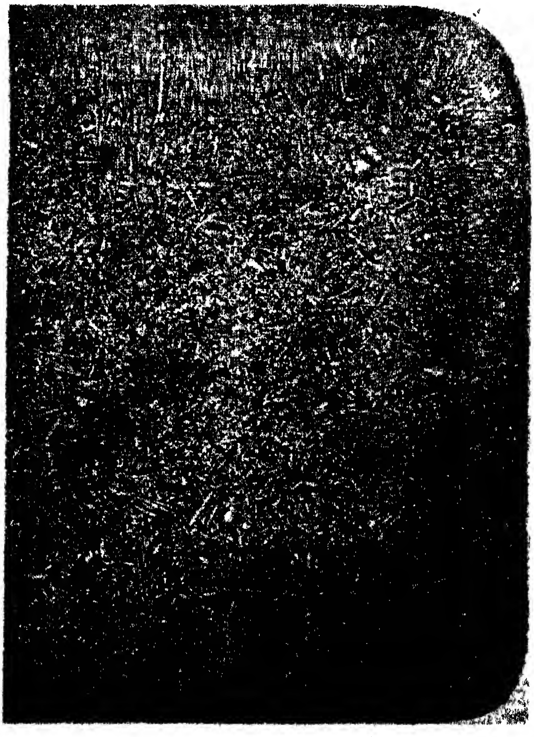


FIG. VIII-8.—Cross-section of 6- by 6-in. straight carbon steel ingot cooled slowly in the mold which was buried in lime. It shows the effect of the rate of cooling on the development of dendritic structure. Carbon, 1.05 per cent; manganese, 0.24 per cent; silicon, 0.20 per cent; phosphorus, 0.027 per cent; and sulphur, 0.009 per cent. (*From Keshian, Trans. A. S. S. T.*, 1930.)

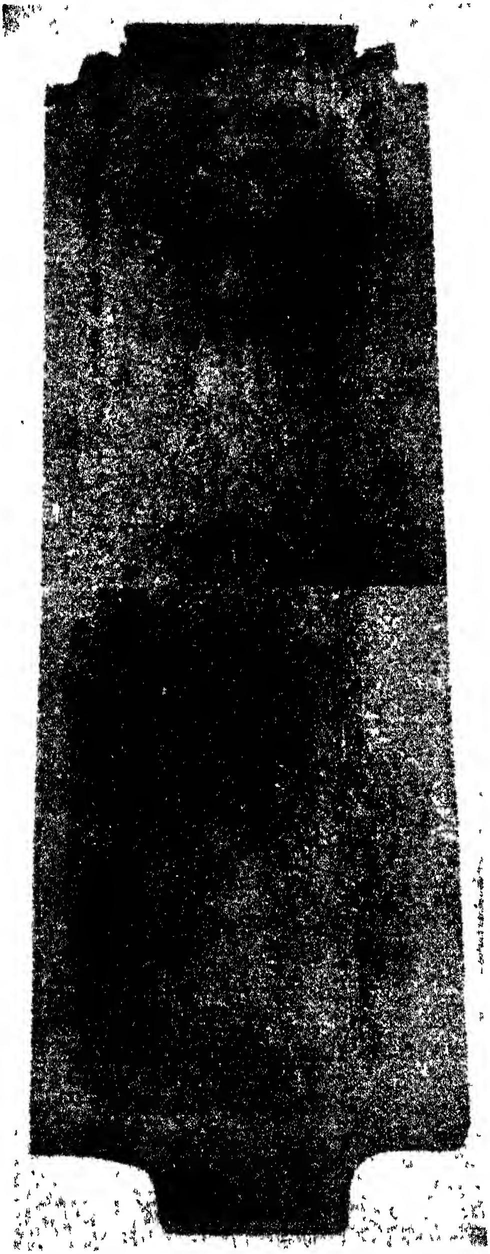


Fig. VIII-9.—Sulphur print of ingot which was put under hydraulic pressure after solidification, so that the walls of the ingot remain constantly in contact with the walls of the ingot mold. (*From Kříž, Jour. Iron Steel Inst. No.* 2. 1930.)

mold, *e.g.*, in the case of ingots. But it is evident that at some period a stage will be reached when all the outside of the ingot, or casting, will be covered by a skin of solid metal while the interior will still be liquid. The liquid interior will continue to freeze and will, at the same time, contract. The result will be the shrinking of the molten mass away from the solid walls and consequently the formation of a cavity, known as a *pipe*, in the interior (see Fig. VIII-2). This pipe will be filled with the gases evolved by the steel during solidification. Professor Howe has shown that the volume of the pipe is too large to be accounted for altogether by the shrinkage of the steel during solidification and that the rate of contraction of the inner walls of the ingot being greater than the rate of contraction of the outer walls a virtual expansion of the outer walls is caused and a consequent enlargement of the pipe.

FIG. VIII-10.—Pipes in steel ingots. (*From James M. Camp, "The Making, Shaping and Treating of Steel," 2d ed.*)

The portion of the steel containing the pipe is, of course, defective and should be discarded at some time subsequent to casting. In the casting of ingots the upper part, which contains the pipe, is cut off during the rolling or forging and goes back to the furnace to be remelted as scrap. In the casting of steel castings there is a large adjunct to the castings situated above it, so regulated in size and otherwise that it freezes after the casting itself and thus always contains a supply of molten metal which runs down and fills any cavity that forms in the casting. This adjunct is cut off when the casting has cooled. In other words, the *riser*, or *feeder*, as this extra part is called, serves the same purpose for a steel casting as the upper part of an ingot does for the ingot.

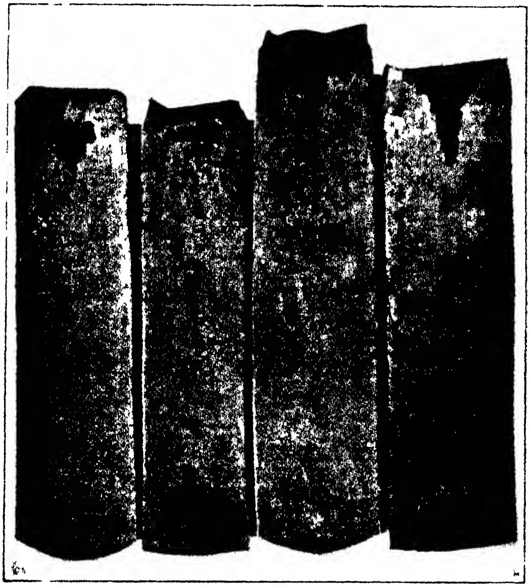


Fig. VIII-11 —Pipes in steel ingots. (*From James M. Camp, "The Making, Shaping and Treating of Steel," 2d ed.*)

Lessening the Volume of the Pipe.—If the steel were poured into the mold so extremely slowly that it would solidify in layers from the bottom upward, there would be no pipe. Therefore one method of lessening the volume of the pipe is by slow teeming. Another is to have the metal near its point of solidification when teemed. We have already noted another method, *viz.*, permitting a small number of blowholes to form, which causes a certain amount of expansion to the steel during solidification and thus diminishes its shrinkage. Another way is to use wide ingots because this reduces the difference in contraction between the inner and outer layers of the ingot. Casting in sand molds has the same effect because radiation is not so rapid through sand as through metal. Still another method is to prevent the steel from forming a solid skin over the top by constantly stirring and breaking it up with an iron rod. This method is often resorted to with the risers of steel castings, with very beneficial results. Still another method is to have the metal walls of ingot molds much thicker at the bottom than at the top. This causes a more rapid radiation of heat from the bottom and concentrates the pipe at the upper end. In some cases a sand lining is placed in the mold at the top to insulate heat radiation and keep the top warm. Most steel works now use refractory tops on their ingot molds, as shown in Fig. VIII-12. The ingot is first filled up to the top of the mold itself, then the ladle passes on to the next ingot; after it is filled, the refractory top on the first ingot is filled. This forms a reservoir of hot metal to feed the top of the ingot, and it results in the shrinkage cavity's being in the top part and not in the ingot, as shown in Fig. VIII-13. The slower the top of the ingot cools in relation to the bottom, the more the pipe will be drawn upward. Another method of accomplish-

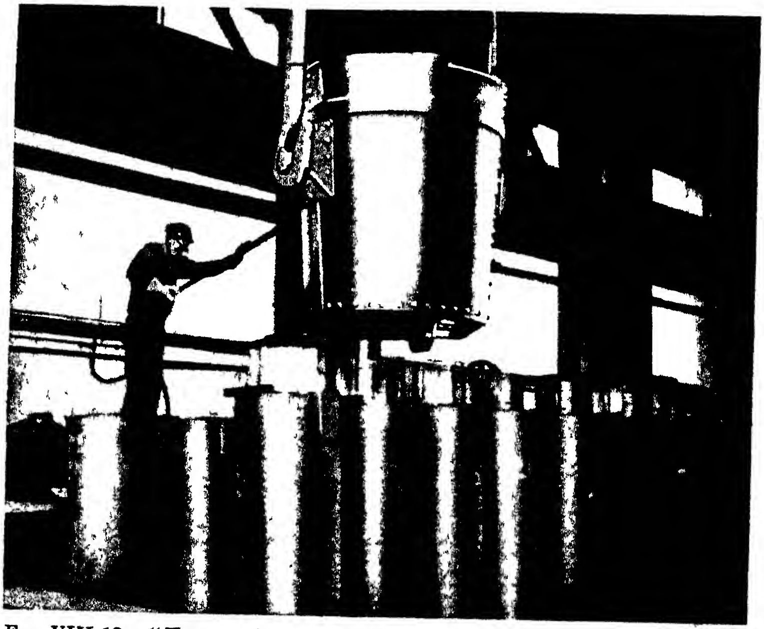


FIG. VIII-12.—"Hot tops" on ingot molds. (*From Bull. SM-1, Electro Metallurgical Co., New York.*)

ing this result is to cool the bottom part of the ingot faster by having thicker cast-iron mold walls there to radiate the heat This is the original idea of Gathmann, one of whose ingot mold designs is shown in Fig. VIII-14.

Castings Ingots with the Large End Up.—Gathmann also developed a method of casting ingots with the large end up, instead of down, and still was able to get them out of the molds. This has a still further effect in drawing the shrinkage cavity to the top. The Gathmann mold has a refractory-lined top. After the ingot is solid on the outside, the top is removed, leaving the risers of the ingots protruding, as shown in Fig. VIII-15. The riser is grasped by the stripping machine, as shown in Fig. VIII-16.

Fig. VIII-13.—Polished and etched section of ingot. (*From "Ingot Contour and Its Relation to Sound Steel," Gathmann Engineering Co., Baltimore, Md.*)

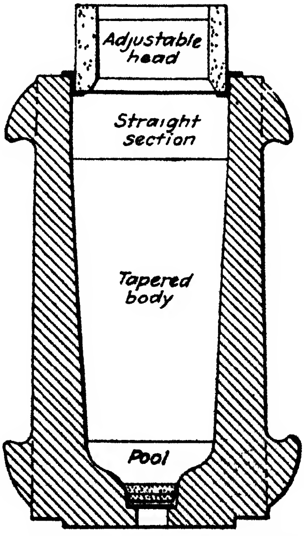


Fig. VIII-14.—Gathmann type of big-end-up ingot mold. (*From "Ingot Contour and Its Relation to Sound Steel," Gathmann Engineering Co., Baltimore, Md.*)

Liquid Compression of Ingots.—If the pipe is caused by the difference in expansion between the inside and the outside of an ingot, it is evident that putting sufficient pressure upon the outside when the walls are solid but the interior is still liquid will prevent the formation of a pipe. Numerous processes have been devised for effecting this liquid "compression," some of which are in operation at steel works and produce ingots that are entirely free from pipes. In Whitworth's system the ingot is raised and compressed lengthwise against a solid ram situated above it, during and shortly after solidification. In Harmet's method the ingot is forced upward during solidification into a tapered mold. This causes a large radial pressure on its sides. The ingot, a part of which is shown in Fig. VIII-5, was cast at the Skoda works in Czechoslovakia by the Harmet liquid-compression process, and this is the way by which contact was maintained between the ingot and its mold walls.

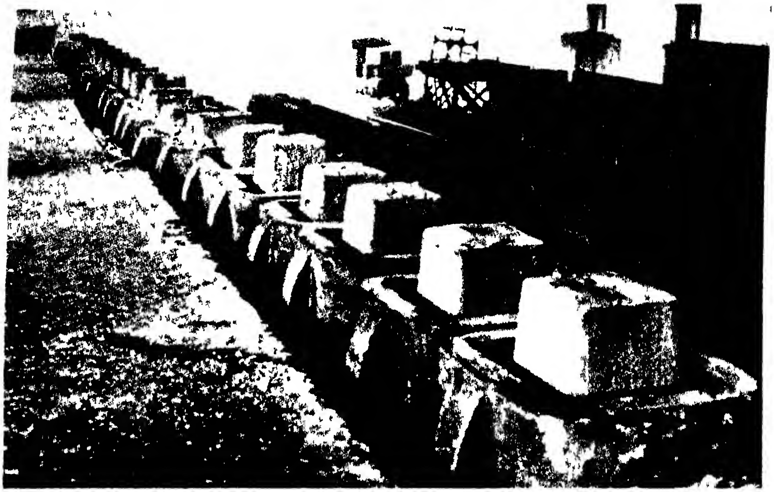


FIG. VIII-15.—Risers on big-end-up ingots. (*From "Ingot Contour and Its Relation to Sound Steel," Gathmann Engineering Co., Baltimore, Md.*)

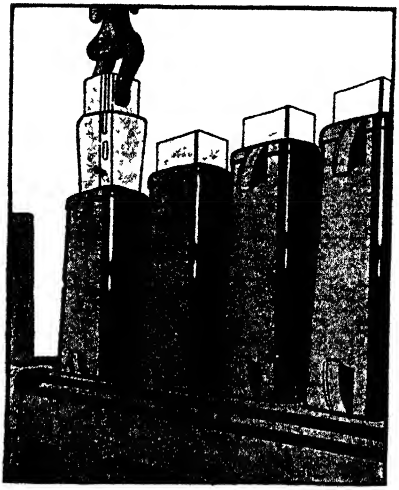


FIG. VIII-16.—Stripping a big-end-up ingot. (*From "Big-end-up versus Big-end-down Ingot Production," Gathmann Engineering Co.*)

Segregation.—When either iron or steel is molten, the various impurities are dissolved in it, and some of them, especially carbon, phosphorus, and sulphur, make the metal more fusible; *i.e.*, they lower its melting point. But the impurities are not so soluble in the solid metal and therefore tend to separate on solidification; so it can readily be conceived how each layer that freezes, beginning at the outside, rejects some of its impurities to be dissolved by the still liquid mass in the interior. When the next layer freezes, that too will tend to reject a part of its impurities into the contiguous molten layer, and thus the concentration will proceed so that as a general thing the portion of the metal richest in impurities, especially in carbon, phosphorus, and sulphur, will be that which freezes last. With ingots, this

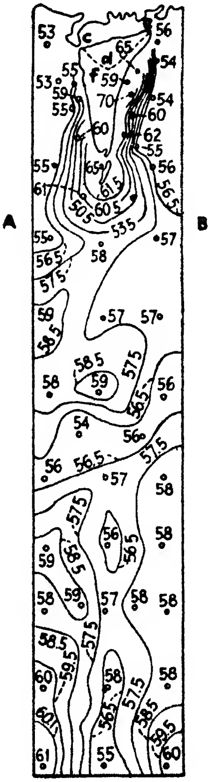
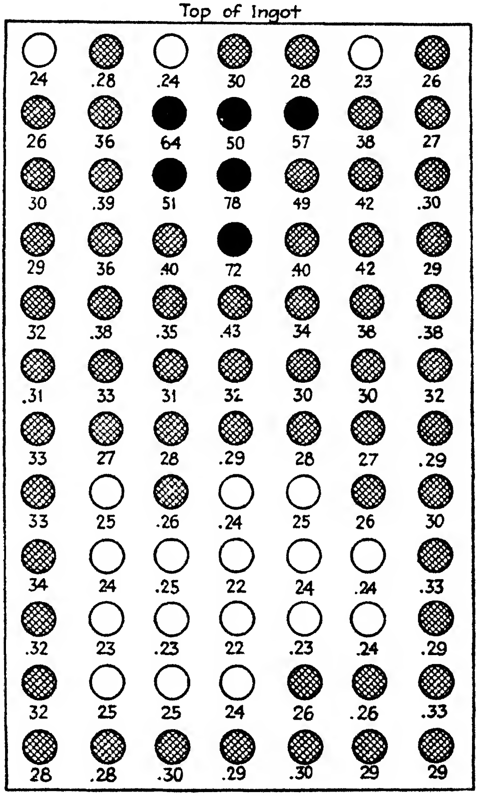


Fig. VIII-17.



○ 24	▨ .28	○ .24	▨ 30	▨ 28	○ 23	▨ 26
▨ 26	▨ 36	● 64	● 50	● 57	▨ 38	▨ 27
▨ 30	▨ .39	● 51	● 78	▨ 49	▨ 42	▨ .30
▨ 29	▨ 36	▨ .40	● 72	▨ .40	▨ 42	▨ 29
▨ 32	▨ .38	▨ .35	▨ .43	▨ 34	▨ 38	▨ .38
▨ .31	▨ 33	▨ 31	▨ 32	▨ 30	▨ 30	▨ 32
▨ 33	▨ 27	▨ 28	▨ .29	▨ 28	▨ 27	▨ .29
▨ 33	○ 25	▨ .26	○ .24	○ 25	▨ 26	▨ 30
▨ 34	○ 24	○ .25	○ 22	○ 24	○ .24	▨ .33
▨ .32	○ 23	○ .23	○ 22	○ .23	○ .24	▨ .29
▨ 32	○ 25	○ 25	○ 24	▨ 26	▨ .26	▨ .33
▨ 28	▨ .28	▨ .30	▨ .29	▨ .30	▨ 29	▨ 29

Fig. VIII-18.

Fig. VIII-17.—Lines of equal carbon percentage in a steel ingot.
Fig. VIII-18.—Carbon percentage at different parts of a steel ingot.

will evidently be at a point just below the bottom of the pipe (see Fig. VIII-17), and it is found to be so in the great majority of cases; but the location of the richest segregate is very liable to vary, and rules can be used only for general guidance. In the case of iron and steel castings, the most impure point will generally be near the top of the thickest section of metal. In iron castings which contained on an average less than 1 per cent phosphorus and 0.1 per cent sulphur, the author found on one occasion a segregated portion containing 1.856 per cent phosphorus and 0.144 per cent sulphur; and on another occasion he found one containing 2.43 per cent phosphorus and 0.236 per cent sulphur. An extreme case of segregation in steel is shown in the following analyses:

Analysis representing	Percentage				
	C	Si	Mn	P	S
Average	0.24	0.336	0.97	0.089	0.07
Richest segregate	1.27	0.41	1.08	0.753	0.418

The riser is calculated to be the last portion to freeze and the richest segregate should be located in it. Thus the position of the shrinkage cavity is seen to be of great importance because it also indicates the probable location of most impure metal. Ingots vary in analysis in all portions owing to the fact that freezing occurs by the growth of crystals out into the liquid mass. The metal that grows on these crystals tends to be relatively pure, but sometimes several crystals interlock and isolate liquid pools of metal between them. The proportion of impurities in these pools may be different from that in another liquid portion of the ingot. In some cases, in order to guard against segregation, purchase specifications require that the analysis of drillings taken from any portion of a steel member shall not vary more than 10 per cent from the analysis upon which the steel was bought.

Treatment of Segregated Steel.—Segregation cannot be prevented, although, of course, it seldom takes place to the degree shown in the extreme cases cited above. Nevertheless, there are always certain portions of the ingot or casting which are richer in impurities than other. An attempt is made to get this richer portion into the upper part of an ingot or into the riser of a casting, and then it is cut off when the ingot is rolled or when the riser of the casting is removed. It is therefore advantageous to cause the segregate to go as high up in the ingot or casting as possible. Whatever tends to raise the pipe higher up in the casting would, in general, tend to raise the segregate also. Wide ingots or ingots cast in walls with low conducting power, though they tend to decrease the volume of the pipe, would not necessarily raise the segregate to a higher point. Furthermore, wide ingots will probably have a much greater degree of segregation than narrow ingots, other things being equal, because the wider the ingot, the greater will be the number of layers of solidification and consequently the greater concentration of impurities in the center.

Lessening Segregation.—Benjamin Talbot has shown that quieting the steel by adding aluminum to it will lessen the segregation. J. E. Stead argues that this result is due to the branches of crystals (commonly called *fir-tree crystals*) which grow perpendicularly to the cooling surfaces when steel solidifies mechanically entangling some of the impure metal, thus preventing it from traveling inward. Professor Howe calls this type of freezing the *landlocking type*. When the steel is violently agitated by the escape of gas, its rapid movement washes off the fir-tree crystals and prevents them from growing out into the liquid mass and entangling the impure metal. The quietness produced by aluminum, however, makes this growth possible.

Another important means of lessening the segregation is by making ingots narrow, *i.e.*, by reducing the area of the horizontal cross section; but this is often difficult of accomplishment. For example, if we cast 50 tons of open-hearth steel out of one ladle, it will take a very long time to cast all of this into small ingots, and therefore the first ingots cast will be too hot or else the last ingots will be too cold. There is a difference of opinion as to whether or not rapid cooling decreases or increases the degree of segregation, and it seems probable that it acts in both directions, sometimes prevailing one way and sometimes in the opposite. On first thought it would seem that slow cooling must necessarily increase segregation, because it would allow more time for the impurities to separate from one layer of metal and dissolve in the next. On the other hand, slow cooling also favors the growth of the fir-tree crystals and therefore opposes segregation. It does not seem possible, at the present time, to tell under what conditions we should have the one influence prevailing or the other.

It seems to be pretty well established that the greater the percentage of impurities present, the greater will be the extent of the segregation. Therefore high-carbon steel should be cast with due care and narrow ingots used wherever possible. Generally when the phosphorus and sulphur are low (say not more than 0.05 per cent each), much segregation is not liable to occur, especially in low-carbon steels. One of the most active causes of segregation is oxidization of the steel as it comes from the furnace. This appears to be the most potent influence next to excessive phosphorus and sulphur.

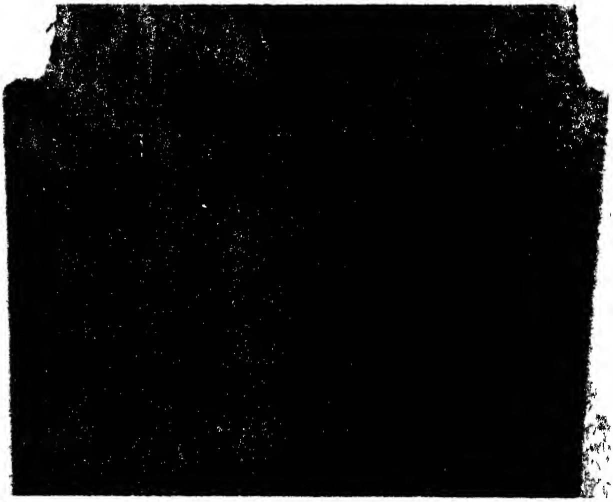


Fig. VIII-19.—Sulphur print of a part of an ingot near the top. This ingot was not held against the ingot mold walls during solidification and its sulphur segregation should be compared with that in Fig. VIII-9. (*From Jour. Iron Steel Inst., No.* II, 1930)

Sulphur Prints.—If a piece of steel be polished and then brought into close contact with silver bromide photographic paper which has been wet with sulphuric acid, there will be a slight evolution of hydrogen sulphide wherever the sulphur in the steel is sufficiently high. This shows as a black spot on the photographic paper. "Sulphur prints" indicate spots to which sulphur has segregated. They may or may not indicate segregation of other impurities also. They are made by some manufacturers to cover the whole section of an ingot 8 ft. long. Such a one is shown in Fig. VIII-9.

Rate of Pouring.—The speed with which the ingot molds are filled with steel has an important influence on the smoothness and the toughness of the skin of the ingot. This speed is regulated by the size of the ladle nozzle, because, if one tries to control the speed by varying the opening between stopper and nozzle, a scattering stream results, which spatters the sides of the mold, either causing them to be burnt and made rough or else freezing shots on the sides, which gives a very bad surface to the ingot. If the mold sides are made very rough, they must be scrapped, because otherwise the tender sides of the red-hot ingots will be torn when they are stripped. The speed with which steel will flow out of a given size of nozzle will depend very greatly upon the amount of metal in the ladle, because the fuller the ladle, the greater the pressure behind the stream. The figures given in Table VIII-I represent actual weights of steel teemed out of a ladle nozzle of the sizes indicated, but they must be used with caution, because different conditions make great differences.

TABLE VIII-I.—NUMBER OF SECONDS REQUIRED TO TEEM 1 TON OF STEEL OUT OF NOZZLES OF THE SIZES GIVEN

Size of nozzle, inches	Number of seconds	Size of nozzle, inches	Number of seconds
$\frac{7}{8}$	80 to 140	$1\frac{1}{2}$	25 to 45
1	50 to 100	2	13 to 25
$1\frac{1}{8}$	40 to 82	3	7 to 12
$1\frac{1}{4}$	35 to 65		

Steel in a 100-ton ladle will cool at the rate of 10°F., more or less, per minute until the ladle has been heated, and then more slowly. The heat should be teemed complete in a total of 60 min. maximum. If 20 ingots, each weighing 5 tons, are to be poured, then 3 min. will cover each ingot, including the time of moving the ladle from ingot to ingot. Let us say 16 sec. per 5 tons, or 3.2 sec. per ton. Obviously a $1\frac{1}{2}$-in. nozzle will be used. If the mold is 84 in. high, then the liquid steel must rise at the rate of 31 in. per minute in order to fill the molds in the time available. This is much too fast. Herty says that 9 in. rise per minute is about the best speed for good surface on the ingots. If it is only 6 in. per minute, the ingots will have surface defects, and the bloom made by the first rolling will require chipping to avoid marks on the finished steel. On the other hand, if the speed is as high as 15 in. per minute, there will also be surface defects. This confirms approximately an investigation made in England in 1917[1] regarding the time of pouring ingots weighing 5,600 lb. each, with 14 ingots per heat. The steel analyzed about 0.45 per cent of carbon. The results follow:

Time of pouring each ingot, minutes	Ingots cracked at forge, per cent	Bars chipped, per cent
2	100	Nearly all
3	50	40
3½	40	30
4	10	8
5	5 (slightly)	4
6	2 (very slightly)	2
7		2

These ingot molds were filled at the rate of about 35 in. rise in liquid steel per minute for those poured in 2 min., and 10 in. (Herty's rate) for those filled in 7 min. The first 6 in. teemed into a mold must be put in cautiously to avoid splash. The top 12 in. must also be put in slowly to allow gases to escape and, in the case of rimming steel, to allow it to rim.

Basic open-hearth steel is tapped out of a basic furnace into a ladle lined with silica brick. While the steel stands in this ladle during the teeming of the heat, there is a slow reaction which takes place taking silicon out of the steel and increasing slightly the phosphorus and sulphur in the steel at the expense of that in the slag. This is another reason for not keeping steel in a ladle more than 50 min.

Temperature of Teeming.—The two factors which have the most influence in ingot practice on the quality of the steel are the temperature of teeming and the rate of rise of steel in the ingot mold. Unfortunately, temperature cannot be well controlled in top-casting practice, because, if it takes 60 min. to pour a 100-ton heat, the steel teemed into the first ingot will be 300 to 600°F. hotter than that teemed into the last one. It is important to complete teeming in 30 min., if possible. The optimum teeming temperature is related to the freezing temperature of the steel, and this in turn depends on its composition. A practical method of determining this is to teem at a temperature which will leave

---

[1] Kilby, *Journal of the Iron and Steel Institute*, No. 1, 1917.

a suitable amount of skull in the ladle. Some superintendents work for about 700 lb. of skull after teeming a 100-ton heat, and others prefer to have about 1,000 lb.

Splash.—Next to rate of pouring and temperature, splash is probably the most important feature of teeming to watch. Many attempts to lessen this by pouring down a pipe, etc., but few such have survived. The Gathmann mold shown in Fig. VIII-14 has a configuration of the bottom part which is especially designed to lessen splashing.

Bottom Casting.—If many ingots must be teemed from a 100-ton heat, then it may be necessary to teem two or more ingots at once. This can be done by using a "pouring box," which extends over two or more molds and has a nozzle over the center of each mold. It receives metal from a large nozzle in the ladle and pours it through a small nozzle into each mold. While this practice seems to be admirable in design, it has not been universally approved in the works. A similar result can be accomplished by bottom pouring, which is illustrated diagrammatically in Fig. VIII-20.[1] The steel is poured into a central

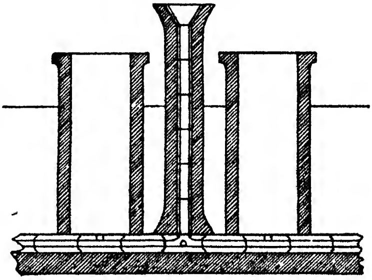


Fig. VIII-20.—A typical bottom-casting arrangement which illustrates the use of male and female runner brick.

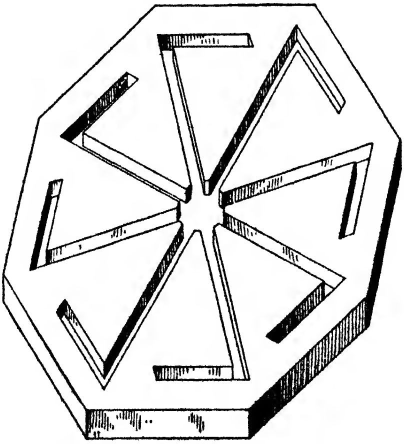


Fig. VIII-21.—Stool for bottom casting.

---

[1] Bitzer, *Blast Furnace and Steel Plant*, December, 1931.

runner and enters each ingot mold from the bottom. This practice is almost universal for teeming ingots to be rolled into plates, because of the great importance of the surface of plates. From 2 to 24 ingots can be bottom cast from each runner, cast-iron stools of various forms similar to Fig. VIII-21[1] being used to hold the refractory runner bricks which lead the liquid stream from the central runner to the exact center of the ingot mold. Bottom pouring avoids all splashing against mold walls and gives great flexibility and control over the temperature at which the ingots are teemed and the rate of rise in the mold. It also better protects the ingots from dirt or slag carried in from the ladle. It produces more scrap, on account of the metal left in the runners and, after teeming, leaves the hotter steel at the bottom of the ingot instead of at the top. Bottom casting also costs more because it cannot be handled on cars.

Internal Checks, or "Flakes."—These may have their origin in stresses in the ingot during the solidification period, and immediately thereafter. This is especially hazardous when making large and wide ingots or castings, which sometimes must be cooled with extreme slowness, even by resorting to the expedient of removing them from the mold and burying them in ashes at the earliest possible moment. Inclusions, by forming points of weakness, form loci of possible internal cracks.

Stresses produced during heating the ingot for rolling may also be a source of internal cracks, and this heating should be very slow, especially with large ingots. The less the number of ingots in the furnace, the shorter the time in which they may be heated from the cold state. Thus, with wide spaces between the ingots in the furnace and ingots of 2-ton size, they may be heated from the cold in 4 to 6 hr.; on the other hand, very large ingots require heating for 36 hr. or more. Even when hot ingots are charged into the heating furnaces as rapidly as they can be stripped and transferred, there must not be too high a temperature of the furnace as related to that of the ingot.

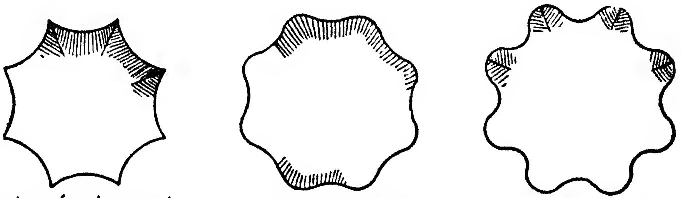
Still another cause of internal cracks is breaking apart of the crystals by mechanical work in rolling or forging. This is most likely to occur in the case of ingotism, dendritic or columnar crystallization.

External Cracks.—Bad pouring which splashes steel on the sides of the molds, where it solidifies, produces scabs on the surface of the ingot, which persist and appear in the final product

---

[1] BITZER, Blast Furnace and Steel Plant, December, 1931.

as marks, slivers, or seams. These splashes may also hinder the free movement of the metal along the sides of the mold and thus give rise to strains which tear the outer surface either during the weak and brittle period when the steel is not quite solid or during the second weak period known as the *blue heat* (300 to 375°C., 572 to 707°F). Rough molds, and those which have cavities burned in the sides, produce the same effect. Finally, "stickers" which have to be removed from the molds by main strength in the stripping machine will naturally be liable to emerge with cracked surfaces. The remedy for this is not to use molds that are too old or rough and to have a good taper on the mold, so that the ingot will free itself easily during the contraction period of solidification. Cracks are also liable to occur on the corners of ingots, owing to the junctions of crystals, as indicated for fluted ingots in Fig. VIII-22. In the case of square ingots the weak line of junction is even more marked than is here indicated, since the crystals normally grow perpendicularly from the surface inward. Pouring at a low temperature and slowly tends to restrain external cracks by giving the walls time to grow in thickness before the ingot gets long and assumes much longitudinal contraction, as well as by decreasing the tendency to form large crystals. The tendency to crack is increased by the expansion of the hotter internal layers of steel at the temperature of about 700°C.[1] (1292°F.) when the colder exterior is shrinking. This effect is intensified in the case of very large



Deep plane of weakness and segregation of chill crystals

No plane of weakness or segregation of chill crystals

Plane of weakness in chill crystals

FIG. VIII-22.—Horizontal sections of ingots to show different forms. Steel crystals grow from the cooling surface inward. The relation between the size of crystals and the radius of curvature of cooling surface will determine the extent of weakness due to crystal junctions.

---

[1] At the critical temperature 700°C., cooling steel passes through a period of inward reheating, or recalescence, during which it grows warmer for a few minutes and expands slightly (see Chap. XI). This action is followed by cooling and contracting.

ingots, which are therefore cast in a fluted form, so that the outer surface can stretch without cracking. Steel of 0.17 to 0.24 per cent carbon is specially liable to external cracks.

Scabs.—During teeming, particles of pasty slag or oxide of manganese, floating on top of the liquid steel in the mold as it fills, may adhere to the side of the mold and appear later as a scab. The plates of oxide of manganese so common on rail-steel ingots do not cause any damage usually, but slag or dirt may produce a permanent defect in the rolled material.

Taper of Ingots.—The taper of molds must be such that the ingot will free itself easily and will strip without tearing even when the mold is somewhat rough from service. The longer the ingot, the greater must be the taper, because the greater the total contraction between top and bottom, and the greater the amount of surface for sticking. Most molds have a taper of about ½ in. per foot of length, but the importance of each decimal of a fraction requires special investigation for every type of practice.

References

Report on the Heterogeneity of Steel Ingots by a Committee of the Iron and Steel Institute of London, *Journal of the Iron and Steel Institute*, No. 1, 1926, 1928, 1929, 1932.

J. H. Kruska: Finishing the Heat of Steel, running serially in *Blast Furnace and Steel Plant*, beginning September, 1932.

CHAPTER IX

THE MECHANICAL TREATMENT OF STEEL[1]

Metals may be shaped either by pouring them while molten into a mold, as described in the following chapter, or by mechanical pressure. The choice of the casting or the mechanical method of shaping will depend on the cost of production, the size and form of the finished product, and the purpose for which it is intended. Some shapes must be produced by casting, because they are either too intricate or too large to be shaped by pressure; others must be produced by pressure, because the service in which they are to be used demands the higher strength and ductility which mechanical work produces. Between these two classes, however, is a large number of forms, each of which is a study by itself. Financial considerations will govern in some cases, and the importance of quality in others. The advantage of quality is usually with the pressed material. Cost is usually in favor of castings except where many pieces are to be produced alike in shape and size. In other words, where we have only a few pieces and/or where they are very large in size, we must employ castings.

Effect of Work.—Mechanical work will multiply the strength of steel from two to five times. In order to accomplish as much as five times, however, it is necessary (1) to reduce the material to very small sizes, in order that the beneficial effect of the kneading action may extend throughout the mass, and (2) to roll at atmospheric temperature, after hot rolling. The ductility will be increased by hot working but again decreases if the metal is worked cold. The increase in strength and ductility is due (1) to decreasing the size of the crystals and closing the grain

---

[1] When the first edition of this book was written, there was no recent book in English on the mechanical treatment of steel. But now a number of excellent reference books are available and the descriptive matter in this chapter has been reduced in order to give more space in this and other chapters to the more strictly metallurgical features of iron and steel manufacture. Some of the reference books referred to are listed at the end of this chapter.

of the steel, (2) to the closing up of blowholes, both large and small, which are almost all welded together under pressure at high temperatures, unless they are near enough to the surface to become oxidized inside, and (3) to increasing the cohesion

FIG. IX-1.—Crystals of cast steel, magnified 100 diameters, showing large size (*Courtesy of James M. Camp.*)

FIG. IX-2.—Crystals of steel like that in Fig. IX-1, but showing small size due to mechanical work in the cold. Magnified 100 diameters. (*Courtesy of James M. Camp.*)

and adhesion of the crystals. All these effects increase the compactness and hardness of the metal and are more effective in these respects, as well as in increasing strength, if hot work is followed by cold work.

Crystallization of Steel.—Metals are crystalline substances, the individual components arranging themselves in regular forms unless opposed by the rigidity of the mass in which they form. Indeed, the metallic crystals, or grains, grow with astonishing rapidity after the metal crystallizes from the molten state (*i.e.*, freezes, or solidifies), or even when it is in a mobile condition (*i.e.*, at temperatures above a red heat). Once large grains have formed, they cannot be reduced in size except by annealing (see Chap. XIII) or by breaking them up by mechanical crushing. See Figs. IX–1 and IX–2. These facts are important, because large grains do not adhere to each other firmly, and thus they cause a weak and brittle mass. Iron and steel follow the same laws as other metals in these respects.

FIG. IX-3.—Straight slip bands in wrought iron magnified 60 diameters. (*Courtesy of William Campbell.*)

FIG. IX-4.—Neumann's lines. Cleavages produced by forging at too low a temperature. (*Courtesy of William Campbell.*)

Effect of Strain.—When a metal is strained, the crystals first stretch, and the amount of this stretching is directly proportional to the strain; when the strain is relieved, the crystals and the mass as a whole return to the original dimensions. If the strain is greater than the *elastic limit*, however, the crystals yield, and the space lattices composing them slip along the cleavage planes, so that a permanent deformation or extension occurs in the direction of the strain. This *elongation* is accompanied by a *reduction in cross-sectional area* and gives warning that the material is suffering from excessive strain. The extent to which these two forms of distortion precede rupture is usually taken as the measure of the "ductility" of the metal.

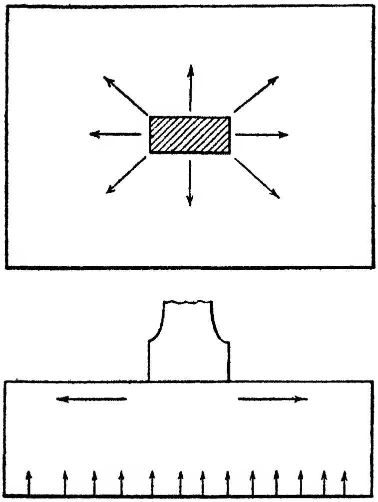


FIG. IX-5.—Effect of a hammer blow on a piece of steel

Rationale of the Effect of Work.—Mechanical pressure upon a metal crushes the grains, mixes them intimately together, and breaks up the cleavage planes along which they would yield. If the work is finished above a red heat where the mass is still mobile, the grains reform to a certain extent. The elastic limit of a structural steel hot-rolled in this way will be a little more than one-half its ultimate strength. If the work is repeated when the metal is cold, there is no opportunity for the reformation of the crystals, and the strength, hardness, and brittleness are much increased. The elastic limit

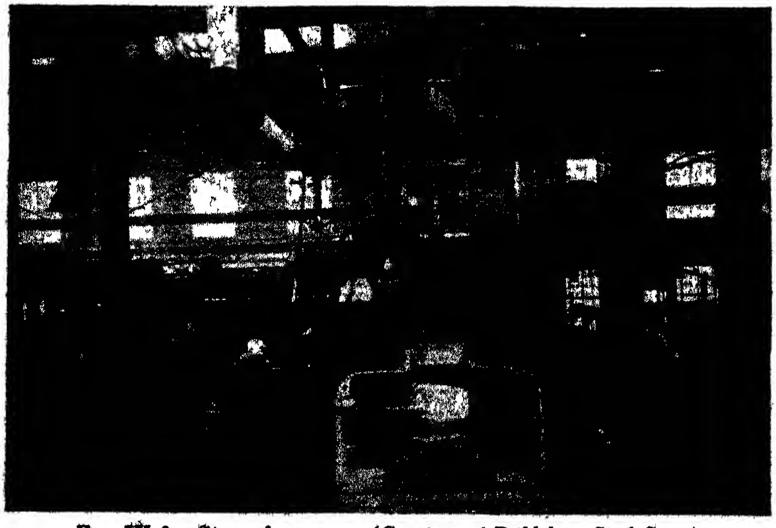


FIG. IX-6.—Steam hammer. (*Courtesy of Bethlehem Steel Corp.*)

of a cold-rolled steel will be 70 to 90 per cent of its ultimate strength.

Methods of Applying Pressure.—Aside from the differences of hot and cold working, the mechanical pressure may be exerted in one of three ways: (1) instantaneously, by a blow, in which method the pressure is relieved before the metal has fully yielded to it, (2) more slowly, by rolling or wire drawing, in which the pressure is relieved almost as soon as the metal has yielded to it, and (3) slowest, by presses, in which the pressure remains fo a second or so after the metal has yielded (see Fig. IX–7a to compare).

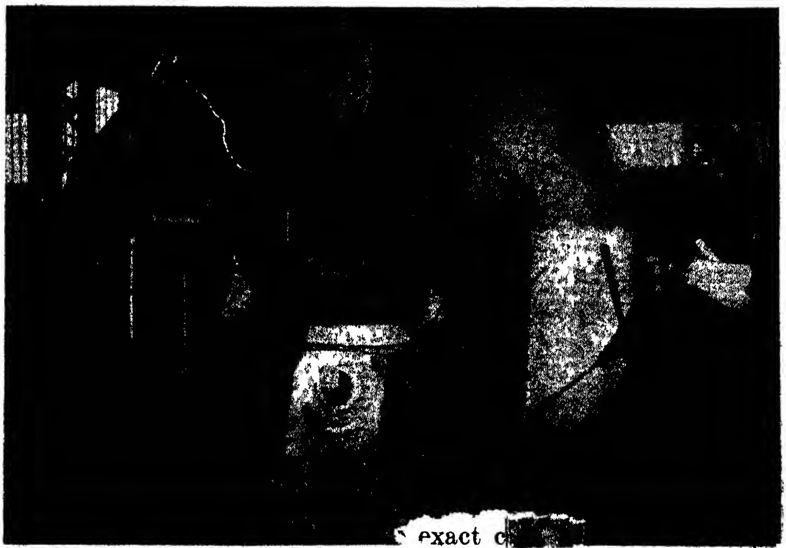


Fig. IX-6a.—Forging a steel wheel. (*Courtesy of Standard Steel Works.*)

The Forging of Metals

The instantaneous application of pressure is man's first method of shaping metals and is accomplished by a blow from a falling weight, frequently aided by so~~me other force~~. Examples of the first practice are found at the present time in the helve hammer or drop hammer still used at many small forges and steel works. After the introduction of steam, however, this was used to raise the weight, and very soon steam power was employed not only to raise the weight but also to force it downward for the blow, whose momentum was thus greatly increased. Hammers of this type,

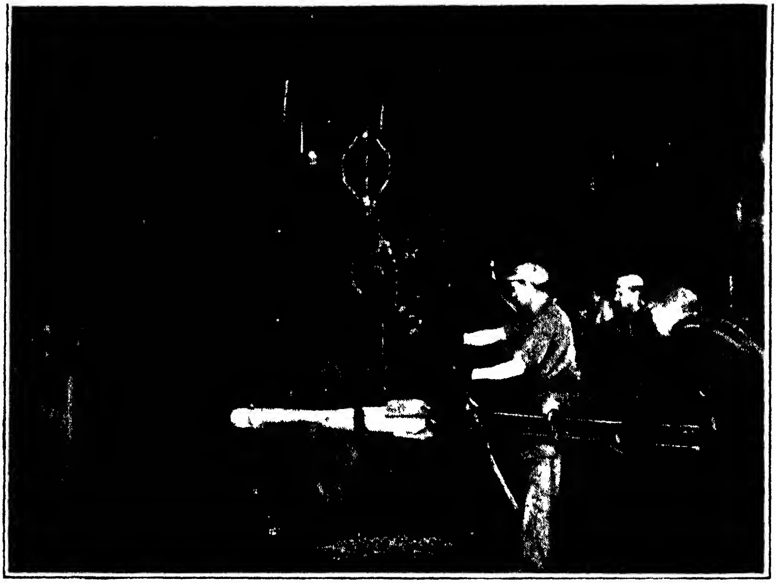


FIG. IX-7.—Forging a small billet under a steam hammer.

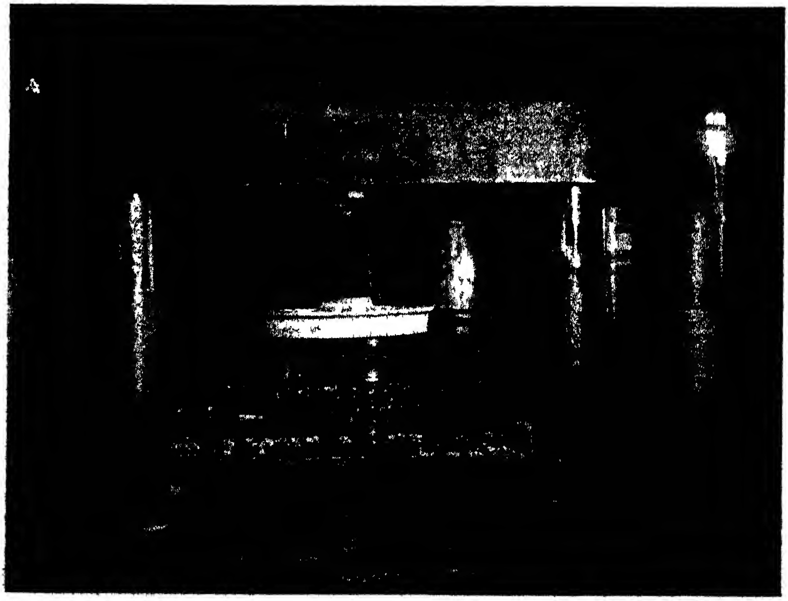


FIG. IX-7a.—One stage in the formation of a steel wheel under a hydraulic press. (*Courtesy of Standard Steel Works.*)

which is now the most prevalent, have been built capable of delivering a blow estimated as equivalent to 150 tons' weight. Such large sizes are not now approved of, however, because of the inordinate expense for foundations, which must be deep and powerful in order to take up the force of the blow, while the constant jarring disturbs the foundations and alinement of machinery, even at distant parts of the plant. For very heavy forging work, such as armor plate, the hydraulic press is therefore preferred, and hammers are not often built in sizes above 30 or 50 tons. *Forging* is the name applied to mechanical work performed either by a hammer or by a press.

Effect of Hammering.—A blow creates in a metal practically nothing but compressive strains, which act chiefly in the vertical direction and, by transmission, in all horizontal directions. Because the pressure is relieved almost as soon as felt, the elasticity of the metal causes it to recover somewhat from the effect. This makes the effect of hammering superficial (see Fig. IX-5). Also the amount of yield to it is not great in proportion to its force, and therefore it takes more pressure to accomplish a result than would be the case if the application were slower. This makes hammering a slow process of reduction but results in a better and more uniform working of the crystals on the surface, which is a reason for the superiority of hammered over rolled material, provided the section is thin. Another and, perhaps, even more potent reason is the exact control of the operation which can be exercised by the expert forger, and more especially his control over the temperature at which the work is finished, and over the varying force of pressure applied at different stages and temperatures. On the other hand, the effect of forging does not extend deeply from the upper and lower surfaces.

Finishing Temperatures for Hot Forging.—Forging must not continue below 700°C. The exact temperature for finishing will depend upon the chemical composition and size of article. The colder it is finished, the closer to the exact size required it can be made, because it has less shrinkage to undergo; but it will also be harder, less ductile, and stronger. The relation between the finishing temperature of hot mechanical work and the critical points of steel will be discussed in Chap. XIII (see also Figs. IX-8*a* and IX-8*b*).

Drop Forging.—There is a large variety of articles, such as parts of automobiles, other machinery, hammer heads, and simi-

Fig. IX-8*a*.—Effect of finishing temperature. Crystals of steel, magnified 100 diameters. Finishing temperature high. The grain is smaller than that of Fig. IX-1 but coarser than that of the steel in Fig. IX-2. (*Courtesy of James M Camp.*)

Fig. IX-8*b*.—Effect of finishing temperature. Crystals of steel magnified 100 diameters. The steel, like that in Fig. IX-8*a*, was subjected to mechanical working while hot, but the finishing temperature was low. (*Courtesy of James M. Camp.*)

lar tools, which are formed by the process known as *drop forging*. In this operation a piece of metal of the desired size is forged by repeated blows between a lower die, upon which it rests, and an upper die attached to the head of the hammer. These two dies are made in the desired form of the finished article, and the metal is squeezed into them until it has assumed the proper shape. Sometimes several pairs of dies are necessary to complete the finished shape. Drop forgings are directly comparable with steel castings, to which they are superior in quality on account

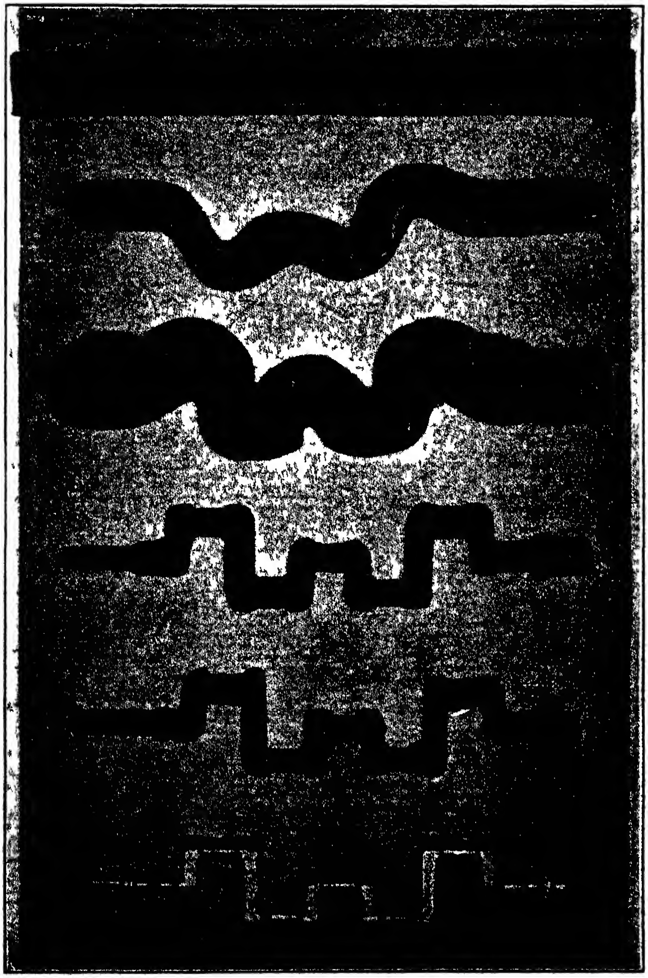


FIG. IX-9.—Stages in making a drop-forged crankshaft from a flat bar.

of the beneficial effect of the working. To be economically made, they must be ordered in large quantities, so that it will pay to make the costly dies of hardened steel—often an alloy. Even then, castings are sometimes cheaper, though forgings are still preferred on account of their quality. There are cases, however, in which drop forgings may be made more cheaply, either because the shape is one that lends itself to rapid production in this way or because it is one liable to checking or requiring a large riser, if cast.

Fig. IX-10.—Fluted ingot for making cannon tube. This form allows what Howe calls "the virtual expansion of the outer walls" (see page 246), without cracking those walls. It also allows the interior to expand without cracking the exterior. Finally, it avoids weakness due to crystal junctions (see Fig. VIII-22).

Die Pressing.—Recently there have been developed machines for forming red-hot steel pieces between dies which are pressed together, instead of hammering. These are especially adapted for forming pieces of large size and have come largely into use.

Forging Bars.—Tool-steel ingots are often forged instead of rolled, because the material will bring a price high enough to pay for the superior method of working it. The ingot, after the top third has been broken off to remove the pipe and segregate, is heated to a bright-red heat, out of contact with the flame and fuel, and then tilted down under a hammer of about 10 to 15 tons' size until it is about one-half as large on the sides and four times as long. One end is then reheated and drawn down to a bar of the desired size, under the same hammer, or under one of less weight, and the long bar is then used as a handle while the other end undergoes heating and reduction. The finished size is produced by light taps of the hammer just before the blue heat appears, and often a piece of cold steel is laid beside it on the anvil to more correctly arrest the downward blow. The finished bar will be so straight and true as to lead one to believe that it was produced by drawing through a die or rolling in grooved rolls.

Pressing

Steel may be pressed either hot or cold, the latter method being used chiefly for thin and soft steel, and the former for very large work, such as heavy machinery, locomotives, armor plate, and cannon, for which hydraulic presses have now largely replaced the heaviest steam hammers.

Effect of Pressing.—The effect of pressing upon the metal differs from hammering in that its action extends deeper into the material, thus giving a somewhat superior texture to the interior. Tests cut from the center of large pieces forged under the press are very much superior to those cut from the same place in pieces forged under the hammer.

FIG. IX-11.—Fourteen-thousand-ton press. (*Courtesy of Bethlehem Steel Corp.*)

Hot Pressing.—Presses vary in size usually from 600 to 14,000 tons. They may be either of the continuous or of the intermittent type. In the latter, the amount of pressure exerted increases step by step as the work progresses. The amount of work that can be done by the press in large-sized pieces is greater than that done by hammers for the same amount of power used. This results in a double saving of fuel, since more work can be accomplished with one heating. By means of the 10,000-ton press at the Homestead Steel Works, a 50-ton armor plate has been reduced 2 in. in thickness and moved forward 6 in. for each squeeze, while a 3,000-ton press at the Firths Works in England has reduced a 30-ton ingot from 49 to 28 in. diameter in

30 min., and from 51 to 26 in. diameter in 65 min. Small pieces can, however, be turned out a little faster under the hammer.

Cold Pressing.—Thin plate for steel railroad-car construction and many other purposes is often formed by pressing it cold between dies under hydraulic presses of from 30 to 800 tons' capacity. In this way bolsters, braces, and many other parts are formed with great economy. Sometimes two or three presses are required with different dies to complete the shaping, and occasionally it is necessary to press some of the work hot, because the distortion is so great that the steel would otherwise be torn.

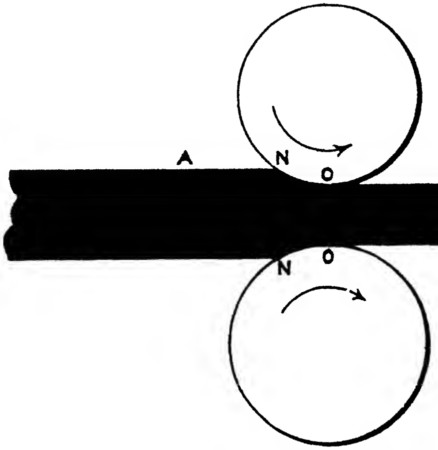


Fig. IX-12.—The reduction of metals in rolls.

Cold pressing is also known as *flanging*. It has one great difference from hot pressing in that there is no reduction in the sizes of pieces treated.

The Reduction of Metals in Rolls

If two rolls rotating as shown in section in Fig. IX-12 be made to grip a piece of metal *A*, they will drag it between them and force it out on the other side reduced in thickness. The metal between the points *OO* and *NN* is being compressed vertically, while its outer layers are suffering tension. In the case of a deep section, the unequal strain produced by unequal speed of travel is liable to tear the steel (see Fig. IX-31). The mechanical pressure is therefore not so uniform as in hammering but acts for a slightly longer period of time. Reduction can only take place vertically, as in forging, there being always a certain amount of expansion sidewise and a large amount of extension in length. In Fig. IX-12, the metal at the points *NN* being forced backward, and that at the points *OO* being forced forward, the ends of the rolled section assume a shape somewhat like that shown in Figs. IX-13 and IX-14. The reduction in area at each "pass" will vary between 5 and 50 per cent of the original, and the work is very rapid. For example, a railroad rail may be produced, from an ingot having a section 18 in. square, in 22 passes, varying in amount of vertical squeeze from 8 to 50 per cent, only about 5 min. being required for the whole operation, the piece traveling through some of the passes at a rate of 10 m. p. h., and in some mills not being reheated after the ingot comes to the first pair of rolls. Some American rolling mills produce over a mile of single rail per hour for 24 hr. a day and 26 days per month. The temperature at which the rolled material is finished is gaged with much less accuracy than in forging operations and is usually too high for the best quality of the steel, because economy of power urges the manufacturer to work the metal hot.

FIG. IX-13.—Shape of ends of rolled metal when the inside is the hotter.

FIG. IX-14.—Shape of ends of rolled metal when the outside is the hotter.

Pull-over Mill.—In a single pair of rolls, such as shown in Fig. IX-15, the metal, after passing between them once, must be handed or pulled over the top of the mill, to be fed in for a second pass. This type of train is known as a *pull-over* or *pass-over* mill. It can be used only for shapes that are small in size and that can be handled readily, and the action is slower than in a continuous operation, such as in a *three-high mill*. The pull-over mill is simple and cheap to construct and operate and is used only for the rolling of small sizes. It is used very largely for the rolling of steel to be used for tin plate. The upper roll is adjustable, so that any thickness may be produced.

Three-high Mills.—When a piece is passed over a two-high mill, it is often rested upon the top of the upper roll, whose travel assists somewhat in the transfer. While watching this operation at the Cambria Iron Company's mill in 1857, John Fritz conceived the idea of the three-high mill, which is shown in section in Fig. IX-16. It will be seen that the piece receives work in both directions. At the present time the great bulk of the tonnage of steel and wrought iron produced, consisting of structural shapes, railroad rails, plates, wire rods, billets, and bars, is finished in this type of mill. The output is large, because the rolls can be run very fast indeed (rod mills running 600 to 1,200 r.p.m. and sometimes passing the rod through at the rate of ½ mile a minute in American practice[1]), and two or more pieces may be passing through at the same time. A disadvantage of the three-high mill is the power necessary to raise large weights to pass over the middle roll. Most Bessemer ingots are cast 2 tons or more in weight, and most open-hearth ingots from 3 tons

FIG. IX-15.—Rolling "black plate" which is coated with tin to make "tin plate" This is an example of a pull-over mill.

[1] The reason for this rapid rolling is not only that the product is large but that the thin rods may not lose their heat during the operation and thus be finished too cold. This rapid work actually raises the heat of the metal faster than it can be radiated, and rods are hotter at the end than at the beginning of the rolling.

②

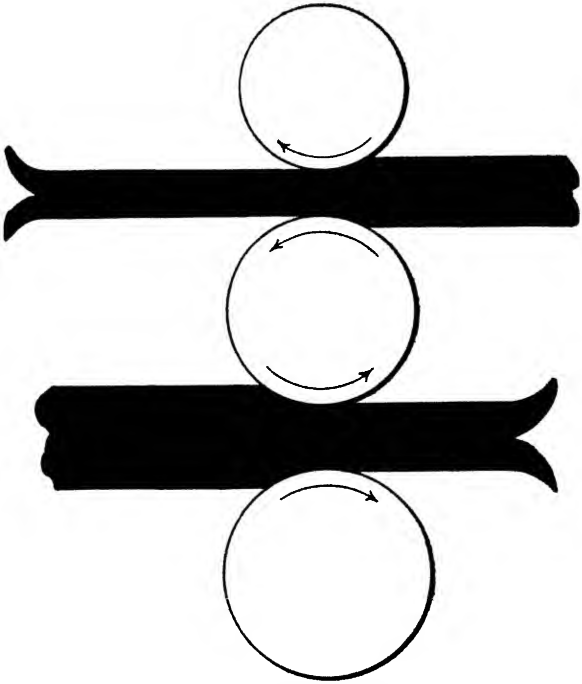


Fig IX-16 Action of three-high rolling mills.

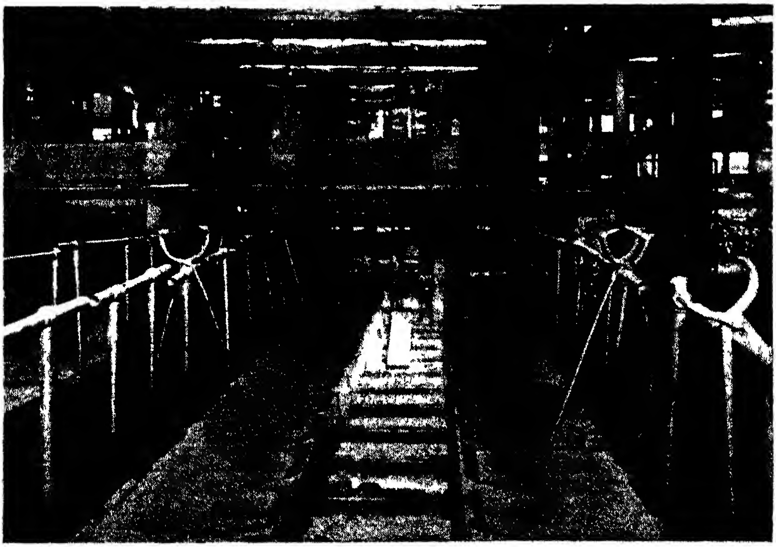


Fig. IX-17.—Three-high mill. (*Courtesy of Bethlehem Steel Corp.*)

to 10 tons or more. Another objection is the inability to adjust the amount of reduction at each pass.

Reversing Mills.—Therefore ingots are often "cogged" in two-high reversing mills. The two-high mills, which have an adjustable upper roll, have the advantage of being able to work an ingot gently at first, in case it shows a tendency to be "tender," *i.e.*, to crack in spots when the pressure is applied. The disadvantages of the two-high reversing mill are its slowness and the severe strain on the engines, which are often reversed while running full speed.

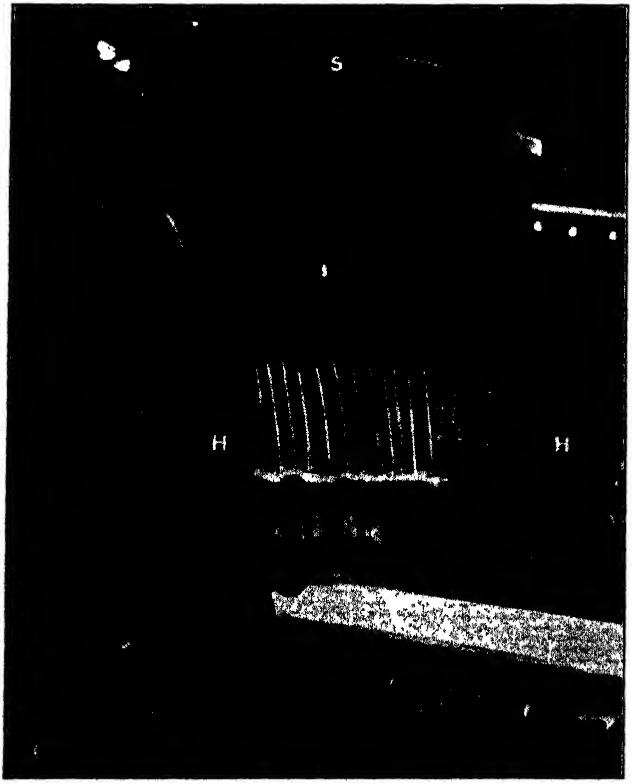


Fig. IX-18.—Two-high reversing blooming mill. *S*, screw-down mechanism. H–H, roll housings. (*Courtesy of United States Steel Corp.*)

Comparison of Three-high with Reversing Blooming Mills.—The loss of power necessary to raise pieces to pass above the middle roll of a three-high mill is more than counteracted by the loss of power due to overcoming inertia and reversing the two-high blooming, or cogging, mill. In the reversing mill 30 per cent of the power transmitted to the rolls is used in deforming the metal, and 60 per cent in the three-high mill. The work of the continuous three-high mill is also faster, turning out about twice as much rolled steel per day. On the other hand, the reversing mill is more flexible as to both the reduction given per pass and the size of products rolled. When we desire to make a different size or shape in a three-high mill, the rolls must be changed. Pieces which become very long during the rolling process can be handled more easily in reversing mills.

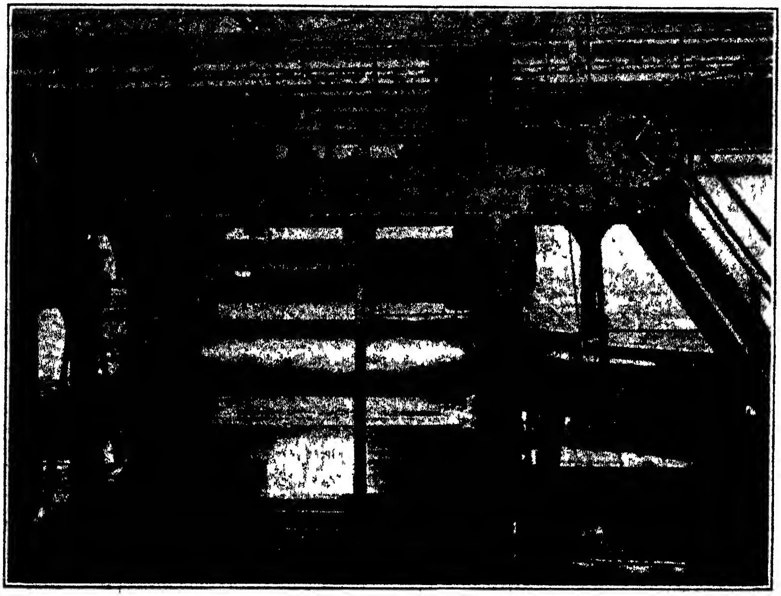


Fig. IX-19.—Reversing plate mill showing the dial which indicates the adjustable distance between the rolls.

Universal Mill.—During the rolling of metal there is a certain amount of expansion sidewise, which gives the piece a cross section somewhat bulging on the sides and makes the edges uneven, unless the rolls have collars which form a groove through which the metal passes. In 1855, R. M. Daelen, at Hoerde, Germany, devised a mill in which even edges could be produced at any width by having an auxiliary pair of vertical rolls, between which the piece passes immediately after it emerges from the horizontal rolls. These vertical rolls are adjustable to any width up to the capacity of the mill and give only enough pressure to keep the edges even without producing any reduction. They are usually made to rotate with a surface velocity greater than that of the horizontal rolls, so as to prevent the serious buckling that would take place if the conditions were reversed. As this tension is not good for the edges of the metal and wears out the vertical rolls, some mills have independent control of drive for each pair of rolls, and others have friction clutches connected with the vertical rolls, which allow them to run faster if pushed by the metal but ordinarily run them at a slower speed. Universal mills are made two high or three high, and with vertical rolls on one or on both sides of the horizontal rolls.

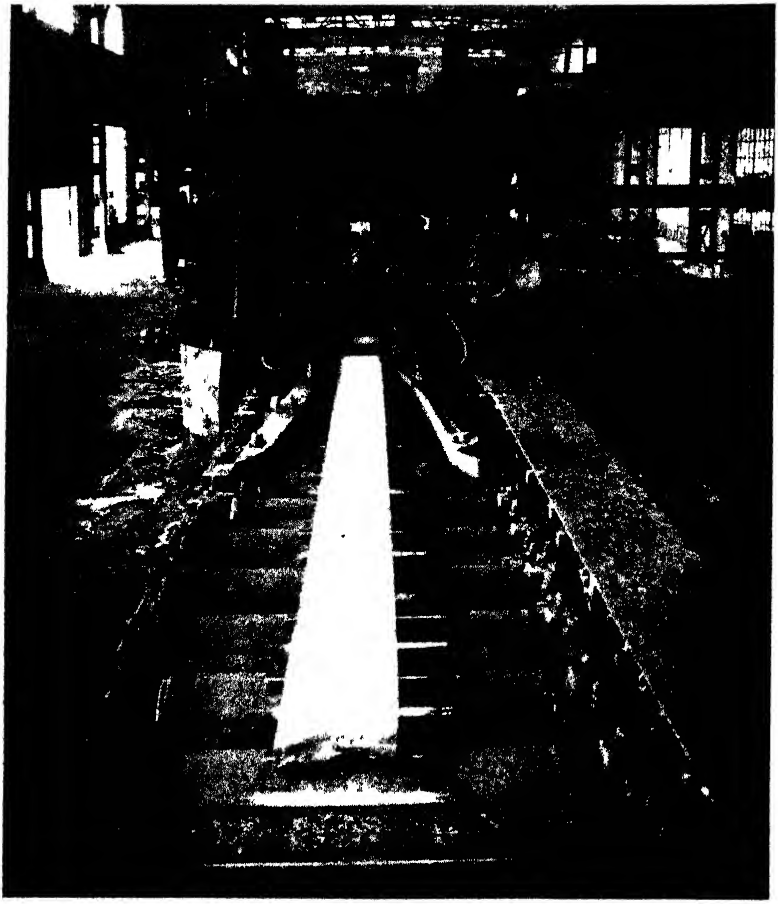


FIG. IX-20.—Universal mill. (*Courtesy of Bethlehem Steel Corp.*)

PARTS OF ROLLING MILLS

Rolls.—Rolls may be plain cylinders, by which plates and rectagonal shapes are produced, or they may be cylinders with "collars" at intervals, as shown in Fig. IX-22, in which large rectagonals with even edges may be produced; and the collars

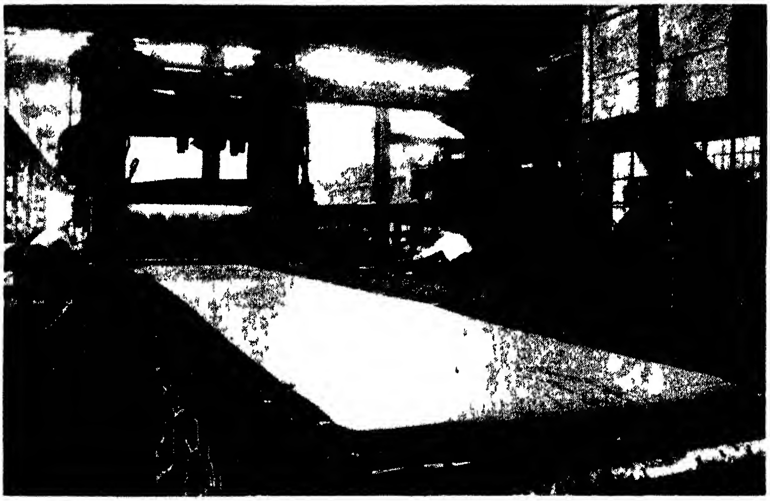


FIG. IX-21.—Plate mill (*Courtesy of Bethlehem Steel Corp.*)

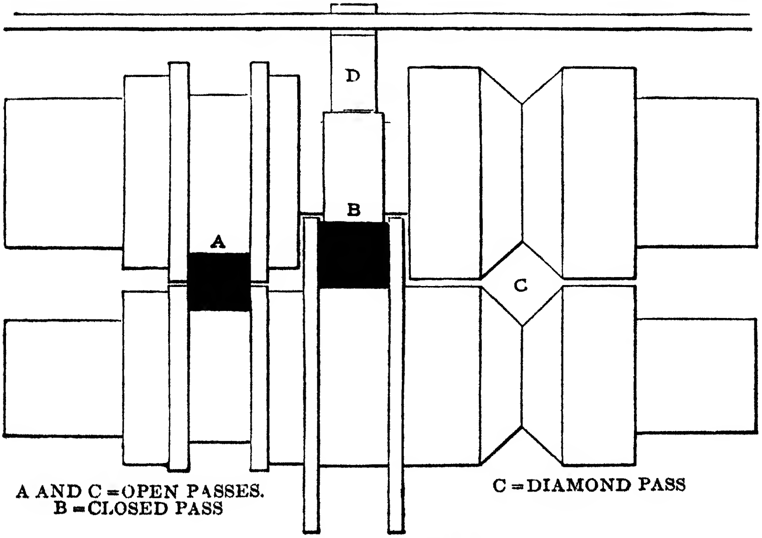


FIG. IX-22.—Rolls for shaping steel.

may be on both rolls, giving an *open pass* or may be on only one roll and extend into grooves on the other roll, as shown in Fig. IX-22, giving a *closed pass*. With open passes, the collars cannot be made quite to touch; hence the name. And the pressure may squeeze some metal between them, forming a "fin" along the side of the piece. This is called *overfilling the pass.* The closed pass makes the upper roll weaker, and there is also a liability of the metal becoming wedged tightly between the collars and thus drawn all the way around the roll, with the result that something will be broken. Wedge-shaped grooves may be cut in the rolls, producing the *diamond* pass, in which small squares are made (see Fig. IX-22); or oval grooves make nearly round bars which are finished round in the last pass with almost no draft. In case rolls are weakened by deep cutting, as shown in Fig. IX-22, they may be strengthened by stiffeners *D*, while long rolls for producing wide plates are sometimes stiffened by an idle roll running on top, lest the springing of the roll make the plate thicker in the middle than at the edges.

Cast-iron vs. Steel Rolls.—Cast-iron rolls are chilled upon the outside so as to produce a surface layer of white iron (see Fig. XIV-7), which, after turning in a lathe, makes a very smooth surface for rolling and is especially advantageous for finishing mills. They are not so good for the mills which do preparatory work, however, because they are not so strong, and because in preparatory work a rough surface is wanted to assist in gripping the metal and drawing it through. Furthermore, they cost more to turn to the desired shape, and they cannot be turned down many times, lest we get below the "chill." The greater cheapness of cast iron over steel, however, counteracts these factors of higher cost. For rolls that must be very strong and yet not too large in diameter, and for sharp corners, which would crumble if made of cast iron, steel rolls are often used. The steel employed should be high in carbon—say 0.50 to 0.75 per cent—but any case hardening of steel is useless here, because the heating of the rolls by the material passing through will soon draw their temper. This heating cannot be prevented altogether, though it is customary to have a stream of water flowing over the rolls. Sometimes nickel-steel rolls are used for strength. An analysis of roll metal of a very large American company is: 0.40 to 0.50 per cent carbon, 0.65 per cent manganese, 3.25 per cent nickel, and 0.15 to 0.20 per cent silicon.

Diameter of Rolls.—With smaller rolls, the amount of power consumed is less because the area of metal under vertical pressure is less. There is a limit below which the diameter cannot go, however, either because the rolls will not be strong enough to give the desired pressure or they will not grip the bar. In order to be gripped, the upper and lower edges of a piece must touch the rolls at a point not more than 30 deg. from the center line of the two rolls (see Fig. IX-23). Every effort is made to use smaller rolls, because the size of all the mill is regulated by them. The surfaces of all but the finishing mill are usually "ragged" (*i.e.*, made rough) to make the rolls give a better grip. Those to receive the ingots are ragged the most, with deep indentations somewhat like the cogs of cogwheels, whence the name of *cogging rolls* for this mill.[1] The next trains, known as the *roughing rolls*, are also deeply marked, but even then the piece must come within the 30-deg. line, or time is lost in trying to make them bite the piece.

ⓤ

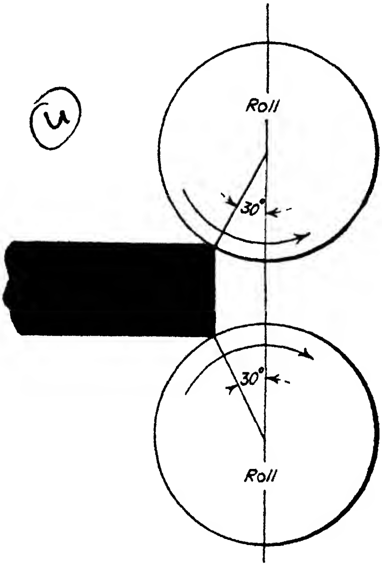


Fig. IX-23.—Limit of gripping power of rolls.

Speed of Rolls.—The more work the rolls do, the slower must they revolve, because the piece entering the train gives a shock to the mechanism that is dependent upon the power exerted and the momentum of the moving parts. Thus (1) the larger the pieces treated (2) the colder they are, and (3) the larger the rolls, the slower must be the speed. Pieces of irregular shape must also be rolled at lower speeds because the faster the metal is deformed, the less time it has to yield to the pressure. Take,

---

[1] In America the train that produces blooms (*i.e.*, pieces of steel usually about 6 to 8½ in. square) from ingots is sometimes, but not always, known as *bloom rolls*, or *blooming rolls*, instead of cogging rolls; and the train that produces "slabs" (*i.e.*, thick, wide, rectangular pieces that are to be rolled into plates) from ingots is known as the *slabbing mill.*

for example, a railroad rail: At the finishing pass the part of the roll which forms the web and base of the flange (see Figs. IX-31 and IX-32) has a peripheral speed 24 per cent faster than that part which forms the edge of the flange. This indicates the extent of the plastic flow which must occur in the metal. In America, speeds are at the high limit. Reversing slab mills may do the work at 20 or 30 r.p.m.; three-high blooming rolls may run over 50 r.p.m.; mills for finishing rails, 100 r.p.m.; and rod mills from 550 to 1,200 r.p.m.

FIG. IX-24.—Trains of rolls for rolling billets into wire rods. (*Courtesy of United States Steel Corp.*)

FIG. IX-25.—A pinion. W, wobbler.

Making of Rolls.—Cast-iron or steel rolls are cast in approximately the desired shape and then turned accurately in a lathe, being fitted exactly to a templet when completed. After rolling some thousand tons of material, they become worn and produce too large a size of finished shapes. They may then be used for a larger size of the same kind of article by putting them back in the lathe and turning to another templet. For example, a roll for a 20-in. I-beam, with a certain thickness and width of flange, may be converted to one for a 20-in. I-beam with thicker web and longer flange.

The Mill.—The different parts of a rolling mill may be seen in Fig. IX-26. The *chocks* are the bearings which support the end of the roll in the *housing.* The *wobblers* (Fig. IX-25) are made of the same cross section as the spindle. The *coupling boxes* (Fig. IX-26) fit over the spindle and wobblers, so that neither can turn without the other. In some mills the coupling boxes are made of cast iron in order that, if any shock comes upon the driving mechanism, the boxes shall give way and relieve the strain. In other mills the boxes are made of cast steel, as it is thought that the constant delays due to broken couplings are more costly than breakages in other parts of the mill. The *spindles* (Fig. IX-26) are at least twice as long as the coupling boxes, in order that they may carry both of them at once when the train is uncoupled. Both boxes slip back upon the spindle.

Pinions (Fig. IX-25) are now usually made of steel for the sake of strength. *Housings* (Fig. IX-26) are made either of steel or of cast iron, depending on the strains to which they are subjected and the opinion of the manager. In America they are usually made so that the top can be removed and the whole train of rolls removed at once, together with the chocks, and several mills have spare sets of rolls all made up ready and carried in a sling, so that a new set may be dropped into place with a crane with the least possible delay to the mill. Delays in rolling mills are very costly, because of the idle labor and capital, and because other parts of the plant may be delayed thereby.

The *screw-down mechanism* (Figs. IX-18 and IX-19) which adjusts the distance between the rolls is operated by hydraulic pressure or by electric motors. It is connected with a telltale gage which advises the roller exactly as to the distance separating the rolls.

Guards (Fig. IX-27) are of steel and serve to peel the piece off the roll and prevent it encircling the roll (called *collaring*) in case it becomes wedged between the collars. They may be upon the lower roll, as shown in Fig. IX-27, or upon the upper roll and

Fig. IX-26.—Parts of rolling mills

H, housing of rolls.
HC, housing cap.
PH, pinion housing.
E, electric roller table motor
S, spindles.
C, chocks
CB, coupling box
GI, guide.
GA, guard
TT, transfer table

counterbalanced to hold them in position, when they are called *hanging guards*. *Guides* (Fig. IX-26) are on the opposite side of the train and assist in conducting the piece straight into the groove.

Roll Tables.—Heavy pieces are handled at the rolls by supporting them upon a series of rollers, situated in front of and behind the roll train, and known as the *tables* (Fig. IX-28). At two-high mills the tables are stationary; at three-high mills the front and back tables are sometimes raised and lowered together by hydraulic or electric mechanism, and sometimes they are pivoted near the middle, so that the end next the rolls can be tilted upward in order to bring the piece between the guides which direct it into the groove. The rollers to handle large pieces are "live;" *i.e.*, they are made to revolve by electric motors and thus move the piece back and forth. "Dead" rollers are used where pieces are to be moved by hand.

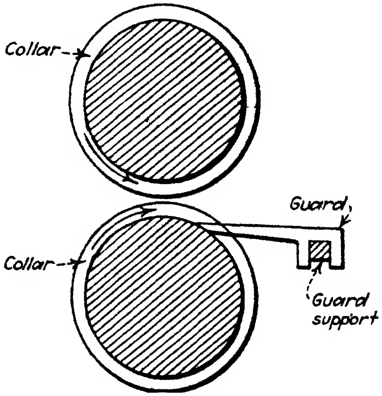


Fig. IX-27.—Section of rolls showing guard.

Transfer Tables.—Roller tables are sometimes made so that they may be moved from one roll train to another, carrying the piece of metal with them, and so connected electrically that the roller can be caused to revolve when the table is in any location (see Fig. IX-17).

Manipulators.—If two or more posts, supported on a carriage which can be moved laterally, project between the rollers of a table, their sidewise motion will transfer the piece from one pass to another. If the table is of the lifting type, the posts, or "horns," or "fingers," can be brought to such a position that the lowering of the table will bring the edge of the piece upon the horns and thus tip it on to the other side. This form of manipulator is much used at three-high blooming rolls and is very efficient and rapid in its work. The same type is used at reversing blooming rolls, but the piece is more usually tipped over by the roller with a tool.

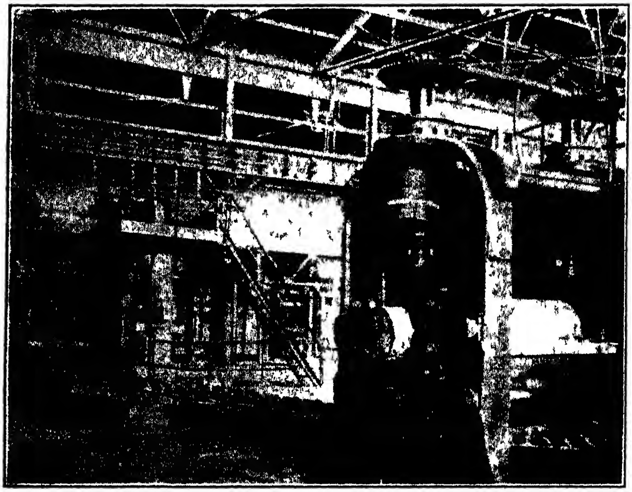


Fig. IX-28.—Table between two trains of plate rolls. (*Courtesy of United States Steel Corp.*)

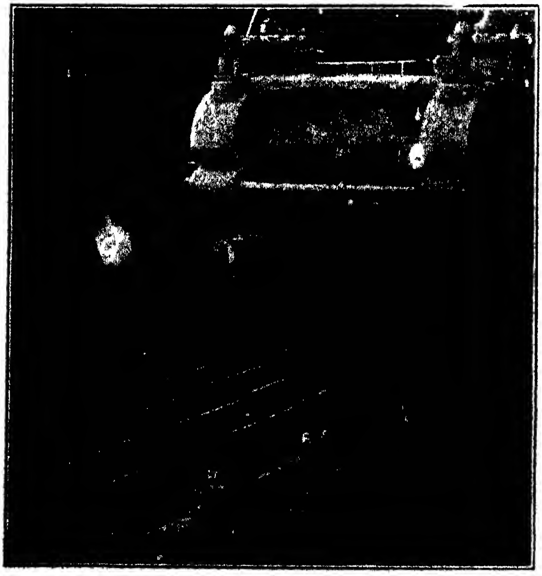


Fig. IX-29.—Table with live rollers. *R R R*, live rollers. (*Courtesy of United States Steel Corp.*)

Roll Engines.—The service on rolling-mill engines is very severe, because the full load comes upon it when the piece enters the rolls and then leaves it as suddenly again. To equalize these sudden variations of power, all but the reversing engines are built with very large and heavy flywheels and run at a high rate of speed (from 30 to 250 r.p.m.), with governors of a quick-acting type.

Piston valves are almost always used for reversing engines which are compounded, so they may never come to rest at a dead point. There is, of course, no flywheel, and the engine is directly coupled from the crankshaft to the roll train in the large American mills but is geared down so that the engine can develop a higher speed than is desired for the rolls, thus requiring less power. Reversing slabbing-mill engines have capacities up to 25,000 hp. each.

Electric-motor Drive.—In many mills in America and Europe electricity has replaced steam for all power purposes. The advantages of electricity over steam are a lower operative cost, greater security of operation, fewer breakdowns, and a more flexible relation between the prime mover and the load, the result of the electric motors receiving a sudden shock more elastically. On the other hand, the advantage of steam, is that, although it receives the load less elastically, it adjusts itself quicker and better to the extreme variations in load that always occur in rolling mills. This is especially true of reversing mills. The initial cost of steam engines is less.

As already noted, the smaller the mill, the less will be the load and therefore the variation in load. Consequently, in England, Sweden, and Germany there are many motor-driven roll trains of the smaller size, and a few up to several hundred horsepower, including one reversing motor of 1,200 hp. Even large mills are now most commonly operated by electric power, if of recent installation, and this applies even to reversing mills. One reason for the extent of this change is, of course, the cheapening of the cost of electricity due to the better utilization of the waste power of blast furnaces at large plants by the installation of gas engines (see motor drive for rolls, Fig. IX-26).

Size of Rolling Mills.—As related to blooming mills the size indicates roughly the diameter of the rolls. But this dimension is only indirectly used; thus, the term "40-in. blooming mill" refers to a mill which is 40 in. center to center of pinions. Obviously, this is approximately the distance from center to center of rolls when one roll rests upon the other, and also the diameter of the rolls when new and unworn. The larger the roll, the stronger it is and the more power required to drive the mill; also the larger piece it will grip (see Fig. IX-23). Blooming mills are used in sizes varying about 28 to 50 in.

The size of plate mills, on the other hand, indicates the width of plate that can be rolled by them. Thus, the "140-in. sheared plate mill" describes a mill which can roll plates 140 in. wide. (The term *sheared mill* indicates a mill producing plates which must be sheared to give straight edges, as contrasted with a *universal mill* [see Fig. IX-20] which rolls them straight.)

ROLLING-MILL PRACTICE

Troubles in Rolling.—There are more difficulties met with in rolling-mill practice than we can discuss here, but it may be said that the seriousness of the difficulty is estimated almost altogether in proportion to the delay it causes in the operation of the mill rather than in the loss of a small amount of material or of a part of the mill itself. For example, the breaking of a table engine, roller, or even a roll is regretted more because of the time necessary to put in a new one than because of the loss of the part. This is one reason why electric motors to operate the tables have replaced small steam engines. The same conditions have also resulted in different parts of the mill being made interchangeable. In many mills it is customary to have spare table engines, or motors, etc., always ready, and the least accident to one of these machines would result in its being immediately replaced by a whole new one.


FIG. IX-30.—Fin.

The most important common troubles in rolling-mill operations, probably, are: (1) bending and breaking of the rolls, due to their being placed under too severe a strain, either because the draft is too heavy or because the piece is cooled too much; (2) fins caused by metal being squeezed out between the collars of the rolls, as shown in Fig. IX-30; these fins, besides spoiling the material, are liable to break the rolls; (3) collaring.

Rolling Plates.—In the rolling of plates an ingot, usually of open-hearth steel and weighing 2 to 10 tons, is first cogged down in the slabbing mill, producing a long flat piece of metal. The slabbing mills are frequently of the two-high, reversing, universal type. The front end of the piece is cut off in a huge hydraulic or electric shear to remove the pipe and then it is cut up into slabs of the desired size or into slabs of a size such that each one will make one plate. The slabs are then transferred to the heating furnace, heated to about 1300°C., and rolled in a three-high or, more rarely, a two-high reversing plate mill (in some cases there is a pair of vertical rolls to keep the edges straight). During the rolling a shovelful of salt is occasionally thrown upon the surface of the plate, which carries in between the rolls some of the water which is always trickling over them to keep them cool. Sand may be used for the same purpose, and in England heather is sometimes used. As soon as this water is pressed against the hot plate it is converted into steam, causing a rapid series of explosions which blow the scale off the upper surface of the plate and give it a smoother finish. As the process continues, the operator tests the thickness of the plate with a gage and, when it is of the desired thickness, it is passed up to the straightening rolls and then to a cooling table, being marked with a distinguishing mark on the way to indicate the heat of steel from

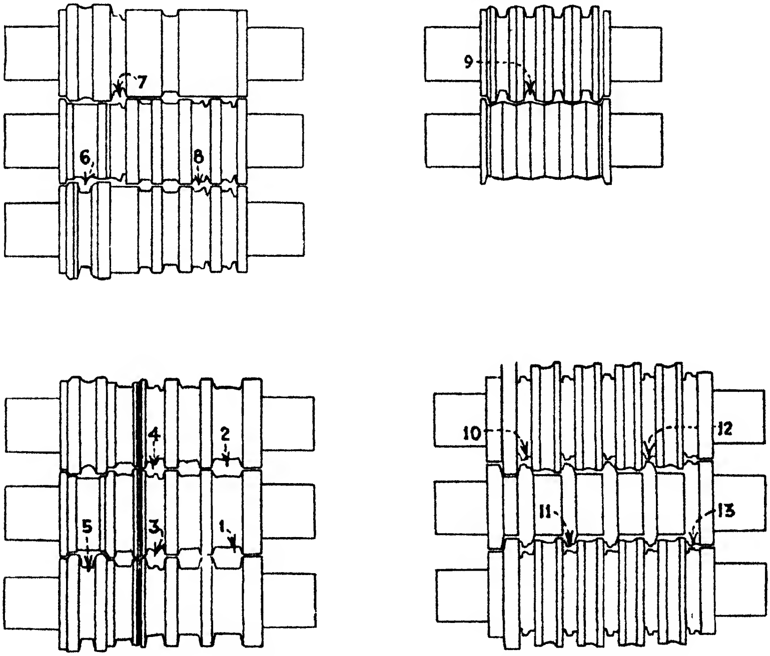


FIG. IX-31.—Trains of rolls showing passes from bloom to rail.

which it was manufactured. When cooled it is sheared to the desired size and shape. The weight of finished plate will probably be not more than 80 per cent of the weight of the steel sent to the rolling mill in the form of ingots.

Rolling Rails.—An ingot of about 3 tons in weight is sent to the rolling mill, where it is kept in the heating furnace for 80 min. or more until the interior is entirely solid and it is of a uniform temperature throughout. It is then rolled into blooms, either in a three-high mill, such as shown in Fig. IX-29, or in a two-high reversing mill. In the three-high mill, an ingot 18$\frac{1}{2}$ in. square at the middle (tapering about $\frac{1}{8}$ to $\frac{1}{4}$ in. to 1 ft. in order that the mold may be more easily removed) will be reduced to a bloom of about 8 in. square in nine passes, the amount of reduction in each pass being about 12 to 18 per cent of the original area. The top end is then cut off to remove the pipe, the bottom end to remove the irregularity due to the rolling, and the piece is cut in two to make two blooms. The blooms are then generally reheated in a heating furnace and passed through the series of changes shown in Fig. IX-32, until they have assumed the proper size and form, the greatest amount of draft being usually not more than 22 per cent, except upon the middle portion of the web. In some cases the blooms are not reheated but go directly from the bloom rolls to the first roughing train. This makes the metal crack more in rolling, however, and these cracks will ultimately

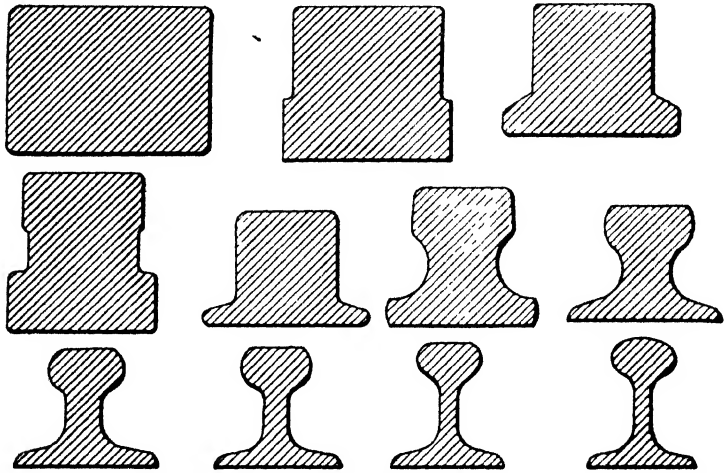


Fig. IX-32.—Sections of successive shapes and sizes of "pieces" from bloom to finished rail.

show as a mark on the finished product, which causes the rails to be classified by the inspector in the second or third class. Railroads will accept only 5 or 10 per cent of their order in second-class rails, while third-class rails are not acceptable and must go into the tracks of the steel company itself or else be reheated and rolled into smaller sizes, where the marks will often be eliminated. If the blooms are reheated before going to the roughing train, many of the cracks formed during blooming will be seemingly closed up or in any event will not show. Furthermore, if this reheating is to take place, the ingots need not be heated so hot in the first instance and therefore will not be so tender and so liable to crack.

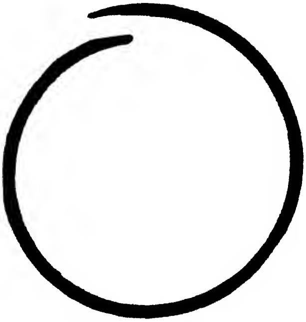


FIG. IX-33.—Cross section of skelp when rolled up preparatory to rolling into lap-welded pipe.

Making Lap-welded Tubing.—The wrought iron or steel low in carbon is first rolled out into skelp about 20 to 25 ft. long and of a width a little more than three times the intended diameter of the tube. The skelp, if large, is then rolled up into a rough form of a pipe, as shown in Fig. IX-33, by passing it sidewise through rolls, which bend it roughly to the shape of a pipe, with edges overlapping. The same is done in the case of small 2- to 8-in. tubes by drawing them through a die. It is then passed at a welding heat through a pair of rolls, with the seam that is to be welded upward. Between the rolls is a mandrel on the end of a

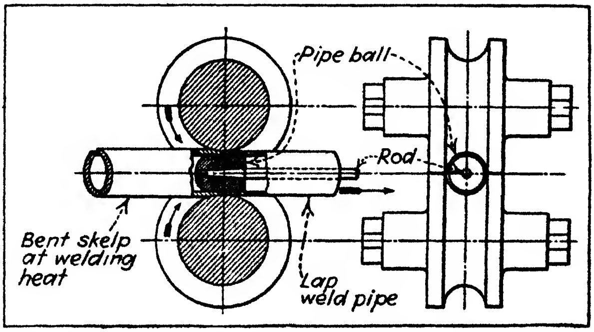


FIG. IX-34a.—Lap-welding steel pipe over a mandrel. (*From "The A.B.C. of Iron and Steel."*)

long rod and of the size of the inner diameter of the tube (Fig. IX-35). The rolls press the two parts of the weld together over the mandrel, and the pipe, after another rolling to give true size and after straightening and testing, is ready for service.

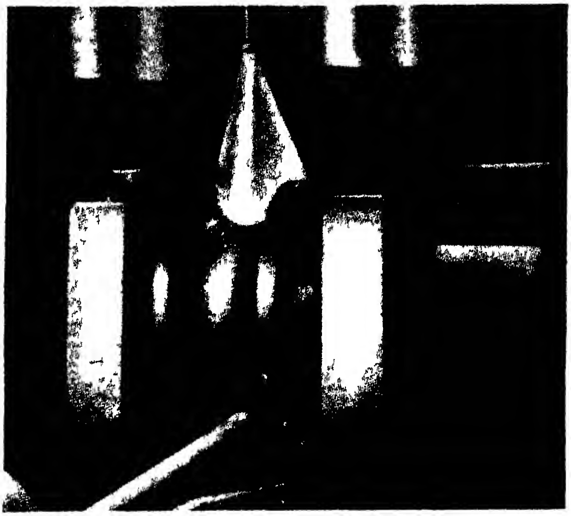


FIG IX-34*b*—Welding rolls showing position of pipe ball or mandrel (*From "The A.B.C. of Iron and Steel."*)

Making Seamless Tubes.—Seamless or weldless tubes are made either by distorting a steel plate between dies, as shown in Fig. IX-36, or else by piercing a hole through the center of a hot steel billet and then rolling it successively between rolls over a mandrel. The hole is sometimes first of small size and then expanded by pressing larger and larger expanders through it. The pierced billet is then rolled over mandrels constantly decreasing in size until the inner and outer diameters are brought to the desired size.

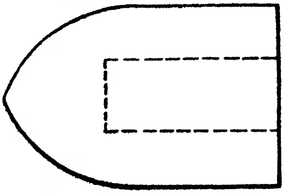


FIG. IX-35.—Mandrel. This sits on the end of the rod and lies between the rolls shown in Fig. IX-34*b* to support the inner diameter of the pipe as it is being welded.

Butt-welded Tubes.—Butt-welded tubes are made by heating the skelp to a welding temperature and then drawing it out of the furnace through a bell, as shown in Fig. IX-37, which curls it up and welds the edges together, without lapping. Butt-welded tubes are not so strong as lap-welded tubes and are not usually used for boilers or high pressures or where they will be expanded much by heat during service. They are mostly made in the small sizes.

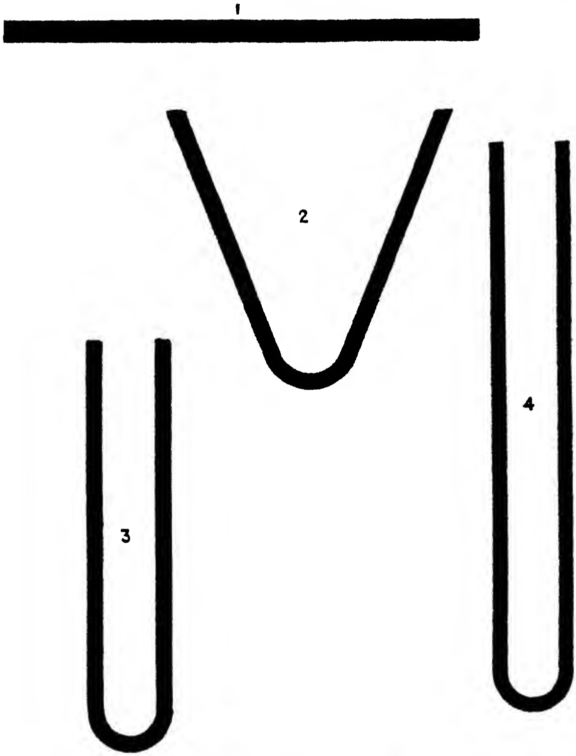


FIG. IX-36.—Steps in making a seamless tube by distorting a plate.

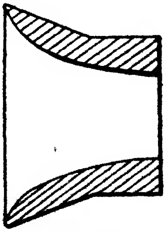


FIG. IX-37.—Section of bell through which small-sized skelp is drawn in order to curl it up and butt-weld the edges together.

Making Pipe by Electric Pressure Welding.—A new process by which has been made a good deal of steel pipe is that of electric pressure welding the joint of the tube, as indicated in Fig. IX-39.

WIRE DRAWING

Wire is a product formed by being drawn cold through a die. The commonest shapes are "rounds," and the next, hollow tubes, but a great variety of forms may be produced at will.

Effect of Drawing.—The effect of the drawing is to produce a very exact size of material and to increase the strength, hardness, and brittleness of the metal. In the drawing of steel, the crystals of the metal are actually pulled apart and flow by each other, the outer layers of the metal being dragged back over the central core, there being at the same time a pressure exerted in all directions toward the center, which results in a certain amount of backward flowing even there. Because the crystals are so broken up during the operation, and because the metal is never heated above its critical temperature during annealing, the grain of the steel is very fine and the crystals are intimately mixed, which is probably the cause of the great strength of wire.

FIG. IX-38.—Pipe rolls showing the welded pipe coming toward the observer over the mandril and rod.

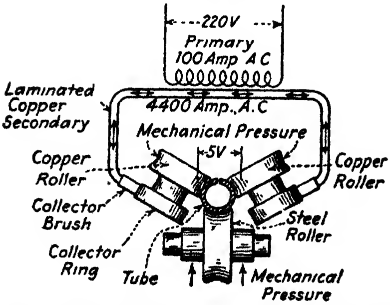


FIG. IX-39.—Making pipe by electric welding.

Annealing.—With each draft the wire becomes harder and more difficult to draw. As it is pulled through the die by a force equal to 40 to 80 per cent of its tensile strength, it is necessary to soften it at intervals by annealing, lest it break. The annealing is accomplished by enclosing the wire in some receptacle that protects it from oxidation and then heating to a low-red heat. In the case of steel, it is required after every eight to three passes, depending upon the amount of carbon in the metal and the amount of "draft," *i.e.*, proportionate reduction in size.

Dies.—Wire dies are usually made of high-carbon steel (1.25 to 2.00 per cent), through which a tapered hole is made, as shown in Fig. IX-40. The object of using this material is that, as it becomes worn in service, it can be reformed and used for larger sizes, which could not be done with white cast iron.

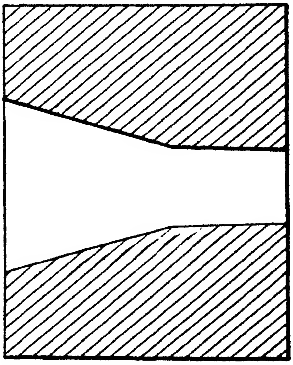


FIG. IX-40.—Section of wire die.

Bench.—A bench on which wire is drawn consists of a reel that holds the coil of undrawn wire, a die support, and a second reel which draws the wire through the die and coils it up and which is driven by bevel gears. The die rests against the support, and the wire, having a tapered point, is thrust through the hole and grasped by a pair of tongs, which pulls it out until it can be attached to the reel. This is then set in motion and draws the wire through. The die holder is heaped up with lubricant of some kind, in order that the metal may pass more easily through the hole. The speed at which wire is drawn will vary from 75 to 750 ft. per minute, depending upon the size and hardness of the material drawn and the amount of reduction during each draft. In many cases there is more than one die, and the wire passes successively through two, three, or more, being constantly reduced in each one. Between each pair of dies is a reel, around which the wire passes two or three times, since the strength of the wire emerging from the last die would not be sufficient to draw it through all of the holes.

Draft.—The heavier the draft, the greater is the hardness produced in the wire and the greater the wear of the dies. The average amount of draft will probably be from 20 to 25 per cent.

Drawing Tubes.—Hollow wire or small tubes are drawn sometimes over a mandrel. This mandrel may be a wire of about the size of the inner diameter of the finished tube. After several drafts, the tube is wedged so tightly on the mandrel that it cannot be separated. It is then given an unbalanced squeeze between a pair of rolls, so that the tube is reduced in thickness, whereby its diameter is increased and the mandrel may easily be withdrawn.

COMPARISON OF MECHANICAL METHODS

Hot Working with Cold Working.—Cold working gives greater strength, a harder material, and more accurate finish as to size than any form of hot working. Furthermore, it produces a finer grain on the surface of the metal. If the cold working is followed by annealing at a temperature below the critical range of the steel (see Chaps. XI and XIII), the material retains its fine grain and is stronger and more ductile in proportion than metal that has been worked hot. Before cold working the metal is pickled in dilute sulphuric acid to remove the scale and is therefore produced with a bright surface which is suitable, without machining, for use as shafting, for nickel plating, etc. The annealing is usually effected inside closed vessels, in a reducing atmosphere of illuminating gas or some similar medium, which prevents the formation of scale. Cold-rolled steel is used for shafting and for articles that are to be drawn or stamped to shape—watch and clock springs, hack-saw blades, corset steels, etc. Cold rolling, wire drawing, and "flanging" are the commonest forms of cold working.

The plastic deformation of wrought iron or steel under pressure is different in nature above than it is below the so-called *critical range*, *i.e.*, the range from 700 to 900°C. (1292 to 1652°F.). At the high heats the steel crystals break up and reform in smaller size; below the range, they are distorted and broken (see the slip bands in Fig. IX-3) but do not reform. The making of smaller crystals improves all the qualities of the metal, but we never can get very great strength by mechanical working above the critical range. Deformation below the critical range greatly increases the strength, elastic limit, and hardness, but at the expense of the ductility. Working near the temperature of 700°C. (1292°F.), where the metal is somewhat mobile and plastic, has a less drastic effect than working at atmospheric temperatures, where repeated deformations destroy ductility and malleability altogether. We can summarize this by saying that hot-worked steel has greater strength and greater ductility than the same metal in the cast condition. Cold working after hot working still further increases the strength and elastic limit but decreases the ductility and may, if prolonged, almost completely destroy it, unless the cold working is followed by annealing.

Working Steel at the "Blue Heat."—At the temperature at which steel assumes a blue color due to formation of oxide coating it is very sensitive to deformation, and mechanical work in this range has a damaging and embrittling effect. This temperature is from about 300 to 375°C. (572 to 707°F.).

Hammering, Rolling and Pressing Compared.—Of all the mechanical methods, rolling gives by far the largest output per day, per unit of power, and usually per unit of fuel for heating. It is therefore the cheapest method, especially for labor. It does not work the metal so well as either hammering or pressing, both of which produce a much better crystalline structure, beside affording a better control of the temperature at which the operation is ended. Pressing works the metal at greater depths than hammering and is therefore especially advantageous for producing large pieces. In such large pieces the size of the hammer which would be sufficiently heavy to forge the piece all the way into the center of the section becomes so large that it is unwieldy. The press turns out a much larger production of large pieces than would a hammer suitable for the same work and is less destructive on the dies and other equipment. The press is also used on special forging work, such as drawing, special punching, and closed die forging, where it is almost impossible to use a hammer. Where a shape is intricate, rolling is more liable to tear the metal than hammering or pressing because, at the point where the roll is deeply cut, its surface velocity is much less than where the diameter is greater, and thus it tends to drag the metal through at different speeds.

The Effect of Hot Work on Steel.—Figure IX-41 illustrates the crushing of grain size when steel is worked at temperatures between its critical range (for which see Chap. XI) and its melting point. The width of the areas in each figure represents the relative size of grain. It will be noted in the left-hand figure that the steel first solidifies at *A*; *i.e.*, it forms crystals. These crystals grow in size until the steel has cooled to the critical temperature; after this they remain the same size. Now, when cold steel of large grain size is heated, it forms a new grain of small size, as it heats through the critical range. But this grain now begins again to grow in size until we reach *W*. Then, at *w*, we begin to roll or forge the metal; its grain is crushed to pieces of small size. If we discontinue the work at *f*, the crushed grains begin to absorb one another and increase in size until the temperature cools to the critical range. But, if we forge from w' to f', the grains grow to a smaller size before their enlargement is halted at the critical temperature. And if we forge from w'' to f'', there can be no growth. This emphasizes the point already mentioned, *viz.*, that steel should be worked down to its critical temperature if we wish to obtain the best and smallest grain size. If we work steel below its critical range—*i.e.*, if we forge from w''' to f'''—we are in danger of putting cracks in it.

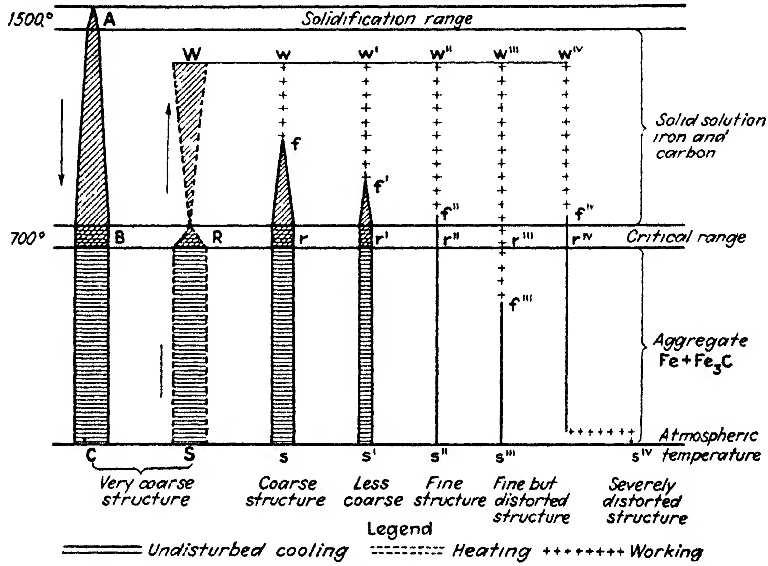


FIG. IX-41.—Diagram depicting the influence of work upon the structure of steel. (*From Sauveur, "The Metallography and Heat Treatment of Iron and Steel," 3d ed.*, 1926.)

Cold Working.—Cold working is illustrated in the right-hand figure in Fig. IX-41. The steel is first hot-worked from a high temperature just to its critical range. Then it is allowed to cool undisturbed to atmospheric temperature, where it is cold-rolled to give the high strength, bright surface, and surface hardness already mentioned.

HEATING STEEL FOR ROLLING OR FORGING

The principles of heating are the same whether we are heating for rolling or forging. Therefore, when heating for forging is mentioned herein, it is understood that heating for rolling is included.

On the technical side, the desirable features of furnaces for heating for forging purposes are that they shall: (1) heat the steel to the correct temperature; (2) heat it slowly and gradually; (3) heat it approximately evenly from all surfaces; (4) heat it to a uniform temperature from surface to center; (5) not scale the surface excessively; and (6) supply heated steel at exactly the rate wanted by the forge. (This feature is technical in one sense but has an enormous economic influence in the operation of the forge.)

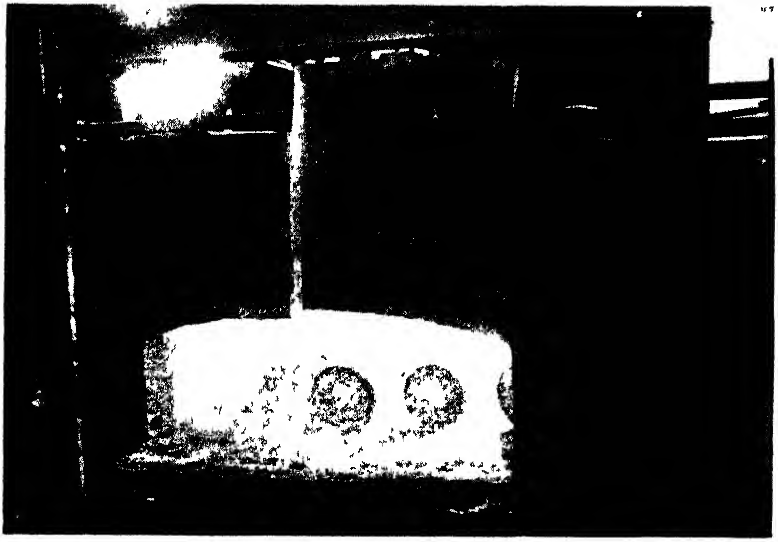


FIG IX-42*a* — Ingots of steel in a batch-type heating furnace. (*Courtesy of Standard Steel Works.*)

On the economical side, the desirable features are that the furnaces shall be: (7) economical in the use of fuel; (8) economical in labor requirements; (9) economical in power requirements; (10) economical in cost of installation; and (11) economical in cost for repairs and maintenance.

Batch or Continuous Furnaces.—A batch furnace is one in which a piece is inserted through a door and laid on the hearth, or other support, until suitably heated (see Fig. IX-42*a*). Then it is removed by the same door. A continuous furnace is one in which pieces enter continuously at one end, travel through the furnace to be heated, and are removed at the opposite end (Fig. IX-42*b*).

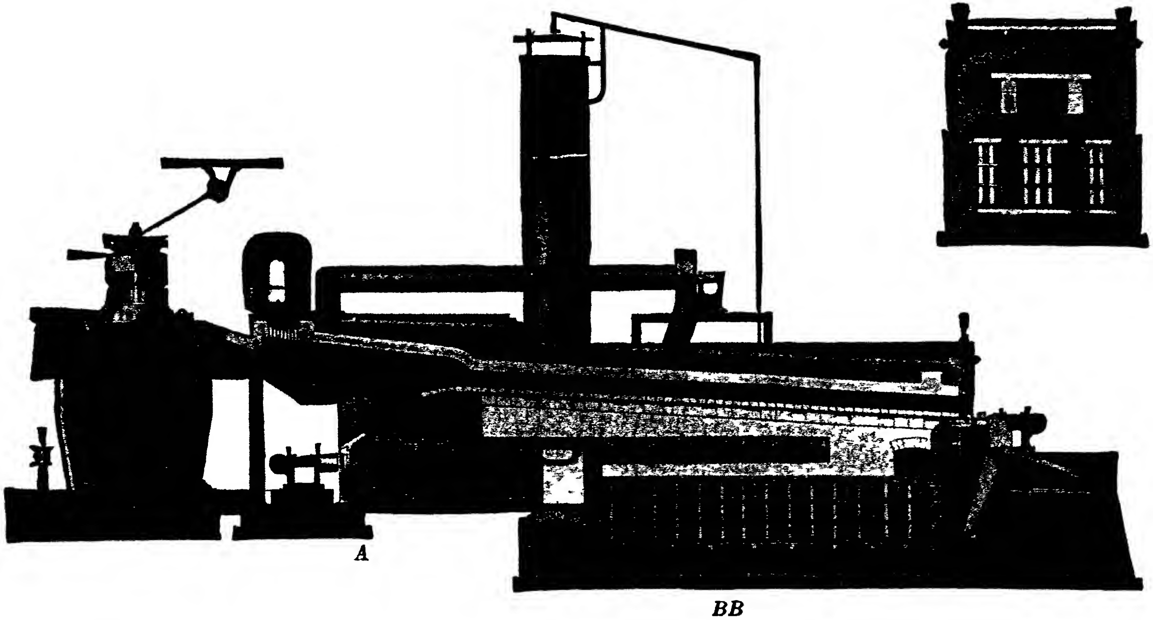


Fig. IX-42*b*.—Continuous recuperative billet heating furnace Cold billets are pushed into the furnace at the right-hand end, heated billets drop out at the left-hand end (just above point *A*) The flame takes the contrary direction, entering at left and passing out at the right-hand end (*Courtesy of Morgan Construction Co*)

1. Heat the Steel to the Correct Temperature.—Heating steel to the correct temperature is the crux of forge-furnace practice. Unfortunately, no method is known at present by which the temperature of the steel itself may be controlled or even determined in a thoroughly satisfactory manner. Optical pyrometers afford the best means known at present, but they are admittedly inaccurate, uncertain, variable, and misleading. This unsatisfactory character of optical-pyrometer observations is due to the circumstance that they depend for their operation on the color of the light emitted by the hot steel, and this color is erratic and variable owing to unreliability of the emissivity factor of hot bodies.

The next best provision for controlling the temperature of the steel is to regulate and control the temperature of the furnace. In forge-heating furnaces, the situation is similar to that in open-hearth furnaces in that the temperature of the product is controllable only through the temperature of the furnace.

Also, in many of the best modern forge-heating furnaces, of both the continuous and batch type, the temperature is controlled through the use of a pyrometer, and sometimes through the medium of a multiplicity of pyrometers so distributed in the furnace as to indicate the uniformity of temperature therein. Excellent pyrometers are now available for this purpose and it is possible to arrange for automatic control of furnace temperature by means of pyrometers. While it is admitted that there is a somewhat irregular variation between the temperature of the steel and the temperature of the furnace, nevertheless, the best results in heating for forging are obtained in furnaces whose temperature is continuously indicated by pyrometers. However great may be the variation between the temperature of the steel and the temperature of the furnace, it is obvious that the steel can never be the hotter of the two. Therefore, if the furnace temperature is held within limits, the safe heating of the steel is insured. Pyrometers situated in various localities in the furnace will also give a very good check on the uniformity of the distribution of heat and, therefore, serve as a valuable aid to the furnace operator.

Not to heat the steel too hot is doubtless the most important single factor in the operation of forge-heating furnaces. In order to forge economically, it is necessary to heat steel, of approximately 0.45 to 0.55 per cent carbon, to a temperature between

1900 and 2100°F. If through any cause the temperature of the steel becomes accidentally much hotter than 2100°F., it becomes "burnt" and its high quality is permanently destroyed. Recent investigations show that steel is burnt at lower temperatures than had previously been considered the danger point. This newly investigated kind of damage shows itself in the formation of internal checks not visible on the surface of the steel nor evidenced by surface scars between crystals, by scintillations, or by similar outward indications. In this connection, the furnace atmosphere is important, because steel is burnt more easily in an oxidizing atmosphere than in a reducing one, and more easily in a turbulent furnace atmosphere than in a quiet furnace atmosphere. The nature of burning is discussed in more detail in Chap. XIII.

2. Heat the Steel Slowly and Gradually.—The colder the steel, and the larger the section, the slower must be the application of heat to it, lest uneven expansion or too rapid expansion, as the heat penetrates, injure its quality. With high-carbon steel, this precaution is even more important than with low-carbon steel. A heating furnace must not be either much hotter or much colder than the steel which is put into it. Furthermore, if the steel is cold, the heating must be applied to it very gradually at first.

There is always greater danger of cracking steel when it is cold, *e.g.*, when heating it from 0 to 1200°F., and especially from 0 to 800°F. This is often met by putting hot steel into a hot furnace whenever possible. Likewise cracking is threatened by too sudden cooling, especially within the temperature range of 500 to 800°F. It is best to have relatively slow penetration at temperatures below 800, whereas rapid penetration can safely take place from 1200 to 2000°F. The rate of safe heat penetration depends somewhat upon the type of steel. Some of the alloy steels will not safely absorb heat so rapidly as carbon steel. It is desirable that the temperature of the furnace atmosphere in the neighborhood of the steel shall rise a little bit ahead of the temperature of the surface of the steel itself. It is usually safe to heat a carbon steel at an average rate of penetration of ½ in. per hour, so that the total time required to heat carbon steel from atmospheric temperature to a forging temperature of, say, 2000°F. shall be twice as many hours as the maximum necessary distance in inches for heat penetration from surface to center.

For example, a bar 8 by 12 in. will require 8 hr. of heating: A piece 8 by 8 in. in one part and 20 by 20 in. in another part must be heated for 20 hr.

Medium-hot steel should not be brought in contact with either a cold or a very hot furnace hearth. Likewise, it is undesirable to have cold air filtering into the furnace through cracks of the doors, etc., and playing on the steel, especially if the steel is between 500 and 1200°F.

3. **Heat the Steel Evenly.**—The heat must penetrate the steel evenly from all sides. The piece should not lie directly on the hearth, because the heat should play all around it. Also the side of the piece nearest the fire or flame will be the hottest; therefore, it is desirable to turn it over and around at intervals.

Likewise the heat must be so uniformly distributed in the furnace that large objects will be heated evenly. A flame must not play on the surface of the steel, because this will not only heat it unevenly but also injure it by overheating. The furnace must have ample room for combustion, so that the fuel will be completely burned and there will be no smothering of the flames. Incomplete combustion not only is uneconomical in the use of fuel but puts hard spots on the steel due to unburned carbon or carbonaceous material settling upon it and carbonizing it. This is true with oil fuel, with pulverized coal, and with other fuels. As an illustration of the extent to which this may be made to occur, it will be observed that armor plate was intentionally carburized by the impinging of an oily flame on its surfaces.

Heating Evenly in Batch-type Furnaces.—Even distribution of temperature in a batch-type furnace is accomplished more easily when there are a multiplicity of burners rather than single burners. Recent types of heating, which carry this principle very far, are the so-called *diffusion combustion*, *surface combustion*, and *electric-resistance* furnaces. In these three types, we have practically whole areas of incandescent bodies which distribute heat very evenly and uniformly in the furnaces. Muffle type of furnaces also heat steel relatively uniformly but are expensive to build, to maintain, and to operate.

Direct-fired batch-type combustion furnaces, where the flame is introduced directly into the heating chamber, are open to objections because of uneven heating and liability of the impingement of the flame on the steel being heated. Combustion furnaces of the batch type are more commonly heated by over-firing, underfiring, or sidefiring, each of which attempts to initiate combustion in a separate chamber and lead the products of combustion into the work chamber of the furnace, as shown in Figs. IX-43, IX-44, and IX-45. In every case, however, the

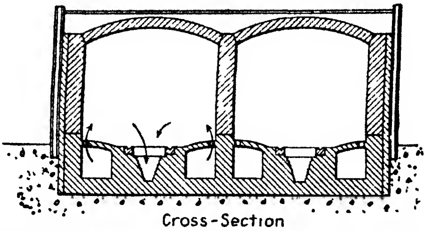


Fig. IX-43.—Underfired furnace. (*From Mawhinney, "Practical Industrial Furnace Design," New York*, 1928.)

transfer of heat to the steel is made by radiation from the flame, and it is obvious that the side of the steel nearer the flame will be heated sooner and to a higher temperature than the opposite side. It is practically impossible for such a type of furnace to heat steel uniformly and the piece must be turned over or around, or both, at intervals. This is not so serious when hot steel is given a "wash" heat, because of the greater hazard in

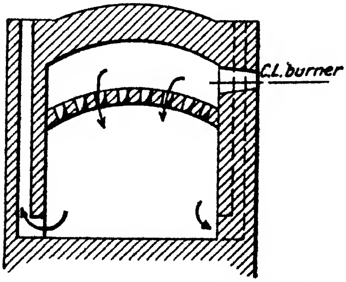


Fig. IX-44.—Overfired furnace. (*From Mawhinney, "Practical Industrial Furnace Design," New York*, 1928.)

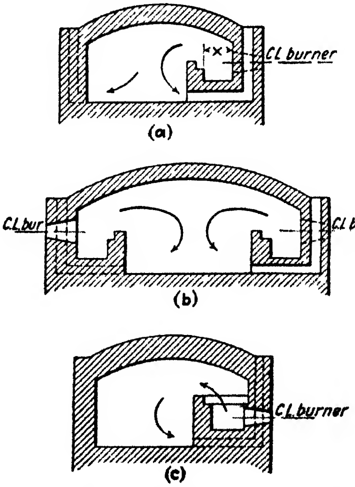


Fig. IX-45.—Side-fired furnace. (*From Mawhinney, "Practical Industrial Furnace Design," New York*, 1928.)

heating steel below 1200°F. (and especially below 800°F.). A wash heat is one by which a red-hot piece is taken from the rolling mill or forge and is raised a few hundred degrees, because it has cooled below the optimum temperature for working.

Batch-type furnaces suffer the hazard of uneven distribution of temperature in them with consequent uneven heating of the steel, and they may actually burn the steel through overheating, even though the furnace in some parts may not be at a dangerous temperature. With these two considerations in mind, it is therefore important, whenever it is in any way possible, always to use continuous furnaces, especially when heating steel from the cold. These furnaces have the double advantage of promoting quality of product as well as economy in operation.

Continuous Furnaces.—When circumstances permit, many of the desirable conditions enumerated above in sections 2 and 3 are accomplished by heating the steel in a continuous-type furnace. Indeed, heating cold steel in a noncontinuous or batch-type furnace is uneconomical, is often a serious delay to the rolling mill, hammer or press, and affords a temptation to injure the steel by heating too rapidly.

Length of a Continuous Furnace.—A continuous furnace must have a minimum length determined by the following factors:

1. The temperature at the flue end of the furnace must be low enough to receive the cold steel introduced into it without danger of cracking it.
2. The steel pieces must travel through the furnace at a rate of speed which will bring them to the correct forging temperature in the correct length of time, *viz.*, in twice as many hours as the maximum heat penetration in inches. For example, ingots 18 in. round must be in the heating furnace at least 18 hr.
3. The furnace must deliver heated steel fast enough to keep the forge mill constantly supplied.

Example.—If a hammer or press will forge 15 ingots per hour and each ingot must be in the furnace at least 18 hr., then there must be at least 270 ingots in the furnace all the time, if the forge is to be kept in constant operation. Then, if these ingots travel through the furnace in a triple row, and each ingot requires a longitudinal distance of 24 in. to accommodate it:

$$270 \div 3 \times 2 \text{ ft.} = 180 \text{ ft.} = \text{length of furnace.}$$

4. Heat the Steel to a Uniform Temperature from Surface to Center.—The heating of the steel to a uniform temperature throughout is a question of heat penetration to the center of the piece at a safe rate of speed. This, therefore, involves heating the steel long enough and evenly enough, as already discussed under sections 2 and 3.

5. Do Not Scale the Surface Excessively.—The more oxidizing the furnace atmosphere, and the higher the temperature, the greater will be the amount of oxidation or scaling in a unit time. Consequently, of course, the longer the time, the deeper will be the coating of scale formed on the surface, other things being equal. Furthermore, the longer the time that scale is in contact with the surface of the steel, the deeper will be the decarburization of the steel itself, first by oxidation of carbon in the outer layers, and then either by a migration of carbon atoms from lower layers to the outside or else by a penetration of the oxidizing influences deeper into the metal.

Scaling is also objectionable because it represents a loss of weight of steel and consequent decrease in output. Another objection is that steel cannot be forged or rolled until the scale is removed.

Steel will scale when heated even in a reducing furnace atmosphere, although not so much as when the atmosphere is oxidizing. Ordinarily, however, it is necessary that furnace atmospheres be oxidizing, because the requisite temperatures cannot be economically obtained unless an excess of air is used for combustion. The lessening of scaling in furnaces has been brought about in modern furnaces by the following methods:

1. Diffusion combustion, with gas flames being also admitted in the floor of the furnace to produce a strongly reducing atmosphere around the pieces being heated.
2. Surface combustion, in which high temperatures and complete combustion are obtained without exposing the steel to the products of combustion of the furnace.
3. Reducing of the oxidizing gases by the presence in the furnace of glowing charcoal, coke, or similar reducing agent, which lessens oxidation of the steel as well as contributing a little heat. Sometimes free carbon is blown into the furnace and serves the double purpose of reducing the oxidizing atmosphere and increasing the luminosity of the flame.
4. Preheating the air by modern recuperative or regenerative methods, which enable the necessary temperature to be obtained without as intensive oxidizing furnace atmosphere.
5. Avoiding infiltration of air into the furnace by keeping the furnace chamber under a slight pressure.

6. Supply Heated Steel at Exactly the Rate Wanted by the Forge.—The forge-heating furnace capacity must be equal to the maximum capacity of the forging operations if the work is to be performed economically, because, if the furnaces delay the forge operations, there is a great deal of waste of money by increased cost of operation; whereas the furnaces may slow up their operations, provided the forge is not up to maximum capacity, without serious increase in cost of their operation. The possible supply of steel pieces for forging purposes per hour from any furnace can be obtained by dividing the number of pieces which a furnace can hold at any one time by the number of hours during which it is necessary to heat the piece for forging.

Example.—If a furnace will hold 150 pieces and each piece must be heated for 10 hr., then 15 pieces per hour is the maximum rate at which the furnace can continuously supply steel for forging.

7. **Economy in the Use of Fuel.**—Economy in the use of fuel can be obtained in four ways: (1) using a fuel of low cost per unit of calorific power; (2) economically converting it into heat; (3) designing the furnace so as to use the heat efficiently; and (4) employing the waste heat usefully, and crediting the furnace-fuel account correspondingly.

Considering these factors in detail:

Using a Fuel of Low Cost per Unit of Calorific Power.—Common forge-heating fuels are: (*a*) soft coal, (*b*) pulverized coal, (*c*) oil or tar, (*d*) natural gas, (*e*) artificial gas, and (*f*) electricity.

The relative cost of these varies with the locality and special conditions of supply, except that there are only a few places in the world where electricity is a relatively cheap fuel.

Economically Converting Fuel into Heat.—Doubtless the largest factor in this category is automatic maintenance of good combustion conditions, such as (*a*) correct proportioning of fuel and air, (*b*) efficient and intimate mixing of fuel and air, (*c*) use of preheated air, (*d*) sometimes the use of stokers has proved its economy.

In connection with good combustion there can scarcely be any doubt that efficient automatic maintenance of correct combustion conditions, which have proved so valuable and money saving in open-hearth furnace operation, will be found equally economical if and when applied to forge furnaces.

Designing Furnace so as to Use the Heat Efficiently.—It is said by some authorities that the use of chimney draft is uneconomical and that actual control and regulation at will of the velocity of the air entering the furnace and the velocity of the gases leaving it, by means of fans or similar devices, more than pays for itself in improving the fuel economy and better furnace operation.

The maintenance in the furnace of a slight pressure, so that flame will come out of the furnace at each door crack, or other opening, instead of air filtering in, is an important factor in maintaining correct combustion conditions and fuel economy. This is so important that the maintenance of pressure gages is now standard practice in open-hearth furnaces, and it is believed that they will pay for themselves in forge-heating furnaces.

The correct arrangement of suitable combustion chambers and flue openings of correct size and location, so that the heat will be efficiently produced and uniformly distributed to different parts of the furnace, requires no special comment here. We have already mentioned the smothering of combustion when too small combustion chambers are provided. It is obvious that the flue openings must be of such a size in relation to the volume of gases and the draft pull that all parts of the furnace will be under a slight and nearly uniform pressure.

Doubtless the most important achievement in promoting not only fuel economy but also safe and gradual heating of steel is the continuous furnace.

Employing the Waste Heat Usefully and Crediting the Furnace-fuel Account Correspondingly.—The commonest method of employing waste heat from forge furnaces is by the use of waste-heat boilers.

Another method of employing waste heat is to use it for preheating the air or gas, or both, entering the furnace for combustion purposes. This can be done by either recuperative or regenerative methods, and both systems are being employed in increasing amounts in forge-heating furnaces. Important improvements have recently been made in refractory materials so as to improve their heat conductivity for use in recuperators.

The extent to which the heat in excess gases can be usefully employed is limited only by the amount of heat necessary to leave in the gases in order to maintain a draft in the chimney. In several cases it has been found more economical to absorb the latent heat of the waste gases to the fullest possible extent and then to produce a draft by means of a fan or similar device. This results in improved operation of furnace combustion, because the extent of the draft may be regulated at will and may be automatically controlled in connection with combustion conditions so as to obtain the maximum net efficiency.

8. Economy in Labor.—Economy in labor should include not only the labor of operating the furnaces but also the labor of charging and discharging them. Continuous furnaces have been one of the chief means not only of economizing fuel, as previously mentioned, but also of economizing labor, especially where the pieces are passed through the furnace by mechanical means instead of manually.

FIG. IX-46.—Electric manipulator for handling wheel blanks to be heated in batch-type furnace. (*Courtesy of The Wellman Co.*)

Automatic control of furnaces includes: (*a*) control of rate of heating steel; (*b*) control of temperature of furnace; (*c*) control of combustion conditions; (*d*) control of the furnace draft; (*e*) control of internal furnace pressures; and (*f*) control of delivery of heated steel.

All of these automatic appliances obviously reduce the labor cost on the furnace and especially the use of high-priced labor. In addition they greatly improve the quality of the product and some of them improve economy in the use of fuel.

Heating Slowly in Batch-type Furnaces.—Cold carbon-steel pieces up to 4 in. in section may be put without damage into furnaces which are at a forging temperature. Pieces from 5 to 12 in. may be put cold into furnaces not exceeding 1600°F.

Larger sizes must be put into cold furnaces and heated very slowly or else must be brought hot from the steel mill (say not less than 700 or 800°) or preheated to preferably 1100 or 1200°F. before being put into hot furnaces.

Some alloy steels are very sensitive to damage from heating and must be treated even more tenderly than indicated in the previous paragraph. Low-carbon steels can suffer more drastic changes in temperature than can high-carbon steels.

Steel containing more than 0.35 per cent of carbon and of thicknesses exceeding 8 in. cannot even be put into a cold furnace and allowed to be heated by using the regular furnace fuel. They must be warmed up through the danger zone to a temperature of at least 500°F. on the outside, by building around them a wood fire on the hearth of the furnace or by some similar means of warming very slowly, before the pulverized coal flame or oil flame can be turned into the furnace. Exceptions are made in furnaces especially designed for very low fires when desired.

Consequently, batch-type furnaces for heating cold ingots are inefficient, slow, and uneconomical. Batch-type furnaces for heating for forging are also hazardous as to steel quality under any circumstances, because of the universal liability to human error even when strictest instructions are issued as to safe methods to be employed.

References

J. Puppe and G. Stamber: "Walzwerkswesen," Berlin, 1929.

Wilhelm Tafel: "The Theory and Practice of Rolling Steel," translated by Richard Rimbach, Cleveland, 1927.

W. Trinks: "Roll Pass Design," Parts I and II, Pittsburgh, Pa., 1930.

F. H. Kindl: "The Rolling Mill Industry," Cleveland, 1913.

Thomas P. Hughes: "Principles of Forging and Heat Treatment of Steel," Minneapolis, 1928.

Alastair Thomas Adam: "Wire-drawing and the Cold Working of Steel," London, 1925.

R. W. Shannon: "Sheet Steel and Tin Plate," New York, 1930.

Matthew H. Mawhinney: "Practical Industrial Furnace Design," New York, 1928.

Erich Siebel, translated by John H. Hitchcock: "The Plastic Forming of Metals," appearing currently in *Steel*, beginning Oct. 16, 1933.

A. Nádai: "Plasticity," New York, 1931.

E. V. Crane: "Plastic Working of Metals and Power Press Operation," New York, 1932.

CHAPTER X

IRON AND STEEL FOUNDING

Founding is a mechanical art and consists in pouring melted metal into a mold of any desired size and form, which the metal assumes and retains when cold. The mold is made of some kind of sand, with rare exceptions to be mentioned hereafter. The art is a very complex one, added to which it is now passing through an important transition period in which science is very rapidly taking the place of rule of thumb. It is impossible to treat the subject adequately in a single chapter, but several books are now available, to which foundrymen, metallurgists and chemists are referred, and which are also recommended to all engineers, to whom a knowledge of the art is of prime importance.

The Making of Molds

There are various kinds of sand molds made for foundry work, but the three principal kinds are *loam molds, dry-sand molds,* and *green-sand molds.*

Loam Molding.—In molding with loam, sand is usually built up into the required shape by hand, aided by machines. Figure X-1 shows the molding of a gear in which the parts are built up of brick and sand and then formed into the desired shape by means of a machine. Large wheels and gears are often swept up, the teeth being formed subsequently by means of a small pattern that is moved around as the molder progresses, or by means of a machine, as shown in Fig. X-1. In the case of a gear, the arms are usually formed by placing within the swept-up mold forms of sand known as *cores,* as shown in Fig. X-2. Loam molding is common in iron foundries but less often used for steel castings.

Pattern Molding.—To only a limited class of work is loam molding applicable, and the commonest manner of making a mold is to press or ram sand around a pattern, which is subsequently removed, leaving the desired cavity. Usually the pattern is enclosed by a "flask" much larger than itself, between which and the pattern the damp sand is rammed. The pattern (sometimes) is split into halves, one-half being in the lower part, or "drag," of the flask and the other half being in the upper part, or "cope"[1] (see Fig. X-3). The cope is now taken off and turned upside down; after this a lifting screw is inserted into each half of the pattern in turn, by means of which it is drawn from the sand; and when a "gate" is cut through the cope, the flask is again fastened together, and a receptacle is formed of the shape of the pattern into which the metal may be poured.

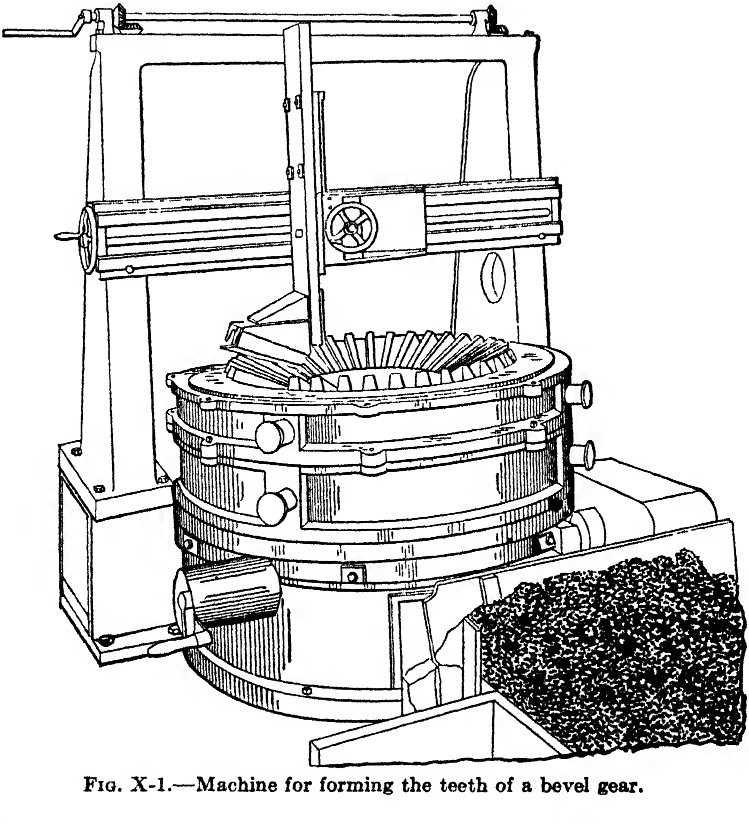


FIG. X-1.—Machine for forming the teeth of a bevel gear.

The art does not consist of these simple operations alone, however, for in drawing the pattern from the sand, even though the lifting screw be lightly tapped with a hammer in four hori-

---

[1] The old English word *cope* meaning a covering for the head, from which the word cap is derived.

FIG. X-2.—Placing cores in a mold.

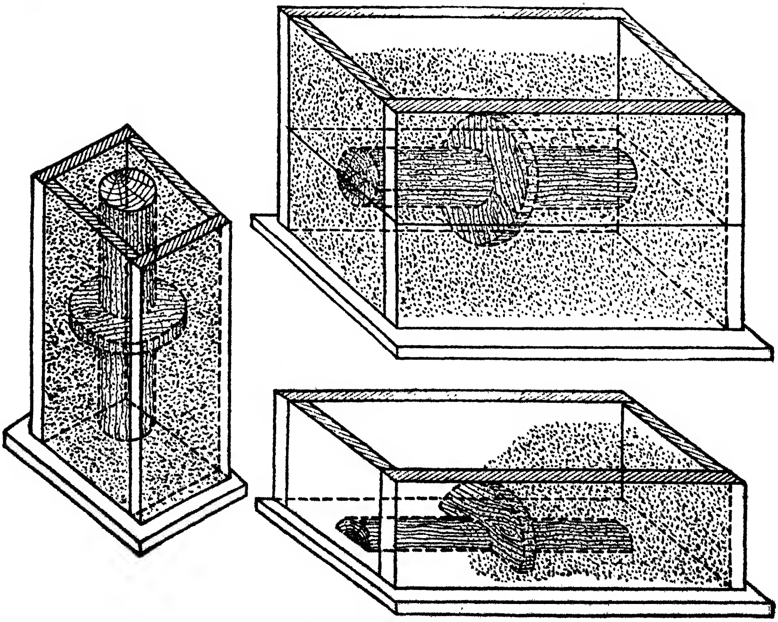


FIG. X-3.—Pattern in sand.

zontal directions to loosen the pattern, the slightest tremble of the molder's hand, or of the crane used for lifting, may cause the sand to be broken in places, and the chief skill of the molder as well as a large share of his time is employed in repairing the damage thus produced. Furthermore, the mold may be "washed"—*i.e.*, painted inside—the proper cores must be put in place; parts of the sand liable to drop off must be nailed in place with thin, large-headed wire nails thrust in with the thumb; before the pattern is taken from the sand the cope must be "vented"—*i.e.*, made porous—by jamming a wire into it many times and pulling it out again, so that the air and gases will escape when the metal is poured in; and so on.

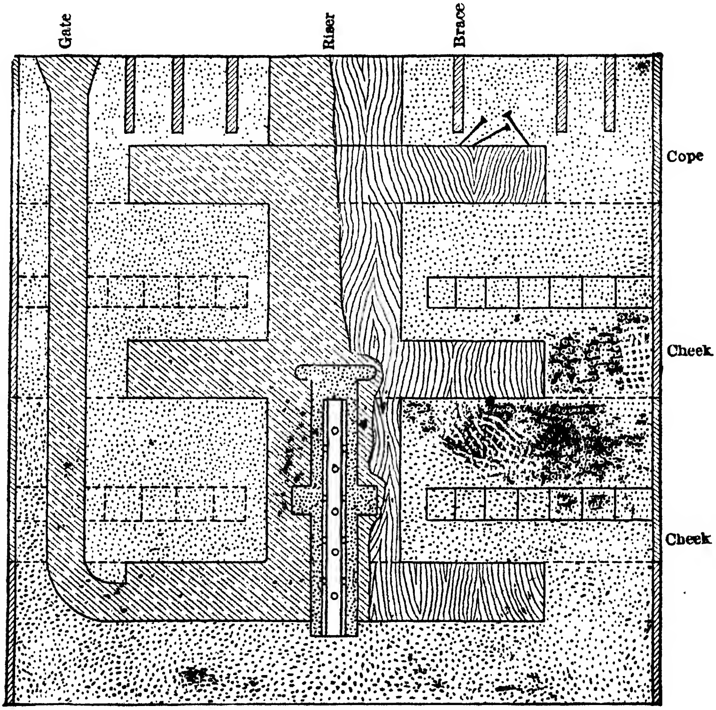


Fig. X-4.—Section of flask and pattern.

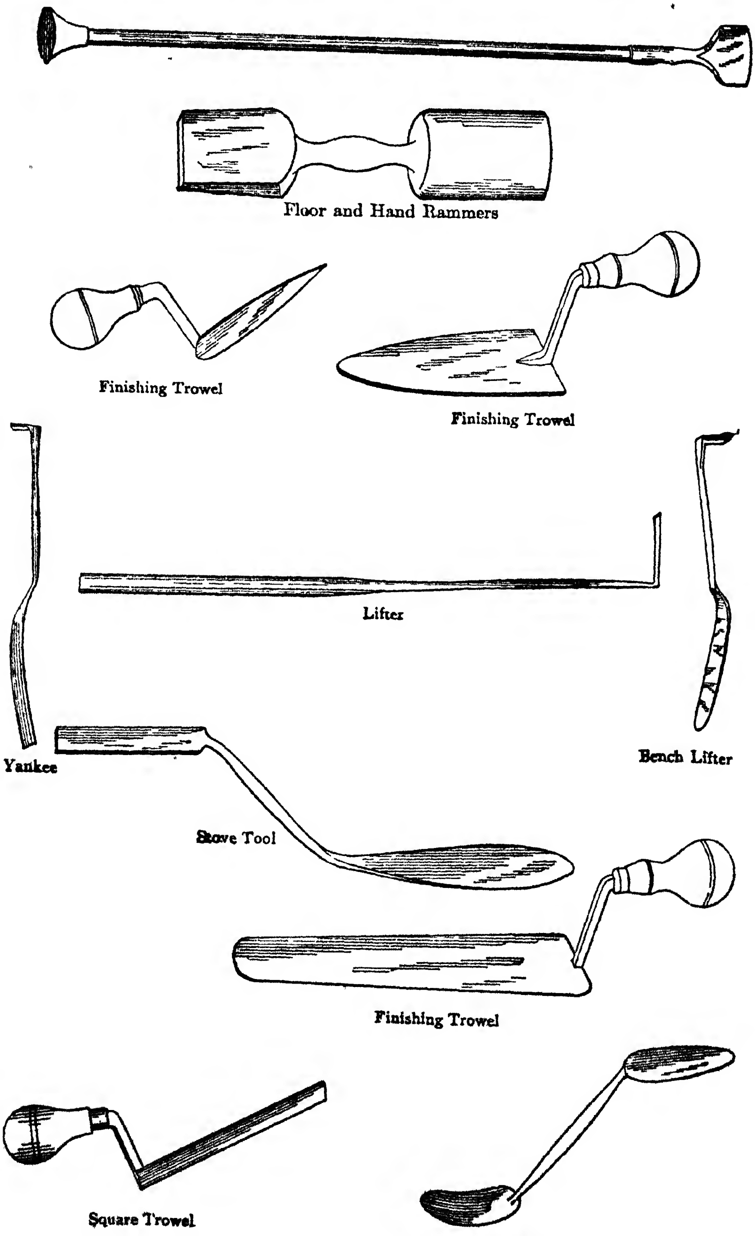
Furthermore, it may readily be imagined that parts of the pattern as shown in Fig. X-4 might be of such a shape, with flanges on the bottom or something of that kind, that they could not be drawn without breaking the sand. In the case of such a design the pattern and flask must be split into three or more parts,[1] or else a core must be put in to make an offset. It will be evident to every engineer that he will have to pay more for making a casting so designed.

Ramming.—In pattern molding it is essential that the pressure of the sand around the pattern shall be nearly uniform in all places, because (1), when the metal is poured into the mold, it drives out the air already there by forcing it through the interstices between the particles of sand, and, if the sand is too hard in any place, the pressure of air collected there is liable to form a depression in the casting; and because (2), if the sand is too loose in any place, the pressure of the metal upon it is liable to "swell" it outward and thus cause an enlargement of the casting at that point. To obtain uniformity it is necessary that the sand be packed around the pattern, and not the pattern pushed into the sand. Thus packing is accomplished by the hands for the sand immediately adjacent to the pattern and by rammers for the layers farther distant. In the case of bench molding hand rammers are used, and for making larger molds on the floor long iron rammers are employed. The molder's skill is shown in applying the proper amount of power in ramming each different kind or part of pattern.

Dry-sand Molds.—After ramming up the mold, drawing the pattern, and applying the *wash*, the mold may be used green (when it is called a *green-sand mold*), or it may be put in the ovens and dried (when it is called a *dry-sand mold*). The drying has the effect of driving off the moisture and leaving a firm, hard mass, semibaked into a sort of brick. Sand for these molds should have slightly more clay than for green-sand molds; otherwise, instead of baking into a hard mass, they would be liable to crumble with the heat. The temperature of drying ovens should be about 350 to 400°F. (170 to 200°C.), and they are heated by coke, coal, gas, or oil. If the temperature is too high, the mold will be burned; *i.e.*, it will crumble under the fingers after drying; if not hot enough, the mold will not be baked hard. The length of time in the oven will depend upon the size of the mold and will vary from an hour or so to a day or so. During the drying the molds are liable to shrink somewhat, owing to the action of the clay in binding together.

---

[1] The bottom and top parts being still known as the *drag* and *cope*, respectively, while the intermediate parts are known as *cheeks*.



Floor and Hand Rammers

Finishing Trowel

Finishing Trowel

Lifter

Yankee

Bench Lifter

Stove Tool

Finishing Trowel

Square Trowel

Slick and Spoon

Fig. X-5.—Tools used in molding.

Fig X-6 —View in a foundry

Green-sand Molds.—Green sand requires less clay than dry sand, because it has a certain coherence due to its dampness. Many natural sands are found suitable for both the green-sand mold and the dry-sand mold, or they can be made up as desired by mixing a good clay with a sand rich in silica. Green-sand molds must not be rammed so hard as dry sand, so the moisture may more readily evaporate.

Washes.—For iron castings the common wash is graphite dust, which is made up into a paint with water and applied with a brush or dauber to the inside of a dry-sand mold before it goes to the oven. In the case of a green-sand mold, pulverized coal is dusted on to the surface through a piece of cloth and then spread uniformly with the "slicker." In the case of a dry-sand steel casting, the wash is composed of pulverized silica rock, running from 98 to 99 per cent silica, which is made up into a thick paint with water, thickened with molasses, and applied to the inside of the mold with a brush or dauber before the mold is dried. Green-sand molds for steel castings cannot ordinarily be washed. Graphite washes cannot be used for steel molds, because the hot metal attacks the graphite and becomes rough upon its surface.

The functions of washes are (1) to make a very smooth face on the sand, so that the surface of the casting shall be smooth (this they accomplish by the very fine size of their particles); (2) to give a surface that shall resist the melting and chemical action of hot metal, so the castings may be easily cleaned of sand.

Skin-dried Molds.—The inside surface of green-sand molds is occasionally dried by painting or spraying it with some inflammable liquid, such as gasoline, and then applying a match. This is more common in steel-foundry than in iron-foundry practice, and produces a little better surface to the casting.

Dry- vs. Green-sand Molds. *For Iron Castings.*—Dry-sand molds are often cheaper to make and require less molding skill for the following reasons: (1) The sand does not have to be tempered so carefully, *i.e.*, brought to the proper condition of dampness, since the moisture is eventually to be driven off by the drying. In green-sand molds, if the sand is too wet, it is liable to "cut" (be eroded by the stream of metal) and get dirt into the casting, and also to be impervious to the gases. (2) The sand requires less care in ramming, because, whether too hard or too soft, the expansion and contraction in drying will adjust its firmness and porosity. (3) Furthermore, the dry sand is stronger, which is an advantage, when the sand is liable to be under pressure from the metal, or to have the metal fall upon it from a height. (4) Dry-sand castings are also more liable to be sound, because there is less gas in the pores of the sand.

The disadvantages of dry-sand castings are: (1) The mold is liable to shrink during drying and therefore be less true to the pattern; (2) the castings are more liable to "check" (*i.e.*, crack in cooling), because the mold is firmer and so does not give way so easily to the crushing action when the casting contracts; (3) molds exposed to the direct action of the flame during drying, or heated too hot, are liable to be burnt and therefore rendered useless, causing a loss; (4) in handling, the molds are liable to be damaged; and, furthermore, it is more costly to repair a dry mold than a damp one, because the adjacent sand must first be damped, the damage repaired, and then a flame applied to dry the wound; (5) it takes longer to complete an order. The actual cost of heat is not very great and usually is less of an item than the extra labor of handling for drying.

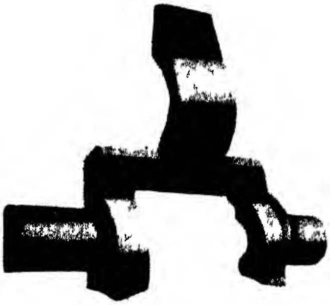


FIG. X-7 —Core.

For Steel Castings.—Dry-sand steel castings have a surface superior to those made in green sand. They are also stronger and more liable to be sound. Soundness is much more difficult to obtain in steel castings than in iron castings. Green-sand molds, however, have the great advantage of allowing their sand to crush more easily when between two parts of the casting that are being drawn together by the shrinking of the metal. This is doubly advantageous in steel work, because steel shrinks twice as much as cast iron and is therefore more liable to checking. Special means may be employed for making the sand easily collapsible after the metal is poured, such as mixing with it an inflammable substance like flour, chopped hay, hay rope, sawdust, coke, etc., which burns away after the hot metal is poured in.

Cores.—The function of cores has already been referred to. They are set inside the mold proper to assist in forming the metal. The commonest use for them is to extend through a casting in some place to make a hole, as, for instance, the inside of a cylinder or the bore of a pulley. In this position they are subjected to great crushing strain when the metal shrinks, and therefore the bond which keeps the sand together, consisting of linseed-oil or flour paste, a patented core compound, etc., must be of such a nature that when subjected to the heat of the liquid metal it will burn away and allow the sand to disintegrate, which both prevents its bursting the shrinking casting and permits of its being more easily cleaned out. Cores are often built up around an iron pipe riddled with holes, so that the gases formed may readily escape through this "vent." In the case of large cores the pipe is frequently wound with hay rope, or some similar material that will burn away and make the sand more collapsible. Some cores have coke breeze or spongy cinder in the center to make them light as well as porous.

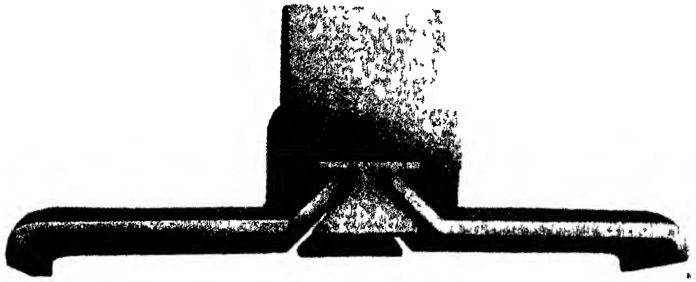


Fig. X-8.—Core.

Cores are supported sometimes by being set in the drag, sometimes by being hung in the cope (see Fig. X-9); but it is more common to have a hollow adjunct to the mold, known as a *core print,* into which an extension of the core fits. Sometimes both ends of the core are so supported, and sometimes only one end, while the other end rests upon a metal chaplet that is absorbed in the casting when the metal is poured. Cores are often dried, lest their gases make the casting unsound or cause it to blow, *i.e.*, boil with the rapid escape of gas through the metal.

Chill Molds.—It is often desired to chill certain parts of a casting or cool them more rapidly than the remainder, in order either to make a thick part of a casting solidify as soon as, or sooner than, the thinner portions, or else to produce white cast iron at that point. The former may be desirable in the case of

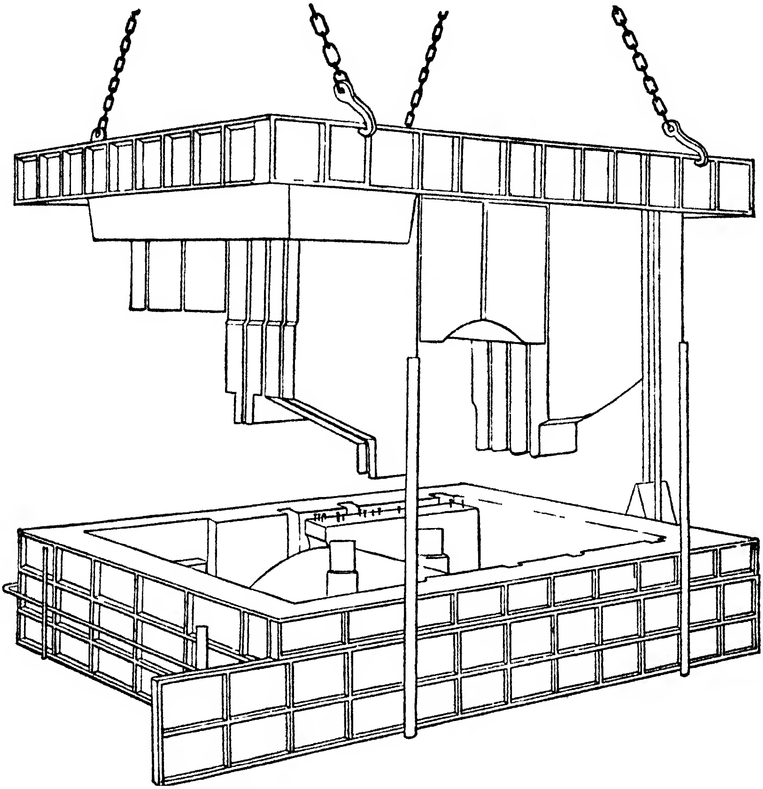


Fig. X-9.—Cores hung from the cope.

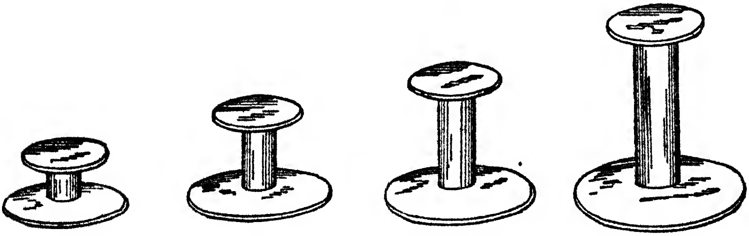


Fig. X-10.—Chaplets.

either an iron or steel casting, because the shrinkage cavity occurs in the last portion to freeze, and therefore hastening local freezing may be necessary to bring the pipe into the riser or feeder. The latter applies only in iron-casting work in which it is desired to make the outside of a casting very hard. The chilling is usually accomplished by embedding pieces of metal in the sand, against the face of which the casting is poured. This metal is oiled, blackened, or "washed," so that it does not stick to the casting.

Permanent Molds.—A great deal of expense in foundry work is due to the fact that a sand mold must be made anew for every casting, and the subject of permanent molds has occupied the attention of foundrymen for a great many years without the problem's being completely solved. When a casting is knocked out of the mold, the sand is usually knocked out also and its form destroyed. In the rare case of a smooth cylinder, or something of that kind, the casting may be withdrawn without damage except to the face of the sand, and this can sometimes be repaired and swept up anew without reforming the entire mold. Again, molds for railroad-car wheels, which have a metal "chill" all the way round the tread and flange, in order that the cast iron may be white at the point to withstand the grinding action on the rails, have a certain amount of permanency. Finally, molds carved out of carbon which has been preheated to a very high temperature are said to withstand the action of the melted metal and to last for a large number of castings.

Centrifugal Casting.—For some years cast iron has been successfully cast in rapidly rotating molds which throw the metal around the sides and so produce under the pressure of centrifugal force a hollow pipe. The pipes are cast with the flanges on them, as shown in Fig. X-11, and are taken out of the mold while still red hot and put into annealing ovens. The texture of the metal is finer and closer grained and the cast iron is stronger per square inch than that which is cast under static conditions. At the Watertown Arsenal in Massachusetts liquid steel is brought at a high temperature from a high-frequency electric furnace and poured into a rotating refractory-lined mold, for the making of hollow cannon tubes.

Gating of Patterns.—The gate of a mold is the place into which the liquid metal is poured (see Fig. X-4), while the sprue extends from the gate to the casting proper. The placing of gate and sprue is governed by certain principles whose best application can be learned only by experience Referring especially to

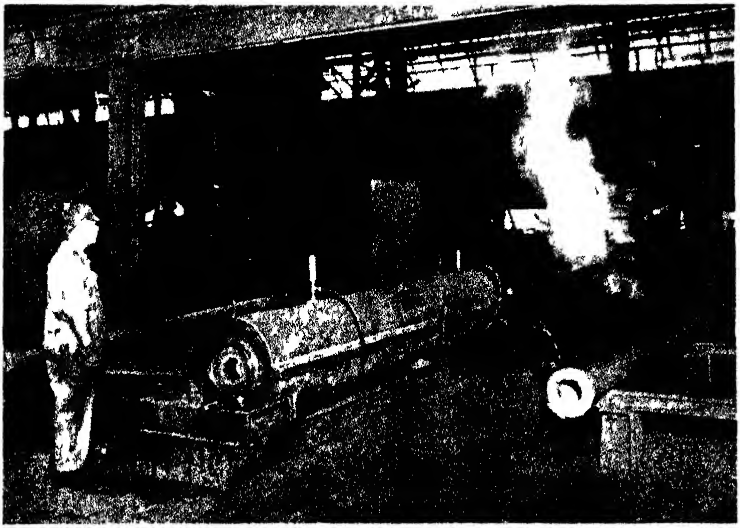


Fig X-11 —Centrifugal casting of cast-iron pipe (*From General Catalogue, United States Cast Iron Pipe Co* 1925)

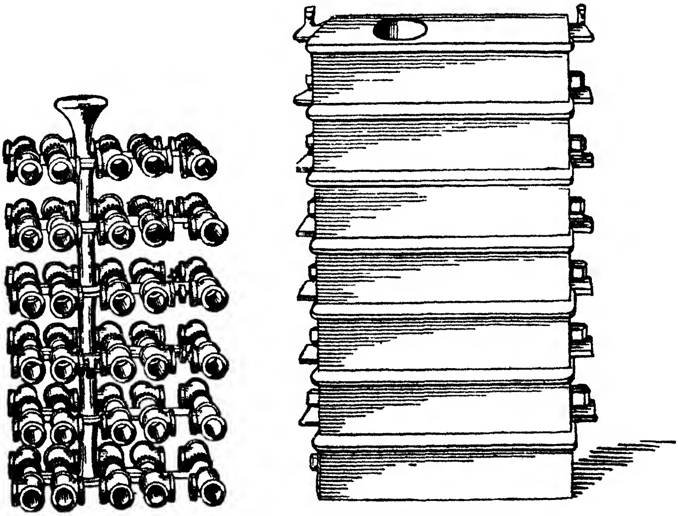


Fig X-12 — Multiple mold and casting

Fig. X-4, we see for example that, if the metal were poured into the riser of the casting, it would drop upon the core and knock this to pieces. Even if this core were absent, the metal in dropping from such a height on to the sand bottom of the mold would wash sand from it and make a defective casting because of the cutting of the mold at this point as well as the probable inclusion of some of the sand in the solid metal. Furthermore, the metal would spatter on the sides of the mold and frozen drops might accumulate which would afterward form a "cold shut" on the side of the casting. It is rarely good practice to pour a casting through a riser, and, whenever the metal is poured from a height, it is well to insert a refractory fire brick upon which the stream shall strike. Steel castings are almost always poured from the bottom in a manner in general similar to Fig. X-4, and this method is often followed in case of gray iron as well. The general principles of gating may be very briefly summarized as follows:

1. The metal must be forced into the mold fast enough to prevent its chilling at any point, so that sprue and gates must be amply large; in the case of a thin casting, for example, this may necessitate having the metal enter at a number of different points at the side of the mold.

2. On the other hand, unnecessary amplitude is to be avoided since the sprues have only the value of scrap.

3. The stream of metal must not wash against the sand in such a way as to cut it. We may exemplify this by an example in steel castings where the stream of metal is usually brought in at the bottom and with a certain tangential direction so that it shall rise in the mold with a rotary motion.

4. The metal must not have too far to run. In large or long castings this may necessitate gating at several different points.

5. As far as possible we must arrange to pour into a reservoir and to have the rate of pouring such that this reservoir shall be kept as nearly full as possible in order that any slag or dirt accidentally getting in at this point may tend to float to the top of the metal and not be carried into the casting proper.

6. The point at which the metal enters is the hottest part of the casting, and this must be borne in mind when considering the question of feeding, to avoid shrinkage cavities. Sometimes it is desirable to chill this location in order artificially to oppose these conditions.

7. In placing a gate we must remember that, as the metal shrinks, it will draw the sprue toward the casting. Since the

sprue is the hottest part, there may be a tendency for this contraction to tear the metal in two and especially to tear the sprue off at the point where it joins the casting proper, thus making an unsightly defect.

Tests of Foundry Sands.—A mold must be strong and must be permeable to gases. Probably the most important recent advance in foundry practice is the investigation of properties of foundry sands and the development of tests to determine their qualities in advance of use, as well as after mixing, baking, etc. Comprehensive and very useful literature can be found on this subject in the *Transactions of the American Foundrymens' Association,* but it is a mechanical, not metallurgical, subject for study.

Molding Machines.—At the present time various types of molding machines are being extensively introduced into foundries, in order to save some of the labor or skill required in molding, or both. This is also a mechanical feature of foundry practice.

Gated Patterns.—Where the castings are very small, a large number of them will be made into one pattern, fastened on to a common *gate* through which they are poured, which produces very great economy in molding (see Fig. X-12).

Core Machines.—There are also on the market several machines for making cores.

Contraction.—A bar of cast iron 12 in. long will contract about 0.125 in. during solidification and cooling; *i.e.,* it will be about 11⅞ in. long when cold (see page 452 for further details), while a bar of steel will contract about twice as much. In both cases the contraction in sectional dimensions will not be so great as in length.

Design of Patterns

The foregoing description will show what a great financial advantage it is to a purchaser if he designs castings that can be easily molded, and if he can order a large number of castings of exactly the same design. It is certain that a hundred castings of one design can be made with very much greater cheapness than the same number all of different designs, and of this economy the purchaser obtains his full share, because the foundry is glad to encourage such a customer and to make concessions in order to do his work. The author cannot recommend too strongly to engineers the practice of making the castings in all similar machines interchangeable, both for the sake of economy and of avoiding some delay and expense in replacement after a breakdown. The correct design of castings is, furthermore, one of the most important branches of engineering work, since the number of castings used is almost one-half of the total number of pieces used in engineering work, while their weight is equal to about one-sixth of the weight of all the iron and steel employed. The following general hints are therefore offered to assist in this design; but each casting is a study in itself, in order that the various desiderata referred to may be obtained.

To Avoid Checks.—The commonest error in engineering designs of castings is to make the corners too sharp, which makes them very liable to check, because of the crystalline character of iron and steel. This is the more important, because the greatest leverage comes at the corners, which therefore should be made as strong as possible. Metals are crystalline substances and the crystals grow during solidification. As solidification usually extends from the surface inward, the crystals grow in a direction perpendicular to the cooling surfaces. This results in a line extending inward from all corners, marking the junction of many crystals. As the junction lines of crystals are not so strong as the crystals themselves, this makes a line of weakness on corners, which is the more marked the sharper the corner is. In case a casting is to be machined, it is much better to put a large fillet in all the corners, even if the rounded metal must be cut away later, as greater strength is obtained in this way.

The checking of castings comes from the strain produced by the contraction of the metal tending to crush the sand. This is the more intense the greater the distance between the two crushing parts, because they must approach each other by an amount exactly proportional to the length of metal between them. It is therefore wise, wherever possible, to avoid long lengths of metal connecting two parts which project into the sand.

Unequal cooling strains will also cause a check. This may be illustrated by a pulley with thick arms and a thin face. The face will solidify first and therefore yield very little to the subsequent contraction of the arms. Moreover, the face, being cooler, will then be stronger and the tendency will be for the arms to tear themselves in two. To avoid this it is common practice to chill the arms either by setting metallic pieces in the mold or by means of a *water gate.* A water gate is a loose column of coke molded into the sand of the cope, down which water may be poured.

To Avoid Shrinkage Cavities.—The formation of a *pipe,* or shrinkage cavity, has already been explained. Such a defect in a casting would be intolerable and is commonly avoided by having a reservoir of metal situated above the casting proper and large enough to keep it supplied with molten metal until it has completely solidified. This reservoir is known as the *riser,* or *header* (sometimes merely *head*), or *feeder.* The riser is included as a part of the mold when it is made but is cut off the finished casting and used over again as scrap. Sometimes castings are so designed by engineers that a heavy section of metal must be molded underneath a thinner section. As the thinner section will solidify first, it cannot "feed" this lower heavy section; and therefore a special form of riser is required, or else the heavier section must be artificially cooled. Iron castings usually do not form shrinkage cavities, but steel castings must be fed carefully to all parts.

Cupola Melting of Iron for Castings

Iron for castings is melted in either the cupola or the air furnace,[1] although *direct castings, i.e.,* castings made from the metal just as it comes out of the blast furnace, are used in many cases, and especially for cast-iron ingot molds at steel works. For this practice it is necessary to employ men with sufficient expertness to be able to judge by eye the character and the analysis of the liquid iron as it flows from the furnace, because the metal may vary greatly and without warning from one cast to another. Sometimes, also, metal mixers are used, similar to those at steel works. Ford makes automobile-engine castings by mixing in a ladle iron taken liquid from his blast furnaces with iron from cupolas. Most large modern cupolas have mechanical means of charging raw materials, instead of hand charging. This promotes speed and economy.

In the cupola (see Fig. X-13) a layer of iron rests on top of a bed of white-hot solid fuel. Air is blown against this fuel; the oxygen unites with carbon, and the resulting hot gases, as they pass upward, melt the iron. The layer of iron is not deep; it

---

[1] The air furnace is used in gray cast-iron, chilled-iron, and malleable cast-iron foundries and will be discussed in Chap. XV.

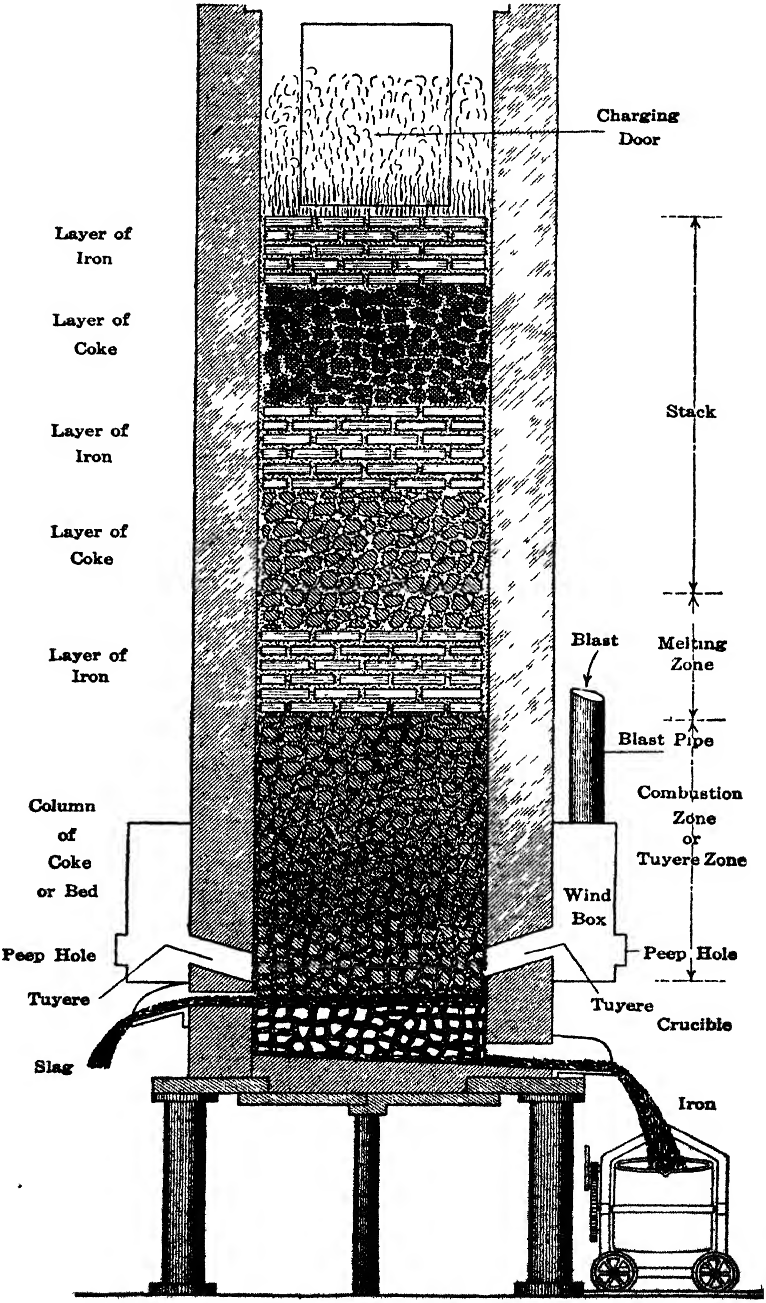


FIG. X-13.—Iron cupola.

should therefore all be melted in less than 5 to 10 min. During this interval the fuel is being consumed also. Now a new layer of fuel rests on the bed to replace what has been burned, and a new layer of iron on top of that. By correct proportioning of the alternate layers of fuel and iron, the new layer of iron will occupy exactly the position of its predecessor, this location being the *melting zone* of the furnace.

Cupola Zones.—The cupola should be so operated that certain well-defined zones of action will be maintained, in order that rapid, hot, and economical melting will result and that loss by oxidation be small. If proper conditions prevail, all of these desiderata may be obtained together, while, if otherwise, wasteful methods may be accompanied by slow, irregular melting and *dull iron*, *i.e.*, iron not sufficiently hot.

Crucible Zone.—The crucible extends from the bottom of the cupola to the level of the tuyères. The object of this part is to form a place in which the iron and slag may collect after they have melted and trickled down. If the tap hole is kept open all the time and the metal allowed to flow out of the cupola and collect in an outside ladle as fast as it melts, the crucible zone will be very shallow, and the tuyères will be situated not more than 2 to 5 in. above the bottom. If, on the other hand, the crucible is used as a reservoir for a large amount of metal, the tuyères are placed correspondingly high. Hotter metal may be obtained by collecting the iron in an outside ladle, because it is not blown upon by the cold blast, and using the cupola as a reservoir is not considered good practice except for short intervals.

Tuyère Zone.—The tuyère zone is the place in which the blast comes in contact with, and burns, the red-hot coke. It is the zone of combustion, and all the heat of the operation should be produced in this place. It is, of course, situated near the tuyères and wherever the raw blast may come in contact with coke. As there is always a column of coke extending to the very bottom of the cupola, combustion will begin immediately above the reservoir of melted metal. Its upper limit will depend upon the pressure of blast, because the greater the blast pressure, everything else being the same, the higher will it extend its zone of combustion. The blast pressure should be such, however, that the top of the tuyère zone, or zone of combustion, should never be more than 15 or 24 in. above the uppermost tuyères.[1]

[1] There are sometimes two rows of tuyères in cupolas (see Fig. X-15).

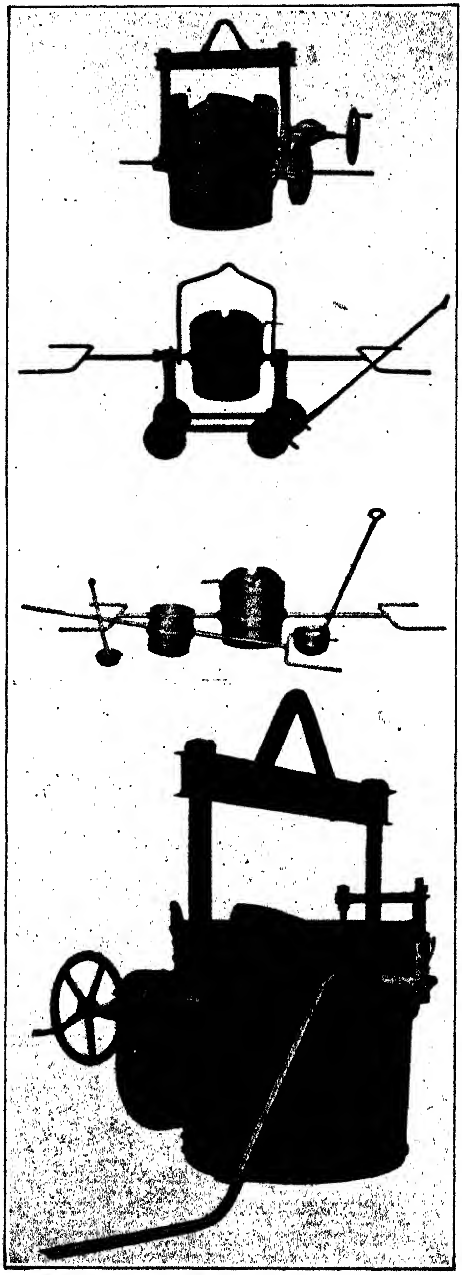


Fig. X-14.—Foundry ladles. (*Courtesy of The Paxson Co.*)

Melting Zone.—The melting zone is the space in which all the melting of iron takes place; it is situated immediately above the tuyère zone. During the melting the iron is supported on a column of coke, which is the only solid material below the melting zone. When each layer or charge of iron enters the melting zone, it should be about 15 to 24 in. above the uppermost tuyères. As fast as it melts, it trickles down over the column of coke to the bottom. It takes about 5 to 10 min. for each layer of iron to melt, however, and during this time the column of coke is burning and sinking. Therefore, the last of the iron will melt at a point about 7 in. lower than the first. Consequently, the melting zone overlaps the upper limit of the zone of combustion. If the layers of iron and coke are properly proportioned to the pressure of blast, each charge of iron will enter the top of the melting zone just before the next previous charge is completely melted at the bottom, and thus a continuous stream of iron will collect in the crucible or run from the tap hole. Also, the coke burned from the column will be exactly replenished each time by the layer of coke coming down, and the position of the melting zone, which is the important consideration, will be maintained within constant limits.

The actual position of the melting zone may always be learned when the cupola is emptied, because the iron oxide formed there will corrode the acid lining, which will therefore be cut away somewhat at this point. Corrections may then be made, if necessary, in the next charge of the cupola. For example, the bed should be so proportioned that it will extend, after the coke is well heated up, to a point about 7 in. above the bottom of the combustion zone. The melting zone itself, as indicated by the cutting of the lining, should not be more than 8 to 12 in. deep.

Stack.—The stack extends above the melting zone to the level of the charging door. The function of this part of the furnace is to contain material that will absorb heat and thus prepare itself for the actions at lower levels and that will also keep the heat down to the melting zone as well as possible.

Tuyères.—The blast enters the cupola through the tuyères, of which there are usually one or two rows. The lower tuyères are made of iron castings. The opening they make into the inside of the cupola should form a practically continuous slot around the inner diameter of the furnace. The position of the upper row of tuyères determines the position of the melting zone in the cupola. Two rows of tuyères give faster melting in the cupola than one row but cause greater oxidation and the consumption of more fuel on the bed, because since the melting zone is higher in the cupola it requires a larger bed to start with.

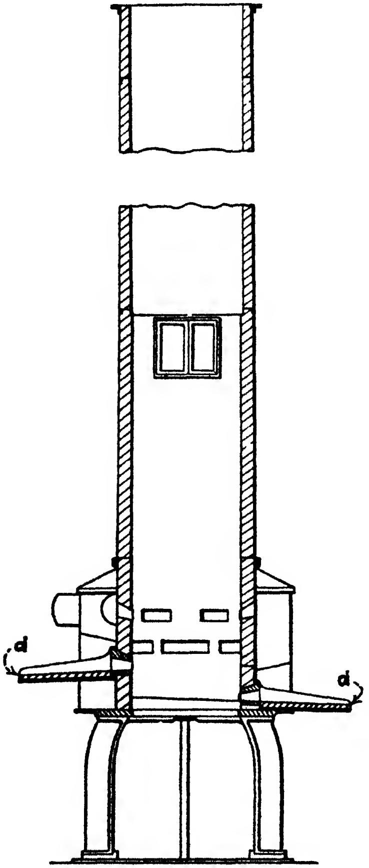


Fig. X-15.—Section of cupola showing almost continuous slot for lower tuyères. The best practice would have even less space between.

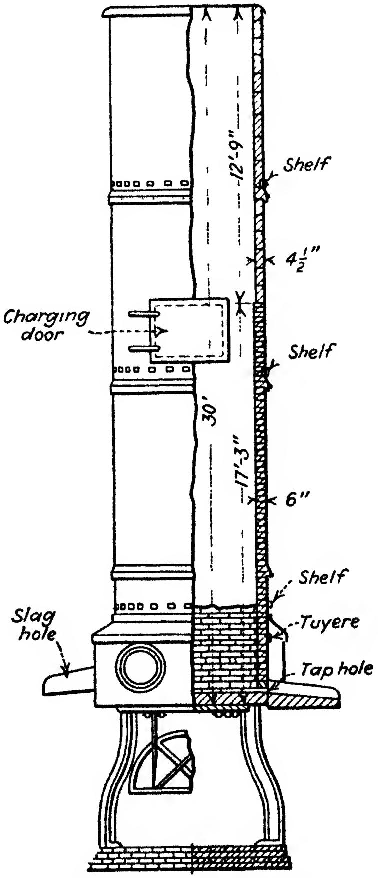


Fig. X-16.—Section of cupola of 60 in. inside diameter.

Blast.—The blast pressure will depend somewhat upon the size of the cupola, but the present prevailing opinion is in favor of pressure not exceeding 1 lb., even for the very largest cupolas, and diminishing to ½ lb. or so for the smaller sizes. Fan blowers, although cheaper, are giving place to pressure blowers, because, if the former are opposed by pressure in the cupola stack, they revolve without blowing any wind. The common type of blower used in America is of the two-impeller type, an example of which is shown in Fig. X-17. It takes about 64 cu. ft. of air to burn 1 lb. of coke,[1] from which may be calculated the size of blower necessary for each cupola, allowing about 50 to 100 per cent excess for leaks and incomplete combustion. The volume of the blast is the real factor in cupola melting, and recent cupola improvements comprise volume meters to indicate volume as well as pressure.

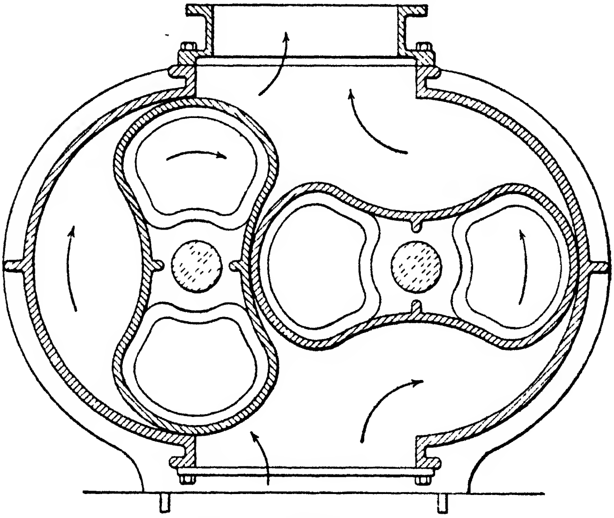


Fig. X-17.—Section of positive pressure blower of the two-impeller type, capable of producing pressures up to 5 lb. or so. The arrows show the direction of rotation and intake of air at bottom; exit at top.

Makers of cupolas and blowers give all the necessary data in their catalogues but advocate too high blast pressures and volumes. If the blast volume is too large, or the pressure is too great, the position of the melting zone will be too high. This means that the bed of coke must be larger to reach to the upper level of the melting zone, which is wasteful. It also means that the melted iron will have a greater height to drop through. It therefore oxidizes more, corrodes the cupola lining more, and

---

[1] $\underset{12}{\mathrm{C}} + \underset{16}{\mathrm{O}} = \mathrm{CO}$. Then 1 lb. carbon requires 1.33 lb. oxygen; = 1.33 × 11.209 = 15 cu. ft. oxygen; 1 lb. coke requires 15 × 90 per cent = 13.5 cu. ft. oxygen; = 13.5 ÷ 21 per cent = 64 cu. ft. air at 32°F. and 14.7 lb. per square inch atmospheric pressure.

consequently causes more waste of iron and more slag. The volume of blast is the most important consideration, but this is difficult to measure, so the pressure is often the substitute.

Loss.—The loss in melting will average about 2 to 4 per cent. It is made up of the silicon burned and the iron oxidized and carried away in the slag. There are other sources of loss in the foundry, such as a second loss of metal remelted—the sprues, risers, etc., which go back to the cupola in the form of scrap; metal spilled during pouring (which may amount to as much as 5 or 6 per cent more), etc. In some foundries it is customary to pass the used floor sand through a magnetic concentrator, in order to recover the pellets of iron spilled during pouring, and important economy is sometimes obtained in this way. The total loss, *i.e.*, the difference in weight between pig iron bought and castings made, will probably be about 7 to 8 per cent of the weight of the iron bought.

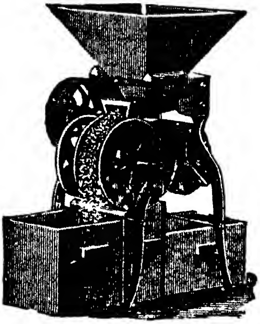


Fig. X-18.—Magnetic concentrator.

Scrap Used.—Scrap pig iron is often mixed with new pig iron for the manufacture of castings, both for the sake of economy and because the scrap iron has a somewhat closer grain or texture, which increases the strength of the mixture. The amount of scrap used will depend upon the materials to be manufactured. Cast-iron pipe is usually made without scrap, this industry amounting to between 500,000 and 800,000 tons per year in the United States alone. Stove foundries, on the other hand, use a very large amount of scrap as a rule, and jobbing foundries, in general, would probably use an average of 30 to 40 per cent of outside scrap, besides the gates, sprues, bad castings, etc., made in their own foundries. The total production of gray-iron castings in the United States will represent about 75 per cent of pig iron plus return scrap, and 25 per cent of bought scrap.

Cupola Run.—The campaign of an ordinary foundry cupola is only 3 or 4 hr. long. As a general thing, the kindling is started about noon and allowed to burn with a natural draft until shortly after one o'clock, when the breast is closed and the blast put on. Metal is then received until four or five in the afternoon, when the last charge is melted. The supports are then pulled out from underneath the door closing the bottom of the cupola, and the sand bottom, slag, coke, etc., left in the cupola is allowed to drop and is quenched with water. In order to allow plenty of room for the "drop" to fall, the cupola is usually elevated above the foundry floor.

Fuel.—The cupola is the cheapest furnace for melting because it affords direct contact between metal and fuel. The amount of fuel will be from one-fourth to one-twelfth of the weight of the iron melted, the former figure prevailing where very much steel scrap is mixed with the charge and where exceedingly hot metal is desired—*e.g.*, for very small castings for malleable cast-iron work—and the latter figure where the melting is continued for several hours and the metal is not made very hot but is to be poured into large castings. Coke is the commonest fuel, with sometimes a mixture of coke and anthracite for the bed.

Cupola Charge.—In the cupola are first placed shavings and wood, on top of which is placed the bed of coke, which should be large enough to reach 15 to 24 in. above the uppermost tuyères after the kindling is burned off. On top of this is placed a layer of pig iron about 6 in. thick, then another layer of coke about 7 in. thick, another layer of iron, and so on. The actual weight of the coke for the bed and of coke and iron for each charge will therefore depend directly upon the diameter of the cupola inside the brick lining, which varies from about 32 to 120 in., or even more in some cases. The weight of the coke in each layer will be about one-sixth to one-twelfth of the weight of iron in each layer. The tuyères and front of the cupola around the tap hole, known as the *breast*, are left open for an hour or so after the kindling is lighted, in order that the draft may draw air in at that point for combustion. When the kindling is thus burned off and the bottom coke well lighted, the breast is closed and the wind turned on. It is very necessary that the bed should be well lighted and level. More recently it has become common practice to light the coke bed with a specially designed oil burner, instead of kindlings, which saves time and labor.

Cupola Melting.—The heat now generated by the combustion of coke begins to melt the iron, and in less than 15 min. after the wind is put on the metal should begin to run from the open tap hole. If it takes longer, then the coke bed was too high which is wasteful. In 8 to 10 min. thereafter the first layer of iron should be all melted. Now the second layer of iron lies upon the column of coke, whose top should again be 15 to 24 in. above the uppermost tuyères. If the layers of coke are too thick, there will be a delay in the iron's entering the melting zone and the extra coke burned will not have been used to the best account. If the layers of iron are too thick, the last of the layer will melt too near the tuyères, which will oxidize it excessively and make it cold. This can be observed during the run by noting if the iron runs first hot and then cold. It is very important to watch the flame that comes off the top of the stack in the cupola. When the blast volume is too large, this flame will be *cutting*, *i.e.*, oxidizing in character. Too great oxidation may also be observed if sparks of burning iron are projected from the slag hole. If the layers of iron and coke are both too thick, there may be a correct relation between the weights of the two, but both of the irregularities mentioned above will be observed. It is probably not possible to have the alternate layers of fuel and iron too thin if the correct relation between them is maintained. Of course, if very hot iron is required, it will be necessary to have thicker layers of coke, and slower melting must be expected.

Chemical Changes.—As the iron drops down over the coke, it absorbs sulphur, the exact proportion depending chiefly upon the relative amount of coke and iron used and the percentage of sulphur in the coke. It will vary from 0.02 to 0.055 per cent of the iron; *i.e.*, if the pig iron charged contained 0.08 per cent of sulphur, there will be from 0.1 to 0.135 per cent in the castings. The sulphur in the first iron will be higher than in that of the middle of the run, because of the extra amount of coke burned before the iron begins to come from the tap hole. The last iron will also be somewhat higher in sulphur, because there is a larger loss of metal during the last of the run, when the oxidizing conditions are more intense, and therefore a concentration of sulphur. The best practice is to cut the blast off progressively as there is less stock in the cupola.

In many foundries it is customary to charge limestone, in the form of oyster shells, marble chippings, or crude limestone, and sometimes with it a little fluorspar, CaF_2, into the cupola. The amount of limestone varies greatly but will average perhaps ½ to 1½ per cent of the weight of the metal. This limestone fluxes the dirt on the metal and the ash of the coke and carries off some sulphur in the slag. Fluorspar makes a somewhat more liquid slag than limestone alone and the more liquid slag is believed to absorb a little more sulphur, and also to make the cupola *drop* more easily, *i.e.*, dump its contents when the campaign is ended, and the bottom is allowed to fall. It also cuts the lining more.

As the metal melts and falls from the melting zone down in front of the tuyères, it suffers oxidation, which carries iron oxide into the slag and also burns up silicon. The melted metal therefore contains from 0.25 to 0.4 per cent less of silicon than the original pig.[1] In other words, if the mixture charged contains 2.25 per cent of silicon, the castings will contain 1.85 to 2 per cent of silicon.

Cupola Gases.—The gases coming out of the top of the cupola charge consist principally of nitrogen from the air, while the remainder is carbon dioxide and carbon monoxide with sometimes a little free oxygen. Free oxygen is evidence of a *cutting flame* and shows too great oxidation in the melting zone. Such a flame may be recognized without the aid of chemical analysis after a little practice by means of the eye. It is "sharper" looking than a richer flame and burns close to the top of the stock. One can identify it definitely by holding an iron rod in it for a while; after the iron becomes red hot, it will oxidize much more rapidly in a cutting flame than in a reducing flame. Again, a reducing flame will usually not burn until it becomes mixed with the air sucked in at the charging door. All the carbon monoxide that goes out of the charge represents incomplete combustion and a waste of heat. It seems to be impossible to prevent this here, however, just as in the blast furnace, the operations of which cupola melting resembles in some general respects.

Burdening the Cupola.—It should be the duty of the foundry metallurgist or chemist to learn from his records, or other approximations, the amount and analysis of all the metal in the yard. The table on page 338 will, for example, show a convenient form of this record.

The price should always be in evidence. It should not be the price at which the material was purchased but the market price at the time the iron is to be used. For instance, if a large amount of high-grade pig iron had been contracted for a year previously and if meanwhile the price of pig iron had been rising, the purchase price of that pig iron would not represent its present value. From the current numbers of such trade periodicals as the *Iron*

---

[1] With good practice it should be no more than 0.30 per cent less.

Age and the *Steel,* one can always obtain the prevailing prices for the different grades of iron.

Suppose now with these irons it is desired to burden a 72-in. cupola with a mixture for making heavy hydraulic pumps for which a satisfactory analysis might be 1.60 per cent silicon, 0.70 per cent phosphorus, less than 0.10 per cent sulphur, and about 0.50 per cent manganese. The first step is to calculate the cupola charges, and the chemist knows by experience with this particular cupola that it will lose 0.25 per cent silicon and 0.10 per cent manganese and it will gain 0.03 per cent sulphur. The average analysis of the mixture put into the cupola must then be 1.85 per cent silicon, 0.70 per cent phosphorus, less than 0.07 per cent sulphur and about 0.60 per cent manganese. The chemist also knows by calculation that about 5,200 lb. of iron will give a layer of the proper thickness in a 72-in. cupola. His problem now is to make such a mixture of the available pig irons that their collective weight will be 5,200 lb. and their average analysis as given above. Moreover if he is a good metallurgist he must aim at using as large an amount as possible of the cheapest materials.

Table X-I.—Sample Foundry Record of Iron in Stock

Kind	Weight, tons	Si, per cent	S, per cent	P, per cent	Mn, per cent	Price
High sulphur, southern...	500	0.70	0.100	1.50	0.30	$18.00
High silicon, Bessemer....	60	2.50	0.025	0.07	0.60	25.00
X No. 1................	100	3.00	0.030	0.80	1.25	24.00
No. 3 foundry...........	150	1.75	0.070	0.30	0.60	22.50
Ferrosilicon A...........	30	10.00	0.040	0.50	0.10	35.00
Ferrosilicon B...........	30	50.00	0.003	0.04	.....	105.00
Machinery scrap.........	100	1.70?	0.100?	1.00?	0.60?	19.00
Miscellaneous scrap......	300	1.50?	0.20?	1.40?	0.60?	15.00
Cast-iron borings.........	100	1.50?	0.20?	1.40?	0.60?	11.00
Steel scrap..............	100	0.10	0.07	0.10	0.60	13.00

He first considers the steel scrap. He knows he cannot use very much of this because too much coke would be required for getting iron of the requisite fluidity, but he estimates that 5 per cent (say 200 lb.) will not increase harmfully the fuel necessary. This figure therefore comes at the top of his list (see Table X-II).

Next he considers the use of machinery scrap, because he knows that his miscellaneous scrap and borings are too uncertain in analysis to be used in a mixture which must give pretty strong and nonporous castings. One thousand pounds of machinery scrap would be about 20 per cent of his mixture, and he knows from experience that this is a fairly satisfactory proportion, so that figure goes down second in Table X-II. The low price of the high-sulphur southern pig tempts him, but he realizes that he must offset the use of this material by some high-silicon low-sulphur iron. And in casting about for such a one he naturally considers first the X No. 1. He cannot use much of this either because of its high manganese and it seems reasonable to mix an equal amount of these two. The only question is: How much of this mixture will the cupola stand? To get an idea of this, he first calculates their average analysis and finds it to be 1.85 per cent silicon, 0.065 per cent sulphur, 1.15 per cent phosphorus, and 0.78 per cent manganese. Evidently the phosphorus is the only element in this mixture that gives him difficulty. Indeed, if that were not high he could make almost his whole charge up of these two irons and the scrap. The phosphorus in this mixture is 0.45 per cent higher than that of his desired mixture. Therefore he knows that he must use a good deal of No. 3 foundry iron to bring this element down. The phosphorus in the No. 3 foundry iron is about as much below the desired phosphorus as that in the mixture of the high-sulphur southern and the X No. 1 is above it. He must not forget, however, that he has already used 1,000 lb. of machinery scrap containing probably 1 per cent of phosphorus. Therefore he must use a correspondingly larger amount of No. 3 iron to offset this also. As a first estimate he therefore considers using 800 lb. of high-sulphur southern, 800 lb. of X No. 1, and 2,400 lb. of No. 3 foundry—*i.e.*, once and a half as much No. 3 as the mixture of the two others. But a little reflection tells him that this mixture is going to be too low in silicon, because the mixture of high-sulphur southern and X No. 1 gave us only 1.85 per cent of silicon, while the No. 3 foundry and the machinery scrap are both below that. There are then three ways open to him. He may use a little ferrosilicon A or he may pound up a little ferrosilicon B and dissolve it in the ladle of iron or he may use a little high-silicon Bessemer iron. Either of these methods would do, but the writer would prefer to use the high-silicon Bessemer because this will have the effect of cutting the sulphur and phosphorus down and the expense is practically the same. (It requires such a small amount of ferrosilicon to give the desired silicon in the mixture that the expense of using it is very small, in spite of its price.) Consequently we put down the weights shown in the second column of Table X-II, and we now figure out the weight of silicon, sulphur, phosphorus, and manganese in the mixture by the methods indicated there, and the average percentage of each element. The latter figures show us that the silicon is too low, and a simple calculation shows us that we need 5 lb. more in the total weight of silicon. We can get this by increasing the amount of either high-silicon Bessemer or X No. 1 and correspondingly decreasing the No. 3 foundry. The high-silicon Bessemer has 0.75 per cent more silicon than the No. 3, so it would take (5 lb. ÷ 0.75 per cent =) about 650 lb. change to make up the difference in this way. The X No. 1 has 1.25 per cent more silicon than the No. 3, so it would take (5 lb. ÷ 1.25 =) 400 lb. change to make up the difference in this way. We naturally would prefer to use the latter, being cheaper, and if we think we can stand all that extra manganese in our castings we probably will do so; if not, we shall have to use altogether 1,000 lb. of high-silicon Bessemer and only 1,400 lb. of No. 3 foundry. We then make up a new table similar to Table X-II and figure out the average analysis as before. It should now come about right.

TABLE X-II.—CALCULATION OF CUPOLA BURDEN

Kind	Weight, pounds	Analysis, per cent				Weight of[1]			
		Si	Sr	P	Mn	Si	S	P	Mn
Steel scrap	200	0.10	0.07	0.10	0.60	0.2	0.14	0.2	1.2
Machinery scrap	1,000	1.70?	0.100?	1.00?	0.60?	17.0	1.00	10.0	6.0
High-sulphur southern	800	0.70	0.100	1.50	0.30	5.6	0.80	12.0	2.4
X No. 1	800	3.00	0.030	0.80	1.25	24.0	0.24	6.4	10.0
No. 3 foundry	2,000	1.75	0.070	0.30	0.60	35.0	1.40	6.0	12.0
High-silicon Bessemer	400	2.50	0.025	0.07	0.60	10.0	0.10	0.3	2.4
Total weights	5,200	.....	.....	.....	.....	91.8	3.68	34.9	34.0
Average, per cent[2]	.....	.....	.....	.....	.....	1.77[2]	0.071[2]	0.67[2]	0.65[2]

[1] Multiply the weight of each kind of material by the percentage of the elements in it.

[2] Divide each total weight of element by 5,200 lb.

MELTING STEEL FOR CASTINGS

Steel castings are made in (1) acid open-hearth furnaces, (2) basic open-hearth furnaces, (3) small Bessemer converters of special design, (4) crucibles, and (5) electric furnaces. The castings are made from the metal just as it comes from the steel furnace.

Open-hearth Furnaces.—The making of steel for castings is practically the same as making steel for ingots, except that foundry furnaces are of smaller size, varying on the average from 15 to 50 tons. In some cases furnaces smaller than this are used, but it is generally believed that circumstances rarely warrant this, since the expense of running the small furnaces is large in proportion. The chief difference in practice is that the temperature for steel-casting work is hotter than when ingots are made. Therefore furnace repairs are higher and the life is shorter. In ordinary open-hearth foundry work the purification is continued to the point where the steel contains about 0.18 to 0.28 per cent carbon after recarburizing, while the silicon will be usually 0.20 to 0.30 per cent.

Acid vs. Basic Open-hearth Steel.—In steel castings it is necessary to have somewhat lower phosphorus and sulphur than in ingots, because the metal is not to receive the beneficial effect of mechanical work and therefore must be purer in order to have a good degree of strength and ductility. Consequently, if we use an acid steel-making process, we must start with very low phosphorus and low-sulphur pig iron, which is costly and becomes more so each year in America. For this reason the Bessemer and the acid open-hearth steel-making processes are more expensive for casting work than the basic open-hearth. The result is a present rapid increase in the use of basic open-hearth steel in America as well as in Germany, and it is now the predominant process for this purpose. This is in spite of the fact that basic steel has very serious disadvantages, chief among which are the amount of oxygen contained in it at the end of the process and the difficulty of keeping the desired amount of silicon in it during teeming. Both of these conditions increase the liability to blowholes, which are especially objectionable in castings, as there is no opportunity of their being welded up and as castings may have to be discarded on this account after a good deal of expensive machine work has been done. On this account the acid open-hearth process long held the predominant position in the steel-casting industry. It is still the only place where the acid open-hearth process now finds important employment on a large scale in this country.

Bessemer vs. Open Hearth.—The open-hearth furnace gives a large amount of steel at long intervals, which is very inconvenient for foundry work, because the molds necessary to take all the metal must be stored upon the foundry floor until the heat is ready to pour, and then those who are to do the teeming must interrupt their other work ½ hr. or more for this purpose. Even where the foundry is large enough to have many furnaces, there is no surety that they will come out at regular and short intervals, because the operation in one may be delayed. Another disadvantage of the open-hearth process is that, in order to be economical, it must be operated continuously day and night, which also is inconvenient for foundry work. Further, it is not possible to get the metal as hot as desired without great damage to the furnace, which is subjected to a higher temperature than the metal. Lastly, since hot metal is desirable for all castings except those of very large size, it is usually necessary to tap all the metal from the furnace at once and recarburize it at once, which prevents castings of special analysis being made, unless ordered in very large quantities. Nowadays, a great many nickel-steel castings are made in open-hearth furnaces, but this requires nice calculations, so that the castings molded shall be just equal to the capacity of the heat, and usually results in a certain amount of scrapping of high-class metal.

All these objections are avoided in making castings in Bessemer converters, but they too have their great disadvantages, chief among which is greater cost. The latter is due principally to the amount of waste in the side-blown converters used for this purpose, and the greater cost of the pig iron used, which must be low in phosphorus and sulphur.

Tropenas Converter.—The largest number of converters for steel-casting work are of the Tropenas type, in which the wind enters the vessel from seven tuyères on the side, and the converter is tipped in such a manner that the streams of air are deflected on to the top of the bath. The impurities are oxidized as in the regular Bessemer process, except that the action is not quite so rapid, and the carbon is burned to carbon dioxide instead of carbon monoxide (see Table X-III), which generates a much larger amount of heat:

$$C + O = CO \text{ (generates 29,160 cal.).}$$
$$C + O_2 = CO_2 \text{ (generates 97,200 cal.).}$$

The pig iron used for these converters runs frequently above 2 per cent of silicon, and this, together with the formation of carbon dioxide, results in very hot and fluid steel, which can be poured into castings of almost any small size. The blows usually last about 15 to 20 min., and the loss is from 15 to 18 per cent of the weight of pig iron charged into the cupola in which it is melted. The vessel can be started up and stopped with very little expense, and this advantage over the open hearth, together with the small amount of capital necessary to build the converter plant and the other conditions already mentioned, has caused many of these converters to be installed in America, and several in France, England, and other countries.

The great disadvantages of the Tropenas converter are the waste and the cost for making repairs. Slight patching can be done through the mouth, but there is a hole in the front of the converter shell, closed by a movable steel plate, through which the operator can dig his way into the interior to perform the necessary repairs. As the lining in the neighborhood of the tuyères is usually worn out in less than 20 blows, this costly method of lining is a serious drawback.

Long-tuyère Converter.—Next to the Tropenas, the greater number of converters at work in America are of the long-tuyère, or Stoughton, type, devised by the writer. The bottom part of this vessel is attached to the trunnion ring by a method similar to that used for regular Bessemer bottoms and may be removed with great ease, thus cheapening and facilitating repairs. Moreover, the chief repairs are in the bottom part at the mouths of the tuyères, and therefore the lining of the upper part does not have to be relined completely for several months, although slight patching is necessary every 25 to 30 blows, when the bottom is changed. This converter is arranged to have but one row of tuyères, discharging the blast immediately at the surface of the metal, and the lining on the tuyère side is thicker in order that the tuyères may be increased in length, which decreases the loss of metal during the process. The excessive loss in the side-blown converters is due chiefly to the spitting, which is very large, especially when the tuyères have become worn away to a short length and the streams of air are badly directed and set up interfering currents.

Another cause of the excessive loss is the large amount of slag formed, because more iron is oxidized, and this corrodes the lining very rapidly. Part of the iron is oxidized at the mouths of the tuyères, and another part is oxidized when the violent agitation of the bath, which occurs in all of these converters, especially during the boil, throws the metal up into the stack, where it meets free oxygen. The loss in the long-tuyère modification is 14 to 16 per cent, including cupola loss.

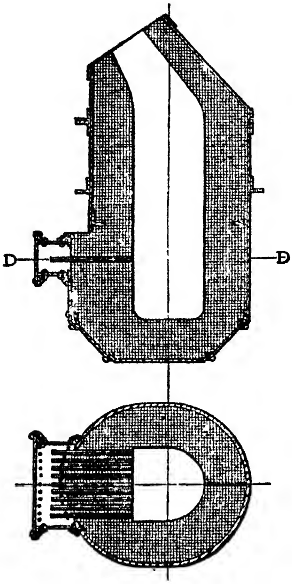


FIG. X-19.—Sections of long-tuyère converter.

Sizes Used.—Most of the small converters have a capacity of about 2 tons, because this is economical and well proportioned to the capacity of an ordinary foundry. There are some 4- and 5-ton converters, however, and some of less than 1-ton capacity. Sizes less than 2 tons are costly to operate in proportion to their output. The blast pressure usually employed is 3 to 5 lb., with an average of about 3¾ lb.

TABLE X-III.—ANALYSES OF SIDE-BLOWN CONVERTER GASES

Sample number	Time after beginning of blow	Analyses, per cent				Calculations from analyses, per cent			
		CO	CO_2	O	N and H	Total O	N[1]	O entering	O burning Si and Fe and Mn
1	4 min., flame starts..	0.0	8.2	1.1	90.7	7.1	88.7	23 6	16.5
2	10 min., boiling.......	0.3	24.3	0.4	75.0	18.3	73 0	19.4	1.1
3	12 min., shortening[2]...	0.4	8.8	0 2	90.6	6.8	88.6	23.5	16.7
4	17 min., after first drop	10.7	13.0	0.2	76.1	15.8	74.1	19.7	3.9
...	21 min., end of blow..								

---

[1] By difference, H being estimated as 2 per cent.

[2] *I.e.*, just before the first drop. There are two drops to the flame in this operation, the second marking the end.

Electric Furnaces.—Electric furnaces are used more than any other type for the manufacture of castings of the highest grade. Acid electric furnaces are used for casting work more than for making steel for forging, and the practice in general is similar to that already discussed in Chap. VII.

References

JOHN HOWE HALL: "The Steel Foundry," 2d ed., New York, 1922.

RICHARD MOLDENKE: "Principles of Iron Founding," New York, 1917.

BERNHARD OSANN: "Lehrbuch der Eisen-und Stahlgiesserei," verfasst für den gebrauch beim unterricht, beim selbststudium und in der praxis, 5th rev. ed., Leipzig, 1922.

ALEXANDER HUMBOLDT SEXTON AND J. S. G. PRIMROSE: " Principles of Iron Founding (and Foundry Metallography)," London, 1911.

EDWIN S. CARMEN: "Foundry Moulding Machines and Pattern Equipment," 2d ed., Cleveland, 1920, a treatise showing the progress made by the foundries using machine moulding methods.

THOMAS TURNER: "Lectures on Iron Founding," London, 1904.

PAUL OBERHOFFER: "Das Schmiedbare Eisenkonstitution und Eigenschaften," Berlin, 1920.

ENGELBERT LEBER: "Die Herstellung des Tempergusses und die Theorie des Gluhfrischens Nebst Abriss über die Anlage von Tempergiessereien," Handbuch fur den Praktiker und Studierenden, Berlin, 1919.

JOHN M. SNODGRASS AND F. H GULDNER: "An Investigation of the Properties of Chilled Iron Car Wheels," Urbana, Ill , 1922.

Giesserei-handbuch; hrsg. vom Verein deutscher eisengiessereien giesserciverband in Dusseldorf, Munich, 1922.

ERNST A. SCHOTT AND A. EINENKEL: "Giesserei-materialkunde," Berlin, 1920.

ERNST A. SCHOTT: "Die Metallgiesserei," 2d ed., Leipzig, 1920.

The Foundry, published monthly in Cleveland, Ohio.

Transactions of the American Foundrymen's Association.

Penton's Foundry List, A list of iron, steel, brass, etc., foundries in the United States and Canada. Editions appear at intervals.

"Foundrymen's Handbook," based on data sheets from *The Foundry*, rev. and supplemented to represent and interpret modern practice, 1st ed., Cleveland, 1922.

La fonderie moderne; revue mensuelle, vol. I, Paris, 1907.

Giesserei Zeitung . . . vol. I, Berlin, 1904 (semimonthly).

R. T. ROLFE: "Foundry Work and Metallurgy," 6 vols., London, 1931–1932.

CHAPTER XI

THE IRON-CARBON EQUILIBRIUM DIAGRAM[1]

Scientifically considered, all of the members of the iron and steel series are alloys of iron and carbon. Therefore a study of the general theory of alloys leads to important information upon iron and steel. The essential feature of an alloy is that, when melted, it shall form a homogeneous fluid. In plain language, this means that, when melted, the different components are dissolved in one another. Melted alloys, therefore, come under the general head of solutions. In fact, the great bulk of our alloys, and especially of iron and steel, are produced by first dissolving the melted components and then allowing them to freeze. The laws governing this freezing, or solidification, have been known only a few years; and if this new knowledge has made great revolutions in physical chemistry, it has led to no less important discoveries in regard to the nature of iron and steel.

Solid Solution.—Suppose, first, we have two metals that are soluble in each other when liquid and also when solid. In other words, the metals of the alloy will be just as completely dissolved in each other after solidification as before. They will then form a "solid solution," and a solid solution bears practically the same relation to a liquid solution as a solid pure metal does to the same metal when liquid. For example, gold and silver dissolve in each other when liquid, and also when solid, in any proportion. Con-

---

[1] Note to Teachers.—Teachers must not expect students and beginners to grasp the contents of this chapter from the textbook alone. The experience of the author is that at least two exercises, consisting of lectures, conferences, and questions, are required for beginners who have had a reasonable amount of general chemistry to understand the equilibrium diagram alone. The teacher will find in Albert Sauveur's "Metallography and Heat Treatment of Iron and Steel" a detailed discussion of the subject, including the equilibrium diagram of iron-carbon alloys. The essential facts of equilibrium changes are contained herewith, but the assimilation of these facts and their retention in memory by the ordinary beginner require more explanation than is possible in the space available in this chapter.

sequently, any solution of these metals will cool to the freezing point and then solidify without there being any important change (from the metallurgical or chemical standpoint) in the relations of the two metals after the freezing. The reason that these solid solutions form in any proportion is that the two metals crystallize alike. It is, perhaps, a new thought to the reader, but it is nevertheless true, that a metal forms a crystal whenever it solidifies. Furthermore, each metal has a particular general shape which its crystals assume, and there is almost no force powerful enough to prevent them from taking that shape in preference to any other.

Tiny as the crystals sometimes are—often requiring the highest powers of the microscope to reveal them—their crystalline forces are very powerful. If, therefore, two metals do not form like crystals, they cannot solidify in solution, *i.e.*, in the same crystal, but freezing must be accompanied by separation. When liquid steel freezes, it forms a solid solution of iron and carbon. For this reason, an understanding of the formation and nature of solid solutions is very important to the steel metallurgist. Furthermore, alloy steels often freeze as solid solutions of iron with the alloying element, such as nickel and chromium.

By European metallurgists solid solutions are often called "mixed crystals" or "isomorphous mixtures," but this terminology is objected to because the relation of two substances when dissolved is far more intimate than any mixture possibly could be. In a mixture the microscope will always be powerful enough to distinguish the different components, but a solution always appears like a simple uniform body. Furthermore, the properties of a mixture are intermediate between the properties of its components, but a solution—either liquid or solid—has some properties which are different from any of the properties of either of its components. Again, the components of a solution are held together by chemical forces, while the components of a mixture are either not held together at all, or only because of close mechanical association. In brief, a solution has some of the characteristics of a chemical compound and differs from such a compound chiefly because the latter must be composed of definite amounts of each component and in some multiple of their atomic weights, while a solution may contain widely varying amounts of each component.

Alloys in General.—Alloys are metallic substances having properties different from those of their components. For instance, steel is stronger than either of its constituents, iron and carbon. Permalloy is more magnetic at low magnetizing forces than either the iron or the nickel of which it is composed, while "Heussler's alloy" is as magnetic as nickel, although none of its components—copper, manganese, and aluminum—is a magnetic metal. However, it is in the study of variations in electrical conductivity, in hardness, in toughness, in strength, and in ductility that a comprehension of the theory of alloys has been most helpful. The theory of alloys is difficult to understand; it requires more than ordinary intelligence and also the capacity of real thought concentration. An understanding of the theory of alloys is demanded now in industry, however, from all those who intelligently buy and use metals, as well as from those who supply them; because commercial metals are alloys on account of the impurities which they contain. As little as one one-thousandth part of phosphorus in steel will ruin its ductility, and a few ten-thousandths of carbon will unfit it for the best electromagnetic purposes.

To obtain a first grasp of the subject of alloys, one must thoroughly assimilate the knowledge that alloys are composed of crystals, and it is the chemical composition, the size, shape, and interrelation of these crystals to one another which determines the characteristics and properties of the alloy, much more than does the character of the metals which form the alloy. Crystals form from a liquid metallic mass when it freezes. What happens during the freezing of alloys, therefore, is the first step in determining their properties.

Definition of an Alloy.—In industry an *alloy* is a substance formed by the solidification of a metallic solution. If metals will not dissolve in each other when molten, they will not form an alloy when solid. To the eye, an alloy looks like a homogeneous union of metals, but under the microscope it is seen to be an aggregation of crystals and these crystals are sometimes chemically alike and homogeneous; sometimes they differ from one another in chemical composition, and in size, hardness, shape, and other properties, such as their individual strength and their strength of adherence to one another.

Iron-carbon Alloys.—Cast iron and steel are primarily alloys of iron and carbon. Therefore the first essential for an understanding of the properties of cast iron and/or steel is a comprehension of the theory of alloys, and, since alloys are solutions when liquid, this involves an intelligent understanding of the actions which take place when solutions freeze into crystals. We shall therefore discuss the general subject of alloys, always bearing in mind that it is the alloys of iron and carbon which we have especially in mind. The change from the liquid to the solid state is evidently a very critical period in determining the properties of an alloy. It is, indeed, this study of the freezing of alloys which has led to the greatest increase in the knowledge of their nature and characteristics. Taking the simplest possible examples, the freezing of alloys is classified in four ways, known as types I, II, and III. For example:

1. The molten homogeneous solution changes to a solid homogeneous solution. The alloys of gold and silver belong in this class. They are soluble in each other in all proportions when liquid and likewise soluble in all proportions when solid. The microscope reveals crystals of the solid gold-silver alloys, but each crystal is identical in chemical composition with every other crystal. Some important industrial alloys belong to the class which forms solid solutions throughout, although numbering perhaps less than one-third of the important alloys. Among them may be mentioned the alloys of nickel and copper, iron and manganese, gold and platinum, nickel and cobalt, tungsten and molybdenum. The freezing of this type of alloys is represented by a type of curve shown in Fig. XI-2.

Freezing of Pure Metals.—If a liquid metal be cooled and its temperature be registered by pyrometer, the latter will show lower and lower figures until the freezing temperature of the metal is reached. Then the temperature will remain constant practically until freezing is completed, after which it will again fall steadily. A so-called cooling curve of this operation is given in Fig. XI-1. A cooling curve of a solid-solution alloy would be somewhat like this except that the line *ab* would not appear horizontal, as explained in Fig. XII-2.

Equilibrium Diagrams.—Equilibrium diagrams of alloys are made up to show the percentages of two components as abscissas and temperatures as ordinates. Illustrations of this are shown in Figs. XI-3 and XI-4. These equilibrium diagrams are made up from a large number of cooling curves, such as those shown in Figs. XI-1 and XI-2. A different cooling curve is determined by experiment for several alloys of different percentages of components, and then the significant points are entered in an equilibrium diagram, as indicated in the explanation underneath Fig. XI-3.

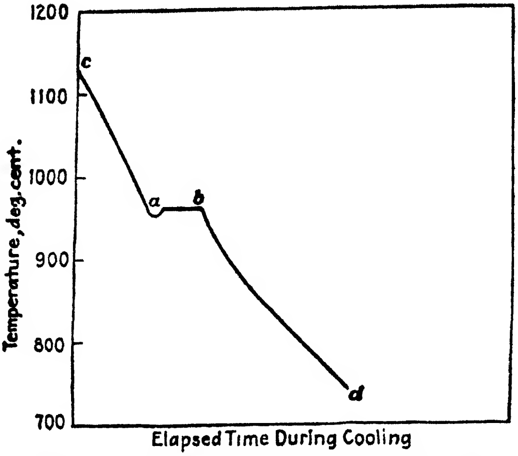


Fig. XI-1.—Freezing-point curve of a pure metal

Equilibrium Diagram of Solid-solution Alloys.—In order to understand the freezing-point curve shown in Fig. XI-3, it is necessary to read thoroughly the legend underneath that figure. A freezing-point curve is also an equilibrium diagram in so far as it relates to freezing. The alloys which freeze as solid solutions throughout their entire series are known as Type I alloys. Therefore the curve shown in Fig. XI-3 is the equilibrium diagram of the freezing of Type I alloys. The curve is made up as follows: The freezing of silver is recorded by a pyrometer and the temperature at which it freezes is indicated, as exemplified in the line *ab* in Fig. XI-1. This temperature is plotted as point *D* in Fig. XI-3. Then

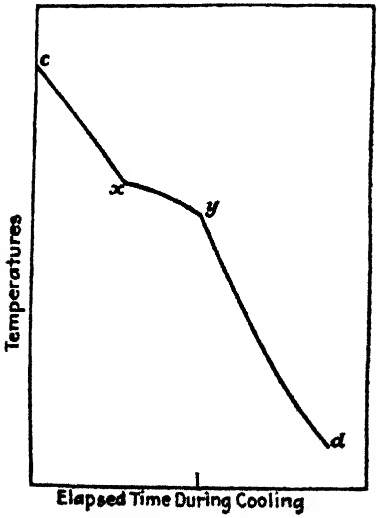


Fig. XI-2.—Freezing-point curve of a solid solution.

the freezing of gold is observed and the temperature at which it freezes is plotted as the point *A* in Fig. XI-3. Next, a liquid solution is taken which contains both silver and gold, say, 50 per cent of each. Its freezing is recorded pyrometrically and it is seen that the temperature curve drops until it reaches same point as *x* (Fig. XI-2). It then proceeds more slowly to the point *y* and continues to drop in a straight line. This shows that the alloy containing 50 per cent of gold and 50 per cent of silver began to freeze at the temperature indicated by *x*, and that the freezing was not all at one temperature but continued down to point *y*. The points *X* and *Y* are then plotted in the diagram in Fig. XI-3. Following this, other liquid solutions are studied and various other points plotted in Fig. XI-3. This results in two curves in Fig. XI-3. The upper line is the line at which all the alloys begin to freeze. This is called the *liquidus*, because every alloy is liquid above this line. The lower line is called the *solidus* and represents the temperature at which the alloys complete their freezing. These lines then divide the diagram into three areas: the area *AB* represents the temperatures and compositions where all the alloys are liquid; the area *CD* represents the temperatures and compositions where

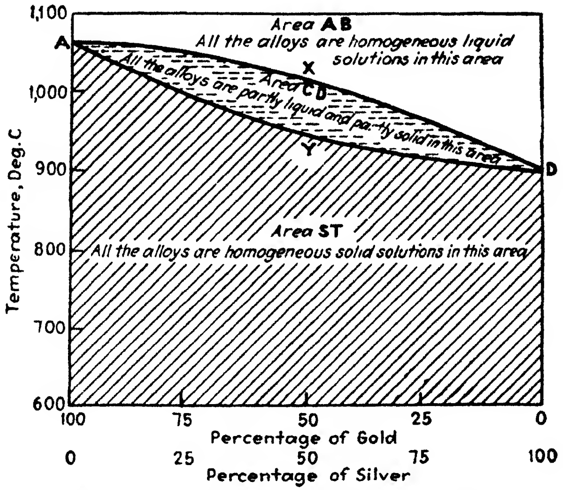


FIG. XI-3.—Freezing-point curve of alloys of Type I, in which a homogeneous (liquid) solution changes to a solid homogeneous solution. The alloys of gold and silver. The point *A* is the freezing point of pure gold; the point *D* is the freezing point of pure silver, while the points *X* and *Y* correspond to the points *x* and *y* in Fig. XI-2.

all the alloys are partly liquid and partly solid; the area *ST* represents the solid alloys.

It is now evident that each of the alloys belonging to Type I is composed of crystals which are chemically all alike. Every alloy is a liquid solution in the area *AB*, and the same alloy is a solid solution in the area *ST*, every crystal in each solid alloy having exactly the same chemical composition as the liquid mass from which it was formed. A very important characteristic of these solid-solution alloys is, therefore, that they are composed of only one kind of crystal. Every alloy which freezes in accordance with Type I freezing has only one kind of crystal in it. (In order to simplify the discussion, the author here intentionally disregards the mechanism of freezing, important as this is from the theoretical standpoint.)

Type II Alloys.—The second type of alloys includes those which freeze and form two kinds of crystals. These alloys are made up of two metals which are entirely soluble in each other when liquid but insoluble in each other when solid. When they freeze, therefore, crystals of individual metals form. There is no solid solution. In the solid state neither metal is soluble in the other. Only a few metals form alloys of Type II. Just as, in nature, there is very little chemically pure water or chemically pure air, so in metallurgy it is very rare that any metal will separate from liquid solution in a pure state. We do not find in any alloy of iron, including cast iron, steel, or alloy steels, an example of this type of freezing, but we do find examples in the separation of iron alloys after freezing.

A freezing-point curve representing this Type II alloy is shown in Fig. XI-4. This is known as the underlined V curve, for obvious reasons. In this curve the area *AB* represents the alloys of different composition which are all molten solutions at the temperatures indicated. The areas *CD* and *EF* represent compositions and temperatures where alloys are partly solid and partly liquid. The area *ST* indicates the entirely solid alloys consisting, as before stated, of individual crystals of two kinds, each kind being the almost pure metal of the alloy couple.

Type III Alloys.—Very few alloys separate from molten solution into two pure metals, as described in Type II freezing. Nevertheless, the great majority of the alloys separate into two kinds of crystals. These crystals are composed of the metals which are not pure but which carry with them some part of the alternate metal in the state of solid solution. In other words, the two metals crystallize out separately, but the crystals are not pure; on the contrary, they contain some of the other metal as a solid solution. The alloys of iron and carbon, *viz.*, steel, are of this class, although it must be remembered that carbon is not a metal. Nevertheless, steel is an alloy, because iron predominates so extensively in its composition that it is a true metallic body. Brass, bronze, duralumin, and almost all the important industrial alloys form crystals on freezing which are solid solutions but with a limit to the amount of dissolved metal that can be retained in the solid state. The freezing-point curve of this type of alloy is shown in Fig. XI-5. For simplicity's sake, consider Fig. XI-5 as a sort of combination of Figs. XI-3 and XI-4. In other words, redraw Fig. XI-5 to the curve shown in Fig. XI-6, in which the dotted lines indicate those alloys which form solid solutions, and the full lines indicate the freezing of alloys exactly in accordance with the principle of the Type II alloys, except that the crystals that are in the solid alloys in the area *ST* will not be crystals of pure metals but crystals of solid solutions of metals. In other words, there will be two types of crystals, each

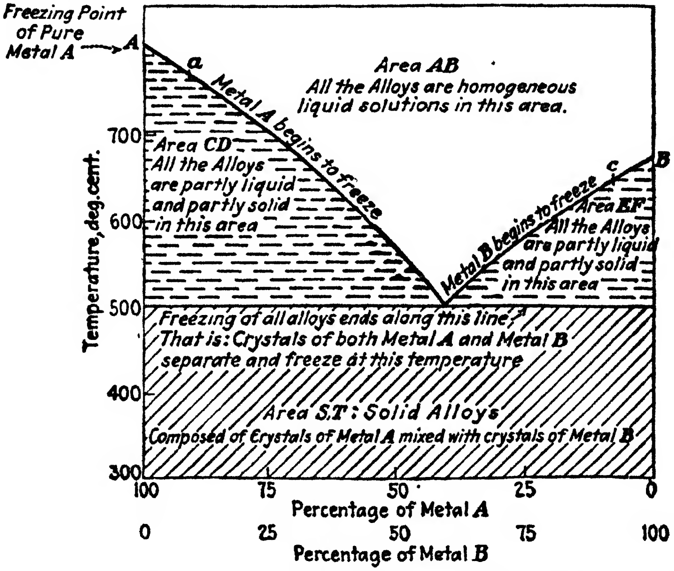


FIG. XI-4.—Freezing-point curve—otherwise known as equilibrium diagram—of alloys of Type II, in which any liquid solution changes on freezing to separate crystals of the two constituent metals.

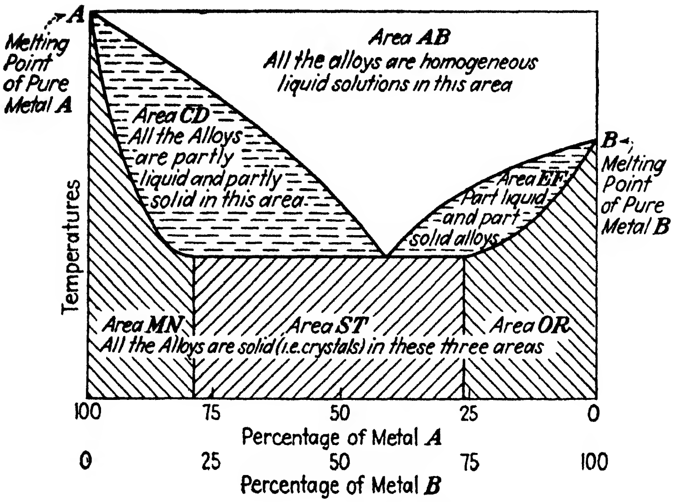


FIG. XI-5.—Equilibrium diagram of the freezing of alloys of Type III, in which each liquid solution changes into either one or two solid solutions. In area *MN* there is only one solid solution in each alloy. In area *ST* there is only one solid solution in each alloy. In area *OR* there are two solid solutions in each alloy, solid solutions consisting of a saturated solution of metal *B* in metal *A* and of metal *A* in metal *B*.

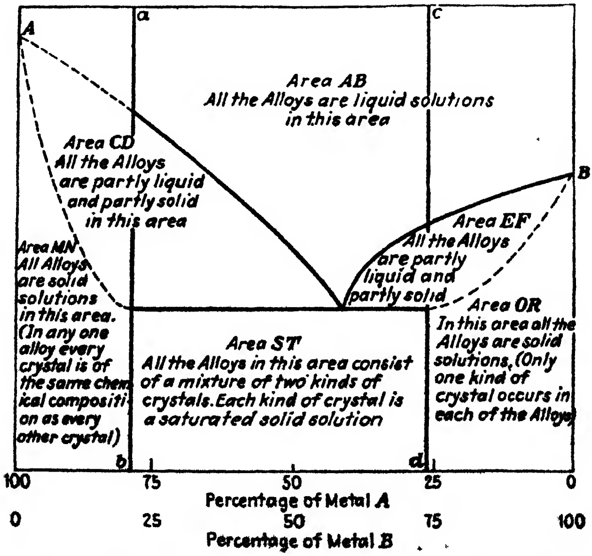


FIG. XI-6.—Equilibrium diagram of Type III alloys, redrawn from Fig. XI-5.

type being the solid solution of one metal with a saturating amount of the other metal dissolved in it. The whole area *MN* will represent solid solutions of metal *A*, containing different amounts of metal *B* up to a limit of 23 per cent. Likewise, the whole area *OR* will represent solid solutions of metal *B* with varying amounts of metal *A* up to a limit of 26 per cent. Then all the solid alloys in the area *ST* will consist of crystals of metal *A* in solid solution with 23 per cent of metal *B* and of metal *B* in solid solution with 26 per cent of metal *A*.

Freezing of Iron-carbon Alloys.—Iron and carbon form a series of alloys which freeze in accordance with Type III alloys. In other words, the iron and carbon are in solution in the liquid state, and, when they freeze, the iron crystallizes with carbon in it in solid solution up to a limit of 1.7 per cent of carbon. We may exemplify this as follows:

1. If low-carbon steel, containing about 0.10 per cent of carbon, be produced in a furnace, as, for example, a Bessemer converter, and the metal is poured into ingots, it freezes into crystals which are all alike; *viz.*, they are crystals of a solid solution containing 99.9 per cent of iron and 0.1 per cent of carbon.

2. If structural steel is made in an open-hearth furnace and contains when molten 0.25 per cent of carbon, it will, upon solidification, form a series of crystals which are all alike and each one a solid solution of 99.75 per cent of iron and 0.25 per cent of carbon. (In this case, as well as in the preceding one, we have neglected impurities which will normally be in the metal. These impurities will, of course, form crystals of their own in combination with iron or other elements, but they may temporarily be neglected in discussing this subject.)

3. Likewise a liquid steel containing 1 per cent of carbon will form a solid mass of crystals, all alike, and all being solid solutions of iron with 1.00 per cent of carbon in them.

4. Likewise a file steel containing 1.50 per cent of carbon will solidify into crystals of solid solution containing 1.50 per cent of carbon.

5. This principle prevails until we get more than 1.70 per cent of carbon. Liquid iron which has more than 1.70 per cent of carbon dissolved in it will form crystals of a solid solution containing 1.70 per cent of carbon, but there will be more carbon than the solid solution can contain, and therefore there will

be more than one kind of crystal. We shall discuss these alloys at a later point.

Definition of Steel.—In view of this difference in freezing between liquid iron alloys which contain any amount of carbon up to 1.70 per cent and iron alloys which contain more than 1.70 per cent carbon, the definition of steel has now been established as: an iron alloy which solidifies from a liquid mass into only one kind of crystal, *viz.*, the solid solution of iron and carbon. Thus steel may contain any amount of carbon up to 1.70 per cent, such as 0.03, 0.15, 0.30, 1.00, and 1.70 per cent. It is true that there are certain special metals, used for special purposes and made in only very small amounts, which contain more than 1.70 per cent of carbon, and which are bought and sold as steel, but they do not come under the strict definition of steel and there is so little of them made that we may disregard them in this connection.

Distinction between Steel and Wrought Iron.—Wrought iron also contains less than 1.70 per cent of carbon, and usually less than 0.12 per cent of carbon. But the characteristic feature of wrought iron is that it contains when it solidifies about 1 or 2 per cent of slag mixed with it in solid particles. The proportion of this slag is very much larger than the proportion of impurities of all kinds customarily associated with steel and especially occluded bodies similar to slag. The presence of the particles of slag differentiates wrought iron from steel.

Distinction between Steel and Cast Iron.—Gray cast iron normally contains about 3 to 3.50 per cent of carbon, but sometimes it is melted in electric furnaces or air furnaces and oxidized until its total carbon is as low as 2 to 2.50 per cent. In other cases steel scrap is melted with the cast iron and its total carbon reduced, the object being in all cases to get cast iron of higher strength which accompanies lower carbon. Malleable cast iron has frequently as low as 2.50 per cent of carbon. This leaves a sort of a "no man's land" in the iron-carbon alloy series between the highest carbon usually contained in steel (which is generally 1.50 per cent) and the lowest carbon customarily found in commercial cast iron (which is about 2 per cent). The exact line of demarcation is, however, 1.70 per cent of carbon.

Freezing of Steel.—All the steels freeze as solid solutions. Let us consider a solution of 99.5 per cent of iron and 0.5 per cent of carbon at 1650°C. This cools until it meets the line *AF* in Fig. XI-7, and now it commences to solidify. For a few degrees of temperature it is part liquid and part solid, but by the time it has fallen to a temperature where it meets the line *AE*, it has become entirely solid, and it is now a solution of 0.5 per cent of carbon in iron. Consider next a solution containing 99 per cent of iron and 1 per cent of carbon. When this cools to the temperature where it touches the line *AF*, it commences to solidify and it is in a partly liquid and partly solid condition until it crosses the line *AE*, upon which solidification is completed and it now becomes entirely a solid solution of 1 per cent of carbon in iron. The same actions take place with an alloy containing 98.3 per cent of iron and 1.7 per cent of carbon. In all these alloys we finally arrive at a solid solution of carbon in iron, and the solid solution always consists of identical crystals, each of which contains the same proportion of carbon as was contained in the liquid alloy. In the freezing of solid solutions there is always an effect known as selective freezing, whereby a metal tends to solidify out of a liquid solution in a somewhat purified condition.[1] The reason for this is that any element will freeze at a higher temperature when in a purer condition. Consequently, the first crystal to freeze will be almost pure iron, the next will have a little more carbon in solid solution, the next still a little bit more, and so on. The result is that, theoretically, a solid solution after complete freezing is composed of a myriad of crystals with slightly different proportion of components. In

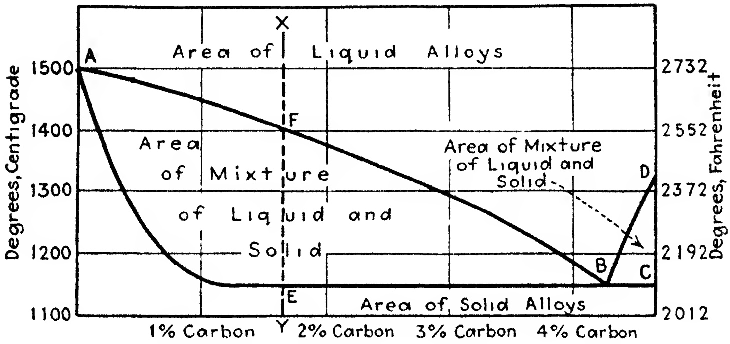


FIG. XI-7.—Freezing of the alloys of iron and carbon.

---

[1] The formation of the solid solution from the liquid solution is discussed in detail in Professor Howe's "Iron, Steel and Other Alloys," but it requires too much space to be discussed here. For our purpose it is sufficient to know that, when freezing is completed, we have a solid solution of all the carbon in all of the iron.

the case of iron and carbon, however, the carbon atom, which is relatively small in size, will migrate rather easily through a solid solution at a temperature above a red heat. In this way carbon tends to travel from those crystals in which it is higher in proportion to crystals in which it is lower. Therefore there tends to be an equalization of composition in the iron-carbon solid solutions, so that the practical effect is that the carbon is almost uniformly distributed throughout all the crystals of the solid solution within a few seconds after freezing is complete, provided the carbon in the metal is low. The unequal distribution of carbon, which we have already discussed under the head of Segregation, is more likely to be observed in the case of tool steels having about 1 per cent of carbon. In the case of 90 per cent of all steels made we may safely say that the carbon is uniformly distributed throughout the crystals of the solid solution in the same proportion as it existed in the liquid mass. To this solid solution the name of "austenite" is given, and this name applies no matter how much or how little carbon is in solid solution. In other words, all steels are in the condition of austenite as soon as their solidification is complete.

Theoretical Freezing of Cast Iron.—Figure XI-7 is drawn to illustrate the freezing of iron-carbon alloys. This diagram is somewhat simplified for explanation purposes and should be used only in this connection. More accurate data are given in Fig. XI-9. The freezing of cast iron is illustrated by the top-heavy lines to the right of 1.7 per cent carbon. All the alloys in the area between the lines *AB* and *AEB* are mixtures of liquid solutions and solid solutions. All the alloys below the line *AEC* are completely solid. Let us illustrate the freezing of cast iron by considering a liquid alloy which is cooling down the line shown at 3 per cent of carbon. When this alloy cools to the point where it meets the line *FB*, it begins to separate out solid crystals. Each of these crystals will consist of iron containing 1.7 per cent of carbon in solid solution. The more this alloy cools, the more solid-solution crystals will be formed and the less liquid alloy will be left. Each of these solid crystals will contain 1.7 per cent of carbon. Since the liquid alloy contains 3 per cent of carbon and the solid crystals contain only 1.7 per cent of carbon, there is going to be relatively more carbon left in the liquid mass in direct proportion to the amount of solid crystals that freeze out. We may illustrate this as follows: If we assume a liquid alloy of this analysis weighing 100 lb., this will contain 97 lb. of iron and 3 lb. of carbon. Suppose the alloy cools until it contains about 20 lb. of solid crystals and 80 lb. of metal still liquid. The solid crystals will contain 19.66 lb. of iron and 0.34 lb. of carbon (= 1.7 per cent). The liquid metal will contain the difference, viz., 77.34 lb. of iron and 2.66 lb. of carbon, which is 3.3 per cent of carbon. When the alloy has cooled to the line *EB*, which is a temperature of 1140°C., it is at that temperature when everything remaining liquid must freeze before any further cooling takes place. At this point the alloy will contain approximately 46.8 lb. of solid solution crystals and 53.2 lb. of liquid.

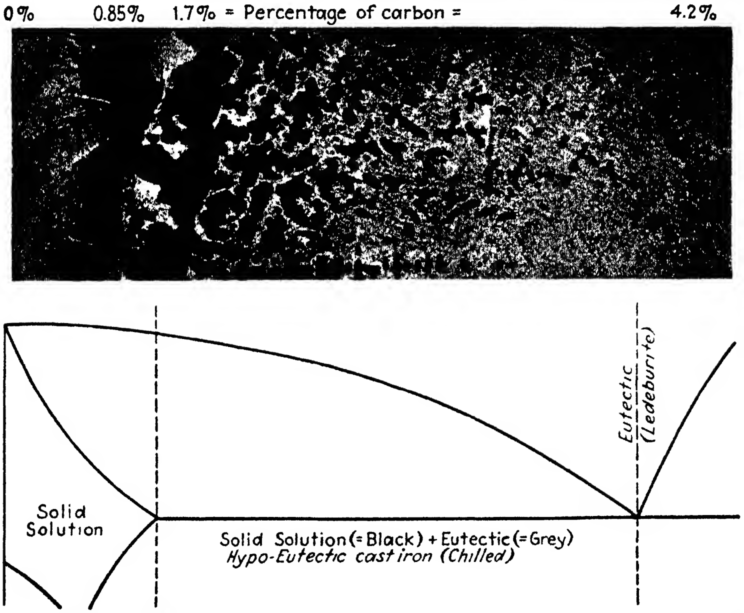


FIG. XI-7*A*.—Micrograph at 100 diameters of a piece of iron-carbon alloy containing 5 per cent of carbon at one end and practically zero carbon at the other end. (*Sample prepared and micrograph made by W. P. Sykes.*)

A sample of almost pure iron was made to contain about 5 per cent of carbon on the surface, decreasing in carbon content by almost regular intervals until it contained practically zero carbon at a point 0.036 in. below the surface. It was cooled as rapidly as possible, in order to prevent any changes in its primary crystallization after solidification. It was then photographed microscopically to show its structure. It will be noted that it consists entirely of solid solution at a carbon concentration of 1.7 per cent, with gradually decreasing proportions of solid solution and increasing proportions of eutectic structure, until it is entirely eutectic at 4.2 per cent of carbon. With less than 1.7 per cent of carbon, there are seen to be patches of Fe_3C or ferrite, as the case may be, except just at 0.85 per cent of carbon. The reason for this is that no cooling method has yet been discovered rapid enough to prevent some decomposition of solid solutions of iron and carbon as they cross the lines *ES* or *SG* in Fig. XI-8.

The solid crystals will contain approximately 46 lb. of iron and 0.8 lb. of carbon, leaving 51 lb. of iron and 2.2 lb. of carbon in the liquid solution. This corresponds to approximately 4.2 per cent of carbon in the liquid, which is the maximum proportion of carbon that liquid iron can dissolve at a temperature of 1140°C. The liquid iron has now reached its limit of saturation in carbon at the temperature of 1140°C. and also the lowest temperature to which it can go without freezing. If it cools further it all solidifies at once, as distinguished from the progressive solidification which took place when the solid-solution crystals were freezing out of it. To summarize: the solid solution will separate from the liquid solution by degrees until the liquid solution has been so concentrated in carbon that it is saturated at the temperature prevailing. To continue our illustration: the 53.2 lb. of liquid metal now solidifies into 24.4 lb. of solid-solution crystals, each containing 1.7 per cent of carbon and 28.8 lb. of cementite crystals, each containing 6.7 per cent of carbon. To sum up: the 100 lb. of liquid alloy with which we started has now solidified to produce about 71 lb. of solid-solution crystals and 29 lb. of cementite crystals, which shows by calculation 97 lb. of iron and 3 lb. of carbon.

The lines *FB* and *BD* represent equilibrium between temperature and the amount of iron or carbon, respectively, that will saturate a liquid solution. Let us take another example: If a liquid alloy containing 5 per cent of carbon be allowed to cool until it reaches the point *D* in Fig. XI-7, it will then commence to separate out crystals of cementite. Each of these crystals will contain 6.7 per cent of carbon. If we had 100 lb. of liquid alloy to start with, then, by the time this alloy had cooled to the point *C*, it would have separated out 34.1 lb. of cementite crystals, which would contain 2.3 lb. of carbon and 31.8 lb. of iron. This leaves in the liquid state a solution containing 63.2 lb. of iron and 2.7 lb. of carbon (= 4.2 per cent of carbon). The temperature will now be 1140°C. With any further cooling, all the liquid part of the alloy would solidify into 31 lb. of solid-solution crystals (1.7 per cent of carbon) and 34.9 lb. of cementite crystals. In summary, we have about 69 lb. of cementite (containing 4.5 lb. of carbon) and 31 lb. of solid solution containing 0.5 lb. of carbon.

If we start with a liquid alloy which contains 4.2 per cent of carbon, it will cool uninterruptedly to the point *B* before it will begin to freeze, but at that temperature it will all freeze into about 48 per cent of solid-solution crystals and 52 per cent of cementite crystals. This alloy is known as the eutectic alloy, because it is the alloy which cools to the lowest temperature without any solid crystal being formed. "Eutectic" comes from a Greek word meaning "well melting," because when heated it reaches an entirely melted condition at a lower temperature than any other pure iron-carbon alloy.

Summary.—To sum up, then: all the solutions of iron and carbon containing less than 1.7 per cent of carbon will consist, after solidification, of a solid solution of iron and carbon having the same chemical composition as the original liquid solution, and being a solution of one in the other. There can be no eutectic form if there is not more than 1.7 per cent of carbon. All the solutions with more than 1.7 per cent of carbon will consist, after solidification, of a eutectic together with a certain amount of previously precipitated cementite or of previously precipitated saturated austenite, as the case may be.

Graphite in Commercial Cast Iron.—The reactions described above will yield in each case a cast iron containing cementite, *i.e.*, white cast iron. It would seem then that gray cast iron is an anomaly, and this is indeed the case: pure iron and pure carbon, slowly cooled, will never yield a gray cast iron, *i.e.*, a cast iron with 2 or 3 per cent of carbon in the graphite form. To secure such a product we must add other elements to the mixture, such as silicon, for example. Since commercial cast irons always contain graphite when slowly cooled and tend to contain combined or dissolved carbon when rapidly cooled, it has been maintained that austenite-graphite is the normal eutectic, and that austenite-cementite is the metastable condition. But recent researches indicate that austenite-cementite always forms in alloys of pure iron and pure carbon, and that graphite can be obtained only by means of the presence of some other element, such as silicon. It is silicon, then, which produces gray cast iron, and commercial cast iron depends on silicon to make it gray instead of white. Figures XI-17 and XI-18 show the fractures of white cast iron and gray cast iron, respectively. The gray cast iron is gray because, when it breaks, it breaks through the middle of the crystals of weak graphite and therefore its fracture shows almost entirely graphite surfaces on both sides. We may then summarize this part of the subject by saying that purity of the iron-carbon alloy and rapid cooling keep the carbon in dissolved form. Rapid cooling keeps the carbon in dissolved form even in the presence of small amounts of silicon. This is illustrated in the "chilling" of cast iron, for which see pages 363 and 321. But silicon of more than 1 per cent will usually bring out some graphite, even with a moderately rapid rate of cooling. We must always bear in mind that carbon is all in solution in iron in the liquid state: normal freezing of a pure alloy brings it out of solution as cementite; rapid cooling may hold some of it in solution in the solid (frozen) state; but silicon tends to bring it out of solution as graphite—to make gray cast iron, in other words. To make malleable cast iron (see Chap. XV), we have enough silicon in the iron to cause precipitation of graphite, but this precipitation is first suppressed by rapid cooling. Later we "anneal" the castings and graphite is precipitated in the frozen mass. Without the presence of some silicon, iron castings would not anneal to bring out graphite.

Effect of Silicon on Freezing.—Silicon tends chemically to precipitate graphite. Also it pushes the point *B* in Fig. XI-7 to the left, so that we would have to draw a new diagram to represent the reactions when iron contains silicon. When blast furnaces are making iron with 1 to 3 per cent of silicon and only 3.50 to 4 per cent of carbon, the point *B* is situated well to the left of 3.50 per cent of carbon, and graphite separates from the iron as it runs molten out of the furnace. This graphite, or "kish," blows in flakes and settles over the sand and parts of the furnace. This represents carbon separating on cooling of the iron below the line *BD*, and above the line *BC* where the iron becomes entirely solid. Strangely enough, more than 3 per cent of silicon has the contrary effect and causes carbon to separate as cementite, instead of graphite, so that gray iron is not produced by silicon above 3 per cent.

Effect of Sulphur on Freezing.—Sulphur has the opposite effect from that of silicon: it tends to hold carbon in the combined form or, if not that completely, to increase the amount of carbon in solution and to cause cementite, instead of graphite, to precipitate. It pushes the point *B* in Fig. XI-7 to the right, and its effect is fifteen times as strong as that of silicon, so that sulphur of 0.06 per cent will counteract the effect on carbon of silicon of 0.90 per cent.

Gray Cast Iron vs. White Cast Iron.—It is now easy to comprehend why silicon and sulphur and the rate of cooling give the metallurgist control over the production of gray or white iron at will. By adjusting the silicon, sulphur, and rate of cooling in the molds, we can get cast iron which is white on the outside, where it cools rapidly in contact with a cold mold, and gray on the inside. This is called "chilled cast iron." It has a hard outside and an interior structure which is not brittle.

The Solid Solution of Iron and Carbon.—We have seen that every alloy of iron and carbon contains, after solidification, a varying amount of the solid solution of iron and carbon. For example, if we started with 0.5 per cent of carbon, then, immediately after solidification, we should have a solid solution of 0.5 per cent of carbon in iron; if we started with 1 per cent of carbon, we should have a solid solution containing 1 per cent; if we started with 1.7 per cent of carbon, then we should have a solid solution of 1.7 per cent of carbon. Even if we start with more than 1.7 per cent of carbon, then the alloy, after solidification, will consist partly of a solid solution containing 1.7 per cent of carbon and partly of cementite, Fe_3C.

Now what becomes of these solid solutions which make up a part or a whole of the cast iron and steel alloys when they freeze? Does the carbon remain in solid solution down to the atmospheric temperature, or does it precipitate, or does it undergo some other change? We find by experiment that the solid solutions do not survive but precipitate at a lower temperature, and the laws governing the decomposition of these solid solutions are similar to the laws governing the decomposition of liquid solutions—*e.g.*, the iron-carbon solutions. In short, we have another series of curves showing the selective precipitation of the constituents of these solid solutions, and the only difference between the nature of these curves and the freezing-point curves is that these represent changes taking place in the solid state, while the freezing-point curves represent changes taking place in the liquid state.

Nature of the Solid Solution.—The solid solution of iron and carbon might be a solution of pure carbon in iron, or a solution of a carbide of iron in iron, *e.g.*, of cementite in iron. Several authorities hold this view, while others maintain that the solution is of elemental carbon in iron. The question is of more academic than practical interest. The important thing is that, when the

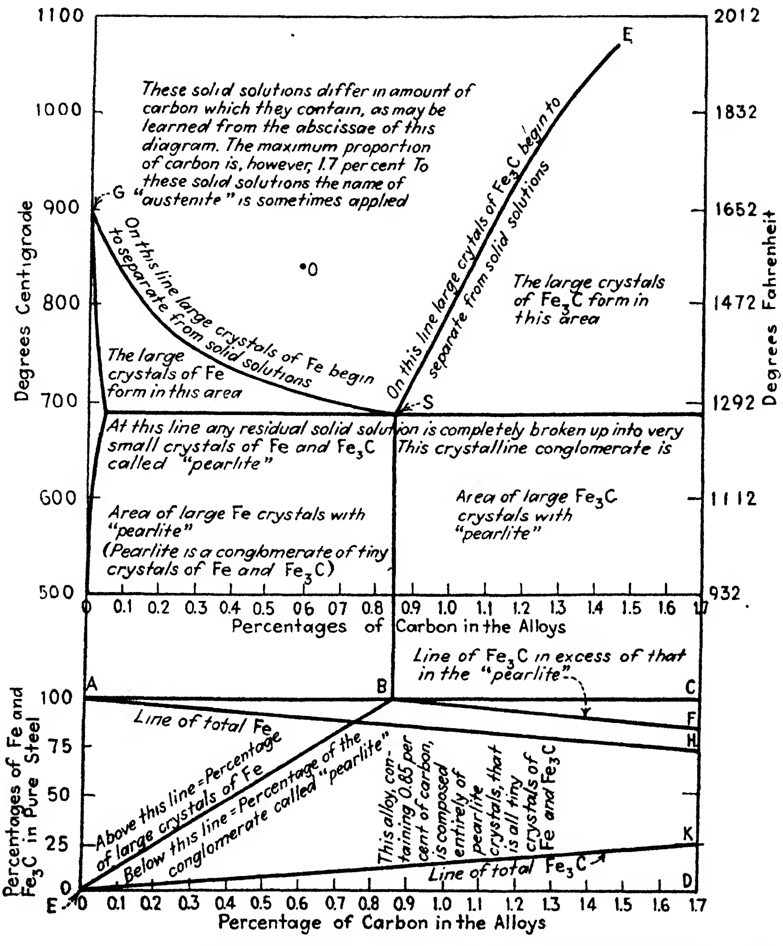


FIG. XI-8.—Constitutional diagram of pure steel (*i.e.*, alloys of pure iron with pure carbon). The lines in this figure represent equilibria and changes which occur on cooling. They are therefore at a somewhat lower temperature than corresponding lines in Fig. XI-9.

The abscissas in these graphs represent percentages of carbon. The ordinates in the rectangle in the lower part of the figure represent percentages of crystalline constituents. If, for example, it is desired to estimate the crystalline constituents of an alloy of 0.20 per cent carbon: at the abscissa of 0.2, where it meets the link *EK*, the ordinate is seen to be 3 per cent. This tells that the alloy in question will contain 3 per cent of total Fe_3C. Following the same practice to the line *AH* it is seen that the alloy contains 97 per cent of Fe. If, instead, it is desired to learn the percentage of large crystals of Fe and of small crystals of both Fe and Fe_3C, the line *EB* is used. Follow up from the abscissa of 0.2 and it is seen that the alloy is composed of 76 per cent of large crystals of Fe and 24 per cent of the conglomerate called pearlite. Now, pearlite consists of one-eighth Fe_3C and seven-eighths (87.25 per cent) Fe. Therefore, the alloy of iron with 0.2 per cent carbon is composed of 76 per cent large crystals of Fe, 21 per cent small crystals of Fe, and 3 per cent small crystals of Fe_3C. Following the same practice it may be ascertained that the alloy with 0.85 per cent of carbon will contain 100 per cent of pearlite, and therefore 87.25 per cent small crystals of Fe and 12.75 per cent small crystals of Fe_3C. Likewise, the alloy of 1.2 per cent carbon will consist of about 5 per cent large crystals of Fe_3C, 13 per cent of small crystals of Fe_3C, and 82 per cent small crystals of Fe.

solution decomposes, it is carbide of iron which precipitates. Those who believe that the solid solution is composed of elemental carbon and iron explain the precipitation of the carbide by maintaining that, when the carbon separates from solution, it immediately unites with iron and forms a carbide, cementite. With this explanation the author will hereafter, for simplicity's sake, discuss the solid solutions as if they were cementite in iron.

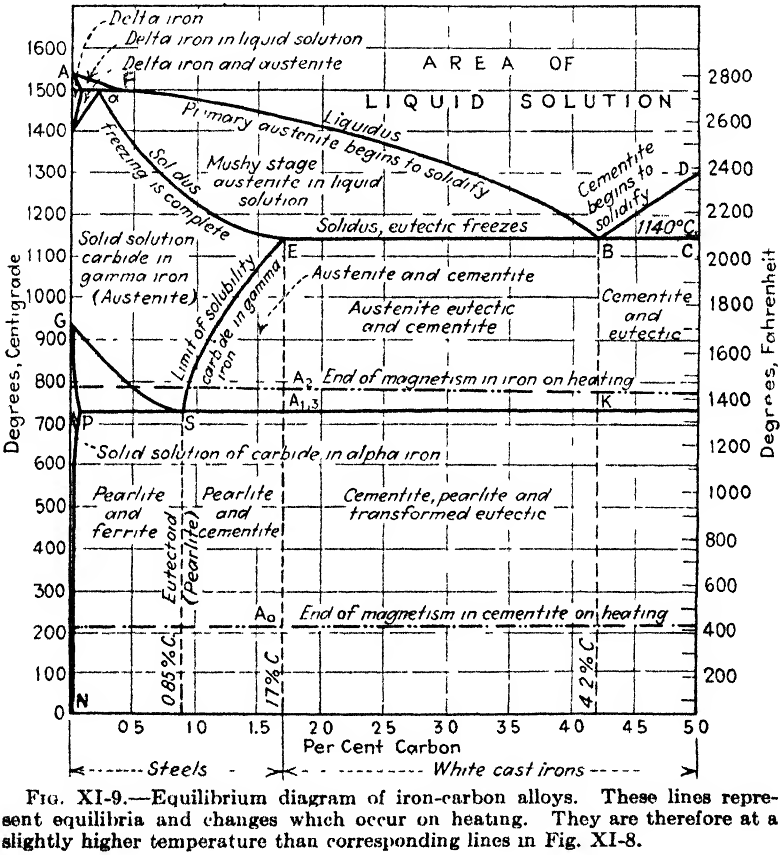


Fig. XI-9.—Equilibrium diagram of iron-carbon alloys. These lines represent equilibria and changes which occur on heating. They are therefore at a slightly higher temperature than corresponding lines in Fig. XI-8.

Decomposition of the Solid Solutions.—The curves of decomposition of the solid solutions are shown in Fig. XI-8. The line *GS* is the line upon which there is selective precipitation of pure iron. To this pure iron the name of "ferrite" has been given by Professor Howe, and this name meets with universal acceptance.

Consider, first, a solid solution containing 0.55 per cent of carbon at a temperature of 850°C. This will be at the point *o* in Fig. XI-8. It will cool until it reaches a temperature of about 720°C., upon which ferrite will begin to precipitate. As the temperature continues to fall, more and more ferrite precipitates, which impoverishes the solid solution in iron and causes it to travel down the line *GS*. By the time the temperature has reached 690°, the solid solution has reached the point *S*, corresponding to 0.85 per cent of carbon.

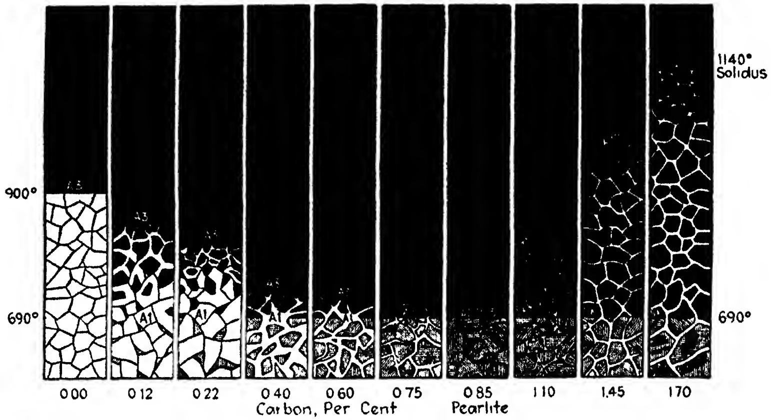


Fig. XI-10.—Changes in structure of steel during cooling from above the critical range. The large white crystals shown in the left-hand bands represent Fe, which begins to separate out at 900°C. when the carbon is extremely low. The thinner white crystals in the right-hand bands represent the Fe_3C, which begins to separate out from the solid at 1140°C. when the carbon is 1.70 per cent. The banded structure is the solid left by the precipitation of the excess Fe or excess Fe_3C, as the case may be, separated into minute banded crystals of Fe and Fe_3C. (*Howe, "The Metallography of Steel and Cast Iron,"* 1916.)

Consider, next, an alloy containing 1.30 per cent carbon at 1100°C. This will be above *E*. It will cool until it reaches a temperature of about 975°, at which carbide of iron, Fe_3C, will begin to precipitate. This precipitation continues as the temperature falls, constantly decreasing the amount of carbon in the solid solution, which therefore travels down the line *ES* until, at 690°, it reaches the point *S*, where there is 0.85 per cent of carbon in solution.

A similar precipitation will take place with all of the solid solutions of iron and carbon: If they contain less than 0.85 per cent carbon, they will begin to precipitate out ferrite when they fall to the line *GS*. If they contain more than 0.85 per cent of carbon, they will begin to precipitate carbide of iron when they meet the line *ES*. In either case, the residual solid solution will travel down the line *GS*, or else *ES*, until it reaches the point *S* when the temperature has fallen to 690°C.; we shall then have some solid solution left containing 0.85 per cent of carbon and mixed with this some previously precipitated ferrite or cementite, as the case may be.

FIG. XI-11.—Pearlite, magnified 500 ×. (*W. E. Harvey.*)

FIG. XI-12.—Pearlite eutectoid of iron and carbon. (*F. Osmond.*)

FIG. XI-13.—Pearlite and ferrite. 250 ×.

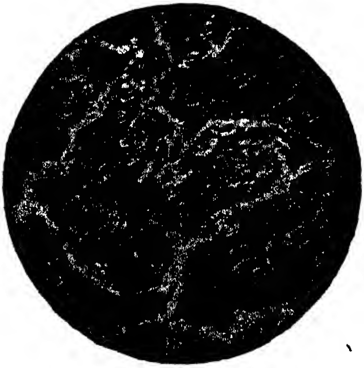


FIG. XI-14.—Pearlite and cementite. 250 ×.

Eutectoid.—The alloy containing 0.85 per cent of carbon is known as the "eutectoid alloy," a name invented by Professor Howe to indicate that the formation of this alloy, which results by selective precipitation of the solid solution, is similar to the formation of the well-known eutectics of liquid solutions. When this eutectoid solid solution cools below 690°C., it is decomposed into its constituents, ferrite and cementite. These constituents precipitate in tiny flakelets, which arrange themselves in the banded structure already familiar to us as the structure of eutectics. A magnified view of the structure is shown in Fig. XI-11 and 12, while Fig. XI-13 shows the magnified structure of a piece of steel composed of a eutectoid together with previously precipitated ferrite; and Fig. XI-14 shows the structure of a steel consisting of the eutectoid with previously precipitated cementite.

It will be evident that there will be some of the eutectoid in every piece of iron or steel, for even the cast irons contain, after solidification, a certain amount of solid solution which precipitated while the liquid alloy was traveling down the line *AB* or during the freezing of the liquid eutectic (containing 4.2 per cent of carbon) or both. The formation and characteristic of this eutectoid are therefore of very great importance. Its presence in iron and steel was known long before the theories that the author has outlined in this chapter had begun to be understood, and the name of "pearlite" was given to it because, under certain circumstances, it has the appearance of mother-of-pearl. The name pearlite is used only to designate the eutectoid after its complete decomposition and the separation of the ferrite and cementite into the banded structure shown in Fig. XI-12.

Iron and Cementite in Steel.—The proportion of iron and cementite in steel may be read off from the diagram in the lower part of Fig. XI-8. The method of doing this is explained below the diagram. Instead of total iron and total cementite, we may read from the diagram the proportion of excess iron and the eutectoid pearlite or the excess of cementite and the eutectoid pearlite. We again emphasize here that excess iron is in larger crystals than the iron occurring in pearlite. The excess cementite is also in larger crystals than the cementite occurring in pearlite. These facts are shown in Figs. XI-13 and XI-14. We also emphasize again that small crystals of iron and cementite occur in every steel, but that we never have together in any one steel an excess of both iron and cementite.

A graphic representation of the temperatures at which large crystals of iron or else large crystals of cementite separate from the solid solution as the steel cools is shown in Fig. XI-10. This figure also shows that nothing but small crystals of iron and small crystals of cementite separate from the solid solution which contains just 0.85 per cent of carbon. In this figure the black area represents solid solution and the sections are arranged in such a way as to approximately represent the slope of the lines in Fig. XI-8. The figure *A*3 corresponds to the change which occurs in pure iron at *G* and in alloys along the line *GS*, in Figs. XI-8 and XI-9.

The Most Soluble Alloy.—A solid solution consisting of 99.15 per cent of iron and 0.85 per cent of carbon will cool to approximately 690°C. (1274°F.), without decomposing. But at this temperature the alloy will precipitate (being in a solid state both before and after precipitation) into separate crystals of iron and cementite. There are many interesting things about this alloy which contains 0.85 per cent of carbon: it is the strongest alloy of iron and carbon, and it is the only one composed entirely of extremely small crystals. Then, to repeat, the only solid solution which will cool to as low a temperature as 690° is the one containing 99.15 per cent of iron and 0.85 per cent carbon. Every other alloy in the steel series will undergo a change before cooling to 690°C.

Cooling of a Structural Steel.—If a structural steel, containing 99.75 per cent of iron and 0.25 per cent of carbon, is manufactured and solidified in the usual way, it will be a solid solution of its two components. But this solid solution will not remain in the state of chemical solution to as low a temperature as 690°C. When it reaches a temperature of approximately 875°C., it reaches the lowest temperature at which so large a proportion of iron will be held in solid solution. Any further cooling will result in the separation of iron crystals out of the mass. Then the piece of steel at yellow heat will consist of crystals of solid solution, and disseminated through these crystals will be separated grains of iron. This will continue as the cooling progresses, there being a constantly increasing number of grains of iron among the solid-solution crystals, until 690°C. is reached. At this point there will be a mixture of a solid solution containing 0.85 per cent of carbon and grains of iron. The proportion of carbon in the solid solution and in the grains taken together will be 0.25 per cent, but practically all of this carbon will be in the solid-solution component and the iron grains will be almost free from it. This situation will exist only as long as the metal remains at 690°C. It cannot cool below this point without a separation of the solid solution into crystal of iron and cementite.

And so we shall have the following sequence: (1) a solid solution exists immediately after freezing; (2) crystals of iron separate out from 875° down to 690°C.; (3) at 690°C. there is a separation into iron and cementite of the solid solution from which these crystals of iron had separated previously. A microscopic section of such an alloy is shown in Fig. XI-13. The large white meshes are the grains of iron which separated between 875 and 690°C.; the gray portions show the conglomerate consisting of tiny crystals of iron and cementite, which separated out at 690°C. One must observe carefully in this connection that the large grains of iron are those which precipitated out between 875 and 690°C., and the small grains of iron (as well as the small grains of cementite) are those which precipitated at 690°C. We may summarize this somewhat as follows: If we have 10,000 lb. of a solid solution containing 9,975 lb. of iron and 25 lb. of carbon (roughly 0.25 per cent), it will be a solid solution above 875°C. On cooling below 875°C., this solid solution will precipitate out crystals of iron. Note that this is the precipitation of a solid mass in a solid mass, no part of the alloy being liquid. When the alloy has cooled to 690°C., about 7,000 lb. of iron will have separated out, leaving a solid solution containing roughly 2,975 lb. of iron and 25 lb. of carbon (0.85 per cent). When this cools below 690°C., the 3,000 lb. of solid solution will break up into approximately 375 lb. of cementite and 2,625 lb. of iron. The final alloy will, therefore, contain approximately 7,000 lb. of large crystals of iron, approximately 2,625 lb. of small crystals of iron, and approximately 375 lb. of crystals of cementite.

The Cooling of File Steel.—When steel for files, containing 1.50 per cent of carbon, is first frozen, it is a solid solution of iron and carbon. When it cools, however, it soon reaches the temperature where so much carbon cannot be held in solid solution. This results in the separation of grains of cementite, and, since cementite contains a relatively large proportion of carbon, the amount of carbon remaining in the solid solution becomes progressively less. When 690°C. is reached, the file steel is composed of part solid solution containing 0.85 per cent of carbon and part of cementite, containing 6.67 per cent of carbon. To summarize again: let us assume a solid solution containing 985 lb. of iron and 15 lb. of carbon at a temperature of 1100°C. When this cools below 1060°C., crystals of cementite begin to separate from the solid solution. When a temperature of 690°C. has been reached, there have separated from the original 1,000 lb. of solid solution approximately 110 lb. of cementite (containing somewhat over 7 lb. of carbon), leaving 890 lb. of solid solution. When these 890 lb. cool below 690°C., they separate into about 113 lb. of cementite and 777 lb. of iron. The original 1,000 lb. of solid solution at 1100°C. will, after cooling to atmospheric temperature, consist of 110 lb. of large crystals of cementite, 113 lb. of small crystals of cementite, and 777 lb. of small crystals of iron.

The Seven Most Important Rules concerning the Formation of Structures in Steel.—It will help all those who are learning to follow the grain formations in steel to memorize the following seven rules:

1. Steel, when molten, is a liquid chemical solution of iron and carbon.
2. All liquid iron-carbon alloys, up to 1.7 per cent of carbon, freeze as solutions of carbon in iron in the solid state.
3. The only solid solution of iron and carbon which will cool unchanged as far as 690°C. is the one containing 99.15 per cent of iron and 0.85 per cent of carbon.
4. All solid solutions with more than 0.85 per cent of carbon cause cementite to crystallize out until the solution remaining when the alloy cools to 690°C. contains only 0.85 per cent of carbon.
5. All solid solutions with more than 99.15 per cent of iron cause iron to crystallize out until the solid solution remaining when the alloy cools to 690°C. contains only 99.15 per cent of iron.
6. At 690°C., every solid solution of iron and carbon decomposes into grains of iron and of cementite.
7. Grains which crystallize out at temperatures above 690°C. are large; grains which crystallize out at 690°C. are relatively small.

Slow Heating and Slow Cooling of Steel.—It is understood that the description of what happens when steel is cooled refers to cooling slowly enough to permit the different changes to occur in a normal way. Each change requires a few moments of time, and a normal result is not obtained unless the proper time is given to complete the normal change. It is also understood that a reverse change to that described in each case occurs when the steel is heated.

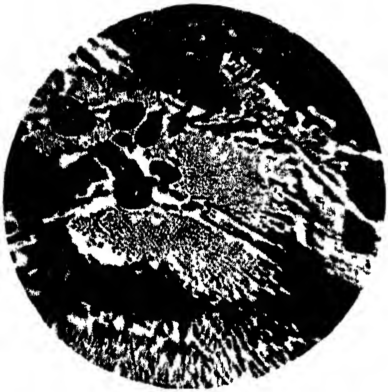


FIG XI-15 Iron carbon alloy containing approximately 4 per cent of carbon and showing a large amount of eutectic structure (*Wilber F. Harvey*)

Summary as to Steel All steels contain tiny crystals of iron and of cementite That steel which contains 0 85 per cent of carbon is composed entirely of these tiny crystals Steels with less than 0 85 per cent of carbon will contain the tiny crystals of iron and cementite and also some larger crystals, which are of commercially pure iron, the less the amount of carbon, the greater will be the proportion of large crystals of iron, as compared with the tiny crystals On the other hand, steels with more than 0 85 per cent of carbon will contain the tiny crystals of iron and cementite, as well as some large crystals of cementite; the more the carbon,

FIG XI-16 —Eutectic structure of iron and carbon As indicated on the micrograph, the eutectic is sometimes called Ledeburite after the famous cast-iron metallurgist (*Roy M Allen*) the greater will be the proportion of large crystals of cementite. This is illustrated in Fig. XI-8, which should be carefully studied with the legend underneath it.

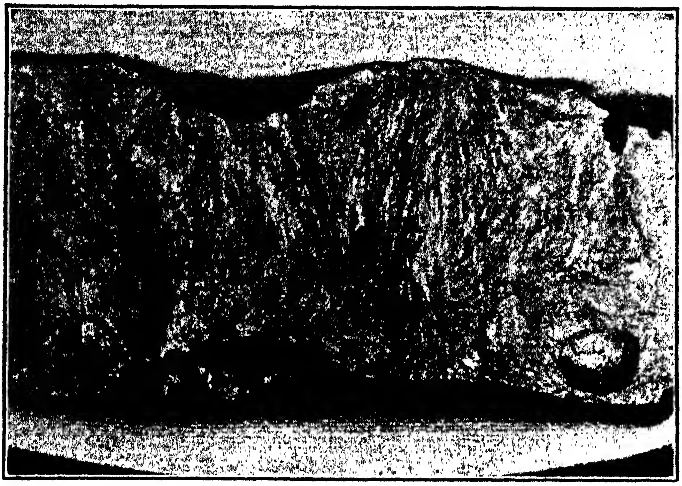


FIG. XI-17.—Fracture of white cast iron.

Iron and Cementite in Pure, White Cast Iron.—It is desirable to emphasize again that crystals of iron and cementite occur in every iron-carbon alloy, and this includes cast iron as well as steel. It will be remembered that cementite is precipitated from cast iron during freezing, except in so far as it is decomposed by silicon into iron and graphite. The preceding discussion has described how the solid solution containing 1.7 per cent of carbon occurs in every cast iron, and we have also learned that this solid solution begins to lose some of its cementite as soon as it cools below 1140°C., losing it progressively until we reach 690°C., when it has only one-half as much carbon dissolved in it, *viz.*, 0.85 per cent instead of 1.7 per cent. Therefore all pure, white cast irons will contain cementite which separates out during

FIG. XI-18.—Gray cast iron, natural size.

freezing, and also between 1140 and 690°C., and additional cementite which separates out at 690°C.

Graphite in Commercial Cast Iron.—Silicon tends to cause graphite to precipitate, instead of cementite, not only during freezing but also when the solid solution decomposes at temperatures between 1140 and 690°C. When the silicon is between 1.50 and 3 per cent, and the range for cooling is controlled suitably, we may have gray cast iron in which there are no large flakes of cementite. In Fig. XI-19 we see a micrograph of gray cast iron containing about 2.6 per cent of silicon and showing only crystals of graphite, large crystals of iron, and pearlite. There are no large crystals of cementite whatsoever.

FIG. XI-19.—Micrograph of gray cast iron containing 2.6 per cent of silicon. Etched in 1 per cent picral. 500×. The only constituents showing are graphite, ferrite, and pearlite. (*Charles A. Turner, Jr.*)

Changes on Heating.—As in the case of the liquid solutions, the changes already described above in connection with the cooling of the solid solutions are reversed on heating. The temperatures at which the reverse changes occur on heating, however, are somewhat higher than the corresponding change on cooling, unless both cooling and heating be very slow. In other words, the chemical changes seem to lag behind the temperature changes. With extremely slow heating and cooling, the lag is but slightly perceptible, and the various changes and reversals take place at almost the same temperature, but with the rates of cooling usually employed in research laboratories at steel works, there is a difference of about 20° between the temperatures of the changes in the different directions. It is customary to plot the curves as in Fig. XI-8, showing temperatures on cooling, and that method has been adopted here.

The Full Iron-carbon Equilibrium Diagram.—The full diagram of freezing and subsequent chemical separation in the solid of the alloys of iron and carbon from 0 to 5 per cent of carbon is shown in Fig. XI-9. The lines in this figure represent the temperatures at which the changes take place on heating, instead of on cooling as shown in Fig. XI-8. The lines are therefore at a slightly higher temperature in Fig. XI-9 than in Fig. XI-8. It should be noted that this diagram includes only the iron-carbon alloys up to 5 per cent of carbon, which is about 75 per cent of cementite. Iron alloys containing as much as 100 per cent of cementite have never been obtained. Theoretically, liquid iron should continue to dissolve carbon until we have, at 6.67 per cent of carbon, 100 per cent of cementite. Actually, however, we must raise the temperature of the liquid iron more and more in order to get more carbon dissolved in it; and before we reach the temperature where iron will dissolve 6.67 per cent of carbon, the heat is so high that iron begins to volatilize. For this reason alloys have never been prepared to enable us to draw the diagram at carbon concentrations higher than 5 or 6 per cent.

Solubility of Carbon in Ferrite.—When iron separates from the solid solution in the critical range between 900 and 700°C., it does not come out absolutely free from carbon but drags with it about 0.03 per cent of carbon. After it cools from 700°C., it tends to deposit some of this carbon along the lines shown between *P* and *N* in Fig. XI-9, so that it contains normally about 0.015 per cent of carbon at atmospheric temperature. While this amount of carbon is apparently insignificant, it, nevertheless, has a very appreciable effect on the magnetic permeability of the metal, as has been shown by Dr. T. D. Yensen.

Definitions.—In connection with the equilibrium diagram in Fig. XI-9 we should call attention to certain names there used and explain their meaning. *Austenite* designates a solid solution of carbon in iron. The name is used for any solid solution whether it contains as little as 0.03 per cent of carbon or any other amount up to 1.7 which is the normal limit. *Carbide* indicates cementite. In this diagram we speak of a solid solution of carbide in gamma iron, but we have already said that it is a matter of controversy whether the solid solution is of the carbide or elemental carbon. *Eutectic* is the name given to the alloy which in cooling remains longest in liquid solution without precipitation. That is to say, it is the alloy containing 4.2 per cent of carbon. Immediately after the alloy has frozen, this liquid eutectic appears as an intimate mixture of small crystals in a cellular structure as indicated in Figs. XI-15 and XI-16. The name eutectic is given to this solidified alloy as well as to the liquid alloy of most soluble proportions. *Eutectoid* is the most soluble solid solution. It contains 0.85 per cent of carbon. It is the alloy which will cool to the point *S* without precipitating either ferrite or cementite. After this alloy has been precipitated into its components (iron and cementite) it also has a banded structure similar to that shown in Fig. XI-11. This is also called the eutectoid, but is more commonly called *pearlite* after the solid solution has broken down and the banded structure shown in Fig. XI-11 is in evidence. *Ferrite* is the crystal of iron which separates from the solid solution. Theoretically it is pure iron but actually it is always contaminated by impurities in industrial steels. *Cementite* is another name given to the carbide, Fe_3C.

Roberts-Austen.—The diagram of Fig. XI-9 is often known as the Roberts-Austen diagram, after Sir William Roberts-Austen, because the cooling curves that located the lines were first determined in his laboratory. However, the diagram in Fig. XI-9 is very greatly altered from the original graphs offered by Roberts-Austen. We also have reason to believe that even this does not represent all the changes which occur in the iron-carbon alloys at different temperatures. Furthermore, there is a controversy as to whether it is cementite or graphite which precipitates under stable conditions of slow cooling when the eutectic freezes, and also along the line *BD*. This discussion belongs to a more advanced treatment of the subject than is possible in the space afforded in this book.

Names Given to These Diagrams.—This type of diagram is known as the *constitution diagram*, because it shows the constitution of each alloy after it has cooled slowly. It is also called the *equilibrium diagram*, because the lines in it are loci of points at which two phases are in equilibrium. In other words, the lines represent the places where one phase changes into another phase, on heating or on cooling, as the case may be.

References

ALBERT SAUVEUR: "The Metallography and Heat Treatment of Iron and Steel," 2d ed., New York, 1916. With great clearness this book teaches the principles of the solution theory as applied to iron and steel, upon which theory all modern conceptions of their nature are based.

HENRY M. HOWE: "The Metallography of Steel and Cast Iron." New York, 1916. A comprehensive study of the theory and practice of the solution theory, constitution, and metallography of iron and steel.

Samuel F. Hoyt: "Metallography." In two parts. Part I, "Principles," Part II, "The Metals and Common Alloys," New York, 1920 and 1921.

Reports of the Alloys Research Committee of the Institution of Mechanical Engineers (England). No. 1, 1891; No. 2, 1893; No. 4, 1897; No. 5, 1899; No. 6, 1904; No. 7, 1905. In this may be followed the development of the first application of the theory to metallography.

Walter Rosenhain: "An Introduction to the Study of Physical Metallurgy," New York, 1915.

"The Alloys of Iron and Carbon," soon to be issued by The Alloys of Iron Research Committee of The Engineering Foundation, New York.

CHAPTER XII

THE CONSTITUTION OF STEEL

The properties of steel depend upon the chemical composition of its constituents as well as upon their size and relation to one another. Enough has been said to show that steel is not a simple homogeneous union of iron with varying proportions of carbon, silicon, manganese, etc., but is built up of individual crystals somewhat in the same way as crystalline rocks are formed—granite, for example. But while the crystals of granite are generally visible to the naked eye, and its structure may therefore be determined by a more or less cursory examination, the structure of steel is visible only by means of the microscope and after careful polishing, sometimes followed by chemical treatment to differentiate between the various grains. Nevertheless, the structure of steel is of great importance and in some cases, perhaps, is even more so than the chemical composition.

The Microconstituents of Steel

In this chapter we shall speak only of slowly cooled steel except where the contrary is indicated. We have already learned that slowly cooled steel must necessarily contain ferrite and cementite, resulting from the decomposition of the solid solution of iron and carbon. In all steels containing less than 0.85 per cent of carbon there will be small crystals of iron and cementite, together with large crystals of iron. In all steels with more than 0.85 per cent of carbon there will be small crystals of iron and cementite together with large crystals of cementite. There are no steels which have large crystals of both iron and cementite at the same time. There are also other constituents which are found under the microscope or separated by chemical analysis, or in both ways. These last constituents are compounds of iron with various other impurities, such as iron sulphide, iron phosphide, and iron silicide; or of two impurities with each other, such as manganese sulphide.

Ferrite.—Ferrite is theoretically pure iron, and especially iron free from carbon. It is weak as compared with several of the other constituents, having a tensile strength of 38,000 to 90,000 lb. per square inch, depending on heat treatment and extent of working in the cold. It is very soft, ductile, and malleable. The effect of cold work on hot-rolled iron of 99.99 per cent purity, which is almost pure ferrite, is shown in Fig. XII-1. It is especially to be noted that the softness and ductility fall off rapidly at first and then remain almost constant with added cold treatment. This characteristic is true also of the reduction of area, not shown in the figure, which starts with about

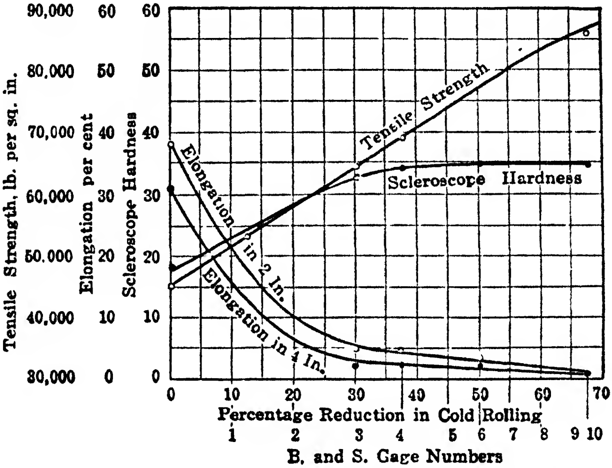


FIG. XII-1.—Effect of mechanical working at atmospheric temperature on the properties of electrolytic iron of 99.99 per cent purity.

60 to 70 per cent, falls to 30 to 40 per cent, and then decreases only very slowly with further cold work. On account of this behavior, pure iron may be rolled or drawn cold to small sizes without intermediate annealings. Ferrite has an elongation of 40 to 50 per cent in 2 in. when in its softest condition. It has a very high electrical conductivity as compared with the other constituents of iron and steel, and about one-sixth the conductivity of copper and silver, the best conductors known. (Copper and silver are of nearly the same conductivity.) Its magnetic force is the highest of any known substance; its magnetic permeability is high, and its hysteresis low. It crystallizes in the isometric system.

Ferrite is an important constituent of all steels and the predominant one in all the low-carbon steels. The largest industrial product approaching ferrite is wrought iron, if we disregard the slag, which, being mechanically mixed with the mass, does not appreciably alter its chemical and physical behavior. It is for this reason that wrought iron is so useful where a soft and ductile material is necessary, as in boilers, for instance; or where high electrical conductivity is demanded, as in telegraph wire; or a high degree of magnetism, as in the cores of electromagnets. The wrought iron made in Sweden, and known as "Norway iron," is preferred for this latter purpose, on account of its purity.

Under the microscope, ferrite may be distinguished from cementite by its softness. If steel containing these two constituents be polished on damp, rough parchment or on chamois skin stretched over a soft background (as wood), the ferrite will wear away below the carbide and appear in intaglio. The same effect will be obtained by Osmond's "polish attack." Ferrite is also distinguished from carbide of iron by the fact that, after being subjected to the brief action of certain reagents, such as 2 per cent of nitric acid or ordinary commercial tincture of iodine, the ferrite is seen in darker grains and the carbide in bright thin plates, unattacked by the reagent. Sodium picrate etching solution will color cementite dark and leave the ferrite bright. When the two are intimately associated in minute grains, as in pearlite, the carbide appears bright and the ferrite dark, because eaten away below the surface by the reagent.

FIG. XII-2.—Big cementite crystal in pearlite. 250×. Polished in relief.

Allotropic Modifications.—There is one peculiarity of pure iron, or ferrite, which deserves special attention, *viz.*, its ability to assume different allotropic modifications at different temperatures. The alpha modification is normal at atmospheric temperatures. It is the soft variety of ferrite with which we are familiar and has high magnetic permeability. The magnetic permeability of this alpha iron decreases, however, as its temperature increases until, when we reach a temperature of about 760°C., the permeability is only about one-half as great as it was at atmospheric temperature. If the temperature be raised further, there is a sudden loss of the remaining 50 per cent of the magnetism, so that the iron, at a temperature of about 770°C. has about the same magnetic permeability as that of copper or lead or other so-called nonmagnetic methods. This change is accompanied by an absorption of heat within the metal. Furthermore, if the iron at 770°C. be cooled, it will undergo a reverse change. That is, it will evolve heat and will regain the magnetism which it lost at 760°C. It was taught that this change in the properties of iron indicated the formation of a new allotropic modification and that alpha iron was said to change to beta iron at about 760°. However, the definition of allotropic modification has been changed owing to the great importance of the space-lattice structure of metals. Alpha iron is known to have the so-called body-centered space-lattice structure. That is to say, all its atoms are arranged in cubes, with one atom at each corner of the cube and one in the center, as indicated in Fig. XII-3. In other words, alpha iron has nine atoms to each space lattice. Millions of these space lattices are joined together in regular geometrical form to produce a crystal. As all metals assume a crystal in form when solidifying, all the atoms will be associated in space lattices and each metal will have its own characteristic space lattice with uniform geometrical pattern and the same distance always between atoms, provided that the metal is in the normal, or annealed, condition. Alpha iron is made up entirely of body-centered space lattices at atmospheric temperature. The form of the space lattice does not change when the iron undergoes a sudden change in properties at 760°C. So, rightly or wrongly, the assumption that alpha modification changes to beta modification is ignored by many metallurgists.

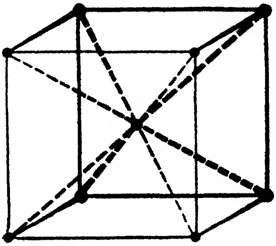


FIG. XII-3.—Space lattice of alpha iron.

But if pure iron be heated to a temperature of about 890°C., it undergoes a change in its space lattice. The body-centered space lattice, with 9 atoms to a lattice, changes to a face-centered space lattice, shown in Fig. VII-4. In the face-centered lattice we have 14 atoms to a space lattice. The size of the cube is somewhat different from that of the body-centered space lattice, and there is a slight change in volume of the piece of iron as a whole when it is heated from below to above the temperature of

890°C. At the same time it changes some of its physical properties, notably its electrical conductivity. The iron above 890°C., with the face-centered space lattice is known as the gamma allotropic modification. It is nonmagnetic and the striking difference between it and the alpha modification is that it normally forms a solid solution with carbon. If pure iron is in the gamma form about 890°C. and is allowed to cool, it will undergo the reverse changes which have already been described as those having taken place on heating. In other words, the change from one allotropic change to another is a reversible change, taking place in one direction on cooling and in the opposite direction on heating. The change on cooling takes place at a slightly lower temperature than on heating. This is not because it is other than a true reverse action but because the change in either direction is necessarily slow and lags a little behind the temperature. The amount of this lag will vary directly with the speed of heating and cooling. In changing from the body-centered iron to the face-centered iron there is a contraction in the volume of the metal in a ratio of about 10:9. In the reversed change on cooling, after we change from the face-

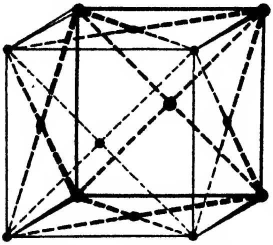


FIG. XII-4.—Space lattice of gamma iron.

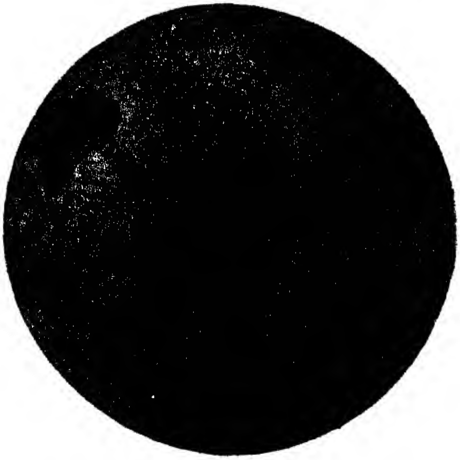


FIG. XII-5.—American ingot iron. This iron contains almost no carbon, and is therefore almost pure ferrite. 100×.

centered to the body-centered lattice, there is a corresponding expansion.

If pure iron be further heated to 1400°C., it changes again from the face-centered lattice to the body-centered lattice, and it retains this body-centered lattice form until it melts at 1535°C. The body-centered iron existing above 1400°C. has been sometimes called the delta allotropic modification. Others call it the alpha modification, because its space lattice is the same as the alpha modification existing at atmospheric temperature. A great difference exists, however, between the body-centered iron above 1400°C. and iron with the same space lattice below 890°, *viz.*, that the body-centered iron at the high temperature is nonmagnetic, and also it will hold carbon in a solid solution up to a limit of 0.07 per cent, while the body-centered iron below 890°C. will hold a maximum of only 0.03 per cent of carbon.

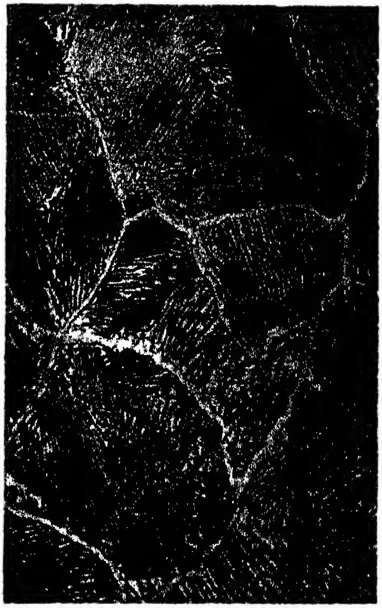


FIG. XII-6.—Crystals of cementite surrounding crystals of pearlite. 500 ×. (*Hanemann and Schrader.*)

Cementite.—The carbide of iron is, next to ferrite, the most important constituent of steel, and practically all of the carbon is present in this form. Cementite is very hard and brittle, scratching glass with ease and flying into pieces under a blow. It crystallizes usually in thin flat plates, which are large in size (sometimes up to ⅛ in. in diameter) when there is much cementite present. It is less attacked by reagents than most of the other constituents and is in this way distinguished under the microscope. It is a little difficult to distinguish, by microscopic evidence alone, between steel consisting of pearlite with a slight excess of cementite and steel consisting of pearlite with a slight excess of ferrite. The practiced eye can usually tell; but a chemical analysis readily distinguishes, since steel with less than 0.8 per cent of carbon will have excess ferrite over pearlite, and that with more than 0.9 per cent will have excess cementite.

A solution of sodium picrate, made by dissolving 2 grams of picric acid in 98 cc. of a 25 per cent solution of NaOH in water if used for 5 to 10 min. at a boiling temperature on a polished sample will color cementite dark, leaving pearlite light. Cementite contains 6.6 per cent of carbon or, roughly, is one-fifteenth carbon. We may therefore tell the amount of cementite in any steel by multiplying the amount of carbon by 15.[1] Cementite may be separated from steel by electrolysis. It is magnetic at ordinary temperatures but not above 230°C. (466°F.).

Fig. XII-7.—Particles of manganese sulphide elongated in the direction of rolling. Etched in 5 per cent nital. 250 X. *(Reprinted by permission from "Photomicrographs of Iron and Steel" by Everett L. Reed, published by John Wiley & Sons, Inc.)*

Manganiferous Cementite.—Manganese forms a carbide having the formula Mn_3C. This is isomorphous with cementite, and we often find the two carbides together in one crystal. The name cementite is still applied to this crystal, although it must be recognized that a part of the iron has been replaced by manganese. The formula for the compound is usually written $(FeMn)_3C$. The amount of manganese in these crystals is very variable, running almost all the way from 0 to 80 per cent. As manganese has an atomic weight almost the same as that of iron (Mn_{55}, Fe_{56}), one weight of manganese will replace almost exactly an equal weight of iron in the crystal. The peculiarity of the manganiferous cementite is that the crystals of free cementite are liable to be larger, especially when the proportion of manganese is large, and are seemingly harder and more difficult to machine.

Manganese Sulphide.—Manganese and sulphur unite to form manganese sulphide, having the formula MnS, and this

---

[1] In other words, steel containing 0.5 per cent of carbon will contain 7.5 per cent of cementite; steel containing 1 per cent of carbon will contain 15 per cent of cementite; etc.

compound is found in all steels. Indeed, all of the sulphur will be found in this combination, provided there is enough manganese in the steel to unite with it. It is necessary to have more than the theoretical amount of manganese for this purpose, however, because unless there is a surplus present the manganese does not seem to catch it all. Steel should therefore always contain about four times as much manganese as sulphur, because it is advantageous to have the sulphur all in the form of manganese sulphide.

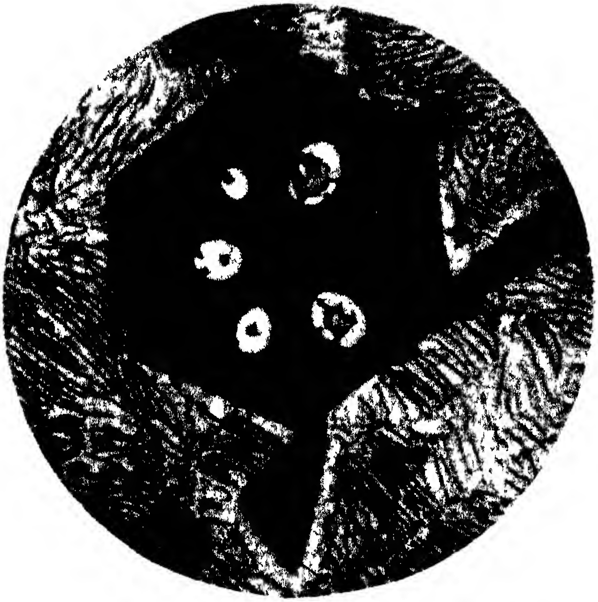


FIG. XII-8.—An almost perfectly formed crystal of MnS found in a sample of cast iron 3,000 ×. Note the particles of some other compound (perhaps silicates) enclosed in the MnS crystal. (*Roy M. Allen.*)

Manganese sulphide is seen under the microscope as a dove-gray substance before the polished material is etched with any reagents. It is usually segregated in round drops, which are sometimes, if large in size, seen to be elongated by the rolling or hammering of the material (see Fig. XII-7).

Manganese tends to make the crystals of steel smaller, which is advantageous but makes the metal more liable to crack in heating and still more so in cooling suddenly from a red heat.

Iron Sulphide.—The bulk of the sulphur not united with the manganese will be found in the form of iron sulphide, FeS. This iron sulphide is more brittle than manganese sulphide, and, instead of coalescing in drops, it spreads out in webs or sheets. It is therefore very weakening to the steel, because the area of weakness is more extensive than the tiny spots of manganese sulphide. Steel containing iron sulphide is liable to show poor tensile test and low ductility. It is at the rolling temperature, however, that iron sulphide produces the greatest weakness. These facts explain the well-known beneficial effect of manganese in counteracting the damage due to sulphur in iron and steel.

Iron Phosphide.—Iron forms at least one phosphide, having the formula Fe_3P, and this phosphide forms with iron a series of alloys, of which the eutectic contains 64 per cent of iron phosphide (10.2 per cent of phosphorus) (see Fig. XII-9). Even 1 per cent of phosphorus will make the melting point of iron very much lower, and it is for this reason that foundry irons are often desired with a high content of phosphorus. Even where there is a smaller amount of phosphorus, there will be some of the phosphorus eutectic formed, and this remains in a molten condition for some time after the bulk of the steel has solidified. This liquid eutectic tends to migrate to the spaces between the crystals, where it remains after solidification and forms a very brittle network, which naturally makes the whole mass more or less brittle. For these reasons, phosphorus is the greatest source of brittleness in steel, and especially brittleness under shock, and is thus a great enemy to the engineer and other users of the material.

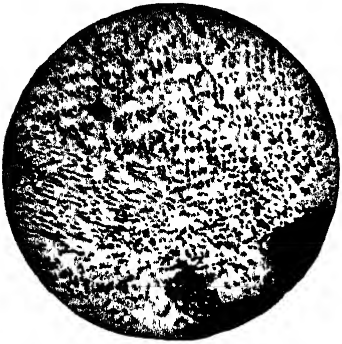


Fig. XII-9.—Eutectic of Fe_3P and iron. 1,000×. Etched with picric acid

Besides forming the eutectic, as has been described, phosphorus tends to produce coarse crystallization in steel, and this makes it both weak and brittle. It is a fact observed many times that the embrittling effect of phosphorus on steel is much less when the steel is very low in carbon, and as the carbon rises the brittleness caused by phosphorus rises. This and other effects of phosphorus have been explained by Prof. J. E. Stead in two very able papers. He has shown that a little phosphorus will dissolve in ferrite and that then the eutectic which produces the brittleness will not form; but as the carbon in the steel increases, it precipitates the phosphorus from the ferrite solid solution and therefore causes the eutectic to form. Hence the more ferrite and the less cementite in steel, the less will be the brittleness produced by phosphorus.

Iron Silicides.—There seem to be three or more silicides of iron, but the one having the formula FeSi seems to be found most commonly in steel. It appears to increase very slightly the strength of steel and also, to a limited extent, its hardness. The chief importance of silicon, however, as already pointed out, is in promoting soundness.

Iron Oxides.—Oxygen occurs in steel in at least three forms: carbon monoxide, FeO, and Fe_2O_3. In any form its presence is very harmful, producing brittleness in both hot and cold steel, besides causing the liability to blowholes already discussed. There is probably no constituent more harmful to steel than oxygen, and unfortunately the chemists are far behind in not yet having found a satisfactory method of rapidly determining small traces of this gas. The effect of oxygen is somewhat similar to that of sulphur and, in common parlance, makes the steel "rotten."

Nitrogen and Hydrogen.—Both nitrogen and hydrogen occur in steel, and one of the theories to explain the superiority of crucible steel is based upon the relative freedom of this material from these two gases. The amount of nitrogen and hydrogen present is usually very small. Hydrogen dissolves very easily in iron at a high temperature but is evolved in part as the metal cools. In order to obtain entire freedom, however, it is necessary to heat and cool several times *in vacuo*. Nitrogen is important in connection with arc welding, when a needle-like constituent appears, which is thought to be a crystal of iron nitride.

THE STRENGTH OF STEEL

The properties of steel most commonly desired are strength and ductility. Unfortunately there is more or less incompatibility between these two. That is to say, as the strength of steel increases, the ductility usually decreases; and, conversely, as the ductility increases, the strength usually decreases. There are other properties of steel which are likewise of importance, either because they are desired or the reverse. Among these we shall especially discuss hardness, brittleness, electric conductivity, magnetic permeability, magnetic hysteresis, permanent magnetism, and weldability. Pure iron has a tensile strength of about 38,000 lb. per square inch, when in its softest condition, at which the ductility is great, being approximately equal to that of copper (see Fig. XII-1), and the malleability is equal to or greater than that of copper. Different authorities give varying estimates of the compressive strength, from 55,000 to 80,000 lb. resistance of a 1-in. cube. The variation depends largely on the opinion of the observer as to what constitutes the limit of "yielding" to compression, and this problem would seem to resolve itself into a matter of civil engineering rather than of metallurgy; *i.e.*, a question of strength of columns of different sizes and design, rather than the strength of a 1-in. cube of the metal. The strength of iron is increased by the presence of several ingredients customarily accompanying it in industrial use, but the most important strengthener is carbon, because this will increase its strength with the least decrease in ductility.

The steel manufacturer must work to meet the specifications of the civil, mechanical, electrical, or chemical engineer, as to strength, ductility, hardness, lack of brittleness, resistance to shock, etc. And, because the usual tests are admitted not to be perfect safeguards, the latter is permitted by custom to limit the percentage of such dangerous ingredients as sulphur, phosphorus, and (under certain circumstances) manganese. As the work of the chemist advances, it is also probable that upper limits may be placed on the allowable percentage of oxides and other inclusions, as well as oxygen, hydrogen, nitrogen, carbon monoxide, and other gases. But it is now generally recognized that, beyond this point, the purchaser has no right to trespass on the work of the metallurgist, who should be permitted to put into his product the proportion of carbon, etc., which will give the desired qualities. This agreement has been achieved in America largely through the efforts of the American Society for Testing Materials.

The metallurgist, then, must be an authority on the effect of the ingredients, in order that he may regulate the analysis of the product to meet the specifications. The first requisite is to know that the qualities of the steel depend on the processes of manufacture: Bessemer, open-hearth, and electric steel will differ in properties even when alike in analysis. The second is to recognize that the extent of reduction in rolling must be taken into consideration: Granted that the steel has had enough work to knead the crystals thoroughly, nevertheless plate of $\frac{3}{8}$-in. thickness will have higher strength than plate of $\frac{5}{8}$-in. rolled from the same ingot. The finishing temperature of rolling and the rate of cooling from rolling heat will also have their effect; *e.g.*, the web and flange of a railroad rail are stronger and harder than the metal of the head. Every manufacturer has tables, based on the experience of his plant, to adjust the chemical composition to the practice of his steel making and rolling mill. The general rules given below will then be varied to meet the conditions in each plant.

Carbon.—Each increase in carbon (cementite) gives an increase in tensile strength until we reach a maximum of about 0.8 to 0.9 per cent of carbon (12 to 13.5 per cent of cementite). With increase in cementite above 15 per cent there is a decrease in tensile strength. It is probable that the reason for this maximum tensile strength at approximately the eutectoid ratio of the steel is due largely to the small crystallization and the intimate mixture of the crystalline constituents when the steel is at, or near, the eutectoid proportions. With less carbon, the grains of pearlite are surrounded by a network of ferrite; with more carbon, the grains of pearlite are surrounded by a network of cementite; and both of these networks have a weakening effect upon the material by decreasing the adhesion of the crystals.

TABLE XII-I.—EFFECT OF CARBON ON IRON
(Other elements being low)

	Carbon, per cent	Tensile strength of annealed metal		
		Ultimate, pounds per square inch	Elastic limit, pounds per square inch	Elongation, per cent in 2 in.
Very mild steel	0.05 to 0.15	40,000 to 48,000	24,000 to 30,000	34 to 28
Mild steel	0.15 to 0.25	48,000 to 60,000	30,000 to 36,000	28 to 25
Low-carbon steel	0.25 to 0.40	60,000 to 70,000	36,000 to 40,000	25 to 22
Medium-carbon steel	0.40 to 0.60	70,000 to 80,000	40,000 to 48,000	22 to 18
Higher-carbon steel	0.60 to 0.70	80,000 to 94,000	48,000 to 56,000	18 to 14
Spring steel	0.70 to 0.80	94,000 to 108,000	56,000 to 64,000	14 to 8
Pearlitic steel[1]	0.85	120,000	70,000	5
Hypereutectoid steel	0.90 to 1.70	119,000 to 100,000	67,000 to 60,000	5 to 1

[1] Also called eutectoid steel.

TABLE XII-II.—CARBON CONTENT OF WROUGHT IRON AND STEELS FOR DIFFERENT USES

	Material		Carbon	
	Usual	Preferred	Desired	Limits
Axles	B.O.H.	El.	0.40	0.25 to 0.70
Axles, cold-rolled	B.O.H.	O.H.	....	Not over 0.40
Alternate stress, resistance to	B.O.H.	El.	0.50	0.45 to 0.75
Boiler plate, steel	B.O.H.	A.O.H.	0.12	0.08 to 0.18
Boiler plate, wrought-iron	W.I.	W.I.	0.10	0.08 to 0.18
Boiler tubes, steel	B.O.H.	B.O.H.	0.10	0.08 to 0.18
Boiler tubes, charcoal wrought-iron	C.W.I.	C.W.I.	X	
Castings	O.H.	El.	....	0.12 to 0.30
Carpenter's tools	......	Steel	....	0.50 to 1.20
Carpenter's tools, hammers	M.C.I.	Steel	....	0.50 to 0.80
Carpenter's tools, wood-cutting tools	Steel	Cr.#	1.15	1.10 to 1.20
Case-hardening stock	O.H.	......	0.12	0.10 to 0.20
Chain, steel	B.O.H.	O.H.	Min.	0.04 to 0.15
Chisels, granite-cutting	Cr.#	Cr.#	1.05	1.00 to 1.10
Chisels, cold chisels	Cr.#	Cr.#	0.75	0.70 to 0.80
Cold-rolled steel	B.O.H.	......	....	Not over 0.40
Concrete-reinforcement bars	Bess.	O.H.	....	0.40 to 0.70
Culverts for water disposal	O.H.	El.	Min.	0.00 to 0.10
Crankpins for wearing resistance	O.H.	......	0.30	0.25 to 0.35
Crankpins for resisting shocks and reversals of stress	O.H.	El.	0.50	0.45 to 0.55
Dies, for making drop-forgings	B.O.H.	O.H.	0.65	0.60 to 0.70
Dies, for metal cutting	B.O.H.	El.	0.85	0.80 to 1.20
Dies, for thread cutting	Cr.	Cr.#	1.15	1.10 to 1.20
Dies, for wire drawing	Cr.#	Cr.#	1.50	1.30 to 2.00
Drills, rock drilling	Cr.#	Cr.#	0.85	0.80 to 0.90
Engravers' tools	Cr.#	Cr.#	1.35	1.30 to 1.40
Files for metal smoothing	B.O.H.	B.O.H.	1.25	1.20 to 1.30
Forgings, ordinary	B.O.H.	A.O.H.	0.25	0.20 to 0.30
Forgings, strong	B.O.H.	A.O.H.	0.40	0.35 to 0.60
Gears, except case-hardened	B.O.H.	O.H.	0.35	0.30 to 0.60
Lathe tools	Cr.#	Cr.#	...	1.00 to 1.20
Machinery steel	B.O.H.	O.H.	0.35	0.30 to 0.50
Machinists' tools	Cr.#	Cr.#	....	0.70 to 1.20
Nails, wire	Bess.	Bess.	0.10	0.08 to 0.15
Nails, cut	W.I.	W.I.	0.10	
Pipe, steel	Bess.[1]	......	Low	
Pipe, wrought-iron	W.I.	W.I.		
Plates, tank	Bess.	......	0.12	0.08 to 0.15
Plates, structural	B.O.H.	A.O.H.	0.30	0.25 to 0.40
Punches	.....	Cr.#	....	0.80 to 1.00
Railroad-car wheels, steel	B.O.H.	O.H.	0.70	0.60 to 0.85
Railroad rails, small sizes	Bess.	B.O.H.	....	0.37 to 0.50
Railroad rails, large sizes	B.O.H.	O.H.	....	0.50 to 0.75
Rivets	B.O.H.	B.O.H.	0.05	0.05 to 0.20
Screws for wood	Bess.[1]	Bess.[1]	0.10	0.08 to 0.16
Set screws	B.O.H.	Cr.#	0.65	0.60 to 0.70
Saws, band	Cr.#	Cr.#	0.75	0.70 to 0.80
Saws, circular	O.H.	Cr.#	0.85	0.80 to 0.90
Saws, for cutting steel	Cr.#	Cr.#	1.55	1.50 to 1.60
Shafting, for transmission purposes	B.O.H.	B.O.H.	....	Not over 0.4
Shafting, for crankshafts	O.H.	Cr.#	0.50	0.50 to 0.60
Staybolts, wrought iron	W.I.	W.I.		
Shock-resisting steel	O.H.	O.H.	0.50	0.45 to 0.55
Stone-cutting tools	Cr.#	Cr.#	1.35	1.30 to 1.40
Structural shapes, small	Bess.	O.H.	0.25	
Structural shapes, important structures	O.H.	A.O.H.	0.25	
Springs	B.O.H.	Cr.#	0.95	0.90 to 1.15
Tubing, steel	Bess.[1]	O.H.	0.08	0.05 to 0.15
Tubing, wrought-iron	W.I.	W.I.		
Valves for resisting wear	B.O.H.	O.H.	0.30	0.25 to 0.35
Wire, for electric conductivity	Bess.	Bess.	Min.	0.05 to 0.10
Wire, for fencing and chicken wire	Bess.	Bess.	Low	
Wire, for structural steel	A.O.H.	A.O.H.	0.80	0.75 to 0.85

A.O.H. = acid open-hearth steel; B.O.H. = basic open-hearth steel; Bess. = Bessemer steel; Cr. = crucible steel; Cr.# = crucible or electric steel; El. = electric steel; W.I. = wrought iron; C.W.I. = knobbled charcoal wrought iron; M.C.I. = malleable cast iron.

[1] Or B.O.H.

The Work of W. R. Webster on Open-hearth and Bessemer Steels.—H. H. Campbell and W. R. Webster have studied exhaustively the effect of carbon, manganese, and phosphorus on the strength of basic open-hearth and acid Bessemer steels, the two largest sources in America of rolled steel. Knowing these influences, the manufacturer has a good working basis, because the only other common ingredients are sulphur and silicon, and neither of these is present in rolled steel in amounts sufficiently variable to exert a controlling influence on the strength or ductility. Sulphur is limited by the purchaser to amounts which will ensure the ductility desired, and the manufacturer must also limit it in order that the steel will roll well. In Bessemer steel it will usually not exceed 0.08 per cent, and its effect is taken into consideration by the metallurgist as a condition of the Bessemer steel problem. In basic open-hearth steel it will usually not exceed 0.05 per cent (except in special products whose strength and ductility are not controlling conditions).

W. R. Webster gives two working tables. See Table below, taken from Transactions of American Institute Mining and Metallurgy Engineers, vol. 67, pp. 227–8, 1922, which are given below for the guidance of metallurgists. From these tables it will be evident that the effect of all three elements is dependent on the others. We may summarize for carbon, as follows: When the phosphorus is 0.02 per cent and the manganese 0.40 per cent, each 0.01 per cent of carbon will increase the tensile strength by 800 lb. per square inch. When the phosphorus is 0.08 per cent and the manganese 0.80 per cent, each 0.01 per cent of carbon added will increase the tensile strength by 1,000 lb. per square inch.

Silicon.—The effect of silicon on strength is probably very small in the case of rolled steel. In the case of castings, however, an important increase in tensile strength may be obtained by increasing the silicon to 0.3 or 0.4 per cent. This practice results in practically no decrease in ductility, but it is necessary to supply larger risers on account of the deep piping that will be produced. It is probable that the beneficial effect of silicon in this case is due very largely to its producing soundness.

Sulphur.—H. H. Campbell says that the effect of sulphur on the strength of acid and basic open-hearth steel is very small. It is probable, however, that this statement is true only when the sulphur is in the form of manganese sulphide, because the

TABLE XII-III.—STEEL WORKS A, BASIC OPEN-HEARTH STEEL

Phosphorus under 0.031 per cent; manganese 0.34 to 0.60 per cent, varying by 0.02 per cent; carbon 0.10 to 0.40 per cent, varying by 0.1 per cent. Average of actual tensile strength of ¾-in. round test bars rolled from test ingots.

When phosphorus is greater than 0.02 per cent, the figures should be increased at the rate of 1,000 lb. for each 0.01 per cent that the phosphorus exceeds 0.02 per cent.

Carbon, per cent	Manganese, per cent													
	0.34	0.36	0.38	0.40	0.42	0 44	0.46	0.48	0 50	0 52	0 54	0.56	0.58	0.60
	Tensile strength, pounds per square inch													
0.10	50,145	50,595	50,950	51,300	51,700	52,100	52,440	52.720	53,000	53,400	53,800	54,200	54,600	55,000
0.11	51,410	51,790	52,090	52,390	52.720	53,050	53,340	53.595	53,850	54,245	54,640	55,025	55,390	55,760
0.12	52,675	52,980	53,235	53,480	53,740	54,000	54,245	54.470	54 700	55,090	55,485	55,850	56,185	56,520
0.13	53,945	54 175	54,375	54,570	54,760	54,950	55,145	55,350	55,550	55,940	56,325	56,670	56,975	57,280
0.14	55,210	55,370	55,520	55,660	55,780	55,900	56,050	56,225	56,400	56,785	57,170	57,495	57,770	58,040
0.15	56,475	56,565	56,660	56,750	56,800	56,850	56,950	57,100	57,250	57,630	58,010	58,320	58,560	58,800
0.16	57,040	57,140	57,240	57,340	57,435	57,530	57,675	57,860	58,050	58,445	58,840	59,180	59,455	59,730
0.17	57,605	57,710	57,820	57,930	58,070	58,215	58,400	58,625	58,850	59,260	59,675	60,035	60,350	60,660
0.18	58,170	58,285	58,405	58,520	58,710	58,895	59,120	59,385	59,650	60,080	60,505	60,895	61,240	61,590
0.19	58,735	58,885	58,985	59,110	59,345	59,580	59,845	60,150	60,450	60,895	61,340	61,750	62,135	62 520
0.20	59,300	59,430	59,565	59,700	59,980	60,260	60,570	60,910	61,250	61,710	62,170	62,610	63,030	63,450
0.21	59,775	60,025	60,275	60,510	60,785	61,055	61,365	61,700	62,040	62,470	62,905	63,320	63,720	64,120
0.22	60,245	60,615	60,985	61,320	61,590	61,855	62,155	62,495	62,830	63,235	63,640	64,030	64,410	64,790
0.23	60,720	61,210	61,700	62,130	62,390	62,650	62,950	63,285	63,620	63,995	64,370	64,740	65,100	65,460
0.24	61,190	61,800	62,410	62,940	63,195	63,450	63 740	64,080	64,410	64,760	65 105	65,450	65,790	66,130
0.25	61,665	62,395	63,120	63,750	64,000	64,245	64,535	64,870	65,200	65,520	65,840	66,160	66,480	66,800
0.26	62,285	63,020	63,755	64,410	64,700	64,990	65,310	65,660	66,010	66,335	66,660	66,990	67,325	67,660
0.27	62,905	63,650	64,390	65,070	65,405	65,735	66,085	66,455	66,820	67,150	67,480	67,820	68,170	68,520
0.28	63,530	64,275	65,020	65,730	66,105	66,480	66,860	67,245	67 630	67,970	68 305	68 655	69,020	69,380
0.29	64,150	64,995	65,655	66,390	66,810	67,225	67,635	68 040	68,440	68,785	69,125	69,485	69,865	70,240
0.30	64,770	65,530	66,290	67,050	67,510	67,970	68,410	68,830	69,250	69,600	69,945	70,315	70,710	71,100
0 31	65,800	66,585	67,370	68,155	68,560	68,960	69,370	69,785	70,200	70,570	70 940	71,305	71,670	72,030
0.32	66,835	67,645	68,455	69,260	69,610	69,955	70,330	70,740	71,150	71 545	71,935	72,295	72,630	72,960
0.33	67,865	68,700	69,535	70,370	70,655	70,945	71,295	71,670	72,100	72,515	72,930	73,290	73,590	73,890
0.34	68,900	69,760	70,620	71,475	71,705	71,940	72,255	72,655	73,050	73,490	73,925	74,280	74,550	74,820
0.35	69,930	70,815	71,700	72,580	72,755	72,930	73 215	73,610	74,000	74,460	74,920	75,270	75,510	75,750
0.36	70,665	71,530	72,400	73,265	73,545	73,825	74,170	74,590	75,000	75,455	75,910	76,295	76,610	76,920
0.37	71,400	72,250	73,100	73,950	74,335	74,720	75,130	75,565	76 000	76,450	76,905	77,320	77,710	78,090
0.38	72,130	72,965	73,800	74,630	75,120	75,610	76,085	76,545	77,000	77,450	77,895	78,350	78,805	79,260
0.39	72,865	73,685	74,500	75,315	75,910	76,505	77,045	77,520	78,000	78,445	78,890	79,375	79,900	80,430
0.40	73,600	74,400	75,200	76,000	76,700	77,400	78,000	78,500	79,000	79,440	79,880	80,400	81,000	81,600

TABLE XII-IV.—STEEL WORKS A, ACID BESSEMER STEEL

Manganese 0.34 to 0.60 per cent, varying by 0.02 per cent; carbon 0.10 to 0.40 per cent, varying by 0.01 per cent. Average of actual tensile strength of ¾-in. round test bars rolled from test ingots.

Carbon, per cent	Manganese, per cent													
	0.34	0.36	0.38	0.40	0.42	0.44	0.46	0.48	0.50	0.52	0.54	0.56	0.58	0.60
	Tensile strength, pounds per square inch													
0.10	64,440	64,480	64,480	64,500	64,600	64,700	64,800	64,900	65,000	65,120	65,240	65,340	65,420	65,500
0.11	64,665	64,695	64,720	64,750	64,900	65,055	65,190	65,310	65,430	65,585	65,740	65,885	66,020	66,150
0.12	64,890	64,930	64,965	65,000	65,205	65,410	65,580	65,720	65,860	66,050	66,245	66,430	66,615	66,800
0.13	65,120	65,160	65,206	65,250	65,505	65,760	65,970	66,130	66,290	66,520	66,745	66,980	67,215	67,450
0.14	65,345	65,395	65,450	65,500	65,810	66,115	66,360	66,540	66,720	66,985	67,250	67,525	67,810	68,100
0.15	65,570	65,630	65,690	65,750	66,110	66,470	66,750	66,950	67,150	67,450	67,750	68,070	68,410	68,750
0.16	66,155	66,245	66,340	66,430	66,810	67,190	67,500	67,735	67,970	68,345	68,720	69,090	69,445	69,800
0.17	66,740	66,860	66,985	67,110	67,510	67,910	68,245	68,520	68,790	69,240	69,695	70,105	70,480	70,850
0.18	67,320	67,480	67,635	67,790	68,210	68,630	68,995	69,300	69,610	70,140	70,665	71,125	71,510	71,900
0.19	67,905	68,095	68,280	68,470	68,910	69,350	69,740	70,085	70,430	71,035	71,640	72,140	72,545	72,950
0.20	68,490	68,710	68,930	69,150	69,610	70,070	70,490	70,870	71,250	71,930	72,610	73,160	73,580	74,000
0.21	69,755	69,975	70,200	70,420	70,900	71,380	71,795	72,145	72,495	73,080	73,665	74,170	74,585	75,000
0.22	71,020	71,245	71,465	71,690	72,190	72,690	73,100	73,420	73,740	74,230	74,725	75,175	75,590	76,000
0.23	72,285	72,510	72,735	72,960	73,480	74,000	74,405	74,690	74,980	75,380	75,780	76,185	76,590	77,000
0.24	73,550	73,780	74,000	74,230	74,770	75,310	75,710	75,965	76,225	76,530	76,840	77,190	77,595	78,000
0.25	74,815	75,045	75,270	75,500	76,060	76,620	77,015	77,240	77,470	77,680	77,895	78,200	78,600	79,000
0.26	75,810	76,075	76,335	76,600	77,100	77,615	77,990	78,230	78,475	78,730	78,990	79,305	79,580	80,050
0.27	76,810	77,110	77,400	77,700	78,155	78,615	78,970	79,225	79,480	79,785	80,090	80,410	80,755	81,100
0.28	77,810	78,140	78,470	78,800	79,205	79,610	79,945	80,215	80,490	80,835	81,185	81,520	81,835	82,150
0.29	78,805	79,170	79,535	79,900	80,250	80,605	80,925	81,210	81,495	81,890	82,285	82,625	82,910	83,200
0.30	79,800	80,200	80,600	81,000	81,300	81,600	81,900	82,200	82,500	82,940	83,380	83,730	83,990	84,250
0.31	80,610	80,990	81,370	81,750	82,050	82,350	82,660	82,980	83,300	83,695	84,090	84,410	84,655	84,900
0.32	81,420	81,780	82,140	82,500	82,800	83,100	83,420	83,760	84,100	84,450	84,805	85,095	85,320	85,550
0.33	82,230	82,570	82,910	83,250	83,650	83,850	84,180	84,540	84,900	85,210	85,515	85,775	85,990	86,200
0.34	83,040	83,360	83,680	84,000	84,300	84,600	84,940	85,320	85,700	85,965	86,230	86,460	86,655	86,850
0.35	83,850	84,150	84,450	84,750	85,050	85,350	85,700	86,100	86,500	86,720	86,940	87,140	87,320	87,500
0.36	85,310	85,610	85,905	86,200	86,505	86,810	87,150	87,525	87,900	88,150	88,395	88,630	88,845	89,060
0.37	86,775	87,065	87,360	87,650	87,960	88,265	88,595	88,950	89,300	89,575	89,850	90,115	90,370	90,620
0.38	88,235	88,525	88,810	89,100	89,410	89,725	90,045	90,370	90,700	91,005	91,310	91,605	91,890	92,180
0.39	89,700	89,980	90,265	90,550	90,865	91,490	91,490	91,195	92,100	92,430	92,765	93,090	93,415	93,740
0.40	91,160	91,440	91,720	92,000	92,320	92,640	92,940	93,220	93,500	93,860	94,220	94,580	94,940	95,300

effect of iron sulphide would be to lower the strength and the ductility of the material. The worst effect of sulphur is undoubtedly its production of "red-shortness," *i.e.*, the liability to cause checking during rolling or, in the case of a casting, during solidification and cooling.

Phosphorus.—Campbell's and Webster's results show that each 0.01 per cent of phosphorus increases the strength of the steel by 1,000 lb. per square inch. It should be observed, however, that this increase of strength is measured by the resistance of the material to stresses slowly applied and that it ceases with 0.12 per cent of phosphorus and is reversed. In the case of vibratory stresses and sudden shocks, phosphorus is probably the most harmful of the elements, so that it is undesirable to increase the strength of steel by means of this element. This is the more true because of the brittleness produced by phosphorus, for an increase of strength obtained through this medium is accompanied by a much greater decrease in ductility than when the same increase in strength is obtained through the medium of carbon.

Manganese.—The beneficial effect of manganese on tensile strength begins only when the manganese is above 0.3 or 0.4 per cent. With less manganese than this, in the case of open-hearth and Bessemer steels, the presence of some other condition, probably iron oxide, masks the effect of manganese. It will be remembered that, when the manganese is low, open-hearth and Bessemer steels are harmfully charged with oxygen. Furthermore, the effect of manganese is dependent upon the amount of carbon present.

Webster uses a uniform figure of 170 lb. per square inch increase of tensile strength for each 0.01 per cent of manganese added to basic open-hearth steel, beginning only at 0.30 per cent of manganese. Campbell, on the other hand, estimates that the effect of manganese increases with the content of carbon. His results for acid and basic open-hearth steel are given on page 395. It will be observed that, when the carbon is 0.20 per cent, his figure for manganese agrees with that of Webster.

In studying this table it will be interesting to note that some of the manganese added to basic steel is probably used up in neutralizing the effect of oxygen, before it can exert its influence in strengthening the steel itself. The result is that manganese in basic steel does not produce the same strengthening effect as the same percentage of manganese in acid steel.

TABLE XII-V.—EFFECT OF EACH 0.01 PER CENT MANGANESE ON OPEN-HEARTH STEEL

Carbon, per cent	On acid steel, pounds per square inch	On basic steel, pounds per square inch
0.05	....	110†
0.10	80*	130
0.15	120	150
0.20	160	170
0.25	200	190
0.30	240	210
0.35	280	230
0.40	320	250
0.45	360	
0.50	400	
0.55	440	
0.60	480	

* Beginning only with 0.4 per cent of manganese.
† Beginning only with 0.3 per cent of manganese.

Residual Manganese.—For this reason all open-hearth steel is now made with "residual manganese" left in the bath during the whole operation. This produces three effects:

1. It protects the bath from oxygen.
2. It leaves less oxygen in the final steel than can be accomplished by the usual manganese deoxidation.
3. It reduces by an amount equal to its own percentage the manganese necessary to add for deoxidation during recarburizing.

The amount of residual manganese is 0.10 to 0.20 per cent, and it is left in the bath by the practice of starting with an excess of manganese in the charge and then raising the temperature to the point where carbon begins to oxidize before all the manganese is consumed by the oxygen of the ore or flame. Another method recently used is to add manganiferous iron ore, instead of straight iron ore, for oxidizing purposes. This is an economic question, dependent on the relative price of the ore and of high-manganese pig iron. Under special conditions, scrap from manganese steel manufacture may be used to a limited extent.

Copper.—Copper, up to at least 1 per cent, does not appear to have any important effect upon the strength or ductility of low- and medium-carbon steels but increases the brittleness of steel containing 1 per cent of carbon. When the sulphur is more than 0.05 per cent, copper appears to make the steel roll less easily and above 0.5 per cent of copper appears to make high-carbon steel draw less easily into wire.

Arsenic.—Some steels contain arsenic, which does not appear to have any effect when it is below 0.17 per cent, but any larger quantity raises the tensile strength and decreases the ductility to a very important extent.

Oxide of Iron.—All Bessemer and open-hearth steels contain more or less oxide of iron, there probably being more in basic steel than in acid, and more in Bessemer steel than in basic open-hearth steel. It is probable that this oxide of iron has not any very marked effect upon strength, as Campbell quotes some steels containing quantities larger than usual whose strength is good. No data are given as to the ductility, however, and it is probable that oxide of iron has a deleterious effect upon this quality.

HARDNESS AND BRITTLENESS OF STEEL

In this place we shall discuss only the question of rolled or annealed steel. By means of heat treatment we may greatly harden all but the low-carbon steels, but this hardness is lost on annealing. The effect of carbon on hardness, and the effect of the heat treatment known as "hardening," is shown from the following table, taken from Howe, "The Metallography of Steel and Cast Iron," page 598.

As a general thing the hardness and brittleness of steel increase together. The chief commercial application of this property is in such articles as railroad rails and car wheels, bevel and spur gears, axles and bearings, the wearing parts of crushing machinery, etc.[1] To produce hardness in these materials, carbon is the chief agent used, because it gives the maximum hardness with the least brittleness. It is for this reason that railroad rails are now made up to 0.7 per cent of carbon; and although this material is somewhat brittle and breakages occasionally occur, the high carbon is demanded in order that the head of the rail may be durable. Phosphorus increases both the hardness and the brittleness, especially under shock. Manganese likewise increases hardness, and especially the kind of hardness which makes

---

[1] The author purposely omits here the consideration of such hardness as that produced in springs, cutting tools, etc., by heating the steel to a bright-red heat and plunging into water, as this will be discussed in Chap. XIII.

it more difficult and more expensive to machine the metal. With more than about 1 per cent of manganese the steel becomes somewhat brittle. When the content rises above 2 per cent, the steel is so brittle as to be practically worthless. In this connection a curious phenomenon is observed, in that a still further increase in manganese produces a reversal of its influence;

TABLE XII-VI.—INCREASE OF THE BRINELL AND SHORE HARDNESS WITH THE CARBON CONTENT

(Based chiefly on the data of Brinell and of Shore)

Number	Carbon content, per cent	Shore scleroscope hardness			Brinell or ball hardness		Ratio: Brinell ÷ Shore hardness	
		Condition of the metal			Condition of the metal			
		Annealed	Normal merchantable	Hardened	Annealed	Hardened	Annealed	Hardened
1	2.04[c]	....	.....	...	286[c]	Cracked		
2	1.75	40 to 45	50 to 55	110				
3	1.72[d]	....	....	...	286[d]	477[d]		
4	1.50	37 to 40	47 to 50	110				
5	1.25	35	44	110	262[f]	627[f]	7.5	5.7
6	1.00	30 to 35	40	107	259[a]	627[a]	7.4 to 8.6	5.9
7	0.80	28 to 30	38	105	235[a]	648[a]	6.7 to 7.8	6.2
8	0.66	....	....	...	202[b]	578[b]		
9	0.65	....	....	...	235[f]	652[f]		
10	0.60	27	36	102	225[a]	628[a]	8.3	6.2
11	0.50	26	34	96	204[a]	579[a]	7.8	6.0
12	0.45	....	....	...	194[f]	555[f]		
13	0.40	25	32	90	175[a]	478[a]	7.0	5.3
14	0.35	24	30	82	156[f]	402[f]	6.5	4.9
15	0.30	23	28	70				
16	0.25	22	27	58	143[f]	311[f]	6.5	5.4
17	0.20	21	26	50	115[f]	196[f]	5.5	3.4
18	0.15	20	25	43				
19	0.10	19	24	35	97[f]	149[f]	5.1	4.4
20	0.05	18	23	25				
21	0.01[e]	....	....	...	75[e]	107–112		

For footnotes to Table XII-VI, see original reference.

and when we have more than 7 per cent, the metal is not only extremely hard and practically impossible to machine commercially but becomes, after heat treatment, very ductile and tough. This will be considered more fully in Chap. XVI.

Silicon.—Silicon makes the steel slightly harder, but apparently without increasing its brittleness, unless we have more than 0.5 or 0.6 per cent.

ELECTRIC CONDUCTIVITY OF STEEL

The purer the material and the nearer it is to ferrite, the better will be its electric conductivity; therefore only wrought iron, or the softest and purest forms of steel, are used generally for wire for electric conduits.[1] The case is somewhat complicated when we come to third rails for electric railroads, because so pure a material will be very soft and will rapidly wear away under the abrasion of the contact shoes. To increase the hardness of these rails with the least decrease in electric conductivity, it is best to avoid nickel and manganese, which decrease electric conductivity in greater proportion than the other elements, and to obtain the hardness as much as possible from phosphorus, and not from carbon, because phosphorus will give the greatest amount of hardness with the least decrease in the purity of the iron. As high-phosphorus steels are difficult to roll, however, the section of the rail chosen should be as free as possible from sharp corners and thin flanges, in order that the tearing action in rolling may be as slight as possible.

MAGNETIC PROPERTIES OF STEEL

Alpha ferrite is the chief magnetic constituent of iron and steel, and therefore, the greater the amount of this constituent present, the greater will be the magnetic force and magnetic permeability and the less its magnetic hysteresis. On this account the cores of electromagnets, the armatures of dynamos, etc., are commonly made of Swedish wrought iron, which is the purest commercial form of iron made.[2]

---

[1] Omitting, of course, the use of copper and aluminum.

[2] A silicon alloy of iron with a double-heat treatment discovered by R. A. Hadfield, having a very high magnetic force and permeability, will be discussed under the head of "Alloy Steels" (Chap. XVI).

Ferrite has no permanent magnetism but immediately loses its magnetic force when it is out of contact with a magnet or, in the case of cores of electric magnets, when the electric current is cut off. Permanent magnets are therefore made of a high-carbon steel (1 per cent), whose strength and permanency are increased when some alloying elements are present. This steel is heated above the critical temperature and hardened in water, after which it is magnetized by causing an electric current to flow around it for a short time. Steel so treated will retain the magnetic force for many years. Osmond has explained the permanent magnetism of steel in the following very ingenious manner: Each molecule of alpha ferrite is believed to have a north and a south magnetic pole, which, in the ordinary unmagnetized condition of the iron, will be oriented in many different directions, as shown in Fig. XII-10. When this piece of iron is placed in the magnetic field, however, the molecules arrange themselves in accordance with the lines of magnetic force, with their north poles all in one direction and their south poles all in the opposite direction, thus making the whole piece of iron a magnet. As soon as the magnetic force is removed, however, the molecules all return to their original orientation, and the whole piece of iron loses its magnetism. We have already learned that it is only the molecules in body-centered iron which have north and south magnetic poles; and if the steel consists entirely of gamma molecules, it is not capable of becoming magnetic. According to Osmond's

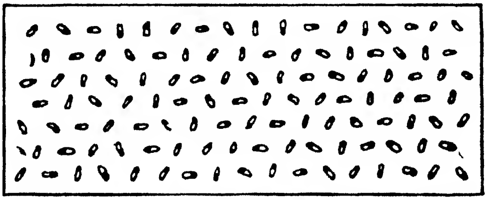


Fig. XII-10.—Iron in an unmagnetized condition.

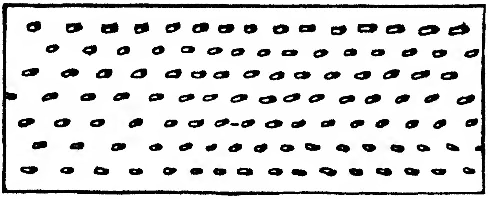


Fig. XII-11.—Iron in a magnetized condition.

theory, when steel is cooled rapidly from above the critical temperature, the shortness of the time taken in reaching the atmospheric temperature is such that only a part of the molecules are able to change to the alpha allotropic form, and the remainder are retained in the gamma form. This retention is assisted by the 1 per cent of carbon present, which acts as a brake to make the change slower. When, now, this hardened steel is subjected to the magnetic force, the alpha molecules orient themselves with their north poles all in one direction; but when the magnetic force is removed, there is a certain number of gamma molecules present to interfere with the free movement of the alpha molecules and prevent them from returning to the original unoriented position. This explanation implies that the magnetic force is sufficient to overcome the resistance of the gamma molecules and force the alpha molecules into a magnetic position, but that the force of the alpha molecules tending to return to their original position is not so great.

References

WILLIAM KENT: "Mechanical Engineers' Pocket Book," 10th ed., New York, 1923.

ARTHUR W. JUDGE: "Aircraft and Automobile Materials of Construction," New York, 1921.

CHARLES A. EDWARDS: "The Physico-chemical Properties of Steel," London, 1916.

LESLIE AITCHISON: "Engineering Steels," London, 1921.

PAUL OBERHOFFER: "Das Technische Eisen," Berlin, 1925.

CHAPTER XIII

THE HEAT TREATMENT OF STEEL

There are seven ways in which heat affects most metals, including steel. They are

1. The properties are different at different temperatures.
2. An oxide or scale forms above certain temperatures.
3. Some temperatures cause an increase or growth in grain size.
4. When the temperature approaches the melting point of the steel, a new damage known as "burning" occurs. (By those only partially familiar with the facts the phenomenon of grain growth is sometimes confused with that of burning, but this is erroneous.)
5. Rapid cooling from certain temperatures will develop hardness and brittleness in steel entirely different from the softness and ductility of the same steel when slowly cooled, as already indicated on page 4.
6. Rapid cooling from other temperatures will increase the strength of the metal over its strength when slowly cooled.
7. In heating or cooling steel, there may be unequalized strains existing in the metal which will be released producing shrinkage or warpage, or else the cooling through given ranges of temperature may produce strains which manifest themselves in warped material. Sometimes the distortion may result in the formation of a crack. In extreme cases, the change in volume may result in actual bursting with explosive violence.

1. VARIATION OF PROPERTIES WITH TEMPERATURE

A few properties of steel are at their highest point at very low temperatures and decrease with temperature rise. The relation is not uniform and regular, however, but sudden changes, or even temporary reversals of trend, occur at certain temperatures, especially at points of allotropic or other critical change. The most important properties which are at their highest at lowest temperatures are strength, elasticity, hardness, brittleness, electric conductivity, and magnetism. These are discussed in greater detail in following sections. Other properties are at their lowest point at low temperatures and rise with temperature, but, again, the relation is not uniform. The most important of these crescendo properties are ductility and malleability.

Changes in Electrical Resistivity.—The formula for the electrical resistivity of metals with change of temperature is as follows:

$$R_t = R_0(1 + \alpha t + \beta t^2).$$

In this formula, R_t equals the resistance at a temperature t figured from the absolute 0; R_0 is the resistance of the same metal at the absolute 0; α and β are coefficients. Since iron undergoes revolutionary changes in resistivity at 760 and 890°C., and since iron-carbon alloys have revolutionary changes where the carbon goes into solution or goes out of it, it is customary to use this formula as if it were $R_t = R_0(1 + \alpha t)$, the value of α being different at different temperatures. For temperatures from 0 to 100°C., it is customary to use a value of α for iron of 0.00657. If pure annealed copper be considered as having a specific resistance of 1.59 microhms per cubic centimeter and a relative conductivity of 100 at atmospheric temperature, then the following figures will apply to iron and its alloys at atmospheric temperature, and at the other temperatures indicated.

	Specific resistance	Relative conductivity
Pure iron	10.0	15.9
Wrought iron	13.9	11.4
White cast iron	about 60.0	2.6
Gray cast iron	about 100.0	1.6
Iron at 100°C.	16.8	9.5
Wrought iron at 100°C.	18.8	8.5
Iron at 500°C.	52.0	3.1
Iron at 1000°C.	about[1] 111.0	1.4
Solid iron at 1500°C.	about[1] 131.0	1.2
Molten iron and steel	about[1] 170.0	0.9
Molten cast iron	about[1] 160.0	1.0

---

[1] So many different estimates are given of the resistivity of iron and steel at elevated temperatures by different researchers that a representative figure can be chosen only with reservations. For example, the resistivity in microhms per cubic centimeter of melted steel is given all the way from 140 to 200, while that of molten cast iron is variously stated as from 160 to 216. Even at atmospheric temperature the resistivity of steel depends so much on its analysis that authoritative figures vary from 14 to 23, depending on the amount of carbon and other impurities.

It may be interesting to note, for comparison, that liquid mercury at a temperature just above its melting point has a specific resistance of 80.

Changes in Magnetism.—The magnetism of iron decreases with rise in temperature until, at about 760°C., it is only one-half as strong as it is at atmospheric temperature. With a further slight rise in temperature, the magnetism becomes as low as that of copper, lead, and other so-called nonmagnetic metals. This revolutionary change was thought to indicate an allotropic change in the metal, as already stated, and there are many advantages of so considering it, although the majority of metallurgists seem to be opposed to this view.

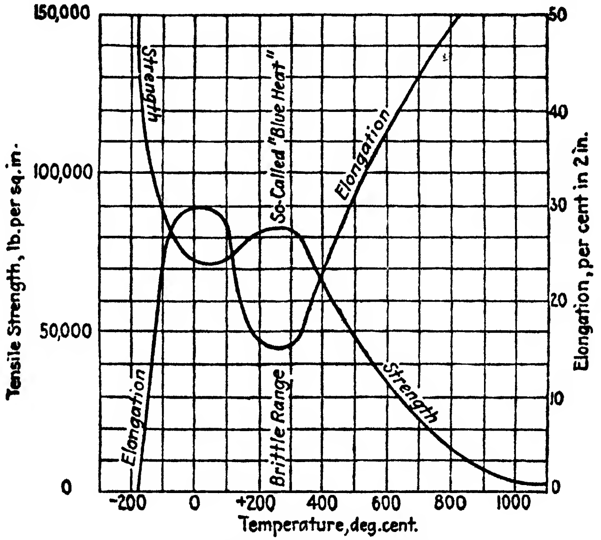


FIG. XIII-1.—Approximate tensile strength and elongation in 2 in. of structural steel at various temperatures from that of liquid air to the usual rolling temperatures.

Strength and Ductility of Steel at Various Temperatures.—Figure XIII-1 gives a general idea of the relative strength and ductility of steel at all temperatures from that of liquid air to that near the melting point. The characteristics of cold steel are important in the design of refrigerating machinery and the like, while the effect of temperatures from 200 to 700°C. influences the use of the material in boilers, pipes, and valves for superheated steam, in blades for steam turbines, in retorts for high temperatures and pressures, such as oil-cracking retorts, and in tie rods for boiler furnaces, etc. Finally, the resistance of steel to deformation at high temperatures is important in connection with exhaust valves for gas engines, and as indicating the amount of power to be expended in rolling and forging steel at temperatures from 700 to 1200°C. (1300 to 2200°F.). It will be observed in Fig. XIII-1 that an average steel is relatively very strong and brittle at the temperature of liquid air, but that both these properties decrease greatly to atmospheric temperature. Then both strength and brittleness increase again, reaching a maximum

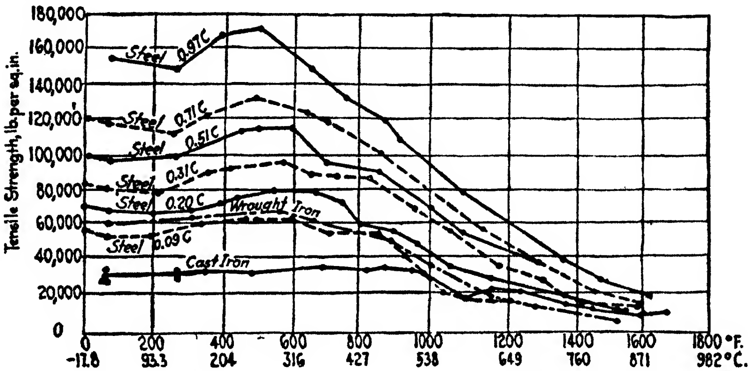


FIG. XIII-2.—Tensile strength of wrought iron and steel at different temperatures (Watertown Arsenal Tests of Metals, 1888). (*From Swain, "Structural Engineering," McGraw Book Company, Inc.*)

at about 260°C. (500°F.). This is called the "blue heat," because a blue oxide will cover steel if it be left a few minutes at this temperature. It is discussed again, for emphasis, in the next paragraph. From blue heat the strength falls off gradually, until it is very small at 1000°C. This portion of the scale is given more in detail, for several ferrous metals, in Fig. XIII-2.

Properties of Steel at Blue Heat.—The temperature of 260°C. (500°F.) has long been recognized as a critical heat for all the ferrous metals. Iron and steel must not be worked or strained at this temperature. They will crack even under light blows and their toughness and ductility are very low. The properties again improve as red heat is approached.

Impact Resistance of Steel.—The resistance of steel to shock decreases very much with lowered temperature, so that some steels are too brittle to use in impact service even in cold climates, although they would give satisfaction at all temperatures not far below freezing. At liquid-air temperatures, steel gives very low figures in impact tests; this improves to atmospheric temperature, then becomes much worse at blue heat, but recovers at higher temperatures, until finally the lessened strength of the metal results in lessened impact resistance also. In other words, it is lack of ductility (in this case, brittleness) which causes easy breaking under shock at very cold temperatures and at blue heat, but it is lack of strength at high temperatures.

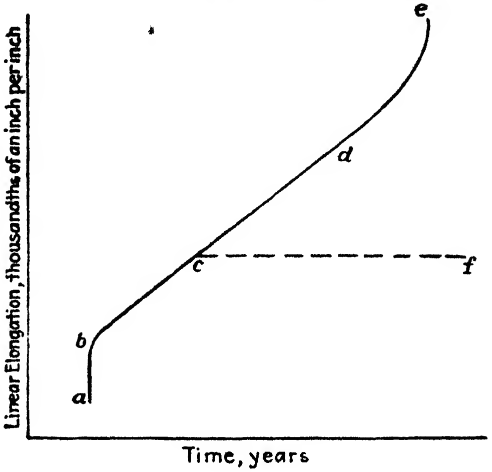


FIG. XIII-3.—Illustrating "creep" in metals.

Explanation: The vertical part of the curve, *ab*, which indicates elongation without the passage of any time, represents the elongation which occurs within the yield point of the metal when the load is first applied. The load is unvarying and continuous over a long period of time. During this passage of time, there is a slow stretching, or permanent elongation of the specimen. Should the deformation result in an increase in the yield point of the metallic body, so that it will no longer give to the strain, linear elongation will cease and the line *cf* will result. If not, then the stretching will continue until the specimen becomes so weakened by the deformation that the curve takes the shape indicated from *d* to *e*, and fracture occurs at *e*.

Creep.—If a very ductile metal or alloy be loaded very slightly beyond its true yield point, it will give slowly for a period of months or maybe years. This often continues to the point of fracture. This phenomenon has been studied in steels, alloy steels, "heat-resisting metals," nickel, light structural alloys, and many others. It is called "creep." It is most important at temperatures where the metal is more ductile and less strong, *e.g.*, 500°C. for steel. The action is illustrated graphically in Fig. XIII-3. One point is to be observed in this connection: To strain a metal beyond its yield point and then to allow it to rest results in what is called a "strain hardening," *i.e.*, an increase in the value of the yield point. The same action occurs in extremely slow straining, so that sometimes an alloy after months

	Fahr.	Cent.	Fahr.	
	2790	1535	2790	Approximate melting point of pure iron.
	2700		2700	Melting point of steels, depending on carbon and other contents which reduce the melting point as their percentage increases.
	2600	1426.5	2600	
	2500	1371	2500	
	2400	1315.5	2400	
	2300	1260	2300	Approximate melting point for Cast Iron.
White	2200	1204	2200	
	2100	1149	2100	Distortion of microscopic intergranular structure of rivets starts, resulting in intergranular rupture after driving.
	2000	1093	2000	Rivets start to spit.
Light Yellow	1975	1065.5	1950	**Do not exceed this temperature in heating rivets.**
	1900	1038	1900	
Lemon	1825			
	1800	982	1800	Proper temperature for driving rivets.
Orange	1725			
	1700	926	1700	
Salmon	1650			
	1600	872	1600	
Bright Red	1550		1550	Scaling starts.
	1500	816	1500	Range of temperatures for refining grey iron castings into malleable iron castings.
	1400	760	1400	
Cherry Red	1375		1350	Approximate critical temperature of tool steels. Colour brightens when cooling past this temperature and expansion takes place. A magnet reacts below but not at or above this temperature.
	1300	704	1300	Heat above here for quenching treatment.
Medium Cherry	1250			
	1200	648.5	1200	
Dark Cherry	1175			
	1100	593	1100	
Blood Red	1050			
	1000	537.8	1000	Maximum temperature at which fireproofed structural steel may carry A. I. S. C. designing stresses. **Do not use gun on Rivet below this temperature.**
Dark Red	900	482.2	900	
	800	426.7	800	Ultimate Strength approximately equal to normal temperature strength of structural grade steel.
	700	371.1	700	At this temperature steel is in brittle condition. Ultimate Strength is 25% to 30% greater than normal temperature strength of structural grade steel.
Blue Heat	600	315.6	600	
	500		500	
	400	204.4	400	
	300		300	
		100	212	
	200	93.3	200	Do no calking above this temperature.
	100	37.8	100	
	32	0	32	

The above data are taken, with slight changes, from a compilation of the American Institute of Steel Construction for the purpose of summarizing the practical application of some effects of different temperatures on structural steel.

of creep will become strengthened by the operation to the point where it will no longer yield to the strain. This is indicated in the line *cf* in Fig. XIII-3.

Heat-resisting Alloys.—A heat-resisting alloy is one that will not be seriously injured by medium-high temperature; *i.e.*, it will not lose much strength or ductility or be badly scaled. Most of these are in the domain of alloy steels, but some nonferrous alloys, like nichrome, are giving good service, especially for resistance to scaling.

2. Formation of Oxide Scale

For thousands of years the color of the oxide coating which formed on steel at certain moderately warm temperatures has been used as a means of "tempering" its hardness after quenching from above its so-called "critical temperature," which, we have already noted, occurs around 700°C. (about 1300°F.). This is shown in Table XIII-I.[1] An oxide coating has also been artificially produced for an unknown number of centuries in order to afford a slight protection to wrought iron and/or steel to rusting. The oxide scale is somewhat similar to rust in its chemical composition but differs chiefly in this respect: Rust, being permeable to the atmosphere, actually promotes rusting by its chemical effect, whereas a firm, continuous, impervious layer of oxide will protect the metal lying underneath it against rusting conditions which are not too severe.

3 and 4. Grain Growth

Grain growth is caused by the elimination of grain boundaries and the merging of two or more grains into one large grain. Some grains grow to large size in a few minutes, and others require months. Everything else being equal, the larger the grains in a metallic body, the worse will be its strength and ductility. Therefore, large grains are dreaded in all metals, but especially in steel, because this is used so much more for structural purposes. The growth of grains has been employed intentionally for the purpose of obtaining single crystals of large size for research purposes. The most effective growth is obtained by repeatedly straining a metal and heating it to its grain-growth temperature between each strain.

Grain Growth in Pure Iron, Wrought Iron, and Very Low-carbon Steel.—The iron-carbon alloys which are very low in

---

[1] See p. 438.

carbon are subject to grain growth at temperatures between about 500 and 850°C. (932 to 1562°F.). This is a very slow growth, requiring weeks or months, but is hastened by repeated strains. It is therefore to be feared in iron chain which is used in hot places, wrought-iron tie rods in furnaces, etc. Grains of this type sometimes grow as large as one's thumbnail. The action is not to be expected in steels with more than 0.12 per cent of carbon. The grains are restored to small size by heating to about 900°C. (1652°F.).

This same steel is subject to another temperature field of grain growth, *viz.*, if it be heated to temperatures between 900 and 1500°C. (1652 to 2732°F.). The action here is much more rapid, and grains may grow to large size in 10 to 30 min. at temperatures around 1300°C. The smallest size is obtained around 900°C.; a slightly larger size is normal at 1000°, still larger at 1100°, and so on. At temperatures above 900°, the size of the grains will depend on the temperature reached and the time of sojourn at that temperature.

Grain Growth in All Steels.—Steels of any proportion of carbon suffer grain growth in consequence of being heated above 700°C. (about 1300°F.). Steels with 0.85 per cent of carbon are the simplest to discuss and will be chosen for this brief summary: This steel, when heated to 700°C., is just at the point of the V in Fig. XI-8. At this temperature it assumes the smallest grain size which can be given to it by heat treatment. The more steel is heated above that temperature, the more the grain will grow in size. This is shown to the eye by Fig. XIII-10. This figure was produced as follows: A bar of steel containing 0.85 per cent of carbon, and about 12 in. long, was heated at one end to a temperature of 1300°C. (2372°F.), while the other end projected from the furnace and was black hot. After cooling, the bar was broken at every inch of its length, and the fractures so made showed the grain size corresponding to the temperature to which it had been exposed. The fractures shown in Fig. XIII-10 represent all those from the hot end to a point just below 700°C. The piece at the extreme right shows the fracture of the steel just as it came from the rolls, while the piece next to it shows the beneficial effect on the grain size of heating just above the critical temperature. The coarse fractures at the left are bright, while the fine fractures are dull looking. The bright fracture is technically called "crystalline" or "fiery," while

Fig. XIII-4.—No. 1*A*. Steel of 0.05 per cent carbon rolled. 40 ×.

Fig. XIII-5.—No. 2*A*. Same as No. 1*A*. Overheated to 1420°C. (2588°F.) 60 ×.

Fig. XIII-6.—No. 3*A*. Same as No. 2*A*. Reheated slightly above AC_3. 40 ×.

Fig. XIII-7.—No. 1*B*. Steel of 0.50 per cent carbon rolled. 60 ×.

Fig. XIII-8.—No. 2*B*. Same as No. 1*B*. Overheated to 1420°C. (2588°F.) 60 ×.

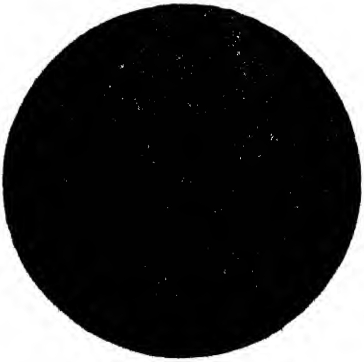


Fig. XIII-9.—No. 3*B*. Same as No. 2*B*. Reheated slightly above AC_{1-3}. 60 ×.

(Series *A* by F. C. Wallower in the Metallographic Laboratory of Columbia University, Department of Metallurgy. Series *B* by G. Rocour in the Metallographic Laboratory of Columbia University, Department of Metallurgy.)

the fine-grained one is called "silky" or "sappy." The size of the crystals may also be learned with great accuracy by means of the microscope (see Figs. XIII-4 to XIII-9). Now, if the steel which was coarse grained after heating to 1100° be heated instead to 1200°, the crystals will be still larger in size; if heated to 1300° they will be larger still, and so on. The size of the crystals will depend, first, upon which of these high temperatures it was heated to, and, second, upon the amount of carbon it contains. Low-carbon steel is normally larger in crystal size than high-carbon steel, as shown in Figs. XIII-4 and XIII-7.

Even the best quality of steel, if rendered coarse grained by "overheating," will suffer in its valuable properties and may become quite unfit for use. Medium- and high-carbon steel will lose both strength and ductility; low-carbon steel will lose strength even up to 50 per cent of the original but does not seem to be materially damaged in ductility unless the overheating is continued for a long time or at a very high temperature.

Steel members of bridges or other structures sometimes break and disclose a crystalline fracture which is often attributed to the effect of vibration. The same thing occurs with points or shanks of rock drills and similar implements. It is the more general opinion among metallurgists that the crystalline fracture in all these cases is due to faulty heat treatment during manufacture, and especially to finishing the forging or rolling while the temperature is still too high. The manufacturers of steel like to maintain the opposite opinion, for obvious reasons, but the author does not know of there ever having been any reliable proof offered that vibration had caused, or is capable of causing, large-sized grain in steel. It may be possible, but the more we learn about the subject the more we are inclined to believe that improper manufacture is the cause, and that the grain was large before the steel was put in service, although its nature was not disclosed until the break occurred.

Cure for Overheating.—Let our first example be steel containing 0.85 per cent carbon, *i.e.*, steel consisting entirely of pearlite. If this be heated from some point below the line *PSK* in Fig. XI-9 to some point above that line, a new crystallization will occur and will largely obliterate previous crystallization. It seems as if dissolving the ferrite and cementite in each other produces forces which obliterate almost all existing crystalline forms. So if this particular steel has been made coarse grained by overheating, we may make that grain fine again by reheating the steel from below the line *PSK* to just above it. This process is known as "restoring" or, by some writers, "refining" the steel. It is an operation which should be thoroughly understood by every metallurgist and engineer. When we reheat the steel, we must be careful not to go to a high temperature again, for a new crystal size is born at the line *PSK*, and the crystals grow with every increase in temperature. The researches of Professors Howe and Sauveur indicate that the size of the crystals is almost directly proportional to the temperature reached above the line *PSK*. If, therefore, we barely cross the line, we shall obtain the smallest grain size that the steel is capable of (see Fig. XIII-10).

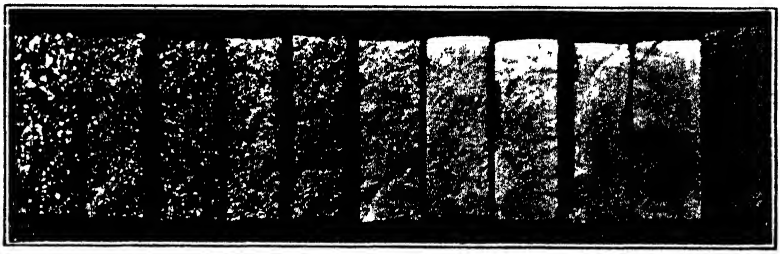


FIG. XIII-10.—Metcalf test. Fractures of steel of 1 per cent of carbon. (*Courtesy of William Campbell*.)

The cure for coarse crystallization in steel with less than 0.85 per cent carbon is to reheat it from below the line *PSK* to above the line *GOS*, at which the last of the ferrite goes into solution (see Figs. XIII-7 and XIII-9). That is to say, the correct temperature for restoring the grain size will depend upon the amount of carbon in the steel; low-carbon steel must be heated to nearly 900°C. (1,650°F.); 0.4 per cent carbon steel must be heated to nearly 800°C. (1,470°F.); and so on.[1] We can never get as small a grain size in steel with less than 0.85 per cent carbon as we can in that which is exactly 0.85 per cent carbon, because a new grain size begins to grow (in that part of the steel which forms a solid solution at *PSK*) after we have crossed the line *PSK*, and yet we cannot entirely eliminate the old grain size until we cross the line *GOS*. Where the lines *GOS* and *PSK* are near together (say, with 0.7 per cent carbon), the new grain size does not have much chance to grow before the restoration

---

[1] It is to be remembered that the changes indicated by the lines in Fig. XI-8 occur at a higher temperature on heating than on cooling; so it is well to heat the steel about 25°C. higher than the points on those lines.

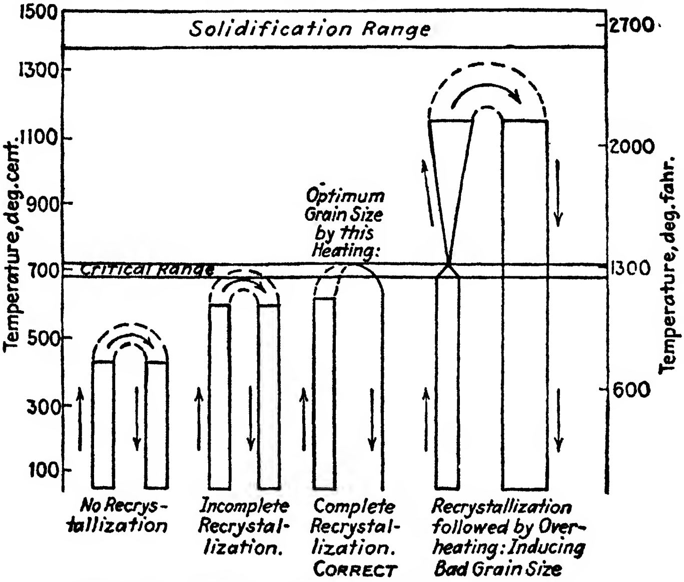
is complete, and therefore we may obtain steel with a rather small grain; but where they are far apart (as in the low-carbon steels), the restoration can never be very thorough, because we have to go so far above *PSK* to obliterate the old grain size that the new grain size will have attained ample proportions. But the evidence seems to show that the best net result is obtained by going just above the line *GOS* in all cases.

In the case of steel with more than 0.85 per cent of carbon a somewhat similar condition exists: We must reheat the steel above the line *SE* in order to produce complete elimination of the previous grain size but a new grain size begins to grow from the crossing of the line *PSK*. But here we disregard the line *SE* and restore our steels in every case by reheating them over the line *PSK*, just as in the case of pure pearlite. The reason for this is that the lines *SE* and *PSK* diverge so rapidly that we have to heat very far above the line *PSK* before we cross *SE*, and therefore the new grain size has grown greatly. Furthermore, the only object of heating above the line *SE* is to take the excess cementite into solution; for the ferrite and cementite in the pearlite all went into solution as soon as we crossed the line *PSK*, but the amount of excess cementite is always small in proportion and therefore in its influence on restoration. Even with steel containing 2 per cent of carbon the excess cementite is only 16 per cent. This is different from the low-carbon steels, where the excess ferrite will be usually over 80 per cent.

It is emphasized that steel must be *heated* to the appropriate temperature, because the result cannot be produced by cooling to the temperature. Once steel has acquired a coarse grain structure, it will remain coarse until *heated* through the critical temperature. This is illustrated in Fig. XIII-11.

Recrystallization of Steel.—The recrystallization temperatures for steel are at and above 700°C. (about 1300°F.), *i.e.*, above the line *PSK* in Fig. XI-9. The steel containing exactly 0.85 per cent carbon recrystallizes just at the point *S*; the steels with lower carbon recrystallize between the lines *PS* and *GS*, while the higher carbon steels recrystallize between the lines *SK* and *SE*. Since the steel with 0.85 per cent carbon is the simplest, its grain growth and recrystallization will be illustrated in Figs. XIII-11 and XIII-12.

Effect of Mechanical Work on Grain Structure.—With steel of 0.85 per cent carbon as an example, the effect of rolling at high temperatures on grain size is illustrated in Fig. XIII-12. It is seen that the grain size of the steel becomes somewhat large by heating to 1100°C. (2012°F.) for rolling or forging. But the mechanical work crushes the grains to smaller size, and this crushing is repeated until the final shape of steel is produced. The best grain size is obtained if the steel is worked until the temperature drops to 700°C. Then the grain size may be even smaller than can be obtained by mere heating to the recrystallization temperature. Moreover, the grain size remains small unless the steel is heated above 700°C. If, however, the mechanical work is stopped at a temperature well above 700°C., then the grain size grows in a few minutes to a size appropriate to the temperature. The higher that temperature happens to be above 700°C., the worse the grain size will be (see Figs. IX-8 and IX-9).



NOTE: Abscissae Width of Rectangles Represents Size of Grain

FIG. XIII-11.—Correct and incorrect heatings to produce recrystallization and optimum grain size in steel of 0.85 per cent of carbon.

NOTE: There is no reduction in grain size unless the steel is heated quite *through* the critical range, which is at about 700°C (1292°F.). Also note that heating above the critical range causes a harmful growth in grain size, which is not reduced when the steel cools.

Several rules affecting the final size of grain seem to be virtually established: (1) It is more advantageous to have the mechanical work applied continuously from the highest temperature employed down to the finishing temperature rather than to have long waits during which the steel cools; and especially is this true when the amount of work put upon the metal at the lower temperature is small. In other words, if the steel is formed roughly to shape and size at a high heat, is then allowed to cool, and a little work is done upon it at the lower temperature, the grain

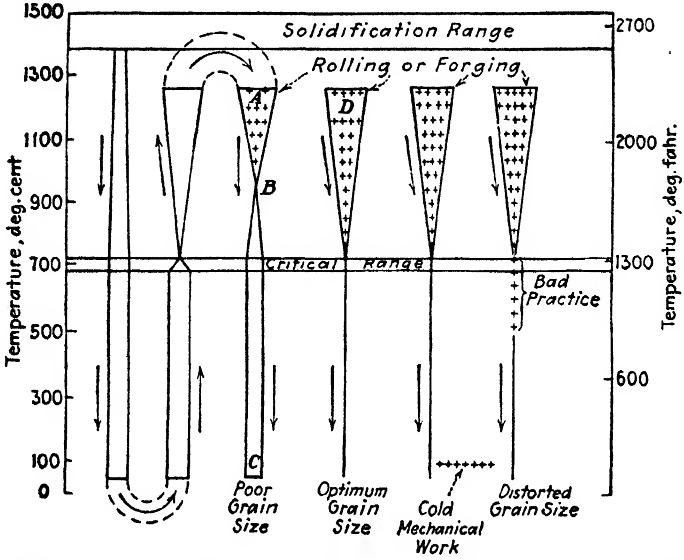


FIG. XIII-12.—Grain growth, recrystallization, and grain reduction in steel of 0.85 per cent of carbon.

Explanation: When steel freezes, crystals form during the crystallization range (see diagram at left side). After solidification, these crystals increase in size as they cool through the so-called "zone of grain growth," and then reach the critical range at about 700°C. (1292°F.). There can be no change in grain size in cooling from the critical range to atmospheric temperature. But, if the steel is reheated, it "recrystallizes" on *heating through* the critical range. On heating through this range, the crystals of iron and those of cementite dissolve in one another and form a solid solution. The act of forming this solid solution causes the grain size to assume a minimum. This is illustrated in the second column from the left. Further heating engenders a growth in grain size. The grains grow in proportion to the temperature to which they are heated above the critical temperature (note this relation carefully), and in accordance with the length of time during which they are held at the high temperature. Cooling will *not* make the grain size smaller, but mechanical work will do so.

If the steel is forged or rolled at the high temperature, the crystals will be broken up, but, if the work is stopped at some intermediate temperature, such as *B*, the crystals will grow again in size from *B* to the critical temperature. This will leave them with a bad size. But, if mechanical work is continued to the critical temperature, there can be no more grain growth, and the steel is left with the optimum grain size. See *D*.

If steel is to be cold rolled, it must cool from the critical temperature to atmospheric temperature between workings: it is bad practice to work steel between 700 and 200°C.

will not be its best. (2) It is best for the metal to be worked by several passes through the rolls, or many blows of the hammer, rather than to effect the same amount of reduction by a lesser number of heavy drafts. (3) The greater the amount of reduction the better; *i.e.*, to work a large piece down to the desired article gives a better structure. (4) The best temperature at which to finish the work is probably upon, or slightly below, the lines *GOS* or *SK* in Fig. XI-9.

Action in Rolling.—The exact crystalline action that takes place under mechanical treatment is not definitely known. In the case of rolling, Professor Howe has tentatively assumed the conditions graphically shown in Fig. XIII-13, in which the line *DG* represents the size of grain at the different temperatures. At 1400°C. (2550°F.) the grain size is represented by the distance of the line from the axis *OO*. On the first passage through the rolls the grains are crushed to a very small size, but on emerging again they grow very rapidly. Meanwhile, however, the metal has been cooled, and this fact, as well as the inability of the grains

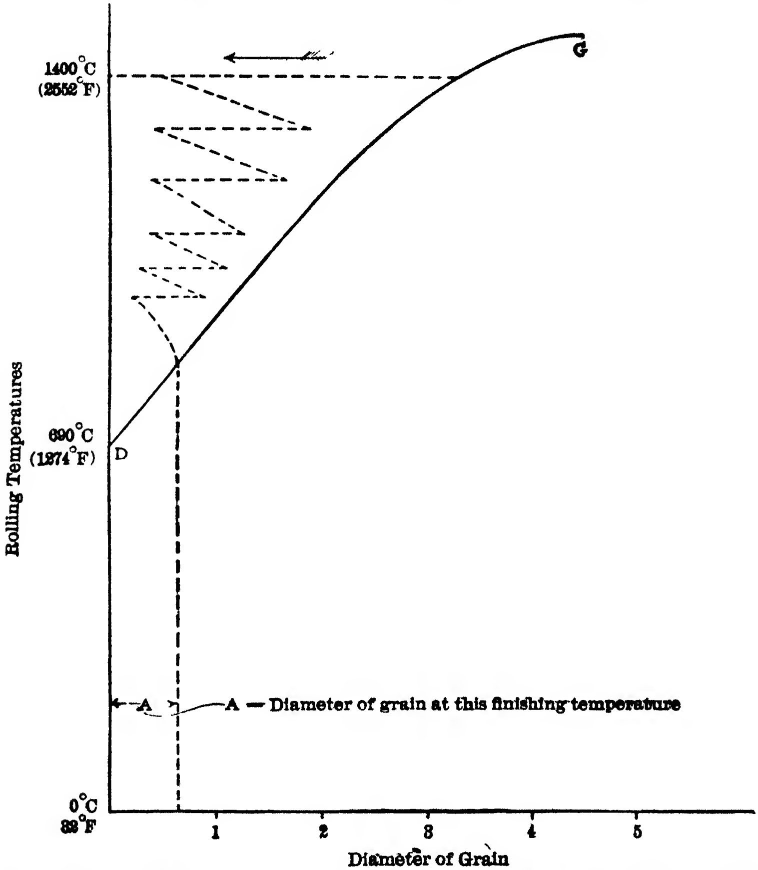


FIG. XIII-13.—Size of grain in metals as affected by pressure in rolling. (*From Howe, "Iron, Steel and Other Alloys."*)

to grow instantly, causes the new size of grain to be smaller than before. Therefore, each passage through the rolls renders the crystals smaller in size, the final size depending upon the temperature and the amount of pressure in the last pass. The only abnormal assumption in this argument is that the crystals grow rapidly after the crushing, whereas we know that, when steel is heated to any of these high temperatures, the growth is relatively slow. This objection is not strong enough alone to refute the theory, but other hypotheses may be advanced for those who require further explanation. For example, it may be supposed that the steel is so mobile at the very high temperatures that it yields to distortion, not altogether by the crushing of the crystals, but by the sliding of the crystals past one another; as the temperature becomes lower, however, the mobility of the mass becomes less, and less sliding is possible, so that more crushing of the crystals takes place.

Finishing Temperatures.—William Campbell has studied the finishing temperature of steel containing 0.5 per cent carbon and finds that the very best qualities are produced in the steel if mechanical work is ended just at the time when ferrite begins to separate from solid solution, *i.e.*, just when the steel is below the line *GOS* in Fig. XI-9. Work below that temperature greatly increases the brittleness of the material, while finishing the work at a higher heat results in lower strength. Upon the evidence at hand, we may tentatively assume like conditions for steels of any carbon and expect the best results if mechanical work is ended when the steel is at a temperature which brings it exactly upon the line *GOS* or *SK*, but we may reserve, perhaps, the right to change this statement slightly when more data are obtained.

Hammer Welding.—This brings us to the subject of forge welding, or the joining of two pieces of wrought iron or steel by pressing or hammering them together while at a very high temperature. In this way a joint may be made which cannot be seen by the eye unless the steel is polished and etched with acid, which usually develops the junction line very clearly. The exact temperature of welding is not known, but probably it is very near the melting point, where the steel is in a soft and almost pasty condition. Low-carbon steel welds most easily; moreover, all impurities, especially silicon and sulphur, reduce weldability. The procedure in welding is very simple and consists in heating the two pieces that are to be welded to a high temperature, dissolving off the iron oxide, and then pressing the two pieces together forcibly. The dissolving off of the oxide is usually accomplished by rubbing the metal in some flux, such as borax.

In the actual manipulation for welding, the two pieces that are to be joined together are usually "upset," or in some way enlarged in size, so that, after the junction, the part of the bar right at the weld is larger in size than the remainder. This part is then hammered continuously until the metal is at a red heat, the object being to break up the coarse crystals produced by the high temperature and, by having a low "finishing temperature," to obtain a small grain size. With proper welding this object will be attained as far as the metal immediately adjacent to the weld is concerned, but there is always a spot within 6 in. or so of the weld which must necessarily have been overheated without subsequently receiving mechanical treatment, *i.e.*, "hammer refining," down to the proper finishing temperature. Thus it is that most welded pieces break at a point not far from the junction and under a strain less than the original strength of the bar. Blacksmiths and experienced welders are wont to declare that if a welded bar does not break in the weld itself, then it must be as strong as the original metal. However, this is by no means true. In a welding test carried on with great care in this country by skillful and experienced welders who were placed upon their mettle, the strength and elastic limit of the welded bar was almost never as great as in the original bar and in some cases was less than half. In ductility even worse results were obtained. In a similar test carried on at the Royal Prussian Testing Institute the average strength of welded bars of medium steel was only 58 per cent of the original, that of softer steel only 71 per cent, and of puddled iron only 81 per cent, while the poorest results were only 23, 33, and 62 per cent respectively. It was seen that bad crystallization adjacent to the weld was the cause of the damage.

Welded steel and iron bars should therefore always be reheated after cooling to a temperature just above the line *GOS*, in order to restore by heating the grain size of all parts.

Burning.—In the vernacular of the trade, all overheated steel is termed "burnt," but this is not correct usage, because true burning takes place only when the overheating is most abusive, and, indeed, when the metal is heated almost to its melting point. It is probable that steel is burnt when it is heated close to the line *AE* in Fig. XI-9. Alfred Stansfield has studied this question very ably and distinguishes three stages of burning. The first stage is reached when the steel barely crosses the line *AE, i.e.*, when the first drops of melted metal begin to form in the interior of the mass. They segregate to the joints between the crystals and cause weakness. Stansfield thinks that steel burned only to this stage may be restored by reheating it first to a high temperature, cooling, and then heating again to a temperature just above the lines *GOSK*. The second stage in burning is reached when these liquid drops segregate as far as the exterior and leave behind a cavity filled with gas. Stansfield thinks that steel burned to this stage might be restored by combined reheating and forging. As a matter of safety, however, the author believes it would be well to remelt all such material, in other words, send it to the scrap pile. The third and last stage of burning is reached when gas collects in the interior of the metal under sufficient pressure to break through the skin and project liquid steel, which produces the well-known scintillating effect at this temperature. Into the openings formed by these minute explosions air enters and oxidizes the interior. There can be no remedying of steel which has been burned to this extent, except remelting.

Castings Do Not Burn.—It might be thought that every steel casting would suffer the injuries due to burning because it is cooled through the space between the lines *AB* and *AE*. Such injury, however, does not ordinarily take place, and this fortunate circumstance is explained in part by each of three differences existing between the heating and cooling of steel: (1) When steel is heated into the area where burning takes place, it is subjected longer to the burning temperature, because it generally takes longer to heat steel than to cool it. (2) When steel is being heated, the heat is traveling inward from the outside, and therefore all parts are expanding, and there is some opportunity for the crystals to draw apart and form cavities. On the other hand, when it is cooling from the molten state, the outside layers are the cooler and tend to contract upon the interior and hold the crystals more firmly together, as well as to prevent drops oozing out. (3) When steel is cooling from a molten state, it is constantly giving off from solution hydrogen and other deoxidizing gases which are soluble in it while liquid, and these gases prevent the oxidation of the crystal faces by the percolation of air into the interior.

Ingotism.—The author has already discussed ingotism and said that the crystals in cast steel are larger than those of rolled steel, owing to growth while the metal is at a high temperature, and has stated that sometimes these crystals are very large, because the conditions of casting cause the steel to occupy a longer time in cooling from the liquid state down to a black heat. It is probable that ingots and castings do not show the effects of ingotism to any marked extent unless they are a long time above 1100°C. (2010°F.). In case these coarse crystals do form, they may be restored to some extent by reheating the casting to a point just above the line *GOS*.

Stead's Brittleness.—In addition to the damage caused by overheating, steel very low in carbon (say under 0.15 per cent) is subject to another and peculiar danger; for if this soft steel be held for a very long time at temperatures between 500 and 750°C. (930 and 1380°F.), the crystals become enormous and the steel loses a large part of its strength and ductility. Fortunately it takes a very long time—in fact days—to produce this effect to any alarming degree, so that it is not liable to occur, even through carelessness, during manufacture or mechanical treatment. But steel is sometimes placed in positions where it may suffer this injury, *e.g.*, in the case of the tie rods of furnaces, supports for boilers, etc., so that the danger should be borne in mind by all engineers and users of steel. The author recalls an instance where the breaking of a piece of chain that supported one side of a 50-ton open-hearth ladle caused a loss of life under the most horrifying conditions, owing to the fact that the wrought-iron chain had been heated up many times to a temperature above 500°C. (930°F.) and had finally reached a condition of coarse crystallization, so that it was unable to bear the strain upon it when the ladle was full of metal.

This phenomenon of coarse crystallization in low-carbon steel is known as "Stead's brittleness," after J. E. Stead, who has explained its cause. The effect seems to begin at a temperature of about 500°C. and proceeds more and more rapidly with an increase in temperature until we reach 750°C., above which no growth seems to take place. The damage may be repaired completely by heating the steel just above the line *GO*. In other words, the remedy for coarse crystallization in this case is the same as that for coarse crystallization due to overheating, and all steel which is placed in positions where it is liable to reach these temperatures frequently should be restored at intervals of a week or a month, or as often as may be necessary.

Zones of Grain Formation.—When steel solidifies, it forms crystals. The more the carbon, the longer the range of temperature during which crystals are successively being borne out of the liquid mass, as already described. These crystals grow in long dendrites perpendicular to the cooling surface, as shown in Figs. XIII-14 and XIII-15. One of the chief purposes of forging or rolling is to distribute this dendritic structure in order to improve the properties of the steel. The zone of temperature and carbon content during which this crystallization occurs is shown in Fig. XIII-16, which is seen to be a part of the equilibrium diagram. This zone is called "the zone of primary crystallization." In it solid solutions form from liquid solutions. The solid solutions subsequently cool through the next zone, which is called "the zone of granulation." In this zone the dendrites break down into a number of smaller grains. The

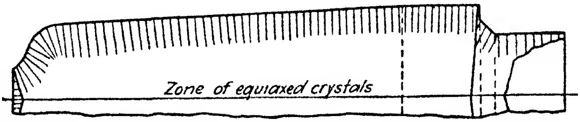


FIG. XIII-14.—Longitudinal section of steel ingot, showing location of dendritic crystals.

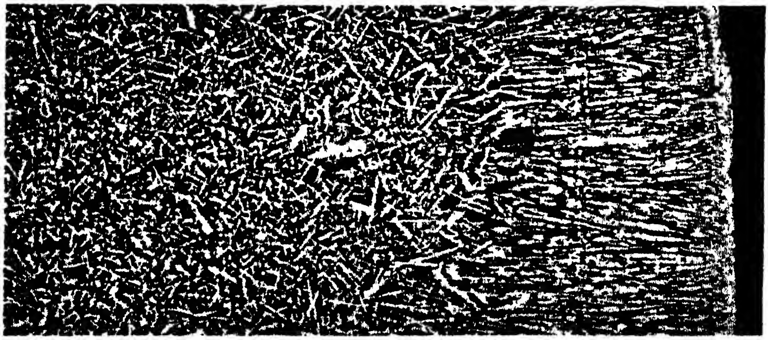


FIG. XIII-15.—Dendritic structure in steel. (*From Vsevolod N. Krivobok through Metal Progress.*)

Structure, one-third, of a 24-in. round ingot of steel for seamless tubing. Ingot cut off square, smoothed, and etched. Composition: carbon, 0.44; manganese, 0.75; silicon, 0.15, phosphorus, 0.04, sulphur, 0.04. Horizontal section.

dendrites disappear; nevertheless we can reveal their original structure by etching, because their boundaries are marked by metal which, on account of selective freezing (*i.e.*, segregation), reacts differently to etchants than do the grains into which the dendrites have transformed. Below the zone of granulation occur two zones of "secondary crystallization," *i.e.*, zones in which the solid solutions begin to decompose.

Widmanstaetten Structure.—The zones of secondary crystallization are those regions in which crystals of Fe ("ferrite") or else of Fe_3C ("cementite") are being precipitated out of solid solutions (see zones below the lines *EGI* and *DI* in Fig. XIII-16). In other words, they are the zones in which the solid solutions are dropping out either ferrite or cementite, as the case may be, in order that the solid solution in question may preserve its solubility until it comes automatically and simultaneously to a composition of 0.85 per cent of carbon and a temperature of approximately 700°C. The grains of solid solution have an octahedral crystal habit and tend to precipitate out their excess constituent along their octahedral planes. For a steel which has cooled through the secondary crystallization zone below the line *EGI*, this structure is illustrated in Figs. XIII-17 and XIII-18. This type of structure is observed in very slowly cooled steel, such as the interior of steel castings and of meteorites, and is named after Widmanstaetten, who first observed it in meteorites. It results in a metal which yields rather easily to distortion under stress; its strength is therefore lower than that of the same type of steel with different structure. It forms slip planes easily but these slip planes develop comparatively quickly into fractures, so that its ductility is not very good. This type of structure can be

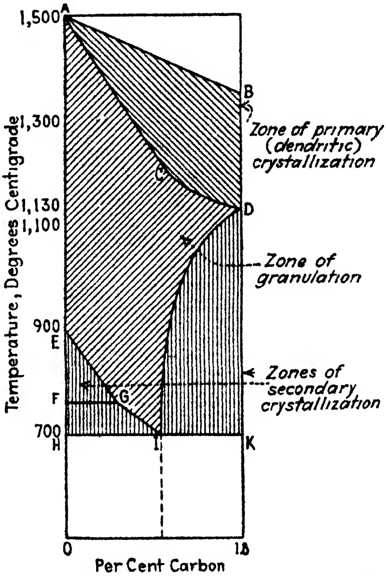


FIG. XIII-16.—Part of iron-carbon diagram showing the three zones of structural changes occurring in dendrites according to Belaiew.

remedied, although not entirely cured, by heating well up into the zone of granulation and absorbing all the excess ferrite into a

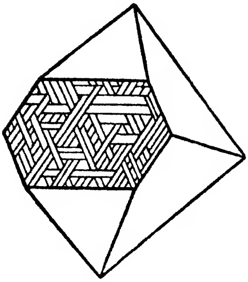


Fig. XIII-17a —Section parallel to the surface of a dodecahedron. 20 ×. (Tschermak.)

Fig. XIII-17b —Steel. Carbon 0.55 per cent. Section parallel face of a dodecahedron 20 ×. (Belaiew.)

Fig. XIII-18.—Steel. Carbon 0.55 per cent. Widmanstaetten structure. 4 ×. (Belaiew.) (*From Sauveur.*)

solid solution, and then cooling rather quickly through the zone of secondary crystallization. Usually this treatment is repeated at least once. Steel which cools through the secondary crystallization zone where cementite is the excess constituent will have a structure in which cementite needles are distributed along the original octahedral planes of the solid solution grains, somewhat as shown in Fig. XIII-19. These cementite needles cause comparatively easy breaking of the steel under stress. A more or less complete remedying of this structure is obtained by "spheroidizing" the cementite needles into quasi-globules by long-continued heating in the neighborhood of 700°C.

5. HARDENING OF STEEL BY QUENCHING

If steel be raised to a bright-red heat and then rapidly cooled, as, for example, by plunging it into water, it becomes very much harder and at the same time stronger and more brittle. One circumstance is absolutely necessary to produce the increase in hardness, *viz.*, that the temperature from which rapid cooling takes place shall be above the critical temperature of the steel. Take, for example, steel containing 0.85 per cent carbon; we may heat this ever so little below the point *S* in Fig. XI-9 and no increase in hardness will take place, even though we cool with extreme rapidity. On the other hand, if we cool the same steel rapidly from ever so little above the point *S*, it will be hard enough to scratch glass and brittle enough to fly into pieces under a blow of the hammer. This is the maximum practical hardness which can be obtained in this steel, for, if we quench it at a higher temperature, the only result of importance is to damage it by increase in grain size. In case we have less than 0.85 per cent carbon in our steel, the best temperature for hardening is just above the line *GOS*, because that gives the maximum hardness and also the best grain size. The best temperature from which to harden steel with more than 0.85 per cent carbon is just above the line *SK*, because that gives the best grain structure.

FIG. XIII-19.—Cementite needles precipitated in the zone of secondary crystallization. (*From H. M. Howe.*)

Carbon and Hardness.—The hardness of slowly cooled steel increases with every increase of carbon. Some carbon is also necessary if rapid cooling is to have a very important effect. Although iron free from carbon is hardened by rapidly cooling from above the point Ac_2 (760°C., 1400°F.), and a little more so when rapidly cooled from above Ac_3 (900°C., 1650°F.), yet this degree of hardness is so slight as to be perceptible only by means of laboratory tests. With 0.10 per cent carbon the hardness begins to be perceptible by crude tests (see Table I-I), but it is only when we get above 0.75 per cent of carbon that ordinary steel acquires sufficient hardness to be used commercially, *e.g.*, for springs, saws, etc. Metal-cutting tools are usually made of steel containing 1 per cent or so of carbon, while very hard implements, such as files, will contain 1.5 per cent or slightly more (see Table XII-II).

Rate of Cooling and Hardness.—The degree of hardness of steel also varies with the speed of cooling from above the critical range of temperature. When the cooling is very slow, *e.g.*, when it takes several days to cool, the steel will be as soft as it is possible to make it. When it is cooled by being taken out of the furnace and suspended in the air or thrown upon a sand floor, it will still be relatively soft. When cooling is still more rapid, *e.g.*, when it is taken out of the furnace at a bright-red heat and plunged into a heavy oil with a low conducting power for heat, it becomes quite hard and springy, provided its carbon is in the neighborhood of 0.8 per cent or above. Quenching in a thin oil from the same temperature makes it still harder. Quenching in water makes it harder still, and so on, the degree of hardness increasing as we quench in liquids which take the heat away from it faster and faster, such as ice water, ice brine, ice-sodium chloride solution, and mercury near its freezing point (−39°C., −38°F.).

What Happens When Steel Is Cooled Rapidly from above Its Critical Temperature?—When steel is at a temperature above approximately 700°C., it is composed partly or wholly of solid solution, depending on whether it contains less than, more than, or exactly 0.85 per cent carbon, and depending on how much above 700° the temperature is. This solid solution is called *austenite*, irrespective of how much or how little carbon it contains in the dissolved state. When austenite cools slowly, it completely decomposes into ferrite and cementite at about 700°. But, if the carbon in solution is near the maximum normal limit for austenite—say, it is 1.50 or 1.60 per cent—and if the cooling is rapid from 1100°C. or higher, the steel can be cooled to the atmospheric temperature with some austenite still undecomposed. A micrograph showing this is seen in Fig. XIII-20. No cooling has ever been accomplished rapidly enough to bring wholly undecomposed austenite to atmospheric temperature, but at least a part of it is always broken down, even when cooling is rapid, into a first decomposition product to which the name of *martensite* is given. This martensite is the hardest constituent of steel obtainable, next to cementite, which is the extreme. It is comparatively easy to quench steel with carbon of any composition from 0.50 to 1.7 per cent so that it shall consist entirely of martensite at atmospheric temperature. But that variety of martensite which contains 0.85 per cent carbon is the hardest martensite there is, not including martensite in alloy steels. It is the hardness of martensite which most serves civilization in cutting tools. Martensite is harder than austenite; therefore, if we have quenched steel so that it consists partly of austenite, we can increase its hardness by warming it to the point where

FIG. XIII-20.—Martensite (dark) in austenite (white). 1400×. (*Micrograph by F. F. Lucas, Trans. Am. Soc. Steel Treaters, September, 1924*.)

this austenite will decompose into martensite. Martensite is too brittle to be used for lathe-cutting tools or for swords or other implements which must bend without breaking. Therefore, it must be "tempered" to reduce its brittleness. After martensite has been produced and tempered, it will remain for thousands of years without further softening. A piece of steel hardened three thousand years ago was found in the pyramid of Cheops with as much hardness as it apparently had originally. It is in the British Museum.

Fig. XIII-21.—High carbon alloy quenched from the cementite secondary crystallization zone. 3500 ×. (*Micrograph by Roy M. Allen.*)

At What Temperature Does Austenite Change to Martensite?—When austenite is rapidly cooled, it passes through the critical range without decomposing but changes over to martensite at about 325°C. on rapid cooling. On the other hand, if we have a steel like that shown in Figs. XIII-20 and XIII-21, we can warm it to 200°C. and change it into all martensite. It is interesting to note that the change occurs along the octahedral planes, giving martensite a triangular type of structure (see Fig. XIII-22).

Critical Hardening Speed.—Every steel has what is called its critical hardening speed. We may take this to be the speed at which steel should be cooled from the critical temperature—about 700°C. or above—to below 325°C. to produce the maximum amount of martensite. If cooled too fast, some austenite may be present; if too slowly, martensite may have partly broken down into softer constituents, which are known as troostite and sorbite.

FIG. XIII-22—Martensitic structure. 1500×. (*Micrograph by F F Lucas.*)

The Nature of Martensite.—Obviously a beginning can be made in explaining the hardness of rapidly cooled steel if we can explain the hardness of martensite. Various theories for the hardness of steel have been offered during the past several thousands of years and have been accepted temporarily, only to fall when further knowledge has shown their inadequacy. It is now known that austenite is a solid solution of carbon, or else cementite,[1] in gamma iron. It has a face-centered space lattice and is

---

[1] We believe that the solid solution consists of cementite dissolved in gamma iron, but there is a small number of very able metallurgists who hold the view that carbon is present as elemental carbon and that it forms cementite, immediately after its separation. While admitting the force of the arguments advanced by these metallurgists, we shall, for simplicity, speak hereafter of the solid solution of iron and carbide.

nonmagnetic. Martensite is intermediate in magnetism between austenite and pearlite; it has been shown to contain some face-centered and some body-centered space lattices and to consist therefore of partly gamma and partly alpha iron. Its microstructure shows that it is not a homogeneous solid solution, but high enough magnifications have not yet been possible to disclose exactly what its nature is. It is admitted to be the first stage in the decomposition of austenite in its progress into ferrite and cementite. In endeavoring to trace the progress of decomposition more in detail, it has been suggested that the first change is the transformation of gamma iron into alpha iron, the solid solution becoming alpha iron and carbide, which is admitted to be an abnormal, or metastable, austenite. In undergoing this change from a face-centered to a body-centered lattice without decomposition of the solution, distortion of the lattice, causing internal stress, has been suggested as the cause for hardness. Another explanation is that martensite is hard because it is a supersaturated solution. Several believe that the extreme fineness of grain, by restraining or preventing slip, is the cause of brittleness and hardness. Another theory is that martensite is a solid solution in which has occurred incipient precipitation of cementite in crystals too small to be identified at the highest powers of the microscope, but which prevent any movement or slip in the space lattices. One suggestion is that carbon atoms, no longer a structural part of the space lattice as they are when in solid solution but situated between the atoms and within the space lattices, prevent slip. And, finally, it has long been suggested that hardness is due to internal stress caused by the suppression of the normal expansion of steel when cooling through the critical range. When austenite is slowly cooled, it expands slightly to form ferrite and cementite and then contracts again. But when austenite is quenched, the cooling is too rapid to permit expansion and austenite contracts to form martensite; later, if martensite is heated, it separates into ferrite and cementite and expands in doing so. The suppression by rapid cooling of the normal expansion at the critical temperature sometimes produces such strains in the steel that it bursts with violence. It may form a hollow place in its center, or it may explode and cause serious damage. For this reason, steel is sometimes quenched in hot water instead of cold water, or even in hot oil instead of cold oil, so that the cooling is not so rapid.

We may summarize the theories of hardness as follows:

1. Slip is prevented by submicroscopic particles of cementite.
2. Slip is prevented by extreme fineness of grain.
3. Slip is prevented by intralattice carbon atoms.
4. Hardness is due to internal stress, because of:
    a. Lattice distortion.
    b. Suppression of expansion at about 700°C.
5. Hardness is a characteristic of a supersaturated solid solution.

Summary of Constituents.—We may discuss the characteristics of the constituents of steel in the approximate order of their relative hardness as follows: *Cementite,* Fe_3C, is the hardest constituent of straight iron-carbon alloys. It is magnetic at temperatures below 230°C. It cannot be made as one piece but occurs only as a crystalline constituent. It occurs in every slowly cooled iron or steel. It is very brittle. *Martensite,* the next in hardness and brittleness, is the first step in the decomposition of austenite. It is slightly magnetic and contains iron in both the gamma and the alpha allotropic form. It transforms from austenite at a temperature of about 325°C., on rapid cooling. When steel containing austenite is heated, the austenite begins to change at once to martensite, and this change is complete at a temperature of about 200°C. Martensite is not homogeneous in structure. It will apparently retain its hardness indefinitely unless warmed. *Austenite* has less cutting, or indentation, hardness than has martensite, but more than sorbite or pearlite. Austenite, however, has great abrasive hardness, or resistance to wear. It has great toughness, moderately high tensile strength, and low elastic ratio; *i.e.,* its elastic limit is 50 per cent, or less, of its ultimate tensile strength, while the elastic ratio of martensite is 80 to 98 per cent. Austenite is nonmagnetic, all its iron being in the gamma form. *Troostite* is less hard, less brittle, and contains much less gamma and more alpha iron than martensite, from which it is obtained by warming. The transformation from martensite to troostite begins when the steel is warmed and is substantially complete at 400°C. Many believe that troostite is not a true constituent but merely a stage in the transition from martensite to sorbite. *Sorbite* might be described as incipient, or colloidal, pearlite. It is obtained when quenched steel is heated to temperatures of 400°C. and above. Its structure seems to be imperfectly separated ferrite and cementite out of a partially decomposed solid solution. The structure is, however, too fine to be resolved by the microscope, and there may be an important amount of imperfectly separated solid solution still present, especially in those steels which have been "sorbitized" near 400°. Sorbite is stronger than pearlite, and it may be both stronger and tougher at the same time. That is to say, steel which has been "sorbitized" by quenching and reheating to 500 or 600°C. will probably be stronger, harder, tougher and only a little less ductile than the same steel which has been slowly cooled so that the ferrite and cementite in it have been separated into individual crystals. It will also be liable to give better resistance to shock. *Pearlite* is a conglomerate of ferrite and cementite resulting from slow cooling of any steel. When the steel contains 0.85 per cent carbon, it consists entirely of pearlite. *Ferrite* is the softest and least strong constituent in steels. It is also the toughest, most malleable, most ductile, and highest in electrical conductivity and magnetic permeability.

FIG. XIII-23.—Ferrite network with troostite in martensite matrix. Carbon steel of about 0.15 to 0.20 per cent carbon. Rivet stock. Quenched from white heat. Etched. Magnified 90 diameters. (*Courtesy, William Campbell.*)

Tempering.—Hardened steel is too brittle to be used without some degree of tempering, except for a small variety of purposes, such as the points of armor-piercing projectiles and the face of armor plate. In order to understand just what tempering does, let us consider the exact condition of hardened steel: It is in a hard and brittle condition which is not natural to it at atmospheric temperatures, but which has been brought down with it from a higher temperature by means of rapid cooling. Theoretically, when the temperature fell below 690°C. (1272°F.), the molecules of steel should have changed over to the soft form. Their hard condition is not in equilibrium at the lower temperature, in the same sense that ice is not in equilibrium in hot weather. Why, then, does not the steel change back into the soft form? Ice, if given time enough, will all change into water when the temperature is above 0°C. (32°F.). The reason the change does not take place in the steel after we have cooled it to the atmospheric temperature is that the mass as a whole becomes too rigid and immobile at the lower temperature to permit any alteration in its molecules to take place.

However, it is only necessary to decrease this rigidity in order to permit a slight change. For example, if a piece of hardened steel be kept in boiling water for some days it will lose a part of its hardness; if it be heated a little more, it will lose more hardness and lose it much more quickly. Each loss in hardness is accompanied by a loss in brittleness as well. If it be heated to about 200°C. (392°F.), quite a little of the brittleness will be lost and a part of the hardness.[1] It is now in condition to be used for steel engraving tools, lathe tools, and other implements to cut metals. If we heat to 250°C. (480°F.), we temper still further, and so on (see Fig. XIII-24).

It is interesting to note that, when hardened steel is tempered, the physical changes produced by the tempering—the decrease in hardness and brittleness, increase in electric conductivity, etc.—precede the separation of carbon from the solid solution. By tempering we may lose 70 per cent of the hardness, 93 per cent of the electric resistance, and nearly 100 per cent of the thermoelectric power produced in the steel by the hardening operation, when only 13 per cent of the carbon has been changed from the dissolved form.

---

[1] After the heating it is immaterial whether cooling is fast or slow, as the same result will be produced.

Hardening, Tempering, and Annealing.—Only quenching in water, or in some other medium which takes the heat away as fast or faster, goes under the name of hardening. Quenching in heavy oil, melted lead, etc., cools the steel less rapidly and makes it less hard and less brittle than quenching in water, so to this operation the name of "tempering" is given. Cooling in sand, in the furnace, or by any other slow method, is called "annealing."

PRACTICE IN ANNEALING, HARDENING, AND TEMPERING

Furnaces.—There is not space here to discuss the many different types of furnaces used for heating for these purposes. Furnaces heated by electricity are now commonly used in the most modern heat-treating establishments and industrial plants, especially automobile plants. Electric furnaces are often automatically controlled as to temperature. They usually cost more for heat but save through less defective work, less labor, and less space required. The requisites of a heating furnace are: (1) It shall be of a uniform temperature in all parts of the heating chamber. (2) It shall heat the pieces uniformly from all sides. (3) Its temperature shall be readily under the control of the operator. It is very desirable also that the temperature should be indicated by means of some scientific instrument instead of the unaided eye of the operator. Skillful as these operators are, it is now generally admitted that a good pyrometer will give more reliable results, and it has the further advantage of giving an autographic record of the temperature which may be

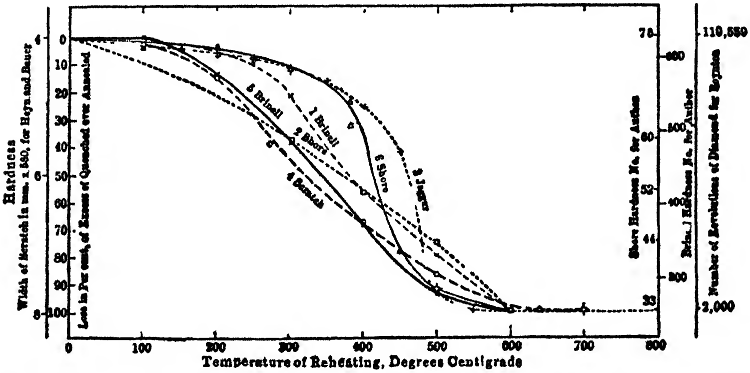


FIG. XIII-24.—Progress of the Loss of Hardness in Tempering Steel. (*From Howe, "The Metallography of Iron and Steel," Fig. 123, p. 599.*)

kept for future reference. (4) The metal shall not come in contact with solid fuel, because the carbon or injurious impurities in this fuel, such as sulphur and phosphorus, will be absorbed by the metal and vitiate it. The usual means of heating these furnaces is the flame from combustion of solid fuel, gas or oil, or heat converted from electric energy. Electric heat, although expensive, gives the most effective control of the temperature and also enables us to get with ease either the highest or lowest temperatures. (5) Ready access to the pieces being heated shall be had so that they may be removed quickly and easily. (6) The pieces shall be so supported as not to bend under their own weight at the heat to which they are subjected. (7) Means shall be provided, where possible, to prevent oxidation of the iron. This is of major importance in the case of small pieces or of pieces which are to be treated after machining, or cold rolling, so that they shall be left with a bright surface and good corners. The means for accomplishing this object are usually to heat the pieces inside muffles around the outside of which the combustion takes place, or else to pack them in air-tight boxes. Sometimes inside these boxes or muffles a stream of reducing gas is led to prevent oxidation. Or else the metal is packed in lime or other neutral material, and sometimes a few pieces of charcoal are put inside the muffle or mixed with the lime to unite with any oxygen which finds its way into the interior. Another method of heating to prevent oxidation, which has the further advantage of obtaining uniform temperature, heating the piece uniformly on all sides, and giving an excellent control of the temperature, is to have the pieces immersed in baths of oil, lead, barium chloride, or other substances in a molten condition. These baths are then uniformly heated and transmit their temperature to the metal.

Magnetism and the Lines *GSK*.—It will be remembered that iron is present in the solid solution in the gamma allotropic form, and therefore the solid solution is nonmagnetic. Therefore all the steels having more than 0.40 per cent carbon lose the last of their magnetism at the same time as they cross the lines *GSK*. These steels comprise all containing 0.4 per cent of carbon and more. To harden, anneal, or restore such steels we may guide our work of heating by means of an ordinary horseshoe magnet, which makes a most accurate and simple tool. Let the magnet hang outside the furnace and take a sample of steel out at intervals to test it. When it no longer attracts the magnet, begin to cool it. For steels with less than 0.4 per cent carbon we can use the magnet to tell us when the temperature corresponding to 760°C. is reached, for all iron loses its magnetism at that point, and then it is a comparatively simple matter to judge by eye the relatively short temperature intervals above that point which it is necessary for the steel to traverse before it crosses the line *GS*. If this method is followed, it will be found in many works that annealing temperatures have been much too high, and that better steel will be obtained in future. We do not get the steel any softer by annealing it hotter, but only by slower cooling from the correct temperature.

Heating for Annealing, etc.—Annealing has for its object the treble purpose of (1) relieving any strains put upon the metal during its cooling, or by mechanical treatment or otherwise, (2) restoring the grain of the metal to that minute size which gives it the best possible qualities, or (3) softening it after hardening. We may accomplish these three objects, or any of them, in one annealing operation. The usual temperatures of true annealing lie between 700 and 1000°C. (1290 and 1830°F.). Temperatures from 200 to 500°C. (930°F.) are sufficient to relieve strains in the metal and to soften it after mechanical treatment or hardening. But, when we desire to produce a new grain size, we must heat above the critical temperature, and we have already explained that for this purpose it is best not to exceed the critical temperature any more than is necessary, with, however, the qualifications noted in the case of very bad overheating or ingotism. Where we have obtained by means of cold rolling, wire drawing, or other mechanical work in the cold, a grain size already small, it is bad practice to form a new grain size, and therefore the steel should then be heated only to that low temperature which will soften it. If steel has been heated above the critical temperature, it must be cooled slowly from that point if it is to be in a soft condition.

Lonealing.—Full annealing is heating above the critical temperature followed by slow cooling. In some operations the practice is followed of heating to some point below the critical temperature, after which the steel is soft whether subsequent cooling is either slow or rapid. This softening at a low temperature is sometimes called "process annealing," which is an insignificant term, so that the name "lonealing" is suggested for this softening at temperatures below the critical range.

Normalizing.—If any steel with less than 0.85 per cent of carbon be cooled slowly from above the line *GS* in Fig. XI-9, it will contain thereafter large crystals of ferrite. This will cause it to have less strength than if the large crystals of ferrite were not present. This is frequently the case in rolled or forged steel, because mechanical work is usually stopped at a temperature above the line *GS*, both on account of expenditure of power and because the ductility of hypoeuctectoid steel (*i.e.*, steel with less than 0.85 per cent of carbon) is reduced if it is worked in its zone of secondary crystallization. To improve the grain structure of this steel it may be heated about 50°C. above the line *GS* and slightly chilled by cooling in air. This is called "normalizing." Often the steel is held for an hour or so at the normalizing temperature in order thoroughly to adjust the solid solution by "soaking."

Spheroidizing.—Steel with more than 0.85 per cent of carbon will precipitate out needles of cementite as it cools from the line *SE* to *SK* in Fig. XI-9. These needles make it less durable. They can be converted into round spheroids by long heating near the line *SK*. Billinger found that the most rapid spheroidizing occurred by a long heating which was alternately slightly above and slightly below the line *SK*. This same process of spheroidizing may also be applied to cementite crystals in the pearlite of steel with 0.85 carbon or less, and the toughness of such steels thereby improved.

Hardening Practice.—When a piece of steel is rapidly cooled, tremendous strains are developed in it as it passes through the critical temperature. We have already studied the phenomenon of recalescence, or liberation of heat within the metal by the chemical reaction of the separation of ferrite and cementite.

The recalescing steel, which has been rapidly contracting owing to the falling temperature, now tends to expand because of this liberation of heat. But, as cooling takes place from the outside inward, the outer shell of steel passes through the recalescence period first and is already beyond that point and contracting further when the interior begins to liberate heat and tend to expand. This brings a double pressure on the steel, and the strains are so large as frequently to cause what are known as "water cracks" in the hardened steel. Sometimes the outer shell of steel actually flies to pieces under the strain, or "bursts," as it is called. Again, a long cavity will be opened down the center of the piece. In the case of armor plate, for example, the appearance of cracks after the hardening of the steel is often welcomed, as it shows that the strains produced in the metal have been relieved to some extent, and a curved turret will actually be stronger under impact after cracking than before, because the latent strains are relieved. The operator must take these matters seriously into consideration, remember that the greatest strains are produced by uneven cooling which may occur through (1) the juxtaposition of thick and thin sections, (2) uneven temperature of the piece which is heated up, which may best be avoided by the slow heating of large pieces, (3) uneven temperature of the bath in which the steel is quenched, or (4) careless immersion in the bath. An uneven temperature of the bath may be avoided by having small-sized baths with abundant circulation of the quenching medium therein, or else by quenching the objects in a voluminous spray of liquid, such as is practiced in the hardening of armor plate, for example. The operator should move the piece around in the bath as much as is necessary to prevent vapor accumulating next the steel and thus forming a place where the cooling is not so rapid, and the piece must be held in tongs and not allowed to drop to the bottom of the quenching tank.

Hardened pieces occasionally warp as a result of the strains set up. This may be prevented to some extent by having the thickest parts of the piece enter the bath first, and also by annealing the specimen at a relatively low temperature before heating for hardening, in order previously to remove all strains. It may be necessary to clamp pieces of very intricate shape in order mechanically to prevent their warping.

Quenching Baths.—The object of the quenching bath is to take the heat away from the metal at the rate of speed best suited for the hardness or other qualities desired to be given to it. Nothing from the bath enters the steel, and it has no virtues other than to remove the heat. It may be, however, that certain baths will cool steel rapidly through the critical range and then slowly thereafter, or *vice versa,* and there may sometimes be virtue in this property. Saturated solutions of certain salts might deposit their dissolved substance uniformly on the surface of the steel and this incrustation may have the effect of cooling the steel more slowly at a lower temperature. Further than this characteristic, the speed of cooling will depend upon the following factors: (1) temperature of the bath, (2) heat conductivity of bath, (3) viscosity of the bath—the importance of viscosity results from the circumstance that liquids carry heat away largely by convection—(4) specific heat of the bath, because the greater the specific heat of substances, the more heat will be absorbed in a given time by the layers adjacent to the quenched body. Furthermore, the greater the specific heat, the greater amount in heat will the bath absorb without rising in temperature, (5) the volatility of the liquid, because the more readily it forms vapor when heated, the more liable is there to be a cushion of vapor between the quenched body and the body of the liquid itself. Mercury, because of its low melting point, can be refrigerated to a low point and this makes an effective hardening medium. Solutions of calcium chloride will act in the same way. On the other hand, liquid air, in spite of its low temperature, is a poor quenching medium because of its ready volatility. If steel is quenched in hot water or hot oil, it will not be in as great danger of cracking, but there is an added danger of bubbles in the quenching medium adhering to the sides of the metal and interfering with the rapid cooling of these spots. This results in soft spots on the sides of the quenched tool. The importance of rapid circulation of the quenching medium so that it passes quickly over all parts of the hot steel, and also so that it does not rise in temperature during use, cannot be overestimated.

Combined Hardening and Tempering.—If steel be cooled from above the critical range by quenching in some slow heat-conducting liquid in the first instance, as cylinder oil, or melted solder at 200°C. (392°F.), the same intermediate hardening and embrittling effect will be produced upon it as if it were first hardened in water and then tempered a certain amount. Therefore the quenching in oil and similar mediums has come to be called "tempering." Another method of combining hardening and tempering after only one heating is used in the tempering of the cutting edges of chisels and similar tools: The end of the tool is first heated just above the critical range, and then the extreme point only is quenched in water until it is black, after which it is withdrawn and rubbed bright upon a piece of sandpaper or upon a brick. This is done merely to give a bright surface upon which to observe the play of temper colors. The heat from the shank now begins to creep down into the point which takes the various temper colors in order, beginning with the lemon. When the desired degree of tempering is reached—say, the pigeon-wing color—the whole tool is put into water. This is merely to "put out the fire" and stop more heat coming down into the tempered point; it has nothing to do with the tempering operation itself.

Reheating for Tempering.—A more accurate method of tempering, because it enables pyrometers to be used and because the operation can be conducted more slowly, is to quench the

TABLE XIII-I.—TEMPERATURES FOR TEMPERING VARIOUS TOOLS

	Degrees Fahrenheit	Degrees centigrade	
	Light	Lemon	Color
Scrapers for brass	437	225	Steel-engraving tools
Light turning tools			Hammer faces
Planers for steel	to	to	Planers for iron
Ivory-cutting tools			Paper cutters
Wood-engraving tools	455	235	Drills
Bone-cutting tools			Milling cutters
Wire-drawing plates	456	236	Boring cutters
Leather-cutting dies			Screw-cutting dies
Taps	to	to	Chasers
Rock drills			Mill chisels and picks
Penknives			Punches and dies
Reamers			Shear blades
Half-round bits			Planing and molding cutters
Gouges			
Plane irons	482	250	Stone-cutting tools
Twist drills	483	251	Flat drills
Wood borers			Pressing cutters
Cup tools	to	to	Coopers' tools
Edging cutters	527	275	
Wood bits and augers	528	276	Cold chisels for steel
Dental and surgical instruments			Axes and adzes
Hacksaws	to	to	Cold chisels for cast iron
Saws for bone and ivory			Chisels for wood
Needles, gimlets			Framing chisels
Circular saws for metal	572	300	Screw drivers
Saws for wood			Springs
	Blue	Color	

piece to be hardened and then reheat it to a desired temperature at which its temper is to be drawn. By this means also we can reheat the piece in baths of lead-tin alloys, melting at low heats, which insures accurate control and that all parts of the piece are uniformly heated.

Temper Colors.—Nature has provided a ready means of determining the temperature of steel between 200 and 300°C. (390 and 570°F.) without the aid of thermometers or other instruments, and, since this is the range of temperatures in which practically all of the tempering of hardened steel takes place, this provision is a most fortunate one. It comes about through the oxidation of the metal at those different points. At 200°C. (390°F.) a thin film of oxide forms upon the steel but is not sufficient to hide entirely the white color underneath, so that the combination produces a light-lemon color. As the temperature rises, the film of oxide becomes thicker and the yellow color darker until, at about 225°C. (437°F.), it has changed to faint straw.

In Table XIII-I are the temperatures and other phenomena relating to the treatment of steel and the temperatures for tempering various tools.

Multiple-ply Steel.—Steel low in carbon is soft and tough but will not withstand wear or abrasion; hard steel, on the other hand, is brittle except, of course, such a steel as manganese alloy steel, whose use is limited by price. Where a steel has to resist a combination of stresses consisting of penetration or abrasion and violent shocks, such a combination of stresses, in other words, as is brought to bear upon armor plate, plowshares, certain gears and pinions, crankshafts, pivots in moving machinery, etc., or a combination of cutting and shocks, such as that which jail bars and burglar-proof safes might have to resist, it is customary to have a combination of metals. Or else we may produce a high-carbon surface on a piece of soft steel by the process known as case hardening or carbonizing. This case-hardened metal is then heat-treated by a hardening or tempering process which makes the outside very hard but leaves the interior tough and ductile. The high carbon of the outside is obtained by virtue of the so-called cementation process.

Theory of Cementation.—The principle upon which case hardening depends is the slow absorption of carbon by iron or steel at a bright-red heat as already partially explained on page 4. If a piece of soft steel be immersed in melted potassium cyanide at a temperature of 900°C. (1650°F.), the carbon contained in the cyanide will slowly penetrate the metal. It enters the steel in the form of a solid solution and the amount of carbon and the depth to which it penetrates will depend upon the following conditions in the order of their importance:

1. The temperature of cementation.
2. Time during which it proceeds.
3. The kind of cement material used; *e.g.*, potassium cyanide gives a quicker penetration than pure charcoal.
4. The kind of steel used; *i.e.*, manganese, chromium, tungsten, molybdenum, etc., in the steel increase the rate of cementation, while silicon, aluminum, nickel, titanium, etc., decrease it.

Temperature of Cementation.—The cementation process takes place with extreme slowness below the critical temperature of steel and increases rapidly with the temperature above that point. It is not advisable, however, to carry it on at a very high temperature because the long overheating gives the core of the steel a coarse structure and makes it weak and brittle. Lake gives the following table for the speed of cementation with different substances at varying temperatures.

TABLE XIII-II.—RATE OF PENETRATION OF CARBON INTO STEEL

Temperature, degrees Fahrenheit	Materials used and rate of penetration in 8 hr., inches				Temperature, degrees centigrade
	Charcoal 60 per cent + 40 per cent of carbonate of barium	Ferrocyanide 66 per cent + 34 per cent of bichromate	Potassium ferrocyanide alone	Powdered wood charcoal alone	
1290	.....	.....	.....	.....	700
1475	0 020	0.033	0.020	0.020	800
1650	0 088	0.069	0.079	0.048	900
1830	0.128	0.128	0.128	0.098	1000
2010	0.177	0.177	0.198	0.138	1100

A very usual temperature for cementation is 900°C. (1650°F.).

Influence of Time on Cementation.—The following two tables from Lake also show the influence of the time on the depth of penetration of the carbon for different materials.

Carbonizing Material.—Iron has been carbonized by means of a diamond as early as 1815 without melting the metal, which shows that pure carbon alone may accomplish the result. How-

TABLE XIII-III.—RATE OF PENETRATION OF CARBON INTO STEEL

Length of time, hours	Materials used and rate of penetration at 1000°C., inches				
	Carbon 60 per cent + 40 per cent of carbonate	Ferrocyanide 66 per cent + 34 per cent of bichromate	Powdered wood charcoal alone	Charcoal and carbonate of potassium	Unwashed animal black
1	0.031	0.033	0.028	0.059	0.035
2	0.039	0.037	0.053	0.078	0.059
4	0.047	0.049	0.063	0.094	0.088
6	0.078	0.074	0.072	0.111	0.106
8	0.118	0.128	0.098	0.138	0.128

TABLE XIII-IV.—RATE OF PENETRATION OF CARBON INTO STEEL

Length of time, hours	Materials used and rate of penetration at 900°C., inches		
	Charred leather	Ground wood charcoal	Barium carbonate and wood charcoal
2	0.045	0.028	0.055
4	0.062	0.042	0.087
8	0.080	0.062	0.111
12	0.110	0.070	0.125

ever, more impure forms of carbon give much more rapid carbonization, and for commercial purposes the materials used are generally charcoal from wood, with which are mixed other substances; powdered bone; charred leather or sugar, this latter being valuable because of the absence of injurious impurities; horn, animal black, lampblack, anthracite, graphite, etc. In the lampblack process it is common to deposit the soot on the surface to be carbonized by means of a smoky gas or oil flame. Gases containing carbon may also be used for cementation, of which carbon monoxide is one of the best; acetylene is also effective. We may also use liquids containing carbon, such as melted potassium cyanide, ferrocyanide of potash (Prussian blue or ferroprussiate of potash). It would appear that the presence of nitrogen assists in the absorption of carbon by the steel and for this reason the various animal and vegetable products mentioned above are preferred to charcoal from the purer materials. It is also common in some cases to introduce gases containing *nitrogen, such as ammonia, into the receptacles where the* cementation is being carried on.

A very important consideration in case hardening is that the carbonized material shall penetrate the steel at all points alike and this is assisted by the more intimate contact between the two, so that carbonizing with gas is often preferred to packing the steel in solid materials. Carbonization in liquid cyanides has the same advantage, and doubtless the nitrogen in these cyanides is an important element in their efficiency. The potassium cyanide bath is a very common means of cementation on account of the convenience of its use and readiness of control. One objection to it, however, is the very bad and poisonous fumes coming from this melted liquid.

Steel Carbonized.—We ordinarily carbonize a steel running from 0.10 to 0.22 per cent of carbon in order to have a very tough core and also to avoid the ill effects of overheating of the core which increases with the amount of carbon. The manganese in the steel should be low, because this not only increases the overheating by lowering the critical temperature but tends to make the outside case brittle. The amount of manganese should generally be under 0.35 per cent and preferably less than 0.25 per cent. Chromium makes the outer surface harder and refines the grain of the steel besides raising the temperature at which overheating occurs. It increases the strength of the material but makes it harder to machine. Many pieces for case hardening contain from 0.50 to 1.50 per cent of chromium. Vanadium and titanium are said to counteract to some extent the effect of chromium in making steel difficult to machine, and to increase its resistance to shock. Nickel is very valuable in case-hardened steel because it increases its strength, decreases the brittleness and the tendency of cracks to spread. From 2 to 7 per cent of nickel is commonly used for high-grade material which can stand the extra price. The amount of silicon is usually kept as low as possible on account of its decreasing the depth and speed of cementation, and phosphorus should be under 0.035 per cent as this makes the metal brittle under shock.

Silicon must be below 0.30 per cent, because it produces a coarse grain structure and tends to make the "case," which is high in carbon, brittle. Sulphur, inclusions, and dissolved oxygen must be low. However, the dissolved oxygen must not have been removed by either aluminum or vanadium when the steel was manufactured, because these two elements tend to make an "abnormal" steel, which will be discussed in more detail later. Nickel is variously used in different grades, such as 1, 3, 5 or 7 per cent, depending on the price which can be asked for the carburized steel. The principal purpose of the nickel is to give a small grain structure, especially to the grains of ferrite in the "core," or inside portion of the steel. Chromium steel is used where a hard outside case is wanted, because chromium greatly increases the hardness of quenched steel. Where the service calls for a strong steel with a hard case and a tough core, a chrome-molybdenum steel is commonly used.

Percentage of Carbon Added.—On the very surface of the case-hardened material, the amount of carbon will usually be nearly 1 per cent or more and will run as high as 2.50 per cent in the case of a very long cementation as in the manufacture of armor plate, for example. Lake cites the case of a round bar that was carbonized to the depth of $\frac{3}{16}$ in. and showed the following percentages of carbon in each $\frac{1}{16}$ in. turned off the outside: 1.24, 0.85, 0.24, and 0.13 per cent. It is commonly assumed that the best carbon in the case is just above the eutectoid ratio, and many carburizing operators aim to get 0.90 per cent. Others aim for 1.10 per cent, and some work for 1.20 to 1.30 per cent, the object being to have some crystals of free cementite in the case after quenching to act as extra hard particles in a hard matrix.

Heat Treatment for Carbonizing.—In some cases it is customary, in order to save time and expense, to quench out the pieces as they come from the cementation furnace, but it is much better practice to cool them down to a black heat and then reheat and harden in a separate operation, because this causes a somewhat better diffusion of the carbon at the point where the case hardening joins the core. This junction line is always a line of weakness and, when the pieces are quenched out from the quenching furnace, there is a distinct line of demarcation, which is notably shaded when the metal is reheated for hardening. Moreover, the reheating restores the grain of the steel which has been somewhat damaged by overheating during the cementation process.

Optimum Heat Treatment for Case Hardening.—After steel has been case carburized, it is not case hardened until it has been quenched from above its critical temperature, because it is only rapid cooling which gives great hardness to the case. For good grain structure in both case and core, at least a double quenching is required, as follows: After cooling the steel subsequently to the case-carburizing operation, reheat to above the A_{c_3} line of the core. Now, if the core contains 0.20 per cent carbon, it will be heated above the A_{c_3} line at a temperature of about 875°C., as we can see from line *GS* in Fig. XI-9. The core is now entirely solid solution of iron and carbon; quench in water and it comes to atmospheric temperature without any large ferrite crystals separating out, which would weaken it if they were present. Now reheat to just above 700°C. Assuming that the case is 0.90 per cent carbon, we now have it entirely in solid solution. Quench again and we have a hard case. The core is tough and strong because it has no large crystals of ferrite in it. It is not customary to "temper" case-hardened steel after the second quenching unless the expected service demands a nonbrittle case.

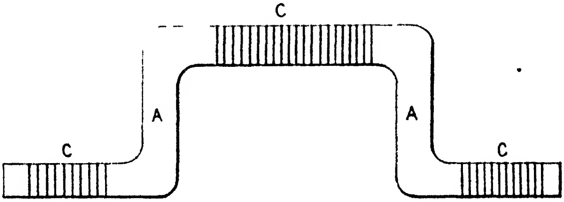


FIG. XIII-25.—Schematic illustration of selective case carburizing. Surfaces at *CCC* are to be carburized, while those at *AA* are to be protected against carburizing.

Before packing this crankshaft in the carburizing compound and heating it to the cementation temperature, the surfaces at *AA* are protected so that carbon will not penetrate them. This may be done by coating or painting the surfaces *AA*, or by electroplating them with tin, bismuth, antimony, or, better, copper This is done as follows: The surfaces which we wish to carburize (*CCC*) are first painted with melted wax; then the whole crankshaft is put in a copper-plating bath and plated. Finally the wax is cleaned or melted off, leaving the surfaces at *CCC* exposed to carbon penetration.

Protecting Surfaces against Carburizing.—Sometimes case carburizing is to be selective in its application. That is to say, we desire to carburize some surfaces and not others. We may illustrate with the single-throw crankshaft shown in Fig. XIII-25.

NITRIDING

In recent years a very important process for putting a hard case on the surface of a piece of steel has been developed and has come into extensive use. It is characterized by the following distinctive features:

1. It uses an alloy steel which is first heat-treated and which has a high combination of strength and ductility.

2. It puts a very hard surface on this steel by soaking it for a long time in an atmosphere of ammonia gas at a temperature of about 510°C. This produces a skin of Fe_2N, about 0.001 in. thick on the surface. This is much harder than a case-carburized and quenched surface.

3. It requires no quenching to make it hard, and therefore it can be used for steel shapes which might distort or crack if quenched.

4. The skin does not lose its hardness even when heated slightly.

Selective Nitriding.—Selective nitriding can be accomplished as well as can selective case hardening, but, in the case of nitriding, the surface must be protected from nitride formation by plating it with tin or nickel.

Advantages and Disadvantages of Nitriding.—As compared with case carburizing, nitriding has the advantage that the surface has a Brinell hardness of 1000 to 1100, as compared with 650 to 720 for case-carburized steel. The alloy used for nitriding is stronger and it does not lose either its strength or its nitrided hardness at temperatures up to 480°C. The chief advantage of the nitrided steel usually is, however, that it does not distort, warp, or crack on quenching, because it is not quenched after nitriding. The chief disadvantages are that nitrided steel is more costly, requires very special apparatus, greater expertness to produce, and a longer time.

6. Heat Treating for Strength

If steel with less than 0.85 per cent of carbon be heated above the line *GS* in Fig. XI-9 and rapidly quenched, its strength will be greatly increased and its ductility lowered. The increase of strength is due chiefly to preventing the precipitating of large crystals of ferrite, which weaken steel. The decrease in ductility is caused by the formation of the hard and brittle martensite always produced when steel is quenched while it is in the condition of a solid solution. The amount of increase in strength and decrease in ductility varies with the amount of carbon in the steel, as shown by Table XIII-V.

In order that this process of strengthening shall be serviceable, it is necessary that the quenched steel be reheated to some temperature between 400 and 650°C., so that martensite is converted into sorbite. This leaves the steel stronger than it was before

TABLE XIII-V.—THE EFFECT OF CARBON ON THE MECHANICAL PROPERTIES OF STEEL AFTER QUENCHING IS SHOWN BELOW[1]

Carbon, per cent	Tensile strength in soft state			Tensile strength when quenched		
	Ultimate, pounds per square inch	Elastic limit, pounds per square inch	Elongation in 2 in., per cent	Ultimate, pounds per square inch	Elastic limit, pounds per square inch	Elongation in 2 in., per cent
0.10	60,300	36,300	29	66,400	40,300	24
0.14	61,500	35,200	27	73,100	39,600	22
0.23	66,500	41,200	26	99,400	54,000	14
0.52	97,800	52,600	20	132,100	81,400	9
0.60	116,400	66,500	14	153,400	102,100	4
0.72	130,700	75,800	9	180,100	105,500	0

---

[1] See E. F. Lake "Composition and Heat Treatment of Steel."

quenching, but also ductile. Any temperature within the range mentioned may be used for reheating, always bearing in mind that strength leaves the steel with every increase of temperature above 400°C., and that ductility is added to it. We choose the temperature which gives us the combination nearest to that desired. The process is much used for heat-treating axles containing about 0.45 to 0.55 per cent of carbon, but its principal use is in heat-treating alloy steels, especially for automobiles, airplanes, locomotives, etc.

References

"National Metals Handbook," 1933 ed., American Society for Steel Treating, Cleveland, Ohio, 1933. For a wealth of practical directions and data this book should be the first to be consulted on any problem in heat-treating steel.

T. G. BAMFORD and HAROLD HARRIS: "The Metallurgist's Manual," New York, 1927.

D. K. BULLENS: "Steel and Its Heat Treatment," 2d ed., New York, 1927.

ZAY JEFFRIES and ROBERT S. ARCHER: "The Science of Metals," New York, 1924.

H. B. KNOWLTON: "Heat Treatment, Use and Properties of Steel," American Society for Steel Treating, Cleveland, Ohio, 1929.

Metallurgical Staff of the U. S. Bureau of Standards: "Principles of the Heat Treatment of Steel," American Society for Steel Treating, Cleveland, Ohio, 1928.

RALPH H. SHERRY: "Steel Treating Practice," New York, 1929.

CHAPTER XIV

THE CONSTITUTION OF CAST IRON

Practically all the cast iron that is not purified is used for making iron castings, so that a study of the constitution of cast iron resolves itself into a study of iron castings. The difference between cast iron and steel is that the former contains less iron and more impurities, especially carbon, silicon, phosphorus, and occasionally sulphur and manganese. The advantages of cast iron, and the reason it is used as much as it is, are its fluidity, lesser amount of shrinkage when cooling from the molten state, relative freedom from checking in cooling, and the ease with which very different properties are conferred upon it at will. Its disadvantages are its weakness and lack of ductility and malleability. The last-named deficiency renders it practically impossible to put any work upon cast iron; hence it can never be wrought to shape and must always be used in the form of castings. Its most important advantages are probably its ready fusibility, which makes it so easy to melt and cast, and its cheapness.

Graphite.—All of the characteristic qualities of cast iron are due to the presence of the large amount of impurities in it. These impurities are the same in kind as the impurities in steel and differ only in amount, with the single exception of graphite. This constituent is almost never found in steel or is found in a very small number of cases, those cases being confined to the high-carbon steels, the amount of which is relatively very small. In cast iron, however, graphite is the largest and one of the most important constituents. It occurs in thin flakes, in sizes varying from microscopic proportions to an eighth of a square inch in area,[1] disseminated through the body of the metal and forming an intimate mechanical mixture, a magnified section of which is shown in Fig. XIV-1. Each flake of graphite is composed of smaller flakes, built up somewhat like the sheets of mica with which all are familiar, but with very little adhesion between

---

[1] In rare and unusual cases the flakes of graphite may be as much as 1½ to 2 sq. in. in area but practically never so large in commercial cast iron.

the small component flakes, so that the sheet of graphite may be split apart with very little force. Graphite is very light in weight, having a specific gravity of only about 2.25 as compared with a specific gravity of 7.86 for pure iron; consequently, although the percentage of graphite by weight is only 4 per cent or less of the iron, its percentage by volume may be, in normal cases, as much as 14 per cent. This may readily be seen by noting the amount of space occupied by the graphite flakes in Fig. XIV-1.

Combined Carbon.—We have already discussed the solidification and slow cooling of cast iron, and it will be remembered that all the carbon which does not precipitate as graphite forms first as austenite, which later decomposes into cementite and ferrite. In short, all the carbon in slowly cooled cast iron will ultimately be found partly in the form of graphite and partly in the form of cementite. The carbon of cementite in cast iron commonly goes under the name of "combined carbon," but it must be remembered that cementite is the constituent which gives the observed effects.

Fig XIV-1.—Gray pig iron. 1.75 per cent Si 0.025 per cent S. 50 diameters. Unetched.

White Cast Iron.—In slowly cooled white cast iron the carbon, amounting often to 3 or 4 per cent, will all be in the form of cementite, which will therefore form 45 to 60 per cent of the material (Fig. XIV-2). Consequently, white cast iron will possess largely the properties of cementite. It is very hard and brittle, being machined only with the greatest difficulty and with special kinds of cutting tools and resisting wear by abrasion very effectively. It is so brittle as to be readily broken by the blows of a hammer and is weak because of the presence of very large plates of cementite, which adhere but slightly to one another. Consequently, white cast iron has few uses and is employed usually only as a hard surface on the outside of gray-iron castings.

Gray Cast Iron.—Gray cast iron may have about the same total amount of impurities present as white cast iron, the only difference then being that the carbon is partly or wholly precipitated as graphite. The gray color of a freshly broken fracture, from which this material receives its name, is due altogether to the graphite present, for this constituent is so weak that the iron breaks chiefly through its crystals, which are rent asunder, leaving one part sticking to each side of the fracture. The weakness of gray cast iron as compared with steel is thus readily understood, since there is but a small proportion of metallic surface to be broken and the graphite splits so easily. An interesting experiment is to take a freshly broken surface of gray pig iron and brush one-half of it for some time with a stiff brush. In this way the adhering crystals of graphite are partially removed and we get a surface which is almost as white as the fracture of white cast iron. This shows clearly that the gray color is due altogether to the graphite and that the metallic part is as silvery white as iron itself. The prevalence of the gray color also shows how completely fracture takes place through the graphite crystals.

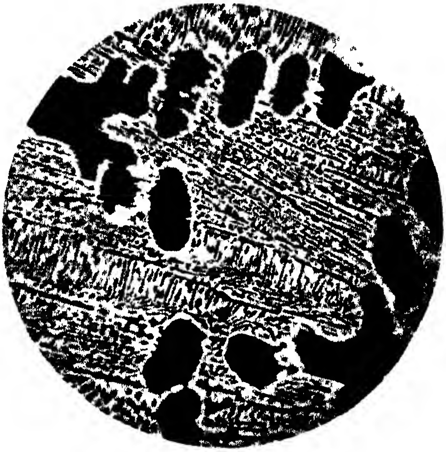


FIG. XIV-2. —White cast iron. 500 X.

Gray cast-iron castings are the more important, and the study of their constitution is the chief object of this chapter. These castings usually contain 2 per cent or more of graphite and less than $1\frac{1}{2}$ per cent of combined carbon. It will be observed that this limit of combined carbon is also the range found in steel. Furthermore, it will be observed that the graphite is not a chemical component of the metallic body but is mechanically mingled with it. In this sense, therefore, we may consider gray cast iron as a very impure steel,[1] mechanically mixed with graphite, and upon this reasoning the study of its constitution becomes much simpler,[2] as we may study first the properties of the metallic part and next that of the graphite and so be able to foretell to some extent the properties of the mixture. Indeed, the properties of the metallic part are already understood pretty well from our knowledge of the constitution of steel, and there is no new constituent or new condition except the larger amounts of silicon and phosphorus, which are of minor importance, because their effect is collectively far less than the weakening and embrittling effect of the graphite. Even though we had a very pure metallic constituent, the strength and ductility of this portion would not be sufficient to prevent the mass as a whole from breaking under a small load and without exhibiting any practical ductility, because of the weakening effect of the crystals of graphite. In other words, it is the carbon which is the great factor in determining the properties of cast iron, for this may be all graphitic or all combined or part in both conditions.

Total Carbon.—By running the blast furnace very hot, we may extend the saturation point of the iron for carbon and thus get a slightly higher total carbon. This is not a very potent influence, however, for we seldom have total carbon more than 4.5 per cent or less than 3.25 per cent. This control, such as it is, may be exercised either during the manufacture of the pig iron or during the remelting in the cupola, because in the latter furnace the liquid iron is in contact with coke and will absorb carbon up to its saturation point at the existing temperature.

Rate of Cooling.—A far more potent effect on the properties of the metal is the transfer of carbon from the graphitic into the combined form, or *vice versa,* by rapid or by slow cooling from the molten condition. It will be remembered that the carbon is always dissolved in the iron when the mass is in a molten condi-

[1] The silicon in gray cast iron is usually between 0.75 and 3 per cent or, let us say, ten times that in steel, while the phosphorus is usually from 0.5 to 1.5 per cent or, again, about ten times or more that in steel. The sulphur varies greatly but is not infrequently as high as 0.15 to 0.2 per cent. Manganese is an exception and is usually no higher in iron castings than in steel.

[2] This theory of the constitution, which meets with very favorable acceptance in many quarters, was independently evolved by J. E. Johnson, Jr., *American Machinist,* 1900; and H. M. Howe, *Transactions American Institute Mining Engineers,* vol. 31, pp. 318–339, 1901.

tion, *i.e.*, when it is above the lines *AB* and *BD* in Fig. XI-7. As we cool from the molten state, graphite precipitates, but this cooling must be very slow indeed for this normal chemical change to take place completely. If, therefore, we cool with great rapidity, as, for example, by pouring the iron into a metallic mold which "chills" it, or by some other form of artificial rapid cooling, we may prevent the precipitation of graphite, by denying the time necessary for the chemical reaction, and obtain a metal in which all the carbon is in the combined form,[1] *i.e.*, white cast iron. It is also evident that, by a rate of cooling intermediate between this rapid rate and the slow rate which permits the precipitation of the normal amount of graphite, we may obtain an intermediate amount of carbon in the graphitic form. Rapid cooling is a very important means of "chilling" the surfaces of gray-iron castings, whereby we may have a relatively soft gray iron in the interior of each article and a hard surface. For example, chilled-iron rolls are made in this way, and also railroad freight-car wheels,[2] which are cast against an iron chill (see Fig. XIV-6), giving nearly an inch depth of white iron around the tread and flange where the metal is to suffer abrasion in grinding over the rails. The web and bore will be of gray cast iron, because cooled more slowly in the sand part of the mold, and thus will be less brittle and better able to withstand the shocks of service and may be machined easily.

THE EFFECT OF CARBON ON CAST IRON

The nature or constitution of gray cast iron is far more difficult to understand than that of steel, and even greater is the difficulty of predicting the effect of any change in composition or in constituents. The chief reason for this complexity is that a change in any one of the constituents of gray cast iron is liable to effect changes in several others as well. The simplest example of this is in the case of the carbon; we have total carbon, graphite, and combined carbon, and if we change any one of these three, we must change either one or both of the other two, and it makes

---

[1] The term combined here is used to include either chemical combination or solution.

[2] It is today more usual to have the car wheels made of steel, as it is believed that the iron wheels are not sufficiently strong and ductile. The manufacture of pressed-steel car wheels is increasing in America.

a great deal of difference which. Indeed, we almost never change the amount of graphite without making the reverse change in the amount of combined carbon and *vice versa.* Thus a very loose system of speaking of these matters has come into vogue among foundrymen. For instance, it is very common to hear a foundryman say: "In order to soften your iron, increase the graphite"; but what he really means is: "In order to soften your iron, decrease the combined carbon." He knows that the one change usually follows from the other, and he speaks of it in this way, regardless of the fact that graphite can be increased (*i.e.*, by increasing the total carbon and leaving the combined carbon the same or a little higher), and yet the iron will not be made any softer but may even be harder.

Graphite and Shrinkage.—The most important effect of graphite on cast iron, aside from causing weakness, is in decreasing the shrinkage. The reason for this will be understood when we consider what happens when cast iron solidifies. It will be remembered that when the eutectic forms, the cast iron breaks up into alternate plates of graphite and austenite. This separation of graphite from solution is the birth of a new constituent, and this constituent occupies space, so that there is an expansion of the mass as a whole in proportion to the amount of graphite that separates. If, therefore, we pour liquid cast iron into a mold, which is, of course, entirely filled at the moment when the iron begins to solidify, the first action that takes place after the beginning of solidification is an expansion, due to the separation of graphite. The expansion continues for several moments until the chemical precipitation is completed, after which the metal begins to contract, as all metals do in cooling from a high temperature; but the preliminary expansion has been so great that the ultimate shrinkage may be only about one-half what it otherwise would have been. We can thus control this shrinkage by controlling the amount of the expansion, through varying the graphite. This point will be more readily understood by referring to Fig. XIV-3, which is taken from an article by Prof. Thomas Turner of England.[1]

Explanation of Fig. XIV-3.—The point *O* marks the position occupied by the end of the bars at the moment of solidification. It will be seen that in the case of copper the metal contracts con-

---

[1] *Journal Iron Steel Institute*, No. 1, p 57, 1906.

tinuously from this point, as shown by the continuous drop of the curve. In the case of white cast iron, the metal contracts continuously until we reach a certain point (which is at a temperature of about 665°C.), when a momentary arrest of the shrinkage takes place, after which the metal again contracts. This arrest is common to all cast iron and steel and marks the decomposition of austenite at the point *S* (Fig. XI-9). Now, see what a difference there is in the case of gray cast iron, which does not shrink immediately after freezing but expands very appreciably, as shown by the rise in the curve. This expansion is due to the graphite that is being expelled from the metal and occupies space between the particles of iron.

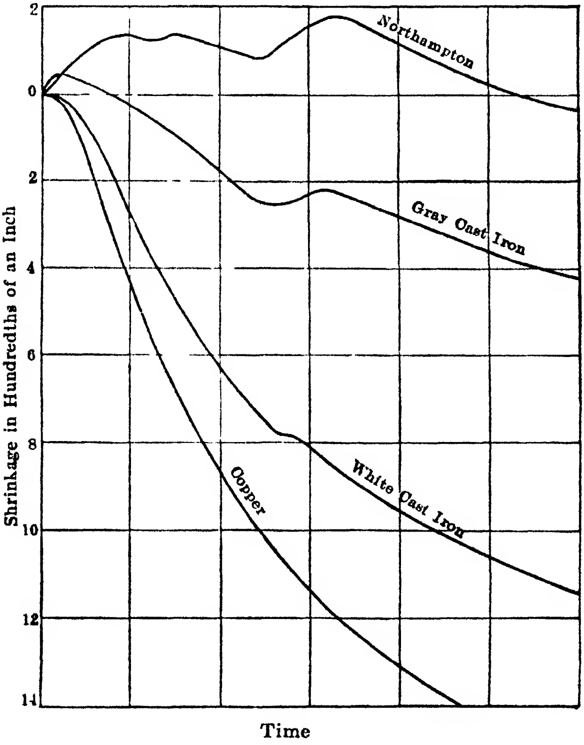


FIG. XIV-3.—Shrinkage curves.

Again, in the case of the Northampton iron, which is high in both graphite and phosphorus, the expansion is very long continued, and the metal cools to almost a black heat before the bar has shrunk again to the size it had when first cast. This expansion is again due to the separation of carbon and is assisted apparently by the phosphorus's keeping the iron in a semifluid condition for a long time and thus allowing the graphite more easily to separate and make place for itself. Here, too, we have an explanation why phosphoriferous irons fill every crevice of the molds so perfectly. Being in a pasty condition for some time and continually expanding, the semifluid metal is forced into the tiniest crevices of the molds, filling all the corners with astonishing sharpness.

It is evident that any increase in graphite, whether caused by an increase in total carbon or by a decrease in combined carbon, will produce less shrinkage. The extent of this may be judged by noting that gray cast iron expands so much in solidifying that no contraction cavity or pipe is formed, such as occurs in the case of steel. If the iron is only slightly gray, or if it is a very large section of metal, then a slight spongy place may be formed in the center, which is the nearest approach to a shrinkage cavity that is normally found in most iron castings.

Graphite and Porosity.—It is evident also that an increase in graphite, whether produced by an increase in total carbon or by a decrease in combined carbon, will increase the porosity of the casting, which is often disadvantageous, as in the case of hydraulic cylinders or other receptacles for holding liquids under pressure. The separation of much graphite usually is accompanied by large-sized graphite crystals, and therefore the crystals of the mass, as revealed by the fracture, appear large and the grain is said to be "open."

Graphite and Workability.—When we come to consider the effect of graphite upon the softness or workability of the cast iron, it is evident that we must consider it in relation to other things; for if we increase the graphite by increasing the total carbon, then we increase the workability of the metal only in so far as the graphite acts as a lubricant for the tool that is doing the cutting. Evidently the tool will have no difficulty in cutting through the soft flakes of graphite; the chief resistance to it will be given by the metallic part of the mixture. Though the lubricating effect of the graphite undoubtedly helps the tool, its presence evidently cannot increase the actual softness of the metallic body with which it is mixed. But, on the other hand, if we increase the graphite by decreasing the combined carbon, then not only have we increased the amount of lubricant but we have, in addition, increased the softness of the metallic part of the mixture by reducing the proportion of cementite in it.

Graphite and Strength.—Everything else being equal, it is evident that, the more graphite we have in cast iron, the weaker it will be, for we have already shown that gray cast iron breaks by the ready splitting apart of the flakes of graphite. Thus, if we make no change in the combined carbon but increase the total carbon of our castings, and consequently the graphite, we should expect a corresponding decrease in strength, and this is in fact found to occur. When, however, we increase the graphite and at the same time decrease the combined carbon, we may or may not get an increase in strength, this depending altogether on how much combined carbon there was before and after the change. For example, if we had 3 per cent of combined carbon and 1 per cent of graphite in a casting, that casting would be weak because of too high combined carbon. To decrease this and increase the graphite would have a beneficial effect on strength. On the other hand, if we had 1 per cent of combined carbon and 3 per cent of graphite, to decrease the combined carbon and increase the graphite would have a detrimental effect on strength. We must therefore consider the question of strength from a much larger viewpoint than by considering any one constituent alone.

Combined Carbon and Shrinkage.—Combined carbon has very little effect on the shrinkage of cast iron except in so far as it changes the graphite. That is to say, if by increasing the combined carbon we decrease the graphite, we shall get an increase in shrinkage, and *vice versa.*

THE EFFECT OF SILICON, SULPHUR, PHOSPHORUS, AND MANGANESE ON PIG IRON

The constitution of cast iron is, furthermore, very complicated because of the double influence of silicon, sulphur, phosphorus, and manganese. Each of these elements has a direct influence upon the properties of the material, which is in general similar to its influence upon steel. For example, silicon produces freedom from oxides and blowholes and makes the iron more fluid; manganese counteracts the effect of sulphur and increases the difficulty of machining the material; sulphur makes the metal very tender at a red heat and therefore liable to checking if put under strain during this period. For example, if a casting in shrinking tends to crush the sand, this strain will be more liable to break it in case the sulphur is high. Sulphur also makes solidification take place more rapidly and causes blowholes and dirty iron. On the other hand, founders sometimes object to too low a content of sulphur on the ground that the iron is soft and low in strength. Phosphorus makes the metal very fluid and reduces its melting point. It also makes it more brittle under shock, especially when cold, and produces a fusible eutectic, a photomicrograph of which is shown in Fig. XIV-4. Phosphorus and sulphur increase the tendency to segregate.

Fig. XIV-4.—Phosphorus eutectic in cast iron. 1,000×. Etched with nital. (*Roy M. Allen, Trans., American Foundrymen's Association*, 1931.)

Furthermore, the various compounds of the impurities with iron and with each other, which we find in steel, are also found in cast iron. Indeed, some of them are far more important in the latter than in the former, because the amount of the impurities is greater. This is especially true of manganese sulphide and iron sulphide, for the sulphur in cast iron is often large in amount, while the manganese is often intentionally small on account of the difficulty which this element produces in the machining of the casting. Therefore we are even more liable to find iron sulphide in cast iron than in steel.

But the direct effect of these impurities is usually far less important than their indirect effect, *viz.*, their influence upon the carbon. After all, it is the carbon which is the chief factor in controlling the most important properties of the cast iron, and we may vary this by either increasing or decreasing the total amount, or else leaving the total amount the same, by increasing the graphite and decreasing the combined carbon, or *vice versa.* It is the ease with which we may vary the amount or the condition of the carbon, and therefore the properties of the iron, that is one of the most important advantages of the material. But, strangely enough, although it is easy to keep this control, it can never be accomplished in a direct way. It will be remembered that the blast-furnace manager can vary the amount of silicon and sulphur in his pig iron at will, that he has only a small control over the manganese and practically none over the phosphorus or carbon, but that the metal always saturates itself with this latter element; and it has also been seen that the limit of this saturation is small.

Silicon.—By means of his control over the silicon and sulphur, the metallurgist exercises indirectly his most important control over the condition of the carbon; for silicon acts as a precipitant of carbon, driving it out of combination and into the graphitic form, so that with about 3 per cent of silicon, slow cooling and very low sulphur and manganese, we may obtain a cast iron in which almost none of the carbon is in the form of cementite. That is to say, the presence of this amount of silicon acts so strongly that it will cause graphite to precipitate instead of cementite, it will cause the solid solution to precipitate with even less than 1.7 per cent of carbon, and it will also cause graphite to precipitate instead of cementite at 690°C. (1275°F.) when the eutectoid decomposes, so that it decomposes into ferrite and graphite instead of ferrite and cementite. The maximum precipitation of graphite seems to occur with about 2.5 to 3 per cent of silicon. With each increase of silicon up to that point (the amount of sulphur, the rate of cooling, and other influential conditions remaining the same), we get an increase in the amount of graphite precipitation; but when the amount of silicon exceeds about 3 per cent, it seems to reverse its effects, and each addition of silicon thereafter causes an increase in the proportion not of graphite but of combined carbon. At this point large amounts of various iron silicides (Fe_2Si, Fe_2Si_3, etc.) make their appearance. Then the color of a freshly broken fracture begins to be bright like a mirror, in contradistinction to the white color of ordinary white cast iron, which has more nearly the appearance of frosted silver.

Sulphur.—The influence of sulphur upon the formation of graphite is almost the exact opposite of the influence of silicon. That is to say, each increase in the amount of sulphur present increases the amount of combined carbon in the iron. It is usually considered that each 0.01 per cent of sulphur will neutralize fifteen times as much silicon (*i.e.*, 0.15 per cent) in its effect upon the condition of the carbon in the iron. It is also very important to note that when the sulphur is in the form of manganese sulphide, it is not so potent in increasing the combined carbon as when it is in the form of ferric sulphide. An interesting example of this is shown in the analysis of the two railroad-car wheels given in Table XIV-I.

TABLE XIV-I.—PROXIMATE ANALYSES OF CAST-IRON CAR WHEELS

	Fe	Total carbon	Si	Mn	P	S	Graphite-	Combined carbon
Good wheel......	94.79	3.84	0 69	0 13	0.43	0.12	3.30	0.54
Poor wheel......	95.00	3.52	0.65	0 12	0.52	0.19	2.35	1.17

Good wheel required 150 blows of 25-lb. sledge to break it. Poor wheel required 8 blow of 25-lb. sledge to break it.

TABLE XIV-II.—ULTIMATE ANALYSES OF CAST-IRON CAR WHEELS

Constituent	Good wheel, per cent	Bad wheel, per cent
MnS........................	0.206	0.195
FeS..............	0.121	0.315
FeSi........................	2.045	1.923
Fe_3P........................	2.755	3.335
Pearlite......................	67.610	84.492
Free ferrite..................	23.963	0.000
Free cementite................	0.000	7.390
Graphite......................	3.300	2.350
Totals......................	100.000	100.000

It will be observed that the poor wheel has more than twice as much iron sulphide as the good wheel, although the sulphur in the poor wheel is only about 50 per cent more than the sulphur in the good wheel, the other impurities being nearly the same. When we come to figure out the amount of manganese sulphide and ferric sulphide in the two wheels, we find, however, the explanation of the large amount of free cementite in the poor wheel. We also have an explanation of the poor quality of this wheel in the increased amount of ferric sulphide, iron phosphide, and absence of ferrite.

Manganese.—Manganese increases the total carbon in pig iron. Manganese also increases the proportion of the carbon that is in the combined form, but its influence in this respect is far less than that of the sulphur; moreover, the statement requires the following qualification: as much manganese as is combined with sulphur in the form of manganese sulphide does not increase the proportion of carbon in the combined form. Indeed, it has really the reverse effect, because it takes the sulphur out of the form of ferric sulphide, in which it is most powerful in increasing the combined carbon. In this sense, therefore, the manganese actually decreases the amount of combined carbon.

The excess manganese over that necessary to form manganese sulphide (*i.e.*, the manganese in the form of $(FeMn)_3C$) increases the proportion of carbon in the combined form and also increases the amount of total carbon even more potently than does the manganese which is in the form of manganese sulphide. We therefore have a strange contradiction, in that when the manganese is high an increase in sulphur will, by decreasing the amount of $(FeMn)_3C$, actually decrease the tendency of manganese to raise the total carbon as well as the combined carbon. To sum up: manganese and sulphur both tend to increase the total carbon and the combined carbon, and yet they neutralize each other in this respect.

Phosphorus.—The effect of phosphorus upon the carbon is somewhat self-contradictory; from a chemical standpoint it tends to increase the proportion of combined carbon, and this is especially true when the silicon is low and the phosphorus high (say above 1.25 per cent). But phosphorus also has the effect of lengthening the period of solidification. That is to say, it makes the iron pass through a somewhat mushy stage of solidification, and this mushy stage lasts for several minutes. This lengthening of the solidification period gives a longer time in which graphite can precipitate. Therefore, when the silicon is at least over 1 per cent, and there is consequently a tendency for graphite to precipitate during solidification, this precipitation is actually aided by the phosphorus, and the graphite occurs not only more abundantly but in larger-sized flakes. When, however, the amount of phosphorus is very large, its chemical effect is great enough to retain the carbon in the combined form, in spite of the long period of solidification. We may sum this up by saying that, if the chemical conditions are such that graphite is bound to precipitate, then the physical effect of the phosphorus makes this precipitation the more easy; but if there is enough phosphorus present to produce a strong chemical effect of its own, or if the other chemical influence is not very powerful (*i.e.*, if the silicon is low or sulphur is high), then phosphorus tends to keep the carbon in the combined form.

THE PROPERTIES OF CAST IRON

Let us now consider the properties of cast iron and summarize under the head of each the influence of the various elements and conditions upon them.

Shrinkage.—The shrinkage of cast iron is of more importance than might at first appear, because the greater it is the greater will be the strains set up in the cooling of the casting and consequently the liability to check; also, the greater will be the allowance necessary in order that the casting may be true to the size called for by the drawings. Graphite is the most important impurity in this connection, because of the expansion which its separation causes. This separation should take place at the moment of solidification but is usually not complete then, and therefore the precipitation continues during the fall of the temperature to several degrees below the freezing point. Furthermore, when the silicon is high, graphite instead of cementite separates at the lower critical point (*i.e.*, the line *PSK* in Fig. XI-9). As silicon, sulphur, and the rate of cooling are the chief influences which control the separation of graphite, they become the governing factors in the shrinkage of the iron. Indeed, when sulphur is practically normal and no other unusual conditions prevail, there is such a close relation between the size of the castings[1] and the percentage of silicon, on the one hand, and the

---

[1] Which is the chief influential feature in the rate of cooling.

amount of shrinkage, on the other hand, that any one of the three may be calculated when the other two are known.

Sulphur is important in this connection, and its effect is contrary to that of silicon, because of its tendency to retain the carbon in the combined form. Manganese and phosphorus each has a less important influence. Manganese, by increasing the total carbon, tends to increase graphite and therefore decrease shrinkage. As far as it neutralizes sulphur, moreover, its effect is in the same direction. But the direct chemical effect of manganese is to increase combined carbon and therefore to increase shrinkage when increasing combined carbon means to decrease graphite. Phosphorus decreases shrinkage, both because it contributes to the fluidity of the metal and therefore gives a better opportunity for carbon to separate and also because of the expansion caused when the phosphorus eutectic separates from solution. A hotter casting temperature of the iron has the effect of increasing combined carbon.

TABLE XIV-III.—RELATION OF SHRINKAGE TO SIZE AND PERCENTAGE OF SILICON

Silicon, per cent	½ in. square	1 in. square	2 by 1 in.	2 in. square	3 in. square	4 in. square	Perpendicular readings show decrease due to increase in silicon Horizontal readings show decrease of shrinkage due to size
1.00	0.183	0.158	0.146	0.130	0.113	0.102	
1.50	0.171	0.145	0.133	0.117	0.098	0.087	
2 00	0.159	0.133	0.121	0.104	0.085	0.074	
2 50	0.147	0 121	0.108	0.092	0.073	0.060	
3.00	0.135	0.108	0.095	0.077	0.059	0.045	
3 50	0.123	0.095	0.082	0.065	0.046	0 032	

A table showing the relation between the size of the casting, the amount of silicon, and the shrinkage is given above. Slight changes must be made in this table by each foundry for the conditions of sulphur, phosphorus, temperature, etc., obtaining there; but those given herewith will be found sufficiently accurate for all ordinary purposes where conditions are near normal.

Shrinkage Tests.—At many foundries it is the custom to make a shrinkage test of the iron from each cupola at least once a day. The simplest way of making these tests is to pour into a mold 12 in. long, with a sectional area approximately proportionate to the size of the castings made, some of the iron from about the middle of the cupola run. The casting must be poured flat, and the difference between 12 in. and the length of the cold bar is the shrinkage of the metal. This method is somewhat crude and, although it gives valuable results, has been greatly improved by W. J. Keep and Prof. T. Turner, who have devised simple and inexpensive pieces of apparatus whereby the iron, after it begins its solidification, draws a curve showing first the expansion and later the contraction. It is by means of Professor Turner's apparatus that the curves shown in Fig. XIV-3 were made. With very little care these curves can be obtained to show with sufficient accuracy for all ordinary purposes the percentage of graphite and also (other conditions being normal, or nearly so) the percentages of silicon and combined carbon, and the strength, hardness, and porosity. Indeed, the curves are more useful than many single tests, because they show at a glance the net effect of several varying conditions.

Density.—The maximum density of gray cast iron occurs with about 1 per cent of silicon. With less than that, the iron is liable to contain spongy spots, due to high shrinkage on account of low graphite. With more silicon the separation of graphite decreases density. Above 2 per cent of silicon, the grain of the iron becomes so open as to be actually porous and the density falls off by 12 per cent.

TABLE XIV-IV.—DENSITIES

	Specific gravity	Weight per cubic foot
Pure iron	7.86	490
White cast iron	7.60	474
Mottled cast iron	7.35	458
Light-gray cast iron	7.20	450
Dark-gray cast iron	6.80	425
Sample of gray cast iron when cold	7.17	448
Same, when liquid	6.65	416

Phosphorus has a double-acting influence on the porosity of cast iron: (1) it increases the size of the crystals, decreases shrinkage, and causes a large expansion after solidification, as explained in connection with Fig. XIV-3; but (2) it fills all the crevices between the crystals and in the interior of the iron, which, by decreasing the porosity, counteracts its first influence. When the phosphorus is high, the phosphorus and iron form a eutectic, which remains fluid for a long time and fills the tiniest crevices in the interior of the metal. For this reason, iron for hydraulic work may run up to 0.7 per cent of phosphorus, but above that the iron is liable to be weak and "cold-short," especially under impact. In fact, where very strong iron is desired, the phosphorus should be kept down to 0.4 per cent at most.[1]

Segregation.—A common cause of porosity in castings is segregation, or the collection together of impurities in spots. This segregation is the greater the greater the amounts of phosphorus, sulphur, manganese, and silicon. Phosphorus increases the segregation by making a fluid eutectic, which does not solidify until after the remainder of the casting but then runs into that part of the metal having the loosest texture. This part is usually in the middle of the larger sections of the casting, and, when the silicon is high and there are shrinkage spots, the segregation will be excessive in the neighborhood of these spots. Manganese and sulphur are also liable to collect in the same way and place. These localities, where the segregation is high, and which are known, when very bad, as "hot spots," are sometimes porous or surrounded by porous parts of the casting. They are sometimes so extremely hard that no tool will cut them. One way of getting rid of them is to use very large risers, or headers, which solidify last and serve as feeders for the remainder of the metal. Under these circumstances the segregation occurs in the riser and is thus temporarily removed. This method is not advisable as a regular practice, however, because these risers ultimately find their way back into the cupola as scrap and result in increasing the impurities in a subsequent set of castings.

Headers themselves increase the density of iron castings by feeding the metal and so preventing the porous spots, and also by keeping the metal under a pressure during solidification. This latter is especially serviceable when the phosphorus is high, which tends to make the metal expand during solidification, as has been shown.

Checking.—The time when a casting usually checks is when it is just above the black heat, when the metal is in a weak and tender condition and, as shown by Fig. XIV-3, is under strain

---

[1] See Table XIV-VII (p. 469).

because it is contracting upon the sand. Sulphur greatly increases weakness at this temperature, because both sulphide of manganese and sulphide of iron are now in a pasty condition and therefore offer very little resistance to breaking. The sulphide of iron is much worse, however, because this is spread out in thin plates or membranes which offer much more extended planes of weakness than the sulphide of manganese, which is in small spots or bubbles, resembling blowholes in its effect. Phosphorus, by decreasing shrinkage, decreases the liability of checking, but phosphorus has another influence, shown in the production of large-sized crystals, and in this respect it increases the liability of the metal to check.

Manganese, by decreasing the size of crystals, tends to counteract partially the effect of the phosphorus. The size of crystals can also be decreased to some extent by chilling the weak points and feeding them well under a head of metal. Feeding all localities liable to check has the double advantage of lessening shrinkage and segregation, both of which increase the liability to checking.

Softness, Workability, and Strength.—It is the combined carbon which is the great hardener of cast iron, the other elements producing hardness chiefly in proportion as they produce combined carbon, except manganese, which not only produces combined carbon but also produces a compound having the formula $(FeMn)_3C$, which is very hard and difficult to machine.

Silicon, by decreasing combined carbon, decreases hardness. When we get above 3 per cent of silicon, however, there begin to form new compounds with silicon which make the iron hard. Furthermore, silicon above 3 per cent increases combined carbon, instead of decreasing it.

The maximum softness of cast iron is obtained with about 2.5 to 3 per cent of silicon, the sulphur being not above 0.1 per cent and the manganese not above 0.4 per cent. In large or slowly cooled castings the silicon should be near the lower limit, and in small or rapidly cooled castings near the upper limit, in order that the combined carbon may be down below 0.15 per cent and the graphite more than 3 per cent. Such a cast iron would correspond to a soft steel, mechanically mixed with crystals of graphite. This soft steel would machine with great ease, and the graphite would act as a lubricant for the cutting tool. The mixture will have a transverse strength of about 2,000 to

2,200 lb., will be low in density and open in grain. To increase the strength without increasing the hardness, the best way is to cut the sulphur and phosphorus down to a low point, if possible, because sulphur and next to it phosphorus are the impurities which weaken iron most (aside from their influence on carbon). Another way is to decrease the total carbon, and hence the graphite, because graphite crystals, especially if large, are great weakeners of cast iron.

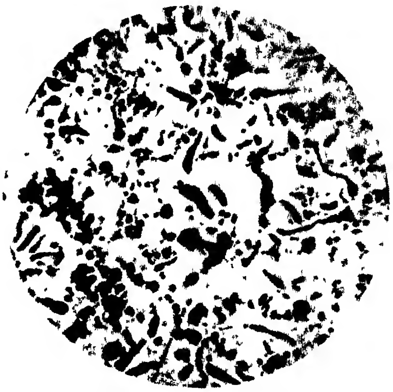


FIG. XIV-5.—Gray cast iron. 100 ×. Unetched. Contains 2.50 per cent Si. Shows crystals of graphite in a metallic background. (*C. A. Turner, Jr.*)

The strength of steel is more than double the strength of cast iron, the difference being due almost altogether to the graphite in cast iron, because silicon in itself (aside from its influence on the carbon) is a strengthener of both iron and steel up to at least 4 per cent.

To a slight extent the total carbon may be reduced by melting steel scrap with the iron, or by decreasing the amount of manganese, provided that the manganese left be always at least twice the sulphur; otherwise the iron will be weak and brittle.

The strength of cast iron may be increased by increasing the combined carbon, but this is done at the expense of softness and workability. Cast iron containing from 1.5 to 2 per cent of silicon (depending upon the size of the castings and rate of cooling), 0.9 per cent of combined carbon, 0.5 per cent of manganese, and not more than 0.08 per cent of sulphur and 0.3 per cent of phosphorus will work without difficulty in the machine shop and have a tensile strength of over 28,000 lb. per square inch. In many cases foundries are unwilling to go to the expense of such a low sulphur and phosphorus. In this case, the strength must be obtained by raising the manganese, which is not advisable, as it decreases the softness more than any other element and causes dull iron and high total carbon.

An important point in connection with the strength of cast iron is the size of the crystals of graphite—the smaller these crystals are the greater the strength, because the smaller are the planes of easy rupture. A notable example of this is malleable cast iron, which may have a tensile strength of 50,000 lb. per square inch, even when the percentage of graphite or temper carbon is as high as 3 per cent. The very small sized flakes of the temper carbon do not reduce the strength as much as the same amount of the larger graphite crystals.

It is believed by many that smaller graphite crystals are obtained by mixing different brands of iron in the cupola, even though the analysis of the mixture may be the same. This, however, is denied by others, and no reliable data exist upon which we can base a definite statement. It is also believed by many that, when the silicon is added to the cast iron immediately before pouring into the molds, the crystals of graphite are smaller than those formed when high-silicon irons are melted in the cupola. The practice of adding a small amount of ferrosilicon to the ladle of cast iron after it is received from the cupola is thus said to be doubly advantageous, because the silicon does not have to go through the cupola, where it suffers some oxidation, and it produces the desired softness by precipitating the graphite, but in a form which does not decrease strength so much.

TABLE XIV-V.—CAST-IRON STRENGTH AND WORKABILITY

	Silicon, per cent	Sulphur, per cent	Phosphorus, per cent	Manganese, per cent	Tensile strength, pounds	Transverse strength, pounds
Soft iron for pulleys, small castings, good tooling......	2.20 to 2.80	Not over 0.085	Not over 0.70	0.30 to 0.70	28,000	2,200
Medium iron for engine cylinders, gears, etc.........	1.40 to 2.00	Not over 0.085	Not over 0.70	0.30 to 0.70	30,000	2,500
Hard-iron cylinders for ammonia, air compressors, etc...	1.20 to[1] 1.60 1.60 to[2] 1.90	Not over 0.095	0.70 to 0.40	Not over 0.60	25,000	2,800

[1] If annealed.

[2] If cooled fast.

To obtain high transverse strength, the silicon should be about 0.2 per cent lower and the combined carbon about 0 2 per cent higher than the figures given for tensile strength. Otherwise the effects are very similar.

Chills.—In the making of cast-iron rolls, railroad-car wheels, anvils, etc., at least one surface of the casting is desired to have great hardness, to resist wear, and to be backed by metal which shall be stronger and not so brittle. This is accomplished by chilling the surface which it is desired to harden and so producing white cast iron to varying depths, regulated at the will of the foundrymen. The making of this kind of casting is one of the most difficult problems of cast-iron metallurgy. The metal must be very close to the given composition, and the temperature of the mold, of the chill, and of the metal when cast must be regulated with care. Therefore, air furnaces are often employed for melting in this class of work, or else uniform conditions of cupola melting are maintained with great care, and very little, if any, scrap which must necessarily be of somewhat uncertain analysis is used, except the return scrap from the

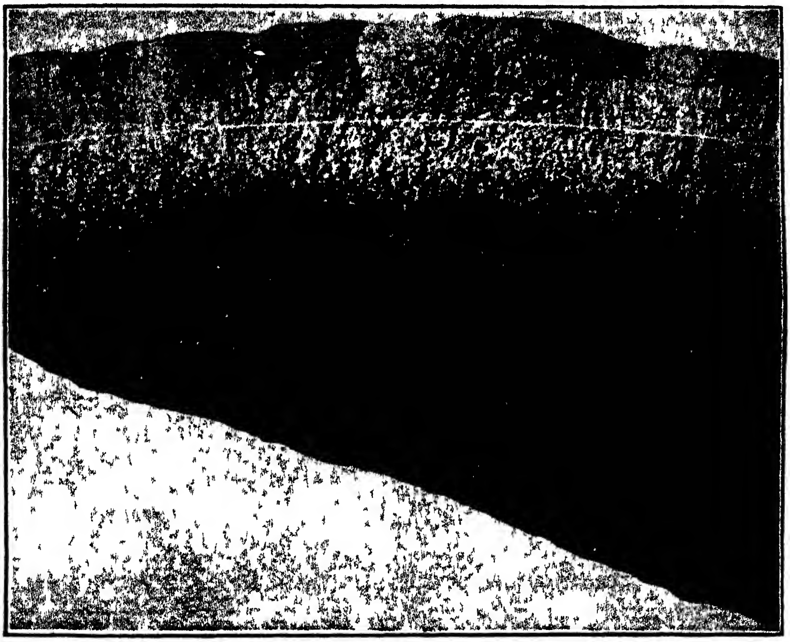


FIG. XIV-6.—Method of measuring the depth of clear chill in a cast-iron roll.

foundry itself, *i.e.*, defective castings, sprues, gates, shot-iron spillings, etc., and also scrap castings of like nature, such as worn-out car wheels and broken rolls. The most important factors in regulating the depth of the chill are the silicon and the sulphur, and in the following table is given the depth of clear chill from the surface for several different percentages of silicon and sulphur. The figures here given must be taken as only approximations, as they will vary to an important extent with different conditions in each foundry; but, starting with this as a basis, one can quickly prepare a table for himself to suit the practice in his foundry. Phosphorus has very little effect on the depth of chill, and manganese is also relatively less effective, although it increases the hardness of the chilled portion. The hotter the iron when cast, the deeper the chill.

TABLE XIV-VI.—DEPTH OF CLEAR CHILL FROM SURFACE IN INCHES

Silicon, per cent	Sulphur, 0 2 per cent	Sulphur, 0 15 per cent	Sulphur, 0 1 per cent	Sulphur, 0 075 per cent	Sulphur, 0 05 per cent
1 25	0 625	0 250	0 125	0 000	0 000
1 00	1 000	0 625	0 250	0 125	0 000
0 75	1.500	1 000	0 625	0 250	0 125
0 50	.....	1 500	1 000	0 625	0 250
0 40	.. ..	.....	1 250	1 000	0 625
0 30	.....	.. ..	.	1 500	1 000

Casting Temperature of Iron.—The strength of cast iron is materially affected by the temperature at which it is cast. Langmuir found that the tensile strength of iron, when cast too hot, was 33 per cent less, and when cast too cold was 26 per cent less, than the same metal cast at the correct temperature. For the cast iron with which he experimented, the correct temperature of casting seemed to be in the neighborhood of 1230°C. (2246°F.).

Recommended Analysis.—Dr. Richard Moldenke,[1] from a wealth of experience in making iron castings in a consulting capacity, suggests the percentages given in Table XIV-VII.

High-strength Cast Iron.—Recent innovations producing cast iron of extra high strength, even though not in the class of alloy cast irons, are discussed in Chap. XVI.

---

[1] *Proceedings American Society Mechanical Engineers*, vol. 42, p. 170, 1920.

TABLE XIV-VII.—RECOMMENDED ANALYSES FOR VARIOUS CLASSES OF CASTINGS

Castings	Light					Medium					Heavy				
	Si	Mn	S	P	T.C.	Si	Mn	S	P	T.C.	Si	Mn	S	P	T.C.
Acid resisting	2.00	0.75	0.05*	0.20*	3.25*	1.50	1.25	0.05*	0.20*	3.25*	1.00	1.25	0.05*	0.20*	3.25*
Agricultural	2.50	0.60	0.06	0.75	3.75	2.25	0.70	0.08	0.70	3.50	2.00	0.80	0.10	0.60	3.25
Air cylinders	1.90	0.70	0.08	0.50	3.40	1.50	0.80	0.09	0.40	3.25	1.00	0.90	0.10	0.30	3.00
Annealing boxes	....	....	....	....	....	0.65	0.20	0.08	0.20	3.50					
Automobile cylinders	2.25	0.65	0.08*	0.40*	3.25*	2.00	0.75	0.08*	0.40*	3.25*					
Balls for grinding	....	....	....	....	....	0.75	0.50†	0.15*	0.40*	3.75†	0.50	0.50†	0.15*	0.40*	3.75†
Bedplates	2.00	0.70	0.08	0.60	3.75	1.75	0.75	0.10	0.50	3.50	1.50	0.80	0.12	0.40	3.25
Boiler castings	....	....	....	....	....	2.00	0.80	0.06*	0.20*	3.50*					
Car wheels	....	....	....	....	....	....	....	....	....	....	0.65	0.50	0.08	0.35	3.50
Chilled castings	....	....	....	....	....	....	....	....	....	....	....	1.00	0.06*	0.20*	3.50*
Chills	....	....	....	....	....	1.00	0.50	0.05	0.20	3.00					
Crusher jaws	....	....	....	....	....	1.00	1.00	0.04	0.20	3.50	0.80	1.25	0.06	0.20	3.25
Dies for hammers	....	....	....	....	....	1.50	0.60	0.05	0.20	3.00	1.25	0.80	0.06	0.20	2.75
Dynamo castings	2.50	0.50	0.05	0.75	3.75	....	....	....	....	....	2.15	0.50	0.06	0.50	3.25
Electrical work	3.00	0.50	0.03	0.60	3.75	2.75	0.50	0.05	0.50	3.50					
Engine frames	....	....	....	....	....	2.00	0.60	0.08	0.50	3.50	1.75	1.00	1.10	0.40	3.00
Fire pots, grates	2.25	0.60	0.05	0.20	3.50	2.00	0.80	0.06	0.20	3.25					
Flywheels	2.00	0.50	0.05	0.50	3.50	1.50	0.60	0.06	0.40	3.25	1.25	0.70	0.08	0.30	3.25
Friction clutches	2.40	0.60	0.10	0.70	3.75	2.00	0.70	0.12	0.50	3.50					
Furnace castings	2.40	0.60	0.05	0.60	3.75	2.15	0.80	0.06	0.50	3.50					
Gas-engine cylinders	2.00	0.70	0.08	0.40	3.25	1.50	0.80	0.09	0.30	3.00	1.25	0.90	0.10	0.20	2.85
Gears	2.25	0.60	0.08	0.70	3.75	2.00	0.80	0.09	0.60	3.50	1.50	1.00	0.10	0.50	3.25
Glass molds, pipe balls	....	....	....	....	....	2.50	0.60	0.04	0.20	3.25					
Grate bars	....	....	....	....	....	2.00	0.60	0.05	0.20	3.50					
Gun iron	....	....	....	....	....	1.50	0.50	0.05	0.30	3.25	1.00	0.60	0.05	0.30	3.00
Hardware	2.50	0.70	0.08	0.80	3.75										
Heat-resistant iron	....	....	....	....	....	2.00	0.80	0.06	0.20	3.25	1.50	1.00	0.06	0.20	3.00
Hydraulic cylinders	....	....	....	....	....	1.50	0.80	0.05	0.40	3.25	1.00	1.00	0.08	0.20	2.85
Ingot molds	....	....	....	....	....	....	....	....	....	....	1.25	0.80	0.06	0.20	3.75
Machinery castings	2.50	0.60	0.08	0.70	3.75	2.00	0.80	0.09	0.60	3.50	1.50	1.00	0.10	0.50	3.25
Mine wheels	....	....	....	....	....	0.90	1.00	0.10	0.20	3.00					
Ornamental castings	2.75	0.60	0.06	0.90	3.75	2.25	0.70	0.08	0.80	3.50					
Pipe (water)	2.25	0.60	0.06	0.80	3.75	2.00	0.80	0.08	0.70	3.50	1.50	1.00	0.10	0.60	3.50
Piston rings	2.00	0.70	0.05	0.60	3.50	1.75	0.80	0.06	0.50	3.25					
Pulleys	2.40	0.50	0.05	0.70	3.75	2.15	0.60	0.07	0.60	3.50	1.90	0.70	0.09	0.50	3.25
Radiators	2.25	0.70	0.06	0.80	3.50										
Rolls (chilled)	....	....	....	....	....	....	0.80	0.06	0.40	3.25	....	1.00	0.08	0.30	3.00
Soft castings	2.60	0.50	0.06	0.60	3.75	2.40	0.60	0.08	0.50	3.50					
Soil pipe	2.25	0.60	0.08	0.80	3.75	2.00	0.80	0.10	0.60	3.50					
Steam cylinders	2.00	0.60	0.08	0.50	3.50	1.60	0.80	0.09	0.40	3.50	1.25	1.00	0.10	0.30	3.50
Stove plate	2.50	0.50	0.06	1.00	3.75	2.25	0.60	0.08	0.80	3.50					
Valves	2.25	0.60	0.07	0.50	3.25	1.75	0.80	0.08	0.40	3.00	1.25	1.00	0.09	0.30	2.85
White-iron castings	....	....	....	....	....	0.75*	0.20†	0.25*	0.75*	2.50†					

* Below.
† Above.

References

J. E. HURST: "Metallurgy of Cast Iron," London, 1926.

WILLIAM H. HATFIELD: "Cast Iron in the Light of Recent Research, 2d ed., London, 1918.

EUGEN PIWOWARSKY: "Hochwertiger Grauguss," Berlin, 1929.

CHAPTER XV

MALLEABLE CAST IRON

Malleable cast iron has physical properties between gray iron and steel castings. Its tensile strength will vary between 50,000 and 60,000 lb. per square inch with an elongation of 10 to 15 per cent in 2 in. and a reduction of area of 5 to 12 per cent.[1] In a transverse test, a 1-in. square bar on supports 12 in. apart should bear a load at the center of at least 3,000 lb. with a maximum deflection of ½ in.; the maximum load may go as high as 5,000 lb. and the deflection up to 2 in. or more. In respect of its resistance to repeated stresses and to blows which flatten the face of the material without extending their influence very deep, malleable cast iron is especially valuable. It also has malleability and (when very thin) is capable of being flattened out or bent double without cracking. A good test for malleable cast iron is the so-called test lug shown in Fig. XV-1. It is bent over in the form of a curled-up shaving by light blows of a hammer, beginning at the knife edge. The distance along the test wedge that the piece will bend before it begins to break, and especially the maximum angle produced, will give a good idea of the softness.

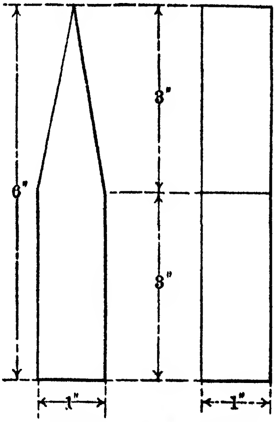


FIG. XV-1.—Test lug for malleable cast iron.

Malleable iron castings are used very largely for railroad work. They have long been used for couplers but are now being replaced to some extent by steel castings for this purpose. On the other hand, malleable cast iron is replacing gray cast iron for other parts, such as journal boxes. Malleable cast iron is also used very largely for parts of agricultural machinery, for

---

[1] In the case of malleable cast iron very carefully melted and annealed in iron oxide, the elongation and reduction of area may exceed these figures.

pipe fittings—*i.e.*, elbows, unions, valves, etc.—for household and harness hardware, and for a great variety of work where many castings are to be made of the same pattern, especially castings of small size. Even hammers, hatchets, skates, wood chisels, etc., are often made of "black-heart" malleable cast iron.

Process of Manufacture.—The process, which was invented by Réaumur in 1722 but has only been in practical use about one hundred years, and of importance less than fifty, is still followed out in substantially its original form in England and Europe to make what is known as "white-heart" malleable castings. In America this process has been modified to make the so-called black-heart castings, as follows: The metal is melted and cast into molds of the desired shape and size, and after cooling its fracture will be entirely white, or else white with a small area of mottled iron in the center of pieces 1 in. thick or heavier. In short, the composition of the metal is such that it is just on the line between the precipitation of graphite and its retention in the form of cementite and dissolved carbon. In all cases the majority of the carbon must be dissolved or combined. After careful cleaning, the castings are reheated

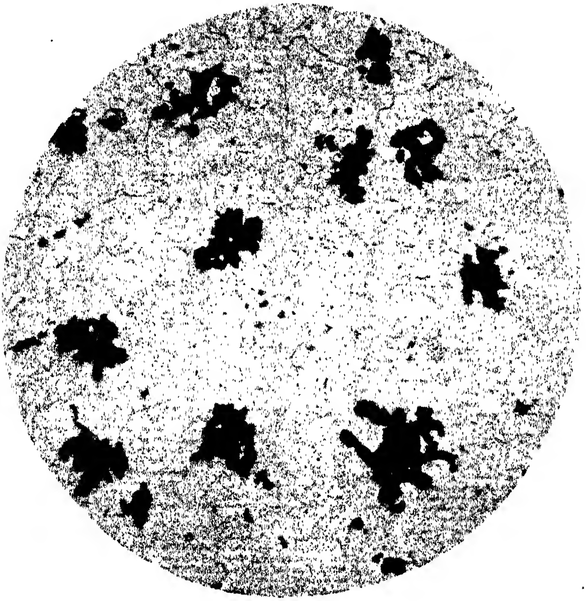


Fig. XV-2.—Annealed malleable cast iron. 100×. Unetched. (*Roy M. Allen.*)

to a temperature of 625 to 875°C. (1250 to 1600°F.), which is roughly 450°C. below their melting point. They are kept at this temperature for some 60 hr. and under these conditions occurs the precipitation of graphite, which normally should have occurred during the first cooling. In the majority of cases almost all the combined carbon throughout the body of the casting is changed to graphite. But the graphite does not here form in flakes, as in ordinary gray cast iron, but in a finely comminuted condition, like a powder, to which the name of "temper carbon" or "temper graphite" is given (see Fig. XV-2). In this form it is not nearly so weakening or embrittling to the casting as flakes of graphite would be.[1]

A broken fracture of such an annealed casting will have a black center with a rim of white, $\frac{1}{64}$ to $\frac{1}{16}$ in. thick around the outside. The dark center owes its appearance to the precipitated temper carbon, and the white outer rim consists of iron from which the carbon has been not only precipitated but actually removed.[2] That is, the metal of this outer rim corresponds to a soft steel impregnated with a great number of tiny cavities formerly occupied by carbon, which act as a cushion to shocks and battering blows of service. This outer rim is the portion of the casting in which the metallic crystals have formed perpendicularly to the cooling surface. The crystalline form in this location favors the reaction for the mechanical removal of carbon which will be explained later.

The Manufacture of Réaumur, or White-heart Malleable.—In the original, and present European, process of making malleable castings, they are made very thin; they are then annealed at the higher temperatures given above and for a period nearly twice as long, with the result that the conditions described above as prevailing in the outer rim extend here throughout the entire casting. In short, the carbon is mechanically removed, even from the center portion. White-heart castings are not so strong as black heart and rarely, if ever, are above $\frac{1}{2}$ in. in thickness.

Manufacture of All-black Castings.—In America, pipe fittings and other castings not requiring much strength are sometimes

---

[1] We may liken this to two samples of putty, in one of which had been embedded a large number of plates of mica, and in the other the same amount of mica ground to powder.

[2] By the material in which they are packed according to the following reaction: $3C + Fe_2O_3 = 3CO + 2Fe$.

annealed in lime, fire clay, or some other substance which decarburizes only a thin skin of the metal. This results in the carbon's being deposited as temper carbon but not being removed. The castings are several thousand pounds per square inch lower in tensile strength and have substantially no white rim.

Iron Used.—The analysis of the "hard castings," *i.e.*, the white castings before the annealing process, should run as in Table XV-I. This analysis is obtained by mixing pig iron with varying amounts of cast iron and steel scrap.

Not more than about 20 per cent of bought scrap is used on the average in American practice, and a good deal of this is steel, on account of the desirability of lower total carbon, and because iron scrap is too impure, too variable, and too uncertain in sampling and chemical analysis for castings requiring strength, such as those for railroads and machinery. There is, however, always a large amount of "return scrap" from the foundry, consisting of defective castings, sprues, gates, etc., which, in the case of small castings, may be greater in weight than the castings themselves. This return scrap is low in total carbon and silicon and high in sulphur, as a result of having already suffered the melting changes. Steel scrap is, of course, a prime factor in reducing the total carbon. The return scrap should all be cleaned from adhering sand to avoid difficulty in melting. The pig iron bought for malleable-iron work is known in the trade under the name of "malleable Bessemer."

TABLE XV-I.—ANALYSES OF "HARD CASTINGS" FOR MALLEABILIZING

	If melted in cupola	If melted in air furnace or open hearth
Silicon, per cent	0.75 to 1.25	0.45 to 1.00
Manganese, per cent[2]	0.20 to 0.60	0.20
Phosphorus, per cent[1]	under 0.225	under 0.225
Sulphur, per cent[1]	0.04 to 0.30	0.04 to 0.07
Total carbon, per cent	about 2.75	about 2.75

[1] In European practice the phosphorus and sulphur are often much higher than this.

[2] The manganese must be at least twice the sulphur.

Silicon.—The proportion of silicon will depend upon the size of the casting and the amount of total carbon, because the greater each of these is the less will be the amount of silicon that will cause a precipitation. Furthermore, cupola metal requires higher silicon by about 0.25 per cent than air-furnace metal because of the difficulty with which it yields to the annealing operation. It might at first appear that the less silicon the better, but this is not altogether so, because temper carbon will not come out during annealing unless a certain amount of silicon is present; and the more there is the more quickly, easily, and completely will the precipitation occur. For air-furnace castings 1 in. thick the silicon may be as low as 0.35 per cent, but this is unusual, as ¾ in. thickness is rarely exceeded. For ½-in. castings the silicon will be about 0.90 per cent, and for very thin and light castings with low total carbon and high sulphur (say 0.2 to 0.3 per cent) the silicon may be up to 1 per cent. To the percentage of silicon desired in the castings, we must add the amount which will be burned out in melting. In the cupola this will be about 0.2 to 0.25 per cent, and in the air furnace from 0.15 to 0.5 per cent, depending on the length of time the metal is kept in the furnace after melting. The hotter we want the iron, the longer this time must be, and therefore the higher the silicon in the original mixture charged.

Sulphur.—Sulphur increases the tendency of castings to check, which is especially important in malleable work on account of the contraction of white iron being nearly double that of gray iron. Sulphur also reduces the strength and the ease of annealing. For this reason over 0.06 per cent should not be permitted in castings requiring strength, but it actually runs up to 0.2 and 0.3 per cent in inferior metal, in both America and England, and especially in small castings, which do not need strength so much, and which, having less length for contraction, are not so liable to be checked by cooling strains.

Manganese.—Low manganese is preferred by many foundries, and one of the highest authorities in America places the limit at 0.3 per cent. It should be remembered, however, that the manganese should be at least twice the sulphur, and preferably three times, except when the sulphur is as high as 0.3 per cent. Manganese of 0.5 per cent tends to decrease checking. It also protects silicon from oxidation during both melting and annealing and on this account hastens and makes more complete the precipitation of temper carbon. It also protects the iron itself from oxidation during annealing and thus prevents the formation of "scaled" castings. More than 0.6 per cent of manganese makes the iron hard and difficult to machine, which is disadvantageous, especially for pipe fittings, which must be threaded with great economy in order to meet the trade competition. It also makes the castings difficult to anneal.

Phosphorus.—Phosphorus makes the metal fluid, which is especially desirable where total carbon and silicon are low, or where sulphur and manganese are high. On the other hand, it diminishes two of the most valuable properties of the material: its malleability and resistance to shocks. It also makes the metal hard, difficult to machine, and liable to check, and amounts over 0.225 per cent should never be permitted by engineers where the castings are subjected to strain.

Total Carbon.—Total carbon below 2.65 per cent gives trouble in annealing and therefore makes the castings weak. It also makes the metal more sluggish. In air-furnace practice the total carbon may be reduced as much as necessary, but it is difficult to keep carbon out of iron in cupola melting. By mixing in large percentages of steel scrap and allowing the metal to run from the cupola as fast as melted, we may get total carbon slightly below 3 per cent. The annealing process also removes carbon, even in the interior of thin castings. The lower the total carbon in annealed castings, the better the quality.

Melting in the Air Furnace.—The commonest melting furnace for malleable cast iron is the air furnace. After the metal is melted, it is retained in this furnace for 15 min. to 1 hr. longer, and test ingots are poured at intervals, from the fracture of which and the temperature of the iron we determine the correct moment for tapping. The fracture of the test plug should be a clear white throughout, except when the castings are to be of very light section, in which case the metal might be tapped when the test sample shows a few specks of graphite in the center. The practice of judging from test plugs is different in each foundry, but there must be some system which insures that the metal shall be of such a composition when tapped that the castings will have not more than a trace of graphite if any at all (say less than 0.15 per cent in small castings and a little more in larger ones). If more than this the annealed castings will be very weak, almost "rotten."

The diameter of the test plug should be at least as large as any section of casting that is to be poured. The usual size is 1½-in. diameter.

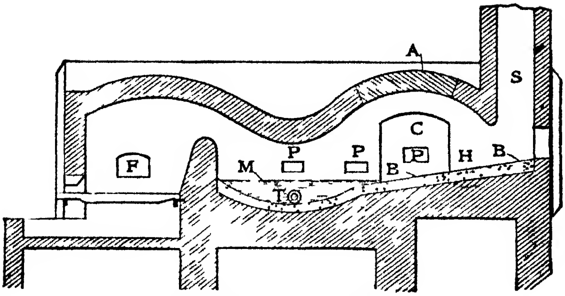
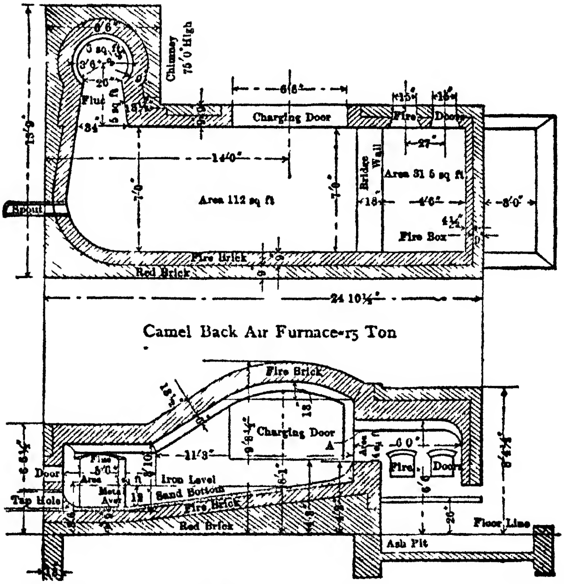


Fig. XV-3.—Air furnace.


Camel Back Air Furnace-15 Ton

Figs. XV-4 and XV-5.—Air furnace.

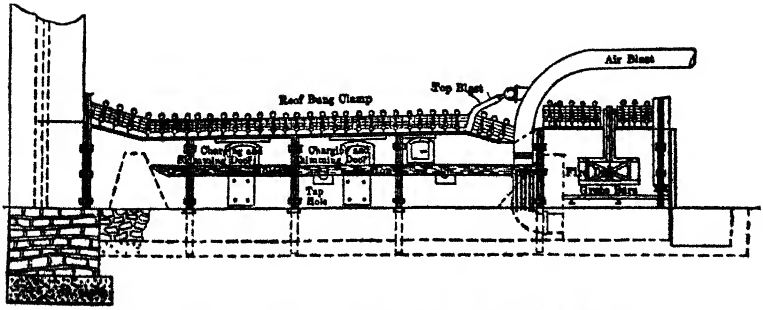
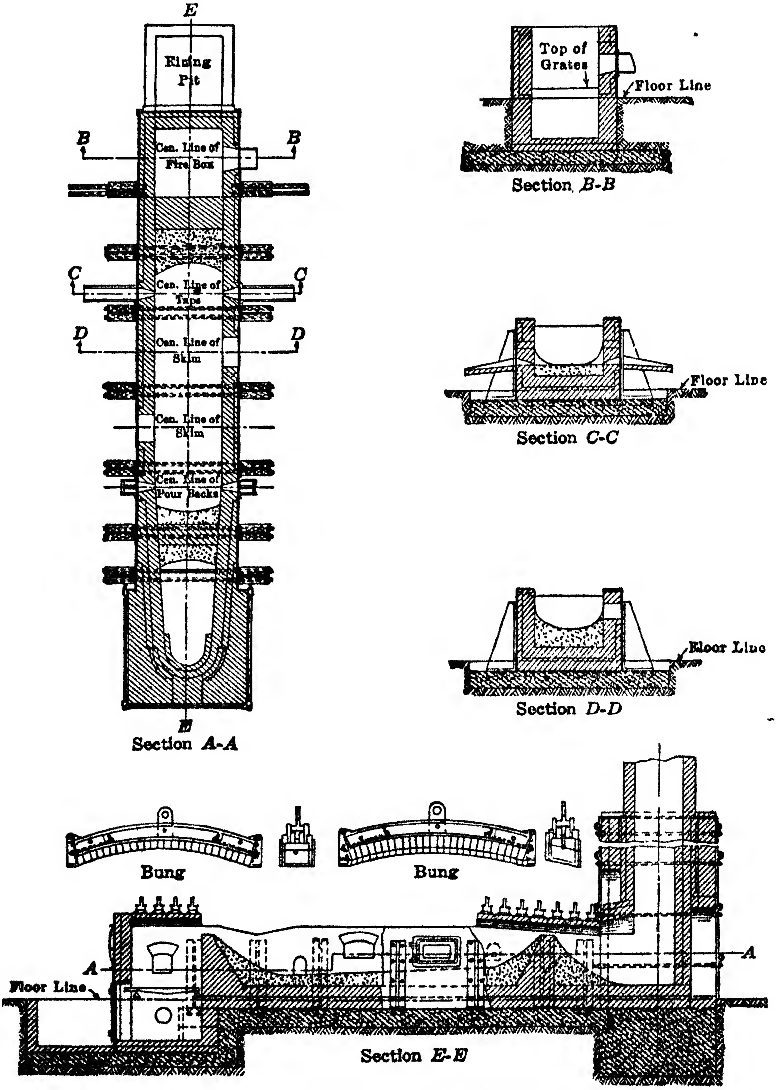


Fig. XV-6.—Air furnace with bungs and forced draft.

Air Furnace.—The air furnace is a reverberatory furnace on the hearth of which pig iron is melted by radiation from the flame of a pulverized coal burner, or of a soft-coal fire, or, more rarely, from a gas flame. The furnace is charged by means of a large side door, or by removing the roof in sections bound together



Figs. XV-7 to XV-11.—Details of air furnace.

with iron, or by taking out the end; and in some cases, to effect an economy in labor, mechanical devices are employed for charging. Several designs of air furnaces are shown in Figs. XV-3 to XV-11 inclusive.

Lining.—The lining of the bottom is made of silica sand of about the same composition as the acid open-hearth furnace, *i.e.*, containing 95 per cent or more of silica, with just enough lime to frit the mass together at the heat of the furnace. A layer about 1 to 2 in. thick is spread all over the hearth and then set on as described in the chapter dealing with the open-hearth process. About five layers are put on in this way, and the bottom lasts on an average of 6 to 12 heats, although some foundries regularly make up a bottom after the third heat; and in other cases the bottoms last as many as 30 heats. Longer life will be obtained if the material is charged carefully so as not to break the sand, and if a strongly reducing flame is maintained during the melting period, when there is not a bath of liquid iron to protect the bottom from the corrosive iron oxide. Mixing broken fire bricks of good quality and refractoriness with the sand seems to give more durable bottoms.

Charging.—The sprues and small scrap are first charged and spread evenly over the hearth and next the pig iron is piled in carefully. The roof of the furnace not being high, the pig iron must be stacked in order to get the necessary amount into the available space. Moreover, when the pig iron is stacked individual pigs can be pushed down into the liquid bath from time to time so that it will not all melt together. Thus it can be handled more easily and the slag comes up better. The steel scrap is charged after the pig and scrap are melted and the slag has come up. This prevents the steel scrap from being oxidized.

Conduct of the Operation.—The purpose of the furnace is to melt the iron and bring it to the proper temperature for casting. Some refining by oxidation is unavoidable, but this is not an intentional feature and the object should be to get the desired analysis by mixing pig iron, scrap, and steel and not by the oxidation of silicon and carbon. A long time in the furnace after melting is especially to be avoided, as the iron is liable to be oxidized and the silicon reduced below the desired point, making the iron "high." After the slag is up, it should be skimmed off, and this may be repeated once or twice. When the test plug shows large, clear, white crystals without any pin holes on the rim and only a slight amount of mottling, the bath is ready to tap. If there are pin holes in the rim of the test plug, it indicates that the metal has been "burned," as it is called. It will usually be dull and there may even be gas in the metal, in which case the iron should be poured into pigs and used over again in small amounts in subsequent heats. If the test plug is mottled, it shows either that the silicon is too high or that the temperature is not high enough, for it will be remembered that the colder the iron the more likely is graphite to separate and *vice versa.* If the iron is too "high," on the other hand, some ferrosilicon should be added and rabbled into the bath. The smaller the castings, the more rapidly will they be chilled and therefore the more silicon should we have in the metal.

American furnaces usually vary in size from 10- to 45-ton capacity, but they are built as small as 3 tons. It takes from about 3½ to 9 hr. to melt down a charge of from 5 to 35 tons, respectively, and the waste of metal by oxidation will be about 2 to 5 per cent of the charge.

Tapping the Charge.—The more rapidly the metal can be gotten out of the furnace and poured, the more uniform will be its composition. Moreover, the metal at the top of the bath is hotter than that at the bottom. For this reason, in many furnaces, there are additional tap holes at a higher level, which are opened first, and also holes on both sides of the furnace which are used simultaneously.

Cupola vs. Air-furnace Melting.—Cupolas used for melting malleable cast iron are similar to those already described but the amount of fuel is larger than for most gray-iron work on account of the higher melting point of the iron and the very small size of castings into which it is usually poured. The fuel ratio will be about one of coke to four of iron.

The advantages of the cupola for malleable cast-iron work are: (1) we get metal having practically the same composition at all times of the heat except the slightly higher sulphur at the beginning and end; (2) the temperature is more uniform throughout the heat; (3) it is cheaper to install and operate and requires less skill for melting labor; (4) it can be started and stopped more readily; (5) we can get hotter iron without prolonging the heat with the resultant danger of burning which exists in the air furnace.

The advantages of the air furnace are: (1) there is not so much sulphur absorbed; (2) with proper manipulation there is not so much liability for the metal to be burned except just at the thin edge of metal near the fire bridge; (3) the metal anneals more easily and is stronger; (4) it is also easier to get a lower total carbon by proper mixing since there is no contact between coke and iron, and therefore not so much opportunity for absorption of carbon; (5) we can work closer to a desired analysis in the air furnace than we can in the cupola.

This last circumstance, as well as the lower sulphur, is the reason why air furnaces are so largely used also for melting what is known as chilled iron castings, such as rolls. The analysis of this chilled iron must be so closely confined within limits that the outside may be white iron where it comes in contact with metallic chills and the interior consist of gray cast iron.

The explanation of the more difficult annealing experienced with cupola metal over air-furnace and open-hearth metal has never been made entirely clear. In general, cupola metal is high in sulphur which opposes annealing, but it is believed that even when the metal is of the same analysis in sulphur it requires at least 150°F. higher temperature to anneal it. Another circumstance in cupola metal is that it is usually higher in total carbon. Consequently, the carbon must be more strongly held in combination to prevent some of it precipitating as graphite in the hard castings. This condition may cause it to yield less completely to the annealing process.

Open-hearth Furnaces.—Open-hearth furnaces of small size, but in other respects like the open-hearth steel furnaces, are used for melting iron for malleable castings in a few important foundries in the United States. The great drawback of this furnace is that it should be operated continuously, day and night, which means more floor space on which to set molds ready for pouring, because molding cannot well be done during the night, as the artificial light casts shadows that make the work of finishing up molds more difficult and confusing.

The advantage of the regenerative open-hearth furnace over the air furnace is better control of the operation and especially of the temperature, shorter heats, and greater fuel economy. The average time of melting in the open-hearth furnace will be 2½ hr. for a 10-ton heat, and 4 hr. for one of 20 tons. The amount of fuel is about 300 to 350 lb. per ton of iron, or twice as much if melting only on the day turn. The lining will certainly last much longer on account of the better control of the character of flame. Moreover, oil can be used for melting in a regenerative furnace, because it is introduced into a very hot atmosphere, which is not practicable in the air furnace, since the fuel condenses in the cooler atmosphere of this furnace, especially when the furnace is cold or when there is a cold charge on the hearth. The disadvantages are high cost for installation, more skilled labor, and more repairs. Open-hearth linings are best made of dolomite, which enables a basic slag to be produced in the furnace and a reduction in phosphorus and sulphur. Cheaper pig iron and iron scrap can then be used. This basic lining is not attacked by the iron oxide and slag produced in melting and will last for hundreds of heats if not allowed to cool off too frequently. Basic linings cannot be employed in air furnaces because dolomite contracts and expands so much on cooling and heating that the bottoms are soon cracked to pieces, for air furnaces are not operated continuously.

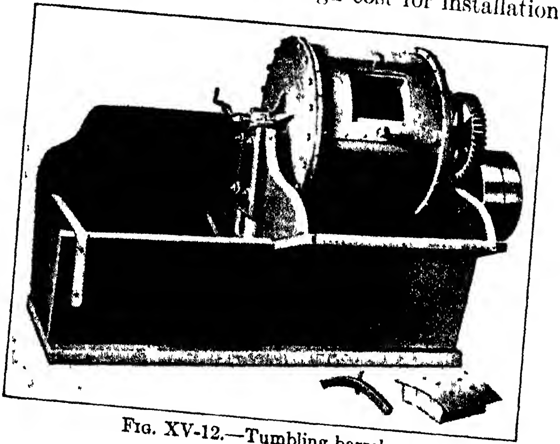


FIG. XV-12.—Tumbling barrel.

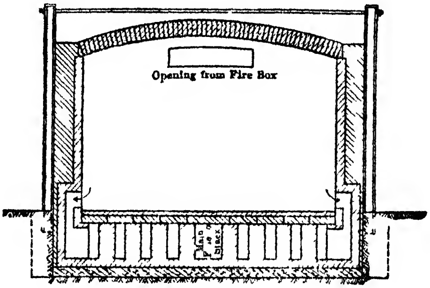
Electric Furnaces.—Electric furnaces have recently been used for melting malleable cast iron. They have the advantage already mentioned of greater flexibility in temperature control.

Molding and Pouring.—Malleable-iron castings are usually made in great quantities from the same pattern, so that this industry offers a special field for molding machines, match plates, etc. It is also a type of molding in which a great many cores are used and especially cores of small size, so that core-making machines are especially advantageous where applicable. The gates and sprues are usually large in size because the metal has a relatively high melting point and is consequently more liable to chill. For the same reason the metal is poured into the mold as fast as possible and the great bulk of the work is done with hand ladles holding 40 or 50 lb. apiece.

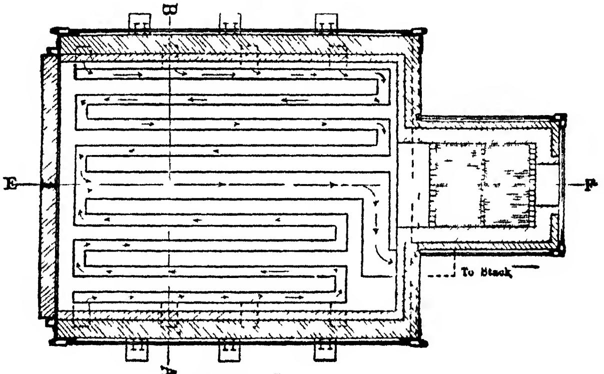
Annealing Boxes.—After the castings are cooled, they are carefully cleaned from all adhering sand by tumbling them around in a tumbling barrel (in which they are mixed with star-shaped pieces of metal something like children's jackstones), or by sandblast, or by some other suitable method. They are then packed in the cast-iron or steel "saggers" or annealing pots, or boxes, together with the packing. Sometimes, though rarely, the tops of the saggers are closed by means of an iron cover, sometimes by a thick layer of the packing in the upper part, and sometimes by clay or wheel swarf. These pots last only from 7 to 20 heats before they are largely oxidized away.

Annealing Ovens.—The boxes are then placed in the annealing ovens in such a way that the flame may play around them as completely as possible. The general form of ovens is shown in Figs. XV-13 to XV-15. The flame usually comes in at the top and goes out at the bottom along the side, and thence through flues underneath the oven. The fuel used may be coke, coal, oil, or gas, the last being preferable on account of the better control of the temperature, which should be increased at a very gradual and uniform rate during the heating up and kept as constant as possible during the annealing period.

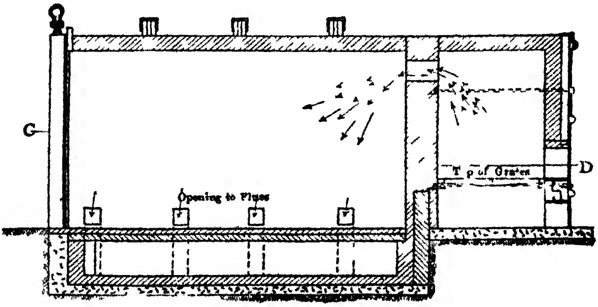
Annealing Practice.—It takes about six and one-half days for the American annealing operation, including heating up and cooling down. Sometimes this can be shortened a little by decreasing the time at the full annealing heat and by cooling rapidly or drawing the saggers out of the oven and dumping them while the contents are still at a dull-red heat. This practice is not conducive to a good quality of castings and should never be permitted in important cases. The time at the full heat should never be less than 60 hr. and preferably it should be more than that. If less, the temperature of annealing must be higher, and this decreases the strength and ductility of the castings. Annealing should not occupy too long a time, however, because the temper carbon tends to draw together to larger flakes; besides which the metal may become overannealed or else oxidized between the grains, *i e*, "burnt." Air-furnace castings should be annealed at 675 to 760°C. (1250 to 1400°F.), and cupola metal at 825 to 875°C. (1500 to 1600°F.). The saggers are cooled as slowly as possible in the furnace; when they are at a black heat they are removed, cooled further, and then dumped.



Section A-B
Cross Section.



Section C-D
Horizontal Section



Section E-F

Figs. XV-13 to XV-15.—Malleable-cast-iron annealing furnace.

Packing.—As originally planned, the castings were annealed in a packing of iron oxide crushed to a size less than a quarter of an inch in diameter. The packing must surround the castings at every place, both inside and out, and no two castings must touch. Iron ore, mill scale, "bull-dog," and similar forms of iron oxide are used for this purpose.

Annealing in iron oxide produces a white skin where the casting has been deprived of its carbon and a black interior, due to the temper carbon; whence the name of "black-heart malleable" for this material. Tests have shown that the casting with this white skin upon it is much stronger than a similar one which has not been decarburized on the surface, and therefore the packing in iron oxide is advantageous, even though not an essential feature of the operation. When the castings are packed in some non-oxidizing material, such as sand, clay, or lime, they may receive as perfect an annealing, so far as the production of temper carbon is concerned, but will be without much white skin and of a lower strength.

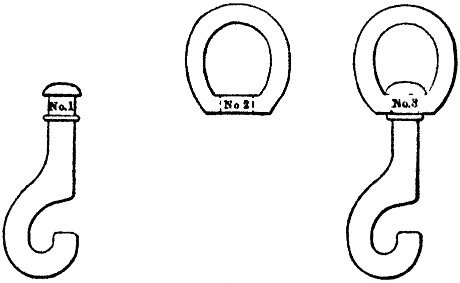


Fig. XV-16.—Harness snap buckle.

Shrinkage.—Hard castings contract in solidifying much like steel, so that, wherever the metal is not "fed," it draws away, leaving cracks or cavities. Therefore the castings may be considered as a continuous shell of metal on the outside with an interior full of cracks and planes of separation. In malleable cast-iron work this is known as "shrinkage." It is a source of weakness in malleable castings and is more effective in round than in square bars because the latter have a thicker solid skin on the corners which reduces the area of the cracked portion.

Contraction.—The contraction of the hard casting is almost as great as that of steel, because almost no graphite forms. The amount of silicon and the sectional area of the castings are still the determining factors in this connection. Indeed, by means of the measurement of the section and percentage of silicon we may estimate the contraction, or by means of the section and the contraction we may estimate the silicon very closely, other conditions and impurities being normal. The following table gives the necessary data for these estimations:

TABLE XV-II.—CONTRACTION IN INCHES PER FOOT OF LENGTH

Percentage of silicon	¼ in. square	½ in. square	¾ in. square	1 in. square
0.35	0.225	0.200	0.190	0.175
0.50	0.220	0.195	0.183	0.170
0.75	0.215	0.190	0.176	0.162
1.00	0.211	0.183	0.137	0.102

Expansion Due to Temper Carbon.—It is a very interesting fact that, when the malleable cast iron is annealed and the temper carbon precipitates, the casting expands to an amount approximately equal to that which would have occurred if the graphite had separated during solidification and gray cast iron had been produced in the first instance. In other words, the temper carbon, although in a very finely powdered condition, occupies about the same amount of space as an equal weight of graphite and causes about the same ultimate difference in size between the original pattern and the annealed casting as when gray cast iron is made. An interesting example of this expansion in annealing is shown in Fig. XV-16, which is a swivel snap for hitching straps. Casting 1 is first poured, cooled, and cleaned. It is then embedded in the sand of a mold and casting 2 is poured around the shank of it, as shown in No. 3 of Fig. XV-16. Casting 2 shrinks upon the shank of casting 1 so as to make a close fit, and no swiveling is possible, but the combined casting is now sent to the annealing ovens and annealed. This causes the expansion referred to, and, as casting 2 is larger in diameter, it expands the more and now turns very easily around the shank of casting 1.

Delicate Adjustment of Conditions.—In no metallurgical process must the conditions of chemical composition, furnace work, heating temperatures, and lengths of operation be adjusted more delicately than in the manufacture of high-grade malleable cast iron, as may be seen by the following changes that the metal undergoes during the final, *i.e.*, annealing, process, as revealed by the appearance of the fracture. The metal as originally cast will have the so-called *crystalline fracture* of white cast iron, with perhaps a little mottle. This fracture should be changed to a black heart after the annealing process, and the metal will have good strength and ductility. If, however, the composition of the metal was wrong in the first instance, it may quite resist the annealing process and precipitate little or none of its combined[1] carbon. Or else, if the silicon was too high, the castings may have already precipitated too much graphite before the annealing process begins, and the deposition of temper carbon may take place so readily during annealing that the castings will be mushy and lacking in strength.[2]

If, however, the composition of the metal and the melting conditions were correct, a good grade of black-heart casting may be produced by a proper anneal, but, should the temperature of annealing be too high or be continued too long, the black-heart fracture may change to a *steely fracture,* showing an iron in which the precipitated carbon has returned to the combined form. Nor is this all; if the annealed castings are cooled too fast after the anneal, or if the black-heart castings, after being successfully made, are reheated and hammered or reheated and quenched in water, the black-heart fracture will change to steely. Even the heating to which the finished castings are subjected when they are dipped in spelter for a galvanizing process and then quenched in water will produce a steely fracture with consequent brittleness if the composition of the metal is not within very narrow limits. There is but one remedy for castings having a steely fracture and that is to reanneal them and produce the so-called Réaumur or white-heart castings. In other words, white-heart malleable iron is the end of a series of changes through which the carbon passes during a long annealing process.

Theory of the Black-heart Process.—By referring to page 457 we see that graphite should normally separate from irons high in carbon during and shortly after solidification. This reaction is avoided in making malleable castings by cooling the

---

[1] The term combined is used here to represent carbon in solution or any chemical combination with the metal.

[2] Iron too high in silicon will precipitate too much graphite during its first cooling and is technically known as low iron; on the other hand, iron with very little silicon is known as high iron.

metal rapidly through this range of temperature. The first effect of the annealing process, however, is a slow readjustment of conditions by the occurrence of the reaction which was previously suppressed. That is to say, the carbon is now precipitated within the solid metal. The temperature at which this reaction occurs during the annealing is not so high as the normal temperature for it but is in the region where cementite, Fe_3C, normally should be produced according to the diagram. If, therefore, the annealing is continued too long, the carbon precipitation is *followed* by its recombination to form the carbide of iron. As the metal is then slowly cooled, this carbide of iron separates and we get the steely fracture, characteristic of over-annealed malleable castings.

If, on the other hand, we have obtained a good black-heart casting and this is reheated into the region where cementite normally forms and suddenly cooled, we produce a metal which consists of cementite, mostly dissolved in an iron matrix. This reasoning fails to explain why the rapid cooling of castings, after a proper annealing, will sometimes produce the steely fracture, and, as far as the author knows, this occasional result yet lacks an explanation.

The reason why cast iron too high in silicon precipitates its carbon too readily and gives a mushy iron is readily explained, since it is known that the presence of silicon will promote the separation of graphite and especially will make the iron open grained and cause graphite to separate in larger flakes.

Theory of the Réaumur Process.—In the original Réaumur process the castings are packed in iron oxide during the anneal, and this operation is carried on at a temperature of about 800 to 875°C. (1472 to 1607°F.) for a period of four or five days after reaching full temperature. In the first part of this annealing process, conditions are produced which tend to result in black-heart castings; then the next step results in conditions that would produce the steely fracture; still the anneal is protracted at the high temperature and, at the end of the 100 hr. or so, we have castings in which the white rim of black-heart metal extends to the very center—the castings being only ½ in. or less in thickness. This white rim, as already explained, is iron from which the carbon has been actually removed bodily, and this decarburization results from a reaction between the iron oxide in contact with the skin of the casting and the carbon in it.

Whether the carbon migrates to the surface and is there oxidized by the oxide:

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

or oxygen penetrates the metal through its pores in the form of carbon monoxide gas, or penetrates chemically by forming iron oxide which is acted upon by the carbon:

$$C + FeO = CO + Fe,$$

is a matter on which authorities cannot agree. The first theory is the one which seems to have the preponderance of evidence in its favor. That carbon will migrate in solution is proved in the cementation processes and, at the annealing temperature, the carbon is normally all in solution, whether it be as free carbon or as carbide. Even the white rim of an ordinary black-heart casting contains some carbon in solution.

References

RICHARD MOLDENKE: "The Production of Malleable Castings," Cleveland, Ohio, 1911

HARRY A. SCHWARTZ: "American Malleable Cast Iron," Cleveland, Ohio, 1922.

E. SCHMEZ and R. STOTZ: "Der Temperguss," Berlin, 1930.

CHAPTER XVI

ALLOY STEELS AND ALLOY CAST IRONS

We have already described ordinary steel (which to distinguish it from the so-called alloy steels is often known as "carbon steel") as an alloy of iron and carbon. But there is another class of materials to which the specific name of "alloy steels" is applied. This comprises steels to which a controlling amount of some alloying element in addition to the carbon is added.

Definitions.—The International Committee upon the nomenclature of iron and steel defines alloy steels as "those which owe their properties chiefly to the presence of an element (or elements) other than carbon." The distinction between an element added merely to produce a slight benefit to ordinary carbon steel and the same element added to produce an alloy steel is sometimes a very delicate one. For example, manganese is added in amounts usually less than 1.50 per cent to all Bessemer and open-hearth steels for the sake of getting rid of oxygen and neutralizing the effect of sulphur. Likewise silicon is sometimes added in amounts of 0.1 to 0.2 per cent to get rid of blowholes. But neither of these additions produces what is known as an alloy steel. When we make "manganese steel" containing 7 to 14 per cent of manganese, the material has new properties quite different from the same steel without manganese and we therefore get an alloy steel. Similarly "silicon steel" containing 2 or 3 per cent of silicon will have an entirely new set of properties due to the silicon and will therefore become an alloy steel.

Influence of Alloying Elements.—The metals or metalloids added to carbon steel in order to make an alloy steel operate to produce one or more of the following changes:

1. To modify the effect of heat treatment, by changing either the temperature of the critical ranges or the mode of occurrence of the critical changes.

This effects, for example:

a. Suppression of the critical range, thus giving austenitic steel at atmospheric temperatures.

b. Change in the rate at which critical changes occur, thus giving extra hard martensitic steel or else sorbitic steel; etc.

c. Suppression of the damage due to overheating, thus permitting quenching from near the melting point.

2. To form compounds or solid solutions with the carbon or with the iron.
3. To remove oxides or gases.
4. To change the form in which carbon occurs.

Almost all alloy steels are used in a heat-treated condition, and they have this peculiarity in common: They retain a fair degree of ductility as represented by the reduction of area even when hardened so as to be very strong.

Binary Alloy Steel.—A ternary alloy, or three-part alloy, is an alloy composed of iron, carbon, and one other influential element. It is called, however, a binary steel, *i.e.*, an alloy of steel with one other element. This class includes alloy steels which are used abundantly by man and the most important of which are nickel steel, manganese steel, chrome steel, tungsten steel, molybdenum steel, silicon steel, etc. There are several other binary steels which have been investigated and used to a small extent, such as boron steels and cobalt steels. The field of useful binary steels has not yet been fully investigated, and a wide scope is left for future inventors. There are many elements whose influence on steel has not yet been studied, and, even among those which are commonly used, there are some of which only limited proportions have been employed.

Ternary Alloy Steels.—Ternary steels consist of iron, carbon, and two other alloying elements. The commonest and most important of these are nickel chromium steels, chrome vanadium, tungsten chromium, nickel manganese, manganese silicon, tungsten molybdenum, nickel vanadium steels, etc. The result produced by adding an alloying element to ordinary carbon steel is astonishing and incapable of being predicated, and that obtained by a combination of two alloying elements is far more so. New products result with properties entirely different from, and in some cases almost the opposite of, those of its constituents, so that almost any combination at random may lead to a surprise, even when the effect of different combinations of the same components is known.

Manufacture of Alloy Steels.—The manufacture of alloy steels is usually very simple and calls for no special comment here. As a general thing the alloying element is added like the recarburizer. For example, in the manufacture of manganese steel the requisite amount of ferromanganese will be added at the end of the process; in the manufacture of nickel steel we may add ferronickel in the same way, but it is more common here to add shotted-nickel during the process and allow it to dissolve in the steel bath and remain there until the metal is tapped; tungsten steels and tungsten chrome steels are often made by the crucible process and the requisite amount of ferrochrome and ferrotungsten, or of metallic chromium and metallic tungsten, is placed on top of the charge when the crucible is filled.

The treatment of some of the alloy steels is not so simple: Nickel steel may be heated, rolled, and forged without any great precaution, but these operations are performed upon manganese, tungsten, and some of the other alloy steels only after great difficulty and experience. Under the head of these different steels will be described the proper method of treatment.

NICKEL STEELS

Nickel steels are the most abundantly used of all the alloy steels. In the ordinary commercial structural alloys the nickel ranges from 1.50 to 4.50 per cent and usually from 2.00 to 3.75 per cent, while the carbon is usually from 0.20 to 0.50 per cent and usually between 0.25 to 0.35 per cent. Not counting armor plate, which is really a quaternary steel, containing nickel, chromium, and vanadium, the most important uses of nickel steel are for structural work in bridges, railroad rails, especially on curves, steel castings, ordnance, engine forgings, shafting, especially marine shafting, case-hardening stock for gears, etc., frame and engine parts for automobiles and airplanes, wire cables, connecting rods, axles, especially for automobiles and railroad cars, etc. We can best learn the reasons for these particular uses by discussing the distinctive properties conferred by the nickel, and their usefulness.

Tensile Properties.—The chief distinction between nickel steel and carbon steel is the higher elastic limit of the former, and especially the fact that this higher elastic limit is obtained with only a slight decrease in ductility. About 3.50 per cent of nickel added to carbon steel will increase the elastic limit nearly 50 per cent, while reducing the ductility only about 15 to 20 per cent. It is this increase in elastic limit which is probably the chief reason for the increased resistance of nickel steel to what is known as "fatigue," *i.e.*, its resistance to repeated stresses and alternating stresses[1] under which all steel will ultimately break down, even though the load is far less than that it can bear indefinitely if constantly applied. It is probable that the minute structure of nickel steel is also advantageous in this same connection. About 3.50 per cent of nickel will give steel approximately six times the life in resistance to fatigue. The records of shipping show that the great majority of accidents to vessels at sea come from the breaking of the propeller shafts, which is doubtless due to alternate stresses, because these long shafts are put out of alignment by each passing wave; so now practically all large vessels use hollow nickel-steel shafts. It is the higher elastic limit that is responsible also for the use of nickel steel in bridges, ordnance, automobile and airplane parts, and wire cables, for we may obtain equal strength with less weight or greater strength with the same weight. Besides the elastic limit the ultimate tensile strength of nickel steel is increased also by the addition of nickel. The increase is not so great in this particular, and consequently the elastic ratio, *i.e.*, the ratio of the elastic limit to the tensile strength, is increased still more greatly. The elastic limit of ordinary rolled carbon steel should be at least one-half of the tensile strength, while that of 3.50 per cent nickel steel should be at least 60 per cent.

Heat Treatment.—By means of heat treatment, the strength, hardness, and ductility of nickel steel may be increased together. The heat treatment consists of quenching in water from 840°C. (1554°F.), which is safely above the top of the critical range, and then reheating to 550°C. (1022°F.), which is about 100°C. below the point at which the lower critical change begins on heating. This change is the beginning of conversion of pearlite to austenite.

Crystalline Structure.—The crystalline structure of nickel steel is more minute than ordinary carbon steel, and this is probably one of the chief causes for the toughness of nickel steel, and

---

[1] Repeated stresses are stresses put upon a body at intervals and relieved meanwhile, while alternate stresses are stresses first in compression and then tension, such, for instance, as the stresses in a wire that is bent backward and forward or in a rotating shaft that is not absolutely in alignment.

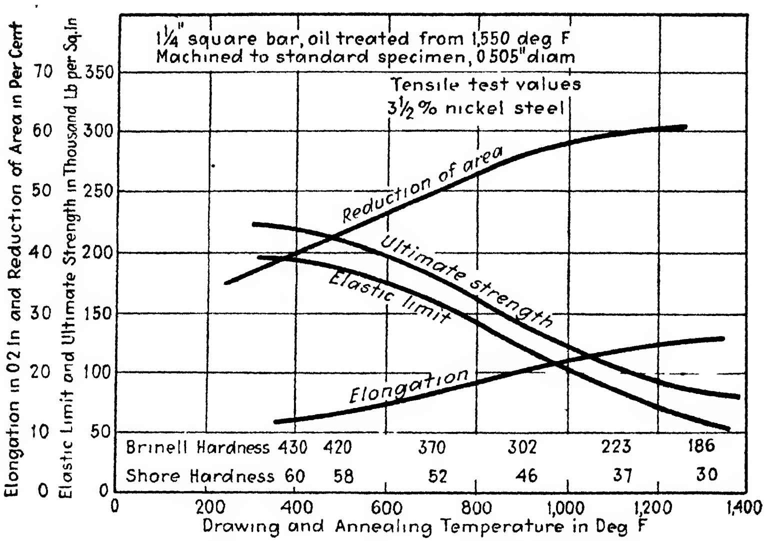


FIG. XVI-1 – Mechanical properties of nickel steel after double heat treatment. (*From "Steels and Alloys for Special Purposes," Crucible Steel Company of America.*)

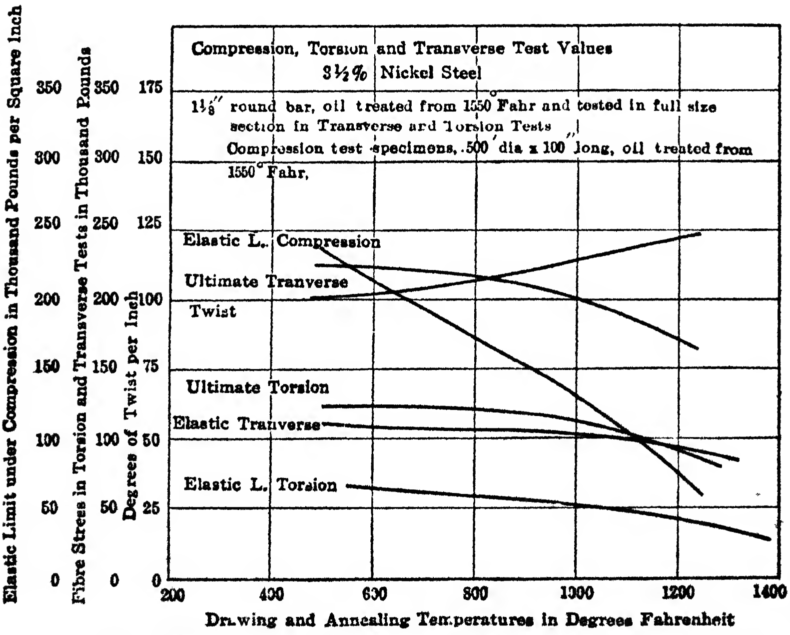


FIG. XVI-2.—Mechanical properties of nickel steel after double heat treatment. (*From "Steels and Alloys for Special Purposes," Crucible Steel Company of America.*)

also for the fact that cracks develop in it relatively slowly; in the yielding of steel to fatigue the damage starts by the opening of a crack of microscopic proportions through the cleavage planes of the crystals, and this crack grows and spreads from crystal to crystal until it is visible to the unaided eye, after which it proceeds with still greater rapidity. As already stated, this development is much slower in nickel steel than in carbon steel. Furthermore, if an armor plate is struck by a projectile, it does not crack so easily, and the cracks do not extend so far if the plate is made of nickel steel. This fact and the greater strength of nickel steel are the chief reasons for the nickel in all modern armor plate.

Modulus of Elasticity.—The modulus of elasticity of nickel steel containing not more than 4 or 5 per cent of nickel is about the same as that of carbon steel, *viz.*, about 29,500,000 lb. per square inch. With higher contents of nickel, however, and especially with more than 20 per cent of nickel, the modulus of elasticity is lower. This results in the steel being much more resilient or springy, and this is one of the important reasons why not more than 4 per cent of nickel is put into structural steels, for a bridge built of steel which was resilient, even though strong, would vibrate so much with the motion of a passing load as to be unpleasant, and even unsafe on account of the repeated stresses set up. The price of nickel, of course, enters into the limitations of the amount used in structural material as well, and it is found that 3.50 per cent can be added without great expense and with beneficial results.

Hardness.—Nickel steel is harder than carbon steel, though not so much so but that it can be machined without difficulty. Advantage is taken of this in the use of nickel-steel railroad rails for curves and other locations where the steel soon wears out. The additional strength of the nickel steel is also an advantage in this connection and nickel-steel rails have been tried with success upon the famous horseshoe curve of the Pennsylvania Railroad and other places. The hardness of nickel steel is also accompanied by a lower coefficient of friction, and those properties, together with the additional strength, are taken advantage of in the use of nickel steel in axles for automobiles, locomotives, and railroad cars. Equal strength can be obtained in an axle of smaller size which has, of course, less bearing surface and therefore still further reduced friction.

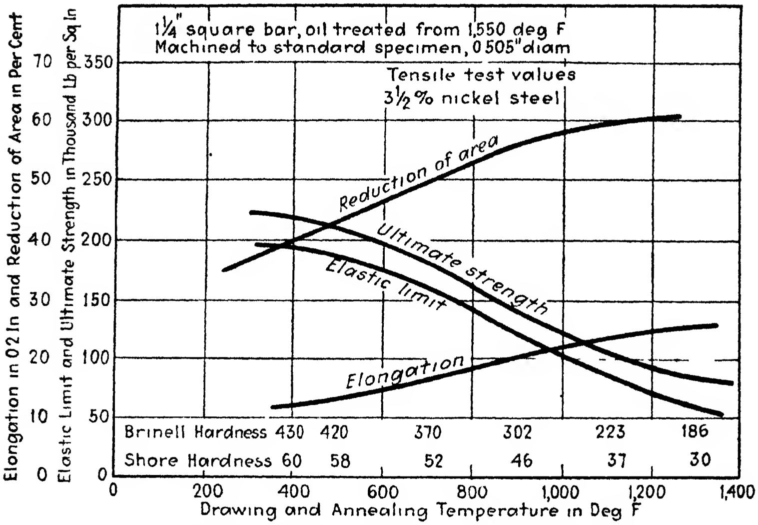


Fig. XVI-1 Mechanical properties of nickel steel after double heat treatment (*From "Steels and Alloys for Special Purposes" Crucible Steel Company of America*)

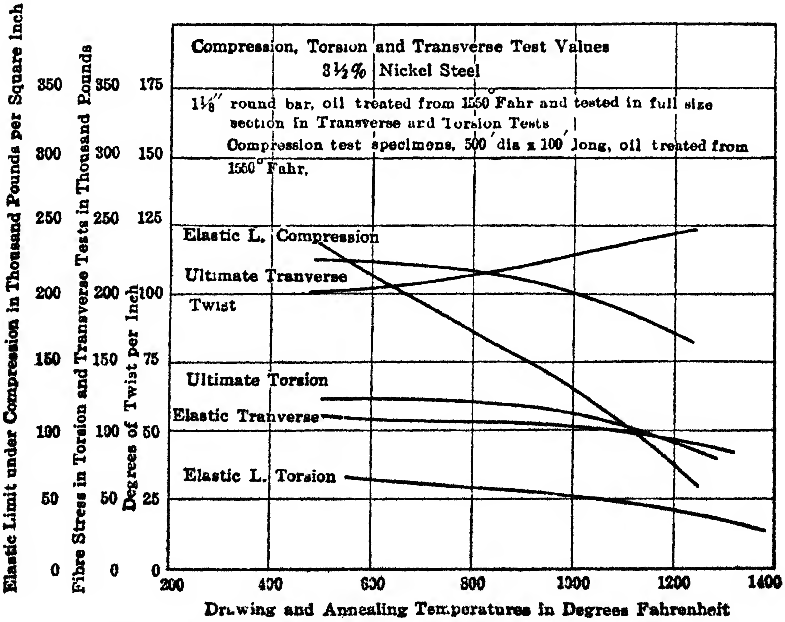


Fig. XVI-2.—Mechanical properties of nickel steel after double heat treatment. (*From "Steels and Alloys for Special Purposes," Crucible Steel Company of America.*)

also for the fact that cracks develop in it relatively slowly; in the yielding of steel to fatigue the damage starts by the opening of a crack of microscopic proportions through the cleavage planes of the crystals, and this crack grows and spreads from crystal to crystal until it is visible to the unaided eye, after which it proceeds with still greater rapidity. As already stated, this development is much slower in nickel steel than in carbon steel. Furthermore, if an armor plate is struck by a projectile, it does not crack so easily, and the cracks do not extend so far if the plate is made of nickel steel. This fact and the greater strength of nickel steel are the chief reasons for the nickel in all modern armor plate.

Modulus of Elasticity.—The modulus of elasticity of nickel steel containing not more than 4 or 5 per cent of nickel is about the same as that of carbon steel, *viz.*, about 29,500,000 lb. per square inch. With higher contents of nickel, however, and especially with more than 20 per cent of nickel, the modulus of elasticity is lower. This results in the steel being much more resilient or springy, and this is one of the important reasons why not more than 4 per cent of nickel is put into structural steels, for a bridge built of steel which was resilient, even though strong, would vibrate so much with the motion of a passing load as to be unpleasant, and even unsafe on account of the repeated stresses set up. The price of nickel, of course, enters into the limitations of the amount used in structural material as well, and it is found that 3.50 per cent can be added without great expense and with beneficial results.

Hardness.—Nickel steel is harder than carbon steel, though not so much so but that it can be machined without difficulty. Advantage is taken of this in the use of nickel-steel railroad rails for curves and other locations where the steel soon wears out. The additional strength of the nickel steel is also an advantage in this connection and nickel-steel rails have been tried with success upon the famous horseshoe curve of the Pennsylvania Railroad and other places. The hardness of nickel steel is also accompanied by a lower coefficient of friction, and those properties, together with the additional strength, are taken advantage of in the use of nickel steel in axles for automobiles, locomotives, and railroad cars. Equal strength can be obtained in an axle of smaller size which has, of course, less bearing surface and therefore still further reduced friction.

Soundness.—Nickel-steel castings are relatively free from blowholes and this, together with the strength, is a reason for the use of this material for castings. They also have a lower melting point and run more easily in the molds.

Expansibility.—The coefficient of expansion of nickel steel is one of its most astonishing and unusual characteristics, for in different samples it varies all the way from practically zero up to the ordinary figure for carbon steels.

Colby gives the following figures for the average coefficient of expansion for each 1°C. temperature:

Carbon steel	0.00001036 (Guillaume)
Carbon steel (0.25 per cent carbon)	0.00001150 (Charpy)
Soft carbon steel	0.00001078 (Browne)
5.00 per cent nickel steel	0.00001053 (Guillaume)

Invar.—The coefficient of expansion with the ordinary atmospheric changes of temperature becomes less and less as the percentage of nickel increases until, when we reach 36 per cent of nickel, it is less than any metal or alloy known and amounts practically to zero. This alloy is patented and sold under the name of "invar" and is used for scientific instruments, pendulums of clocks, steel tape measures for accurate survey work, etc. In a paper read before the American Association for the Advancement of Science, in December, 1906, it was stated that tapes made of invar used experimentally for United States Government survey work showed a very great increase in accuracy over ordinary steel tapes, and also in rapidity of use. These tapes varied an infinitesimal amount during the first few months, after which they became practically constant in length. The cause of this peculiar effect of nickel upon the dilation of steel with an increase in temperature is a result of the effect of nickel upon the critical ranges of the steel, which we shall describe later.

Platinite.—As the amount of nickel increases beyond 36 per cent, there is a slight increase in the coefficient of expansion so that, when we reach about 42 per cent of nickel, the steel has the same coefficient of expansion and contraction with the atmospheric temperature as has glass. In this respect it resembles platinum, and the name "platinite" is therefore given to this alloy. It can therefore be used for the manufacture of "armored glass," *i.e.*, a plate of glass into which a network of steel wire has been rolled and which is used for fire-proofing, etc., because, even though the glass should break, it is held together by the steel network. It can also be used for the electric connections passing through the glass plugs in the base of incandescent electric lights.

Corrodibility.—Nickel steel corrodes less than carbon steel, in the presence of the atmosphere, fresh and salt water, the ordinary acids, the smoke of locomotives, etc. Moreover, the degree of corrodibility decreases with each increase in the amount of nickel present. For this reason 30 per cent nickel boiler tubes have been used, especially in marine boilers. The great expense of this material is, however, an obstacle to its common adoption.

Other Properties.—Ordinary nickel steel containing about 3.50 per cent of nickel has several other properties which distinguish it from carbon steel, among which we may mention its higher compressive strength and greater toughness under impact. This latter makes nickel steel especially resistant to shocks, for it not only takes a greater blow to bend it but it will bend through more of an angle before cracking. Nickel steel also has a greater shearing strength, which makes it advantageous for rivets, because smaller rivets may be used and this means smaller holes in the structural members that are being joined, and consequently a greater area of these members left to support the strains upon them. In this connection, however, it should be remembered that nickel steel does not weld as well as carbon steel, and therefore greater care is required in upsetting the rivets during the processes of construction. Nickel segregates very little in iron and it also has the advantageous property of hindering the other elements from segregation, so that nickel steel is less liable to these irregularities than carbon steel. In steel over 0.50 per cent carbon, nickel has a tendency to make the carbon come out as graphite.

Critical Changes.—Nickel has a very important effect upon the critical changes of iron and steel. This fact will readily be believed because it is known that many of the elements added to steel produce important changes in the critical points. G. B. Waterhouse, while investigating the effect of 3.80 per cent of nickel upon iron, showed that this amount of nickel did not make any appreciable difference in the mode of occurrence of the critical points on cooling, but it did reduce the temperature at which these critical points occurred by about 75°C. (167°F).

As the amount of nickel in the alloys increases, the temperatures at which the critical ranges occur become lower and lower until we reach 24 per cent of nickel with 0.40 per cent carbon, when the critical ranges occur below the atmospheric temperature. That is to say, the steel does not ordinarily cool to the point at which the solid solution is decomposed and the beta and alpha allotropic modifications are assumed.

Irreversible Transformations.—The great peculiarity of the critical changes of the nickel-steel alloys with less than 24 per cent of nickel is that they are irreversible. By this we mean that the change which takes place at one temperature on cooling is not reversed on heating at the same temperature, or anywhere near that temperature. In other words, when we cool a nickel steel containing 20 per cent of nickel, the solid solution is not decomposed and the alpha allotropic modification is not assumed until we get below 100°C. (212°F.). But having cooled the steel to that point and decomposed the solution, we can now heat it nearly to 600°C. (1112°F.) before the reverse change takes place and we again form the solid solution and the gamma allotropic modification. In other words, it is possible to have a sample of nickel steel between 100 and 600°C. which shall be in either condition we like. With 20 per cent of nickel, nearly 1 per cent of carbon, and 1.40 per cent of manganese, the transformation point on cooling is 188° below 0°C. (306° below 0°F.), while the

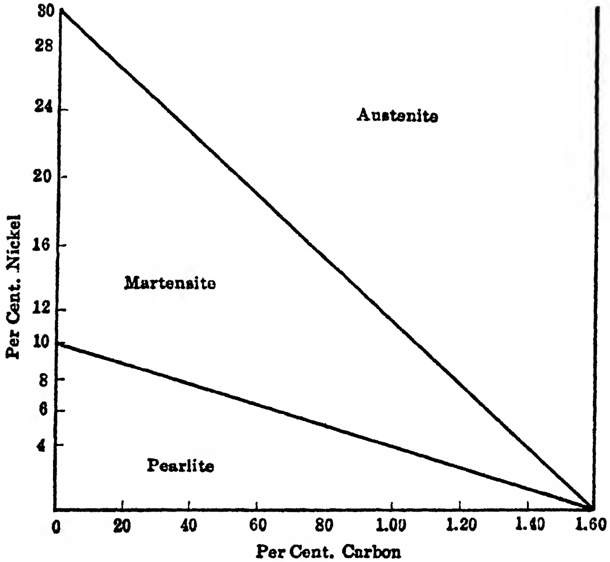


FIG. XVI-3.—Constitution at atmospheric temperatures of slowly cooled steels with varying percentages of nickel and carbon.

transformation point on heating is well above the atmospheric temperature. Therefore at atmospheric temperature we may have such a piece of steel in either condition we like, and a very interesting experiment is formed by having a bar of this steel one end of which has been cooled more than 188° below 0°C., while the other end has not. The end that has been cooled will be magnetic and the other end nonmagnetic.

Microstructure of Nickel Steels.—The effect of nickel on critical changes also shows in the microstructure of the steel, as will be seen from the figure on page 498 (Fig. XVI-3).

This figure is interpreted as follows: Steels very low in carbon have the pearlitic structure until the nickel reaches about 10 per cent, when the structure becomes martensitic. As the carbon increases, the martensitic structure appears with less and less nickel. With 30 per cent of nickel, even low-carbon steels are austenitic in microstructure. This accounts for the nonmagnetic character of steels of high-nickel content.

When we have more than 40 per cent of nickel in our steels, the critical transformations are reversible like ordinary steels. That is to say, they occur at nearly the same temperature on heating as the reverse change does on cooling. It is an interesting fact that the steels in which the irreversibility of the transformation is most marked—*i.e.*, the steels from 12 to 25 per cent of nickel—have the highest strength and elastic limit; at about 25 to 30 per cent of nickel, where the irreversible transformation is most erratic, and beyond that point, the strength is much lower.

Occurrence of Nickel.—Waterhouse tested his steel containing 3.80 per cent of nickel and found that a part of the nickel was dissolved in the cementite which had the formula $(FeNi)_3C$. The amount of nickel in the cementite was not, however, so great as that in the ferrite. That is to say, the steel, as a whole, contained 3.80 per cent of nickel, while the cementite contained only 1.86 per cent, showing that the nickel dissolves more easily in the ferrite than it does in the cementite.

Rationale of the Effect of Nickel.—Nickel decreases the crystalline size of steels and especially the size of crystals of pure iron. For this reason, the addition of nickel to structural steel results in an increase of strength, without proportionately great decrease of ductility. Through the same cause it increases the hardness of steel and is, therefore, used for such purposes as railroad rails on curves. It is valuable in steel that is to be case-hardened, because it decreases the crystal size of the "core." The full benefit of nickel is obtained only when the steel is heat-treated for strength in the usual way; *viz.*, it is heated to the lowest possible temperature to get all the iron and carbon in solid solution, quenched in oil or water to prevent precipitation of Fe crystals in large size, and then reheated to some point below the line *PSK* (Fig. XI-9) to restore ductility to the steel. Nickel steel of 3.5 per cent nickel is superior to carbon steel which has been treated in this way and excels especially in elastic limit.

Manganese Steel

We owe the discovery of manganese steel to the untiring ingenuity of Robert A. Hadfield, of Sheffield, England, and its story will be an inspiration to every inventor, for it resulted in a material whose properties not only are the opposite of what we might reasonably have expected on logical grounds, but whose combination of great hardness and great ductility was hitherto unknown and might readily have been believed to be impossible. Constant study and perseverance must have been the qualities that led to this revolutionary invention, and it has established beyond question the principle that, because a given amount of any element produces a given effect upon steels, it does not follow that a different amount will give the same effect in a different degree. Indeed a different amount may give an entirely different, and perhaps an exactly contrary, effect, as is the case of the effect of manganese upon steel.

When the manganese in steel is over 1 per cent, the metal becomes hard and somewhat brittle, and these qualities increase in intensity with every increase of manganese until, when we have 4 to 5.50 per cent, the steel can be powdered under the hammer. But as the manganese is increased from this point, these properties do not increase and, when we reach 7 per cent, an entirely new set of properties begin to appear. These are well marked at 10 per cent of manganese and reach a maximum at 12 to 15 per cent.

Composition.—Manganese steel usually contains about 11 to 14 per cent of manganese and 1.0 to 1.3 per cent of carbon.[1] With this amount of manganese the strength and ductility of the material reach their maximum. The silicon is 0.3 to 0.8 per cent,

---

[1] Manganese steel that is to be forged or rolled is made lower in carbon than this.

the phosphorus under 0.08 per cent, and the sulphur very low, on account of the easy washing out of sulphur by manganese. The melting point of this steel is 1325°C. (2417°F.).

A cheaper manganese steel is made with 7 to 8 per cent of manganese. It has lower ductility but greater elastic limit than the 13 per cent grade.

Treatment.—After manganese steel has been cast into an ingot or casting and slowly cooled, it is almost as brittle as glass. But it is then reheated to a temperature of more than 1000°C. (1832° F.) and rapidly cooled by plunging it into water. The temperature from which it is necessary to quench it can readily be determined, for it must be so high that, when the steel is quenched, little blue flames of hydrogen will appear on the surface of the water. These are due to the decomposition of water into hydrogen and oxygen by the intense heat of the steel at the moment of touching it. The steel which was very brittle before this treatment is afterward as ductile as soft carbon steel or wrought iron, while its tensile strength is about three times as great. Thus the sudden cooling, which produces brittleness in ordinary steel, produces ductility in manganese steel. The abrasion hardness of manganese steel is about the same in the slowly cooled and in the quenched condition and is so great that it is not commercially practicable to machine it and there is no method known of making it softer.

Manganese steel must be heated very slowly and uniformly lest it crack. It is also very difficult to forge it, and this can be accomplished only within a narrow range of temperature above a red heat and by beginning with very light taps of the hammer. After a little working it becomes so tough that it can be rolled, although somewhat gingerly.

The Effect of Quenching on Manganese Steel.—More than 5 per cent of manganese with 1 per cent of carbon will depress the line where even the most enduring austenite finally decomposes into ferrite and cementite, *i.e.*, the line *PSK* in Fig. XI-9. But it does not materially change the position of the point *E* in Fig. XI-9. In other words, the point *S* drops below the atmospheric temperature, but the line *ES* still begins at about the same place at its right-hand end. Therefore, in the slow cooling of even manganese steel, cementite will precipitate from the temperature at which the alloy crosses the line *ES*. This precipitated cementite makes the steel very brittle. If, however, the steel be rapidly cooled from above the line *ES*, cementite will be held in solid solution, resulting in a tough, ductile steel.

Manufacture.—The metal is first purified in the Bessemer, electric, or open-hearth furnace, and then manganese is added in the form of melted ferromanganese, as in ordinary recarburizing, except for melting and the extra quantity used. Most of the manganese steel made is used in the form of castings, because of the difficulty of forging or rolling, but railroad rails are rolled, and some plate to be perforated and used for screening, etc.

Effect of Working.—Cast manganese steel, after treatment, will have a tensile strength of about 80,000 lb. per square inch, with an elongation of 20 per cent in 8 in. The same material, if forged or rolled and heat-treated, will increase to 140,000 lb. tenacity and 50 per cent elongation. If rolled cold, the strength may increase to 250,000 lb. with elastic limit of 230,000 lb. but without appreciable ductility.

Uses.—High-manganese steel is used chiefly for the jaws and wearing parts of rock-crushing and digging or quarrying machinery, for railroad frogs and crossings, for railroad rails on curves, mine-car wheels, and burglar-proof safes. Its life in these classes of service is very many times that of all other kinds of steel, because it is not only extremely hard but is without brittleness. There is a famous curve on the Boston elevated railroad where carbon-steel rails were worn out in a very short time and the use of manganese steel rails has proved very advantageous and economical. The use of the steel for burglar-proof safes is also very advantageous, because there is no known method of making the steel soft enough to be penetrated by a drill. The uses of manganese steel are limited chiefly because the metal must ordinarily be formed by casting, since machining and cutting to shape are practically out of the question, and forging is difficult. For structural work the advantages of its high combination of strength and ductility are somewhat offset by its low elastic limit, which is only about 35 per cent of its ultimate tensile strength. One peculiarity of manganese steel is that, when it yields to tensile stresses, it is elongated more uniformly over its whole length than carbon steel, which suffers its greatest elongation near the point of final rupture where a certain amount of "necking" takes place. It will be remembered that wrought iron stretches more uniformly over its whole length than steel; manganese steel has this property in a still more marked degree even than wrought iron.

Critical Changes.—The abrasion hardness of manganese steel is due, in part, to the hardness of manganese, but still more potently to the fact that the steel is in the austenitic condition. That is to say, the manganese has reduced the temperature at which the critical changes occur below that of the atmosphere, and therefore manganese steel consists entirely of austenite. It is, of course, nonmagnetic. Now, although austenite is harder than pearlite, it is not nearly so hard as martensite, and true abrasion hardness and toughness are due to the formation of a thin film of martensite by the process known as "work hardening" on the surface of austenitic manganese steel. Therefore, manganese steel which is used for hard service, such as crushing rock, will constantly be hardened on the outside by the formation of a martensitic layer caused by heavy strains transforming austenite into martensite, whereas the same steel will not endure long against abrasion when digging a soft substance like sand.

Medium-manganese Structural Steel.—The manganese in ordinary carbon steel is between 0.40 and 1 per cent. Increasing the manganese to about 1.50 to 1.75 per cent results again in a steel with much higher strength and usual ductility. The steel also withstands the shock test excellently well. For this reason it is being used for railroad rails, which thus develop less easily transverse fissures in the heads, probably caused chiefly by blows from the driving wheels of locomotives. The steel has also been used in place of nickel steel in structural parts of some bridges. Medium-manganese steel frequently has a coarse crystalline structure, which creates a considerable prejudice against it for structural purposes in the minds of many engineers.

Medium-manganese steel is also called "pearlitic-manganese steel" for obvious reasons. It may also be called "wrought-manganese steel" because it is commonly rolled to shape, whereas 7 and 14 per cent manganese steel is usually made in the form of castings.

Constitutional Diagram.—From Guillet's constitutional diagram of manganese steel, shown in Fig. XVI-4, we can select the compositions of those steels which are in the pearlitic, the martensitic, or the austenitic condition at atmospheric temperatures. The martensitic manganese steels are too brittle for present usefulness.

SILICON STEEL

The most important silicon alloy steel is that used for the cores of electromagnets, but several bridges have been built recently in Europe and America using a so-called "silicon structural steel."

Electromagnets.—Silicon increases the electrical resistance of steel; therefore steel with about 4.75 per cent of silicon is universally used in the best magnet cores for alternating-current machinery, because it has high magnetic permeability and high electrical resistance, which reduces the eddy currents, and therefore the energy loss. It is known as "silicon transformer steel" and has saved hundreds of millions of dollars, during the past 25 years, by increasing efficiency. The steel is as low as possible in all elements except silicon and is given a double heat treatment for the purpose of making the smallest possible grain size, in order further to increase electrical resistance by increasing the number of grain boundaries. For less effective electrical results than the 4.75 per cent transformer steel, but much cheaper because they can be worked so much easier in fabrication, are the silicon steels containing respectively 1.25, 2, and 3 per cent of silicon. The steel containing 4.75 per cent of silicon is somewhat hard and brittle at atmospheric temperatures and cracks on the edges when cut.

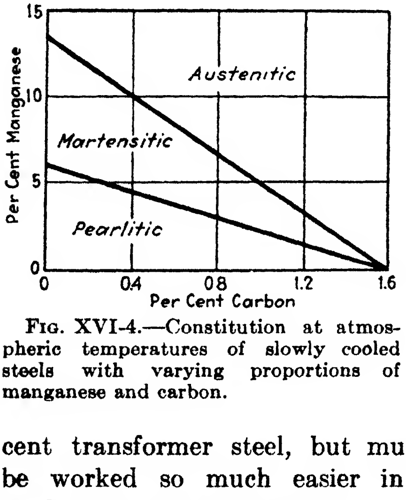


FIG. XVI-4.—Constitution at atmospheric temperatures of slowly cooled steels with varying proportions of manganese and carbon.

Silicon Structural Steel.—Many bridges have been built in the past five years using what is called "silicon structural steel." This is stronger than carbon steel with equal ductility. The silicon is usually between 0.50 and 1.05 per cent, and it is customary to raise the manganese of ordinary structural steel from about 0.50 to between 0.67 and 0.95 per cent. By this analysis the silicomanganese steels, much used for springs, are approached.

Silicon has the effect of decreasing the solubility of carbon in iron, in both the liquid and the solid state. In the solid solution, therefore, the end of the V in Fig. XI-9 is found occurring at a lower percentage of carbon than the usual 0.85 per cent. With 1 per cent of silicon, the solid solution will have its maximum solubility at about 0.45 instead of 0.85 per cent of carbon. Since the point of the V is always the strongest steel, a stronger steel with less carbon in it is obtained in this way and, therefore, greater ductility, because the less the carbon the greater the ductility.

Most of the silicon structural steels are really silicomanganese steels, containing generally between 1 and 2 per cent of silicon and from 0.90 to 1.50 per cent of manganese. They are characterized by high tension strength, good elastic limit, but low toughness and shock resistance. The silicomanganese steels have high resilience and are much used for springs. They are very sensitive to heat treatment and liable to crack when quenched in cold water.

COMPARISON OF BINARY ALLOY STRUCTURAL STEELS CONTAINING NICKEL, MANGANESE, OR SILICON

It is possible to secure a little better combination of strength and ductility in 3.5 per cent nickel steel than in silicon or medium-manganese structural steels. Nickel steel has also had a long service in important structures, as compared with the length of time during which the others have been used. But 3.5 per cent nickel steel costs about twice as much as does either of the others. All three of these alloy steels are generally used in large members of structures without any heat treatment. In this respect, nickel steel has the advantage, because it can be improved to a greater extent by quenching and reheating. All three of the steels, when in the unheat-treated condition, have similar properties, as shown in Table XVI-I.

The nickel, manganese, and silicon structural steels have these points in common: Their carbon content is roughly from 0.30 to 0.40 per cent; they are ductile because they contain much ferrite; they are stronger than straight carbon steel because their ferrite crystals are in an abnormally small size. This is obtained in nickel steels because nickel tends to dissolve in ferrite rather than in cementite; it separates out of the solid solution when the steel cools from the line *GS* to the line *PS* in Fig. XI-9. It has been argued that nickel forms many nuclei for the precipitation of ferrite, causing it to come in many small crystals and not con-

TABLE XVI-I.—SOME MECHANICAL PROPERTIES OF SOME STRUCTURAL ALLOY STEELS

Steel	Analysis, per cent								Ultimate strength, pounds per square inch	Elastic limit, pounds per square inch	Elongation in 2 in., per cent	Reduction of area, per cent	Izod value	Heat treatment	
	C	Mn	Si	Ni	S	Cr	V	Mo						Quench in water or oil at	Then draw at
Silicon	0.10	0.60	1.00	....	....	....	....	....	72,000	52,000	27‡	59	....	As rolled	
Silicomanganese	0.40§	1.00§	0.40§	....	....	....	....	....	93,000	55,000	18‡	>35	....	As rolled	
Silicomanganese	0.55	0.90	1.80	....	....	....	....	....	242,000	230,500	4‡	21	....	Oil, 1742°F.	842°F.
									162,400	142,200	13‡	31	....	Oil, 1742°F.	1112°F.
Medium manganese	0.29	1.60	....	....	....	....	....	....	93,000	40,500*	31	68	45	Normalized	
Medium manganese	0.38	1.75	....	....	0.103	....	....	....	209,000	158,700*	11	45	56	Water, 1475°F.	625°F.
Nickel	0.35	....	....	3.50	....	....	....	....	245,000	220,000	11	38	....	Oil, 1450°F.	400°F.
									202,000	180,000	13	46	....	Oil, 1450°F.	600°F.
									160,000	138,000	16	53	....	Oil, 1450°F.	800°F.
									126,000	103,000	21	59	....	Oil, 1450°F.	1000°F.
									104,000	71,000	25	64	....	Oil, 1450°F.	1200°F.
									95,000	65,000	27	65	....	Oil, 1450°F.	1300°F.
Chrome nickel	0.35	....	....	1.25	....	0.60	....	....	240,000	214,000	8	28	....	Oil, 1500°F.	400°F.
									220,000	195,000	9	30	....	Oil, 1500°F.	600°F.
									180,000	151,000	12	49	....	Oil, 1500°F.	800°F.
									135,000	110,000	17	58	....	Oil, 1500°F.	1000°F.
									108,000	86,000	21	63	....	Oil, 1500°F.	1200°F.
									96,000	74,000	22	65	....	Oil, 1500°F.	1300°F.
Chrome vanadium	0.26	....	....	....	....	0.92	0.20	....	132,000	110,000	19	52	....	As rolled, annealed	
									83,700	61,000	35	66	....		1475°F.
									173,900	149,800	13	57	....	Oil, 1560°F.	750°F.
									171.100	147,150	15	61	....	Oil, 1560°F.	840°F.
									137,500	112,750	21	65	....	Oil, 1560°F.	1020°F.
									131,000	100,000	28	67	....	Oil, 1560°F.	1155°F.
Vanadium-steel casting	0.34	....	....	....	....	....	0.25	....	90,750	67,500	17	28	10.88†	Water, 1650°F.	1200°F.

TABLE XVI-I.—SOME MECHANICAL PROPERTIES OF SOME STRUCTURAL ALLOY STEELS.—(*Continued*)

Steel	Analysis, per cent								Ultimate strength, pounds per square inch	Elastic limit, pounds per square inch	Elongation in 2 in., per cent	Reduction of area, per cent	Izod value	Heat treatment	
	C	Mn	Si	Ni	S	Cr	V	Mo						Quench in water or oil at	Then draw at
Molybdenum	0.35	....	....	....	..		...	0.76	228,000	212,000	10	43	....	Oil, 1550°F.	600°F.
									160,000	136,000	11	49	..	Oil, 1550°F.	800°F.
									140,000	125,000	16	61	......	Oil, 1550°F.	1000°F.
									120,000	106,000	21	66	......	Oil, 1550°F.	1200°F.
Chrome molybdenum	0.35	....	....	....	.....	1.06	....	0.36	205,000	189,000	14	50	......	Oil, 1550°F.	600°F.
									176,000	153,000	15	53	......	Oil, 1550°F.	800F°.
									152,000	132,000	15	61	......	Oil, 1550°F.	1000°F.
									127,000	112,000	23	66	.....	Oil, 1550°F.	1200°F.
Stainless iron	0.11	....	....	....	...	12.5	....	...	202,000	57,000	18	57	49	Oil, 1800°F.	
									193,000	94,000	18	62	60	Oil, 1800°F.	500°F.
									186,000	114,000	18	63	60	Oil, 1800°F.	700°F.
									186,000	112,000	20	62	49	Oil, 1800°F.	900°F.
									155,000	82,500	20	67	31	Oil, 1800°F.	1100°F.
									103,000	63,000	26	70	102	Oil, 1800°F.	1300°F.
									143,000	31,500	18	55	31	Oil, 1800°F.	1500°F.
									81,000		36	75	118	Annealed 1600°F.	
Chrome	0.36	....	...	...	....	0.57	....	....	103,200	76,000	27	62	......	Oil, 1600°F.	1200°F.

* Proportional limit.
† Charpy.
‡ In 8 in.
§ Maximum.

centrate into large crystals. In the case of manganese and silicon steels, on the other hand, the small size of ferrite crystals is due to a lesser number of ferrite crystals separating above the line *GS* and correspondingly more separating at the line *PS*, where the size of separating crystals is much smaller. The reason for this is, as already stated, that manganese and silicon both tend to push the point *S* to the left in the equilibrium diagram, thus making the proportion of ferrite in pearlite larger.

CHROME STEEL

Chromium has the effect of making the critical changes of steel take place at higher than the normal temperature and much more slowly. For the latter reason the effect of chromium intensifies the effect of rapid cooling of steel. For example, a carbon steel containing chromium when quenched in oil will be as hard as or harder than the same carbon steel without the chromium quenched in water. Likewise chromium has the effect of producing a deeper zone of hardness from the surface to the interior of a piece of steel. Chromium is not used very much by itself in alloy steels except for hard objects like parts of rock-crushing machinery, parts of jail bars, burglar-proof safes, etc. Chromium is, however, used a great deal in combination with other alloying elements to produce greater hardness, as in armor plate, armor-plate piercing projectiles, etc. It is also used in combination with other alloying elements to intensify the effect of heat treatment and produce exceedingly strong and tough steels, such as chrome nickel and chrome molybdenum.

Probably the best known use of chromium at the present time is for the production of the so-called "stainless steels" and stainless irons. Not only are these very extensively used for resistance to rusting and corrosion, but they also have a high combination of strength and ductility, as indicated in Tables XVI-I and XVI-II. Steel with chromium under 1 per cent is used for case-hardening purposes; to a very slight extent for strength purposes; and for hardened tool steels. When the chromium is from 1 to 2 per cent, the steel is often used in ball bearings and in crushing machinery, safes, etc. With 2 to 4 per cent of chromium, a steel for permanent magnets is made which has largely replaced the permanent-magnet steel formerly containing about 6 per cent of tungsten. Four per cent chromium and above is almost never used except when added to other alloy steels and also to make the so-called stainless steels, which usually contain 12 per cent or more of chromium, although this has been largely replaced at present by a ternary-alloy steel containing 18 per cent of chromium with 8 per cent of nickel, commonly known as "18:8." For steel to resist scaling at high temperatures, an iron-chromium-carbon alloy containing 35 per cent of chromium is used.

Steel and Cast Iron Which Resist Corrosion.—Nickel steel rusts less than carbon steel, especially if the nickel is 25 per cent and higher. Alloys of iron with not more than 0.50 per cent of copper rust less than plain carbon steel, especially in slightly acidulated waters, such as the rivers which flow from coal-mining districts. Alloys with nitrogen (*i.e.*, nitrided surfaces) also seem by recent studies to have a powerful resistance. The alloys of iron and silicon, beginning about 11 per cent of silicon, not only do not rust at all but offer great resistance to acid attack which dissolves iron readily. This is made useful by making iron castings with 13 per cent of silicon for chemical purposes. But the material which is of most extensive industrial and household importance is the so-called stainless steel.

Stainless Steel.—Stainless steel contains about 0.30 to 0.40 per cent of carbon and 11.50 to 18 per cent of chromium. This is hard without heat treatment, but it is attacked by some acids unless it is heated to the temperature where it is a solid solution and then cooled rapidly by quenching. After this treatment, it is both hard and incorrodible by atmospheric agencies and by many acids. It retains a bright silver-white surface (with slight tinge of blue), so hard that it is not easily scratched, and always brilliant with occasional cleanings with cold water. Hundreds of tons have been used for table cutlery and similar purposes.

Stainless Iron.—If the carbon be kept below about 0.10 per cent, and the chromium above 11.5 per cent, this material will be hard and corrosion resistant without heat treatment. It also has very high properties of strength and ductility combination, as shown in Table XVI-I, after heat treatment and is so pliable that it can be cold-drawn and easily worked. It is very valuable for turbine blades and similar purposes and is the only material known which has a high resistance to both corrosion and fatigue at once, *i.e.*, "corrosion fatigue."

Heat-resisting Alloy Steels.—Tungsten steel is the strongest material known at the temperature of exhaust valves in gas engines, but it scales. High-chromium steels do not scale at

TABLE XVI-II.—EFFECT OF DOUBLE HEAT TREATMENTS ON ALLOY STEELS

Name	Analysis[1]					Heat treatment				Tensile strength, pounds per square inch				Hardness		Authority
						First		Second								
	C	Si	Mn	Ni	Cr	Degrees centigrade	Degrees Fahrenheit	Degrees centigrade	Degrees Fahrenheit	Ultimate	Elastic limit	Elongation in 2 in., per cent	Reduction of area, per cent	Brinell	Shore	
Simple chrome steels	0.70	0.09	0.54	. . .	0.70	816 W	....	593	1,100	129,000	121,700	21	60	235	. .	Hibbard[2]
						816	1,500	649	1,200	110,900	105,300	26	63	195	. .	Hibbard[2]
						816	....	754	1,400	88,000	73,000	36	68	168	. .	Hibbard[2]
	0.40	0.54	0.78	....	0.92	816	1,500	538	1,000	143,500	131,600	18	56	242	. .	Hibbard[2]
						816	1,500	714	1,317	103,200	90,200	26	69	201	. .	Hibbard[2]
	0.64	0.18	0.27	....	1.01	870 O	1,600	400	752	228,000	170,000	5	14	478	.	Camp[3]
						870	1,600	500	932	212,500	155,500	8	20	445	.	Camp[3]
						870	1,600	600	1,112	186,500	128,000	10	22	389	. .	Camp[3]
Simple nickel steel (see also Figs. XVI-I and XVI-II)	0.37	0.22	0.61	3.27	....		Steel as rolled			113,000	69,000	23	48	229	32	Camp[3]
						760	1,400	(Annealed)		99,000	60,000	25	48	183	26	Camp[3]
						815 W	1,499	427	800	185,000	165,000	13	51	352	50	Camp[3]
						815	1,499	538	1,000	148,000	135,000	16	55	293	44	Camp[3]
						815	1,499	704	1,300	98,000	67,000	28	59	179	29	Camp[3]
						815 O	1,499	427	800	168,000	150,000	4	47	331	48	Camp[3]
						815	1,499	538	1,000	133,000	118,000	21	57	262	40	Camp[3]
						815	1,499	704	1,000	95,000	62,500	29	52	179	26	Camp[3]
"Silico-manganese"		1.25 to 2.50	0.50 to 0.70	. . .	....	.... ..	.... .	. . .	.... .	250,000	230,000	9	40	Over 400	. .	Hibbard[2]
										195,000	175,000	9	28	. . .	.	C. S. A.

[1] Sulphur and phosphorus below 0.03 per cent, and usually under 0.02 per cent. Repetitions of analyses avoided for simplicity, but will be understood as following down.

[2] HIBBARD, "Manufacture and Uses of Alloy Steel," New York, 1919.

[3] CAMP (see No. 7).

W = quenched in water.

O = quenched in oil.

C. S. A. = Crucible Steel Co. of America, "Steels and Alloys," Pittsburgh, 1919.

this temperature, but they lack strength. Chromium up to 38 per cent has been used, but the most popular combination is steel with about 18 per cent of chromium with 8 per cent of nickel. This heat-resisting steel is sold under many trade names which give no indication of its analysis.

OTHER BINARY ALLOY STEELS

Vanadium.—Vanadium is one of the most powerful scavengers that can be added to liquid steel for the special purpose of removing oxygen. After removing all the oxygen that can be eliminated by means of manganese and silicon, the addition of 0.25 per cent of vanadium will result in further oxygen elimination, leaving about 0.15 per cent of vanadium in the steel. This vanadium has the effect of increasing the strength and hardness of the metal. In fact, the hardness is increased so much that ordinary alloy steel is not used with more than 0.2 per cent of vanadium remaining in it. Vanadium, like nickel, decreases the grain size of steel, but vanadium acts on the cementite, as well as the ferrite grains, and vanadium also acts apparently during the phase when steel is freezing, so that it is especially beneficial in steel castings, whose properties it improves materially. Except for castings, there is not very much vanadium binary steel made, but vanadium is added in extremely small doses to make ternary and quaternary alloy steels, some of which have great strength or hardness.

Vanadium seems to have a very powerful effect in cutting down Widmanstätten structure, which forms in castings so that it makes the crystal structure finer. Vanadium also goes into solid solution. It stiffens the space lattice very materially (in this respect, it resembles cobalt); and it decreases the segregation of the cementite, in other words, carbon segregation. For that reason also it is valuable in castings. Its most serious handicap is that you cannot have more than 0.20, some say even more than 0.15 per cent, maximum left in steel without making steel very brittle, but it greatly increases the hardness of the steel up to this limit. Its embrittling effect and hardening effect are due to intensely hard carbides and usually the so-called "superhigh-speed steel" contains 2 to 2.50 per cent of vanadium because of the great increase in carbon hardness that you get; 0.15 to 0.20 per cent will increase the tensile strength and elastic limit of carbon steel by about 20 per cent and is exceedingly valuable where you want to increase the unit stress in fatigue. But the principal use of vanadium is in addition to other alloy steels.

Molybdenum Structural Steel.—From 0.25 to 0.75 per cent of molybdenum added to ordinary steel which is then heat-treated produces a structural steel which has increased elastic limit without correspondingly decreased ductility. Molybdenum resembles vanadium in not being used extensively in binary steels, but in being added in small doses to improve the properties of other alloy steels, such as the important chrome-molybdenum steel used much in airplane structures; also nickel-molybdenum. In other alloy steels, molybdenum seems to make the steels easier to fabricate, easy to roll, easy to heat-treat, and easy to weld.

TERNARY ALLOY STEELS FOR STRENGTH

The most important ternary structural alloy steels are: chrome nickel, chrome vanadium, chrome molybdenum, and silico-manganese.

Chrome-nickel Steel.—Thus a steel which contains about 1.5 per cent of nickel and 0.60 per cent of chromium will have, after heat treatment, almost the same strength and ductility as 3.5 per cent nickel steel which has also been heat-treated, but it will not cost so much. Tables XVI-I and XVI-II give data for the comparison of all these binary and ternary structural steels. The heat treatment of chrome-nickel steel is based on the same principle as already given: Heat the steel until the solid solution is complete; then quench in oil or water; and, finally, reheat to some temperature below the line *PSK* in Fig. XI-9 to restore ductility. The best temperature for first quenching must be determined by experiment for all steels of different analysis; the temperature for reheating will depend on how much ductility is estimated to be necessary, always remembering that the more the ductility the less the elastic limit—all of which will be evident after a study of Tables XVI-I, XVI-II, and XVI-III. The largest tonnage of alloy steels in the country are those which contain up to 3.50 per cent of nickel and up to 1.50 per cent of chromium. These two alloy steels and the combination, chrome-nickel steel, represent the largest total tonnage. The ratio of chromium to nickel is almost invariably 2½ to 1. If you have a larger proportion of chromium than that—say 2 to 1—there is difficulty in heating; the limits have to be very narrow. In chrome-nickel steels there are two combinations which are commoner than all

TABLE XVI-III.—EFFECT OF DOUBLE HEAT TREATMENTS OF TERNARY STEELS

Name	Analysis[1]						Heat treatment				Tensile strength				Hardness		Authority
	C	Si	Mn	Ni	Cr	V	Degrees centigrade First	Degrees centigrade Second	Degrees Fahrenheit First	Degrees Fahrenheit Second	Pounds per square inch Ultimate	Pounds per square inch Elastic limit	Elongation in 2 in.	Reduction of area	Brinell	Shore	
Nickel-chrome castings	0.30	....	0.41	3.64	1.49	0.0	Annealed		Annealed		91,500	45,550	17	24	...		Hibbard[3]
	0.33	....	0.39	3.58	1.61	0.0	Annealed		Annealed		90,500	46,500	19	27	..		Hibbard[3]
	0.30	....	0.20	2.50	0.50	0.0	Heat treated				110,000	80,000	20	30	. .		Hibbard[3]
Low nickel-chrome rolled steels	0.39	0.18	0.52	1.18	0.58	0.0	As rolled				99,000	59,000	26	54	208	29	Camp†[4]
							Annealed		Annealed		89,000	54,000	30	57	70	25	Camp†[4]
							845 O	427	1,550	800	139,000	114,000	16	51	331	42	Camp†[4]
							845	538	1,550	1,000	113,000	88,000	18	60	255	54	Camp†[4]
							845	649	1,550	1,200	108,000	81,000	25	65	229	31	Camp†[4]
							845	704	1,550	1,300	97,000	70,000	27	68	207	29	Camp†[4]
							845 W	427	1,550	800	174,000	158,000	14	57	363	46	Camp†[4]
							845	538	1,550	1,000	140,000	125,000	20	55	285	44	Camp†[4]
							845	649	1,550	1,200	110,000	91,000	26	66	229	33	Camp†[4]
							845	704	1,550	1,300	90,000	70,000	34	69	187	25	Camp†[4]
	0.20	....	0.65	1.25	0.60	0.0	870	214	1,598	400	160,000[2]	120,000[2]	15	53	275	46	S. A. E. Specifications
							870	538	1,598	1,000	100,000[2]	74,000	25	74	185	35	S. A. E. Specifications
							870	649	1,598	1,200	84,000[2]	60,000	32	72	160	30	S. A. E. Specifications
							870	760	1,598	1,400	75,000	50,000	35	73	150	28	S. A. E. Specifications
	0.40	....	0.65	1.25	0.60	0.0	870	214	1,598	400	220,000[2]	190,000	8	27	375	55	S. A. E. Specifications
							870	649	1,598	1,200	100,000[2]	84,000	18	60	225	38	S. A. E. Specifications
High chrome-nickel rolled steels	0.34	0.20	0.64	3.65	1.24	0.0	As rolled				172,500	138,000	12	27	444	57	Camp[4]†
							Annealed		Annealed		125,000	78,000	18	47	255	38	Camp[4]†
							845 O	427	1,550	800	190,000	166,000	13	50	415	55	Camp[4]†
							845	649	1,550	1,200	117,000	99,000	23	65	255	37	Camp[4]†
							845 W	427	1,550	800	164,000	152,000	18	56	375	51	Camp[4]†
							845	649	1,550	1,200	120,000	60,000	17	50	369	36	Camp[4]†
Chrome-vanadium rolled steels	0.19	0.05	0.49	0.0	0.96	0.23	850	574	1,562	1,065	146,900	137,200	20	58	.		Camp[4]†
							850	749	1,562	1,380	101,400	91,200	27	69			Camp[4]†
	0.25	0.05	0.30	0.0	0.85	0.14	850	574	1,562	1,065	132,400	125,800	20	64			Camp[4]†
							850	749	1,562	1,380	88,640	78,960	29	77			Camp[4]†
	0.38	0.25	0.41	0.0	0.97	0.24	815	427	1,499	800	177,500	155,000	11	36			Camp[4]†
							815	649	1,499	1,200	118,000	101,000	23	60			Camp[4]†
	0.57	0.27	0.84	0.0	1.36	0.31	Untreated				142,000	114,000	14	42			Camp[4]†
	0.46	0.20	0.45	0.0	1.17	0.14	Untreated				125,000	95,000	20	55			Camp[4]†
	0.18	0.18	8.32	0.0	0.74	0.20	Untreated				65,000	47,000	23	62			Camp[4]†

O = quenched in oil.
W = quenched in water.

[1] S and P below 0.03 per cent, and usually below 0.02 per cent.

[2] Minimum requirement.

[3] "Manufacture and Uses of Alloy Steel," New York, 1919.

[4] "Making, Shaping and Treating of Steel," 2d ed., 1920.

others, *viz.*, 1.50 per cent nickel with 0.60 per cent chromium, and 3.50 per cent nickel with 1.50 per cent chromium. In case one is looking for dynamic strength, such as resistance to shock, like a blow, vibration, alternating stresses, repeated stresses, you get the maximum effect with between 0.40 and 0.55 per cent of carbon. But in case you must have higher ductility, then the carbon must be lowered a little. Chromium-nickel steels have characteristically a very fine, dense structure. They must be heat-treated with much care. In making a chrome-nickel case-carburized crankshaft, for example, we must first normalize. Then, after case carburizing, the temperature of first quenching must not exceed Ac_3 greatly and the second quenching must be as close to Ac_1 as possible. Then, after drawing, the steel must not be cooled slowly, because this is liable to result in what is called temper brittleness, *i.e.*, very low resistance to shock.

Chrome-vanadium Steel.—The principle of heat treatment, and the general combination of strength and ductility of chrome-vanadium steel, will resemble the corresponding facts for chrome-nickel steel. Differences which exist will be seen in Table XVI-III. The differences are important, but lack of space forbids a further discussion of them here. Chrome-vanadium steel passes very slowly through the critical range, both on heating and on cooling. It, therefore, must be soaked a long time before quenching. It has a wider permissible heat-treating range than has either nickel or chrome-nickel steel.

Silico-manganese Steel.—Silico-manganese steel greatly resembles chrome vanadium in strength and for service in springs. The former is very much used in Europe for automobile springs, and to some extent in this country, although some American makers favor chrome vanadium as being less brittle. The differences between these springs may be noted by reference to Tables XVI-I and II.

Chrome-molybdenum Steel.—Chrome-molybdenum steel has not so good a combination of strength and ductility as have nickel, chrome-nickel, and chrome-vanadium steels, but it is very easy to roll and draw into tubes, to fabricate, and to weld, so that it is very popular for airplane structural parts. Its structural properties are also shown in Table XVI-I. The weakness of chrome-molybdenum steel is that, unlike chrome-vanadium steel, it does not have the vanadium to inhibit grain growth, so that chrome-molybdenum steel must be heated with great care to avoid coarse structure. Chrome-molybdenum steel also requires a longer time for soaking than does chrome-vanadium steel.

Steel for Springs.—The highest obtainable elastic limit without brittleness is the desideratum for springs. Some of the heat-treated chrome-nickel steels which have been treated with vanadium have been used with success and are recommended where price is not a limiting factor. A manufacturer gives the following data:

Table XVI-IV.—Deflection Test of Steels for Springs[1]

	Deflection at elastic limit	Load, pounds	Fiber stress per square inch	Tensile strength			
				Pounds per square inch		Elongation in 2 in., per cent	Reduction in area, per cent
				Ultimate	Elastic limit		
Alloy steel (composition not given)	1.006	3,280	301,000	220,000	200,000	13	45
Alloy steel (composition not given)	0.953	3,120	286,000	210,000	180,000	15	40
Chrome-vanadium steel	0.855	2,800	256,000	190,000	175,000	11	30
Silicomanganese steel	0.860	2,820	258,000	195,000	175,000	9	28

[1] This deflection test applied the load midway between supports 10.25 in. apart on a specimen 2½ by 0.259 by 15 in.

Steels of Highest Strength with Safety.—A large American manufacturer gives the following table of heat-treated steels, based on the highest strengths obtainable with safety, which he predicates as elongation not under 12 per cent and reduction of area not under 45 per cent:

SELF-HARDENING AND HIGH-SPEED TOOL STEELS

Self-hardening Steel.—Self-hardening steel is steel which is hard without being subjected to any heat treatment or other process for making it so. It is steel which cannot be made soft, or annealed, by any process known at present. It is often called "air-hardening steel" because, when it cools in the air from a red heat or above, it is not soft like ordinary steel but is hard and capable of cutting other metals. Manganese steel is a self-hardening steel and so obviously is any steel which is in the

TABLE XVI-V.—EXTRA STRONG STEELS

	Tensile strengths			
	Pounds per square inch		Elongation in 2 in., per cent	Reduction of area, per cent
	Ultimate	Elastic limit		
"Airplane" alloy steel (composition not given)	245,000	220,000	11	45
Chrome-nickel gear steel	235,000	208 000	12	45
Chrome-nickel gear steel	192,000	165,000	14	45
Chrome-vanadium forging steel	165,000	150 000	16	45
Simple nickel forging steel	200,000	178 000	14	45
Carbon forging steel	155,000	135 000	12	45

All these steels have been forged, steel castings cannot be made of this quality

If steels are wanted with greater ductility, for which some strength must be sacrificed, their composition and heat treatment may be learned from Tables XVI-II and XVI-III

austenitic or martensitic condition at atmospheric temperatures, *i.e.*, whose critical temperature is below the atmospheric temperature. All the self-hardening steels are therefore nonmagnetic or only slightly magnetic.

Mushet Steel.—The name "self-hardening" steel was first applied to an alloy steel invented by Robert Mushet and which owed its self-hardening properties to the simultaneous presence of both tungsten and manganese. The analyses varied greatly but were probably limited to between 4 and 12 per cent of tungsten with 2 to 4 per cent of manganese and 1.50 to 2.50 per cent of carbon. A typical sample and one having excellent qualities contained about 9 per cent of tungsten, 2.50 per cent of manganese, and 1.85 per cent of carbon. This steel is incapable of being made soft by any known process and is nonmagnetic. It is one of those curious phenomena met in the metallurgy of steel, where a combination of two elements will produce a result entirely different from anything that might be predicated: Tungsten does not lower the temperature of the critical change in steel and 2.50 per cent of manganese has but a slight effect in that direction. Nevertheless, the combination of these two reduces the critical point below the atmospheric temperature.

Mushet steel has been for many years, a famous tool steel because of its capacity for performing a large amount of heavy cutting work. It is very hard and durable and will retain its cutting edge for a long time and under very severe service. It, or its equivalent, is used very largely at the present time for very heavy, or deep, cuts and especially for cutting extra hard metal, such as the roughing cuts on armor plate and other hard alloys. The cutting speed of which it is capable is not much—if any—greater than ordinary carbon tool steel, but the economy of its use is due to the fact that it will take such deep cuts and last so long without regrinding.

Other Self-hardening Tool Steels.—The 2.50 per cent of manganese in Mushet steel can be replaced by 1 or 2 per cent of chromium and again produce a self-hardening tool steel which has the advantageous properties of Mushet steel. This result is even more astonishing than the self-hardening properties of Mushet steel, because chromium has a tendency to raise the temperature at which the critical change comes, and yet the addition of 1 or 2 per cent of chromium to a tungsten steel, which was not previously self-hardening and whose critical temperature was about 600°C. (1112°F.), reduces the critical temperature to below the atmosphere. We may also replace the 9 per cent of tungsten in Mushet steel with 4 to 6 per cent of molybdenum, and it is stated that this latter change produces a self-hardening tool steel which is a little tougher than Mushet steel.

Taylor and White.—Frederick W. Taylor and Maunsel White of the Bethlehem Steel Works experimented for a long time with the self-hardening steels existing in 1899 and previously, for the purpose of improving them by heat treatment. The full record of these and other researches were presented by Taylor in his presidential address to the American Society of Mechanical Engineers in 1906 and form one of the most interesting records of the kind ever presented to the world. The result of these experiments was to produce a wholly new kind of steel which has fairly revolutionized the machine-shop industry of the world. Taylor and White found that, by applying a new method of heat treatment to the self-hardening tool steels, they gave them much greater toughness at a red heat, so that they could do their cutting work at a speed so fast that the point of the tool would become red hot with the heat of friction and the great chips of steel, which were thick and heavy on account of the depth of cut which could be made, were raised to a temperature of nearly 300°C. (572°F.). In other words, the steel tool never lost its temper or its toughness at a red heat. The heat treatment which Taylor and White employed consisted in raising the steel almost to the melting point and then plunging it in a bath of molten lead at a temperature between 700 and 850°C. (1300 and 1550°F.), where it was kept until it was of the same temperature as the bath, and then removed and cooled by plunging into oil. They usually followed this cooling by reheating the steel to a temperature between 370 and 670°C. (700 and 1240°F.).

The first public exhibition of the Taylor and White steel was made at the Paris Exposition in 1900 and created first incredulity and then astonishment. The amount of work performed by a tool was unheard of, as also was the speed at which the tool was made to travel through the metal it was cutting and the length of time that elapsed before it was necessary to regrind it. It was realized that a new epoch in the tool-steel industry had been inaugurated. The fact that the method of heat treatment used by Taylor and White was subsequently shown to be unnecessary and that therefore the manufacture of high-speed steel tools, having qualities like theirs, was begun by everybody in no way lessens the credit due them for teaching the world how to produce a new kind of metal and effecting a tremendous decrease in the price of machine work.

High-speed Steels.—The name "high-speed steels" was not given by Taylor and White to their product but has subsequently been adopted for all steels capable of these rapid-cutting speeds which theirs had. Soon after they had shown the world what could be done, it was found that the only heat treatment necessary to give the steel its peculiar hardness and toughness at a low-red heat was to raise it to a temperature very near its melting point and then cool it with moderate rapidity, as, for example, by holding it in a blast of cold air until it was below a red heat. The essential feature seems to be that the steel shall attain a high temperature (1260°C., 2300°F.), which is so great that melted oxide forms on it, and it is almost ready to scintillate; *i.e.*, it has almost crossed the line *AE* in Fig. XI-9. After this heating it sometimes suffices merely to allow the steel to cool in air, but in this case its hardness is not so great, and cooling in oil is more usual. For some purposes it is reheated slightly above 550°C. (1022°F.) to increase its toughness. The reason why the steel is actually harder after this reheating is because the first cooling, together with the influence of the several alloying elements in the steel, causes it to be converted partly into austenite. Reheating the austenite converts it into martensite. Extreme care is required in heating the steel through the lower critical range; therefore a preheat of the steel in one furnace to a temperature of about 1400°F. at a very slow rate precedes the heating of the steel to 2300°F., from which it is quenched. Large tools are preheated first to about 1100°F. in one furnace, then transferred to another furnace at 1400°, before they are put in the furnace in which they receive their final temperature.

Composition.—It was also soon found that the composition of the self-hardening steels was not the best one for high-speed steel. Tungsten was the element which gave the steel the properties of hardness and toughness at a red heat. After the peculiar heat treatment had been learned and the presence of manganese or chromium in addition to the tungsten was shown to be accessory, it was found that more durable qualities could be obtained by increasing the percentage of tungsten, and steels have been put upon the market with as high as 24 per cent of this element, but 14 to 18 per cent is the usual proportion at present. At the same time the carbon was greatly reduced and at the present usually varies from 0.60 to 0.90 per cent in the best high-speed steels.[1] The manganese is low, 0.15 to 0.35 per cent; silicon, 0.10 to 0.25; chromium, 4 per cent; vanadium, 1 to 2 per cent.

The table[2] on page 520 shows comparative analyses of English, American, and German high-speed steels:

Hardness in High-speed Steel.—Four types of hardness are distinguished in high-speed steel, *viz.*,

1. Red hardness, or hardness for cutting at a low red heat.

---

[1] It is commonly stated in the trade that tungsten will take the place of carbon in producing hardness, but this is not true. It is far more correct to say that tungsten will assist carbon in producing hardness and therefore with high-tungsten steels we may have lower carbon. This distinction may appear merely academic, but it is well worth recognition by those who expect to make a study of these steels. No amount of tungsten or any other element will make steel hard in the absence of carbon, or even when the carbon is low. The tungsten produces hardness by its effect upon the condition of the carbon—*i.e.*, by helping to retain the carbon in its solid solution—and not by any effect of its own. It is for this reason that a lesser amount of carbon will produce hardness in the presence of tungsten or some similar agent.

[2] From Lantsberry, *Transactions American Society Steel Treating*, vol. 11, p. 716, 1927.

2. Carbon hardness, which seems to reach a maximum with 0.70 per cent of carbon, presumably because this particular alloy steel is at the pearlitic ratio of carbon at 0.70 per cent.
3. Alloy hardness, or the hardness due to the alloying elements.
4. Temper hardness, or the hardness due to changing from partly austenitic to wholly martensitic structure.

Table XVI-VI

	English				American			German			
	14 per cent tungsten	18 per cent tungsten	Super	Super							
C	0.6/0.65	0.6/0.65	0.7	0.8	0.68	0.70	0.88	0.5	0.9	0.7	0.64
Cr	3.5/4.0	3/4	3/4	3.8	4.0	3.6	4.3	5.0	5.1	5.0	4.3
W	13/14	16.5/18	18	19	16.2	17.0	18.8	18	18	14.3	16.0
V	0.2/0.5	0.25/0.5	1.26	0.6	1.3	0.83	1.3	0.15	1.2	0.5	1.12
Mo				0.75	1.1			1.6	0.6		0.7
Co				5.43			2.92				5.19

Forging.—High-speed steels can be forged only at temperatures above a bright-red heat, *i.e.*, from 1050 to 1150°C. (1922 to 2100°F.) and higher. The ingot, when first made, must not be allowed to cool to a black heat but must be forged before it cools, in order that carbide segregations in the steel may be avoided.

Annealing.—The heating and annealing of high-speed steels require a great deal of care. They must be heated up to the annealing temperature (say about 800°C., 1472°F.) with extreme slowness and cooled down in lime or ashes or in the furnace. They are then soft enough to be machined easily, but not so soft as carbon steel.

AUTOMOTIVE PARTS

Alloy steels are used so extensively in the automotive industry that some cars are built without any plain carbon steel in their make-up. The supporting portions are frequently made of nickel steel; the axles of ternary steels; the valves of high-chrome steels, which will resist oxidation and corrosion by the hot gases; the wearing parts, such as crankshafts and gears, of case-hardened nickel steel, often containing some chromium to increase the intensity of the heat treatment. The springs are made of a chrome-vanadium or silicomanganese steel for resilience. The ball bearings are of chrome steel, or even of ternary steel, to increase their hardness, etc. What applies to parts of automobiles is still more effectively true of steel for airplanes, which must be as strong as possible, in order to give strength with light weight and reliability.

In Tables XVI-VII and XVI-VIII are summarized the effects of the different alloying elements as they appear in the alloy steels used for different purposes, and below are given the prices of some of the most-used alloy steels:

PRICES OF SOME OF THE ALLOY STEELS

	Cents per Pound
Stainless iron	20.00
3 per cent nickel-chromium steel	6.45
3.5 per cent nickel steel	4.15
1.5 per cent nickel-chromium steel	3.60
1 per cent chrome-vanadium steel	3.60
2 per cent chromium steel	3.45 ±
Silicomanganese steel	3.00 ±
0.5 per cent chromium steel	2.95
Medium-manganese steel	2.90

TABLE XVI-VII.—NATURE OF EFFECT OF SOME OF THE ALLOYING METALS USED IN STRUCTURAL STEELS

(The effect of all these alloying metals is to increase strength)

Kind of steel	Metal	Percentage used	Nature of the influence exerted by the alloying metal	Must this steel be heat-treated?
Nickel	Nickel	3.50	Makes Fe grains small	Better so
Silicon	Silicon	1	Pushes point S to the left in equilibrium diagram	No
Medium manganese	Manganese	1.75	Pushes point S to the left in equilibrium diagram	No
Castings	Vanadium	0.25	Makes grains small	No
Molybdenum	Molybdenum	0.35	....	Yes
Chrome	Chromium	0.60	Intensifies effect of heat treatment	Yes

Nickel and chromium are the two alloying elements most often used. The weight of these two metals used in alloy steels exceeds the weight of all other alloying elements taken together. More than three-fourths of all alloy steels used in America go into automobile manufacture, because automobiles and airplanes

TABLE XVI-VIII.—NATURE OF EFFECT OF SOME ALLOYING METALS IN NONSTRUCTURAL STEELS

Alloying metal	Percentage used	Effect of alloying metal	Cause of effect of alloying metal	Must this steel be heat-treated?
Chromium.	1 to 5	Hardness	Intensifies effect of rapid cooling	Yes
Manganese....	7 to 14	Abrasion hardness	See footnote[2]	Yes
Tungsten[1]. . .	14 to 18	"Red hardness"	....	Yes
Silicon ..	4 75	Greater efficiency in AC magnets	Increases electrical resistance	Yes
Copper	0 15 to 0 50	Reduces rusting	....	No
Chromium.	11.5 to 38	Eliminates corrosion Reduces scaling	. ...	Yes and no
Silicon	13	Lessens acid attack	. .	No

[1] This tungsten is illustrated as if in "high-speed steel."

[2] Manganese lowers the temperature at which the line PSK in Fig. XI-9 occurs. With more than 7 per cent of manganese, this line is below atmospheric temperature. Therefore all such manganese steel will be a solid solution at atmospheric temperature.

require steels of high quality, and can afford to pay the price in excess of the cost of carbon steel. The best alloy steels are made, of course, in the electric furnace or crucible, but 75 to 80 per cent of the tonnage comes from basic open-hearth furnaces. The annual tonnage of alloy steels made in the United States is about 3,000,000 tons, or about one-fourteenth of the total steel made. The proportion is increasing rapidly every year.

HIGH-STRENGTH CAST IRON

There has been in the last five years, and particularly in the last two years, a tremendous amount of interest in so-called "high-strength cast iron." The Germans gave us the first good impetus in that line with their so-called "pearlitic cast iron" and their researches and studies, but a great deal has been done in this country too, and, in order to introduce the subject, let me say that the iron foundryman has been attacked and handicapped on three sides. In the first place, the steel-casting people have turned out a better product than iron castings and by means of new furnaces and improvements they brought their price down to the place where they are pushing the iron foundryman pretty hard; then the malleable cast-iron foundryman has improved the strength of his product from 35,000 to 60,000 lb. per square inch and 8 per cent elongation in 2 in. to 15 per cent elongation in 2 in., so that he has been pushing the cast-iron foundryman pretty hard because of his better product and very little increase in price; and, finally, the welding people have pushed the iron foundrymen. One large electric company has abandoned all its foundry plants, except one, making bases and frames by welding structural steel. The iron foundryman, hemmed in on three sides, has had to develop on the fourth side, *viz.*, better properties, and he has done much in a short time.

Properties of High-strength Cast Iron.—The properties most important in cast iron are (1) strength, (2) resistance to wear, and (3) machinability. It is fairly easy to get the strength up but then the machinability goes down, and, of course, when you get resistance to wear, the machinability decreases, but when you have a long locomotive cylinder, perhaps 48 to 60 in. long, turned on the inside at competitive prices, machinability is important, and, when the piston travels back and forth inside the cylinder and begins to wear an elliptical place at the bottom, it goes out of commission before long and then the customer objects. With the question of strength of these cylinders versus weight, you have a problem. In the matter of machinability, the cast-iron man has only one real competitor and that is the malleable cast-iron man. Malleable cast iron will machine much better than cast iron or alloy cast iron. When a gray iron foundryman turns out iron with 30,000 lb. per square inch tensile strength, he is proud of his figures; 50,000 lb. per square inch is a good figure for malleable cast iron; 60,000 lb. per square inch is a very good figure for alloy cast iron; 85,000 lb. per square inch is a very good figure for steel castings. Of course, cast iron is more frequently judged, or used to be more frequently judged, on transverse strength. There is considerable difference here; transverse strength will be 2,500 to 3,300 lb. per square inch for the standard arbitration test bar of the A.S.T.M., with a deflection of 0.17 in. for 2,500 lb. per square inch and 0.12 in. for the 3,300 lb. per square inch. There are some figures higher than these; the author has a figure of 4,406 lb. per square inch with a 0.10-in. deflection which he knows to be true, but 2,500 to 3,300 lb. per square inch is a good figure for the standard test bar. Resistance to wear is difficult to gage. Foundrymen use either Shore or Brinell test, and probably Brinell is a little better. The improvement that has been made has been through the study by research and theory of the path of rupture. Now the path of rupture through cast iron is made by splitting apart of the crystals of graphite, so that one-half of the graphite sticks to each side and there is very little metallic matrix through which to pass. It is perfectly obvious, then, that the first line of study would be in a better size and better distribution of the graphite flakes. This has been worked on for a long time and more recently German metallurgists began working on the metallic matrix. By increasing the strength of the metallic matrix, one can increase the strength of the whole piece, even though this matrix represents only a portion of the bar through which fracture must take place.

Graphite.—First coming to the graphite: it is obvious that reducing the total weight of graphite is a benefit and that has been done for a great many years by melting steel scrap in the cupola. With even as much as 50 per cent of steel scrap in cast iron, the cost is not increased much. It takes a little more coke to melt it and, if one melts the cast iron and scrap and allows it to run out of the cupola as fast as melted and not saturate itself with carbon, one may get lower total carbon in the iron. Total carbon may be reduced to 3 per cent, and that may be one-third in the combined form, leaving not more than 2 per cent of graphite in the iron. If the total carbon be further reduced from 3 to 2.5 per cent, the strength of the mixture has been much improved. In order to do that, one must have the tuyères situated not high up in the cupola but within 4 in. or so of the bottom of the cupola, the tap hole left open at all times, so that metal and slag run right out of the cupola. The charge melts 15 to 18 in. above the tuyères and, while it trickles down, absorbs a lot of carbon; but if tapped from the cupola as soon as melted and if mixed with 50 per cent steel scrap, total carbon is well reduced. The foundryman has gone as far as he can in this respect. He can, of course, always melt in air furnaces where there are oxidizing conditions above the bath instead of reducing as in the cupola and the carbon can actually be burned off, but one must be careful or one will burn off silicon. It is very simple to get as low as 2½ per cent total carbon in the air furnace but it costs more money.

Moldenke and others have made certain researches and found that by superheating metal, *i.e.*, heating it very hot and pouring at a high temperature and cooling somewhat rapidly, the carbon is in a better state of distribution. The graphite goes out in small particles instead of the larger flakes. The size of the flakes will depend upon the number of nuclei. If graphite commences to precipitate at 1,000 different points, it will precipitate in smaller flakes more widely distributed than if it precipitates in 100 different points and aggregates as it precipitates, so that hot melting, *i.e.*, finishing hot and pouring hot, and freezing rapidly, will have the effect of making a better distribution of the graphite. It is probable when we come to alloy cast iron that nickel, nickel chromium, molybdenum, perhaps more questionably vanadium may provide nuclei to get a better distribution of the graphite. Another way of getting low graphite is to have high combined carbon. There one runs into danger: one gets bad machining qualities and the superintendent of the machine shop is ready to go to the general manager and tell him how glad he would be if some other metallurgist were put on the job. Too much money is lost by bad machining—so much that it would be cheaper to use alloy cast iron, so that there is a limit to the amount of cementite that can be put in.

The Metallic Matrix.—Henry M. Howe pointed out 15 years ago that a metallic matrix in cast iron which was pearlitic would give the best strength, but it was not followed out in this country. It finally was taken up by the Germans and it seems to be definitely advantageous to let combined carbon go to the pearlitic ratio so that the iron consists of graphite and pearlite. This requires a careful adjustment of the silicon, manganese, sulphur, the pouring temperature, and the chilling but also may, under certain conditions, require reheating the castings and cooling them at a regulated rate. Thus we get an improvement in the metallic matrix and a slight improvement if we can thereby decrease the graphite by increasing the combined carbon. If the combined carbon goes too high, machining is apt to be bad. In the old days it was very common to have a small amount of pearlite and large areas of ferrite and large areas of graphite, and that, if it occurs, can be corrected usually by heating above the critical temperature, holding awhile, and slowly cooling. But by adjusting the silicon, sulphur, manganese, and temperature of pouring, by having the phosphorus not too high, and by cooling with a medium degree of rapidity, one can in some instances have graphite with pearlite and no ferrite. In some cases this is brought about by agitating the liquid iron in the ladle, as for example, in a bumper molding machine. It does not seem to be possible to give any general rules for this other than studying the conditions to see what silicon, sulphur, manganese, and cooling temperature will give the pearlitic ratio, but remember pearlitic ratio is not always 0.85 per cent of carbon where there are other elements present. That has to be studied under the microscope.

There is a sentiment in favor of making plain cast iron, even if it is necessary to use an electric furnace for adjusting the melting temperature before pouring. The reason for this is that alloying elements cost money, and also that they vitiate the scrap, so that future castings unexpectedly contain elements which alter their hardness or other properties.

ALLOY CAST IRON

There is a great deal of alloy cast iron made today and there would be more except for the difficulties of making it. Alloying elements can be added either in the melting furnace or otherwise to the melted metal and there is no great difficulty except sometimes with the cupola.

Cupola Melting.—The cupola is the cheapest way of melting cast iron and the commonest way, and, therefore, cupola difficulties have militated a good deal against the making of alloy cast irons. In the cupola we can melt the iron with certain alloying elements which we want to have in it. Or we can use Mayari iron, made from a natural ore which smelts into an iron having roughly 1.5 per cent of nickel and 0.5 per cent of chromium, or thereabouts, which is, therefore, very good nickel-chromium cast iron. Where, however, we add alloying elements in the cupola, a great many irregularities have been encountered. These have been overcome sometimes by making up briquettes of cast-iron chips mixed with alloying elements and melting these briquettes in the cupola. Uniformity is not always obtained by the method of melting ferroalloys, or nickel alloys with ferro-chromium, in the cupola with the charges. Another method of alloying is adding the alloying elements to the ladle, but this necessitates having the metal very hot as it obviously will chill the metal, and there are liabilities of irregularities in composition and irregularities in temperature. A third method is to put the alloying elements in the spout as the metal runs from the cupola into the ladle. This gives better mixing, of course. Unquestionably there are a great many people who are making alloy cast iron in the cupola successfully and overcoming the difficulties, but, on the other hand, there are many foundries that have made an earnest effort to use alloy cast iron and had to give it up. Not only are there the difficulties which have been mentioned, but the scrap is vitiated. Now either the scrap will be vitiated or else the foundry must have a special set of bins and keep the alloy scrap separate. As far as chromium is concerned, not only is money thrown away, but, when chromium-containing scrap is reused inadvertently, one runs into danger of getting hard castings. Enough nickel is being used in cast-iron foundries to make at least 250,000 tons of nickel castings a year.

Air-furnace Melting.—A great many difficulties disappear when one does not use the cupola for melting. Some are using an air furnace. One melts nickel chromium in the bath in the air furnace and brings it to the proper temperature. There is a complete distribution of the alloying elements through the metal. But some foundries are making very good cast iron in their air furnace without alloying elements and selling it in competition with alloy cast iron. They get low total carbon easily enough, high strength, and a temperature they want. It costs more than cupola melting but yields a very excellent air-furnace iron for iron-foundry castings, and they use alloying elements only when some special case requires it or when the customer asks for it and pays for it.

Electric-furnace Melting.—Many foundries are using electric furnaces, particularly the Moore 'Lectromelt furnace, for alloy cast iron. They can do it in either of two ways: Melt down and finish the charge in the electric furnace, or melt it down in the cupola, tap it into the electric furnace, and there add the alloying elements. The success of the electric-furnace method has been so marked that a good many prominent metallurgists insist that good alloy cast iron cannot be made in competition without an electric furnace. The success of the electric furnace has been such that the prices in some industries, *i.e.*, the prices for commercial castings, are based on electric-furnace operation and there are many foundrymen who claim, and doubtless think, that they make a good deal more profit out of alloy cast iron than they do out of plain iron, although the cost of melting and cost of alloying additions have to be taken into consideration. But the number of rejections is considerably less when an electric furnace or air furnace is used. And, in fact, the competitive price is based on a very much lower percentage of rejections.

Machinability and Strength.—Alloy cast iron has the peculiarity that it is machinable with a higher Brinell than is gray cast iron. That is one of the most important points in connection with alloy cast iron, because ordinary gray cast iron, if it has a tensile strength and therefore a Brinell hardness of more than 220 Brinell number, will machine with difficulty, whereas nickel-chromium cast iron with a Brinell hardness of 240, and in some cases 280, will machine effectively and without too much objection from the machine shop. The result has been that almost all the nickel-chromium cast irons have been used for purposes such as automobile cylinders, liners for locomotive cylinders, and other places where strength with good machining qualities is wanted. If you bring out the graphite by means of silicon, you tend to produce the hard spots and chills as well. But if you bring out graphite with nickel and with less silicon, it is less porous and less open and that is the reason for strength—close grain structure and well-distributed graphite. Ordinary cast iron has an upper limit of 30,000 lb. per square inch tensile strength. High-strength cast iron has an upper limit of 35,000 to 38,000 lb. per square inch; nickel-chromium cast iron will have an upper limit of 65,000 to 70,000 lb. per square inch. If the transverse strength of ordinary cast iron is 2,500 to 3,300 lb. per square inch in the arbitration test bar, the nickel-chromium cast iron will have 5,000 to 5,500 lb. per square inch with the same deflection as the plain carbon.

Alloying Elements Used.—The largest tonnage of alloy cast iron used is nickel chromium. Also vanadium has been used for a great many years and is used especially in chilled cast iron, because it greatly hardens and stiffens the chilled surface, so it increases resistance to abrasion and seems to increase the compressive strength and the shear resistance very much. Apparently it does not increase depth of chill, but it does materially increase the hardness.

Aluminum has been used a good deal in recent years. This is not strictly an alloy cast iron, because aluminum is the twin brother of silicon. The principal reason for the use of aluminum is that we get less oxidation of the iron. Some foundries today are making molybdenum cast iron instead of nickel chromium, and there are some advantages. In the first place, it does not cost so much. Molybdenum is used in varying amounts up to 1.5 per cent. Its full benefit seems to be obtained at about 1 per cent and above. Molybdenum is not harmful in the cast-iron scrap. Of course, it is a loss of money to have scrap containing molybdenum, but, as far as properties are concerned, molybdenum seems to do no harm in the scrap. Molybdenum is added in the form of ferromolybdenum or molybdenum metal. In either case there is a very small amount of molybdenum to chill off the metal with less trouble and expense for superheating the cast iron. Adding a definite amount of ferromolybdenum in the spout or ladle does not seem to present so much difficulty as when nickel or nickel chromium is added; it does not reduce temperature so much and one can figure on it somewhat better, and there is only one addition to make, either in the ladle or in the spout. One of the important advantages of molybdenum cast iron is that it holds its strength better at higher temperatures. That is important in steam-engine cylinders with superheated steam. They use superheated steam now all the way from 750 to 850°F. Tungsten and molybdenum do more for steel at high temperature than anything else. Professor Albert E. White of Michigan University holds that nickel does not do any good at all at high temperatures. Molybdenum cast iron is easily made with a tensile strength of 50,000 to 60,000 lb. per square inch when it is made in the electric furnace and with 40,000 to 50,000 lb. per square inch when made in the cupola. Molybdenum seems to have almost no effect in decreasing the difficulty of machining. Ordinary cast iron made in the cupola with total carbon from 3 to 3.25 per cent and with 0.5 per cent of molybdenum has regularly given 40,000 lb. per square inch tensile strength; with 1 per cent of molybdenum, 50,000 lb. per square inch; and with 1.5 per cent, 60,000 lb. per square inch. In order to get strengths higher than that, 0.5 per cent of chromium can be added.

References

J. L. GREGG: "The Alloys of Iron and Molybdenum," New York, 1932.

EARL S. GREINER, J. S. MARSH, and BRADLEY STOUGHTON: "The Alloys of Iron and Silicon," New York, 1933.

ERNEST E. THUM, editor: "The Book of Stainless Steels," The American Society for Steel Treating, Cleveland, Ohio, 1933.

J. L. Gregg: "The Alloys of Iron and Tungsten," McGraw-Hill Book Company, Inc., New York, 1934.

Arthur W. Judge: "Aircraft and Automobile Materials of Construction," vol. 1, "Ferrous," London, 1920.

Marcus A. Grossman and Edgar C. Bain: "High Speed Steel," New York, 1931.

Denison K. Bullens: "Steel and Its Heat Treatment," New York, 1927.

G. Mars: "Die Spezialstähle," Stuttgart, Germany, 1912.

Léon Guillet: "Les Méthodes d'Étude des Alliages Métalliques," Paris, 1923. Bibliography at the end of each chapter.

Thomas H. Burnham: "Special Steels," London, 1923. Chiefly founded on the researches regarding alloy steels of Sir Robert A. Hadfield.

Henry D. Hibbard: "Manufacture and Uses of Alloy Steels," New York, 1919.

"Steels and Alloys for Special Purposes," Pittsburgh, 1919. This is a shop book published by a manufacturing company but contains much very valuable material of a technical character on this subject.

Greswold Van Duke: "Shop Handbook on Alloy Steels," Chicago, 1921. This is a shop book, like the preceding.

INDEX