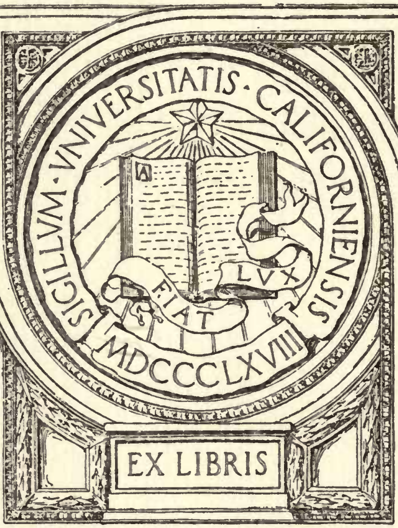
American Malleable Cast Iron

By

H. A. Schwartz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AMERICAN MALLEABLE CAST IRON

By H. A. Schwartz

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To

THE MEMORY OF

ALLEN SMITH BIXBY

TO WHOSE INSTRUCTION, CO-OPERATION AND ADVICE I OWE THE EARLY
OPPORTUNITIES WHICH MADE THIS BOOK POSSIBLE
IT IS AFFECTIONATELY DEDICATED

PREFACE

THE literature of malleable cast iron, in the American sense of that term, is limited to a single book first issued about 10 years ago and now out of print, and to a series of articles of great diversity of character and quality in the technical publications of this country and Europe. Much of the most valuable scientific matter is buried in the purely scientific press, frequently under titles which do not suggest its application to any one not a specialist in metallurgy.

Under these circumstances the preparation of a new book dealing with American malleable cast iron in theory and practice may serve a useful purpose as summarizing and recording, so far as any book can, the contemporary state of the art in the metallurgy of this product.

If in the following pages the specialist finds much which appears to him elemental or trivial or the non technical reader finds matter which appears too complex, the author must plead in extenuation his desire to prepare a book to suit many kinds of readers.

This has necessitated the inclusion of much elementary matter both in metallurgy and mechanics which will be useful only in acquainting the lay reader with the interpretation of terms and data which form the every day vocabulary of the technician.

On the other hand it has seemed that in order that the reader might secure full value from a reading of these pages no known fact or theory should be excluded merely in the interest of simplicity.

Feeling that no single individual is justified in the belief that his own views are final in so complex a subject the author has not hesitated to refer freely to the literature and even to record opinions contrary to his own. So far as possible due credit has been given in all such cases.

Guided by the injunction of Leonardo da Vinci, "Confirm your statements by examples and not by assertions", it has been the author's constant effort to record facts rather than opinions wherever possible. This has been particularly true in the chapters dealing with manufacturing methods. In these chapters the record is one of what has been rather than of what might be accomplished. Much of the experimental work referred to is the work of the author's associates. In this connection special recognition must be given to the very unusual micrographs which are the work of Harrie R. Payne, chief chemist and metallographer of the author's laboratory.

Many of the author's friends within the malleable industry, in the organization of which he has the honor to be a member, and among the business connections of that association have contributed valuable information.

Whenever possible credit has been assigned. In some cases where for obvious reasons it was improper to identify the information the latter has consented to the anonymous presentation of his material. The co-operation of the American Malleable Castings Association in furnishing statistics and of the late Thos. Devlin of Philadelphia, and Alfred E. Hammer, Branford, Conn., in contributing historic matter from their long experience is especially worthy of grateful acknowledgment.

If the following pages contain any information calculated to dispel the many misconceptions as to malleable cast iron and to acquaint the interested reader accurately with the properties and methods of manufacture of this interesting, valuable and characteristically American product, the author's labor will have been richly repaid.

H. A. SCHWARTZ

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American Malleable Cast Iron

I

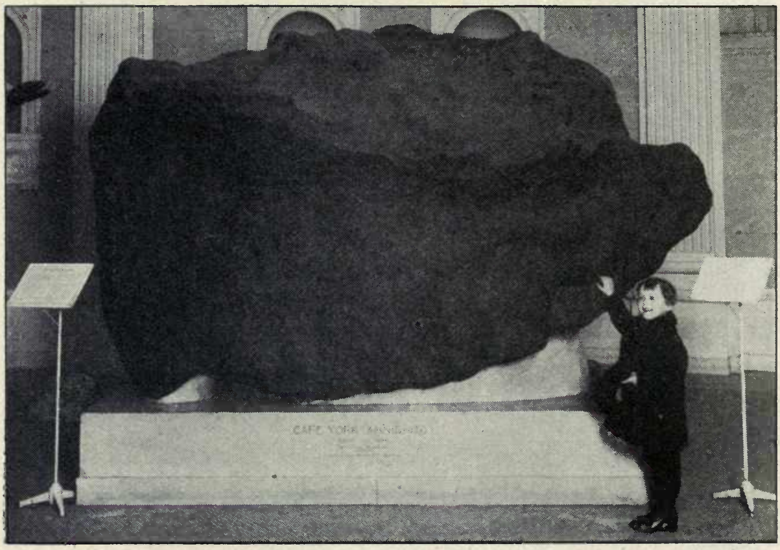
EARLY HISTORY OF IRONMAKING

SINCE the dawn of civilization man has continuously labored to use the natural resources of the world for his own well being. He first adapted to his needs the materials most easily obtained and as his knowledge and skill grew he sought to find or make other materials which would better suit his requirements.

Copper and gold, being found in the metallic state in nature, were the first metals to attract his attention. Moreover, being malleable, these metals were readily fashioned into the shapes desired. Far beyond even legendary history the mound builders used copper utensils while the Incas and Montezumas used gold in domestic articles as well as in ornaments. Of the various metals found as compounds in nature, lead, silver and tin are fairly easily reduced from their ores; hence prehistoric metallurgists soon added these to the list of available materials. Thus the age of copper was succeeded by the age of bronze.

The only free iron found in nature is that of meteoric origin, usually existing in small fragments which easily rust away. However, in a few cases, notably the three large siderites brought from Greenland by Admiral Peary and now in the American Museum of Natural History in New York, meteoric iron has been put to industrial use. Peary's siderites, which are the largest ever discovered, constituted the only source of iron for the Esquimaux of northern Greenland.

Approximately five thousand years ago, one of Pharoah's



Courtesy of American Museum of Natural History

Fig. 1—A meteorite in the American Museum of Natural History, New York, brought from Greenland by Admiral Peary

masons carelessly left one of his tools lying on the masonry where a new stone was being set in building the pyramids. Thus packed in lime, this earliest known piece of man-made iron was preserved for posterity. The method doubtless used by the Egyptian iron masters still persists in many semicivilized communities.

As shown in Fig. 2 it consisted of heating rather finely divided ore in a charcoal fire blown by a hand or foot bellows in a shallow basin in the ground. The charcoal acted both as fuel and as a reducing agent, liberating metallic iron. The temperature being low, the iron did not combine much with the carbon nor did it melt freely. The pasty bloom which accumulated in the hearth was removed and crudely hammered into the desired shape. Obviously the process was laborious, yet it was practiced on a considerable scale. It is believed that the famous pillar of Delhi was made by welding together blooms of the kind just described.

Metal of this kind possessed some of the properties of wrought iron or unusually soft steel of the present day.

However, it doubtless was variable in quality since the carbon content must have fluctuated considerably due to the changing and uncontrolled temperature conditions. Notwithstanding this lack of uniformity, it was decidedly a better metal for tools and arms than the copper and bronze preceding it.

Still before the era of written history there lived a primitive Carnegie whose very name has been lost. This early steel master, probably a native of Greece, determined to engage in the quantity production of iron. He substituted a stack or shaft for the shallow hearth then in use with the hope of rendering the operation continuous instead of intermittent. He introduced blast from the bellows at the bottom, started a fire of charcoal and then began to add alternate layers of charcoal and ore until the shaft was full. Presumably he expected to dig out blooms of iron from the bottom of the furnace at frequent intervals and to supply

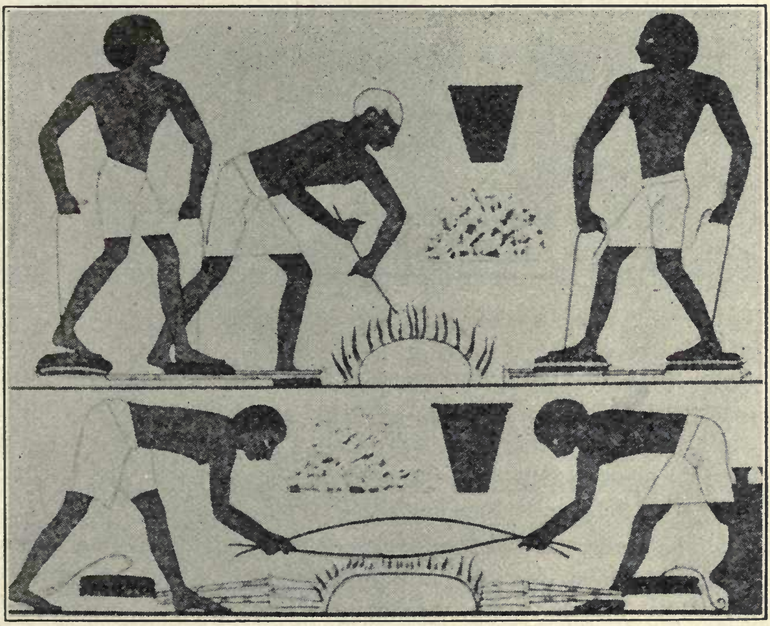


Fig. 2—A primitive furnace, 1500 B. C. The illustration was reproduced from an Egyptian wall painting

charcoal, ore and air continuously. Doubtless he was much surprised when on some occasion instead of iron blooms appearing, molten metal ran from the opening in the stack.

Such was the first production of cast iron. The better utilization of heat in the shaft furnace had produced a temperature high enough to more completely carburize the product. The decreased melting point, coupled with the higher temperature reached, produced a liquid metal probably of white or mottled fracture. Unconsciously this primitive artisan discovered the blast furnace. Even today the process of smelting iron ore is governed by the same general principles which obtained in the early days in Greece. Only the technique has been perfected.

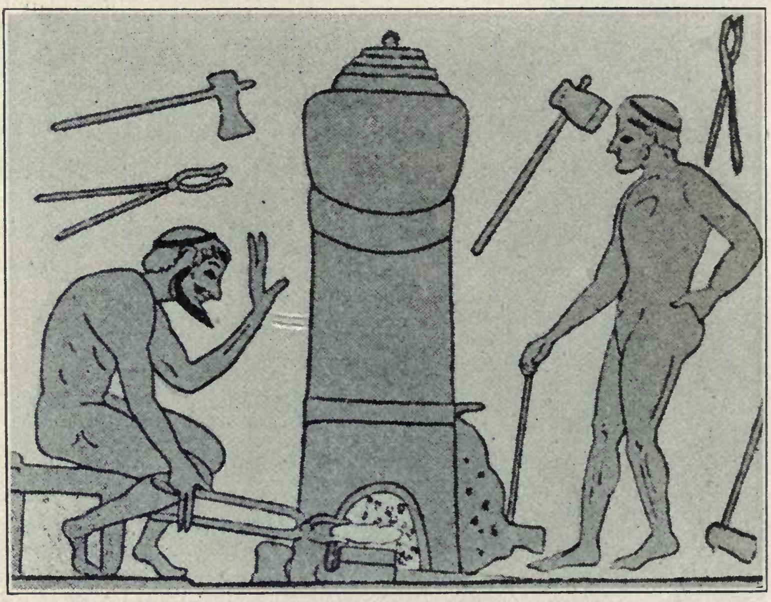


Fig. 3—One of the earliest blast furnaces

The earliest known blast furnace purposely to make pig iron is said to have operated in the Rhine provinces of Germany in 1311. The industry spread over the rest of Europe during the succeeding century.

With the development of the crude blast furnace, one of which is illustrated in Fig. 3, there existed two kinds of iron. The one had to be forged to shape and was rather soft although not easily broken and the other, which could be cast into shape, was rather hard but too brittle and fragile to use. Obviously, a metal of either of these limitations was not exactly adapted to the making of swords, the manufacture of which constituted a most important profession in the early days. Therefore, the most important metal for that age was one not soft enough to be bent and blunted by armor nor so brittle as to be shattered by a sharp blow. In the search for a material to better meet the requirements of the armorer some pioneer found that if the soft iron produced in the forge were heated in charcoal, the surface of the metal could be made harder—in fact the metal could be hardened throughout if the treatment were continued long enough. It was learned that in this manner tools and weapons could be produced with a superior edge.

For many centuries this "blister" or cementation steel was the only steel available. One of its principal shortcomings was its lack of uniformity across the section. However, this was later overcome by remelting the carburized steel in crucibles, thus rendering it homogeneous. The crucible process also was modified by melting wrought iron mixed with sufficient charcoal or cast iron to give the desired properties to the metal. The amount added was determined empirically, for at that time chemical control from the viewpoint of carbon content was unkown.

Thus at the beginning of the eighteenth century three kinds of iron were known to the world. These were wrought iron, soft and worked only by forging; cast iron, brittle and worked by casting; and crucible or cementation steel, sometimes melted in the process of manufacture but always forged to shape, not brittle but hard enough to hold an edge and be tempered.

Steel, however, could only be made from wrought iron, wrought iron only from ore, and neither could be made from the relatively cheap cast iron. The next forward step in the metallurgy of iron and in fact the first since the dark ages, was the invention by Cort of the puddling furnace for converting molten cast iron into blooms of wrought iron by treatment with ore. This invention made possible the reduction of the metal from its ore in the cheaply and efficiently operated blast furnace and its later conversion into malleable and ductile wrought iron.

Steel was still made by using wrought iron, now obtained by puddling, as the raw material. This continued to be the only source of steel until the discovery of the bessemer process in the middle of the nineteenth century and the invention of the open-hearth furnace by Siemens about 15 years later. Both of these processes, which depend for their success on the increased temperatures available, produce liquid steel of nearly any desired carbon content. The former process uses the carbon and silicon content of the molten pig iron for fuel, burning these within the charge by a blast of air. By the removal of the carbon, the cast iron becomes steel which is kept liquid by the heat of combustion of the carbon and silicon.

Siemen's was practically a modified reverberatory furnace fired by gas, the fuel and air for combustion being heated in regenerators by the waste heat of the escaping products of combustion. The oxidation of carbon was accomplished, as in the puddling furnace, by the oxygen of the hematite iron ore added to the slag. The essential difference between Cort's and Siemen's invention was that the latter worked at temperatures sufficiently high to keep the resulting product molten.

A review of the industrial world at about the close of the American civil war indicates that five well established types of iron and steel were being used. Charcoal iron was made directly from ore and charcoal on the same principle used in prehistoric times. This material resembled wrought iron and was practically obsolete from a production viewpoint. Wrought iron was made from cast iron in the puddling furnace. It was a pasty mass and was shaped by rolling and hammering only. This material was soft, malleable and ductile. The railroad iron of which the MONITOR'S armor was made was of this character. A third material was cast iron made in the blast furnace and cast to shape in molds. This iron was incapable of being bent without breaking. The fourth material was blister or cementation steel made from wrought iron in unimportant amounts. This steel had to be forged to the shape desired. The fifth and most important metal was steel made in liquid form by the crucible, bessemer or open-hearth process from cast iron. This had so high a melting point that it was incapable of casting any but large molds, hence it was usually cast into the latter form and rolled or forged to shape. When desired it could be produced of a composition permitting of hardening and tempering.

Fig. 4—An early American blast furnace

A sixth product, then just coming into use is the subject of this volume.

It will be observed that in none of the first five products are combined the properties of malleability of wrought iron and fusibility as found in cast iron. In other words, no material has been described which could be cast into intricate

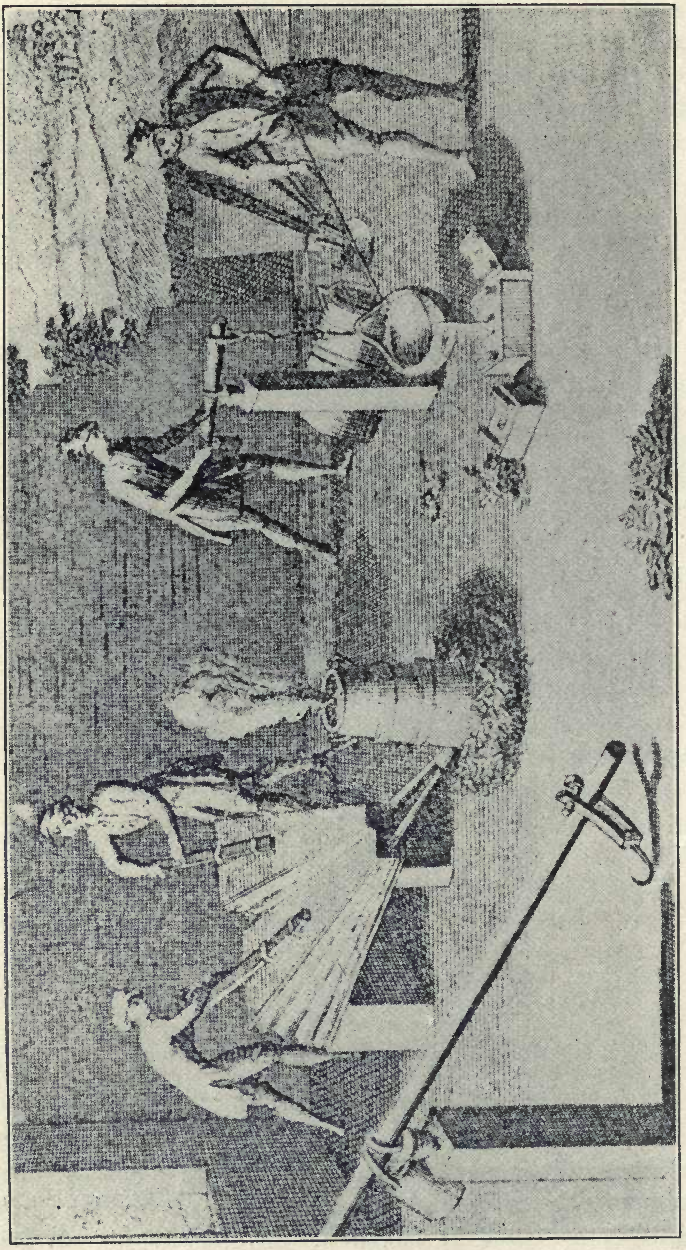


Fig. 5—Reaumur's foundry in 1724. One furnace has just been emptied and the blast is being applied to the other

shapes and which would be in any degree malleable when complete. The problem of producing a malleable cast iron to fulfill these requirements had long occupied the minds of the iron masters. Since Cort had produced wrought iron by the use of ore, a modification of his process which would not involve the melting of the cast iron now seems to us a logical conclusion. In 1722 Reaumur, a French physicist, described a process, not necessarily original with him, for producing malleable cast iron by packing small castings of (presumably white) cast iron in pulverized hematite ore and heating them to bright redness for many days. This method evidently was suggested by the cementation process for making steel from wrought iron, substituting for the charcoal which adds carbon in that process, ore which removed carbon, the same reaction later discovered by Cort as applied to molten cast iron.

Reaumur's discovery, or better disclosure, actually grew into an industry in Europe. It happened that European white cast irons, except in Sweden, were relatively low in manganese and high in sulphur, owing to the available fuels and ores. Being white, it also was low in silicon.

Such conditions are all unfavorable to the formation of free carbon and consequently Reaumur's reaction was never complicated by the formation of temper carbon or graphite. In intention, at least, the annealing removed from his thin castings all the carbon which burned from the carbide of iron.

The amount of the carbon originally present was immaterial, in any event the resulting casting, if the anneal was successful, had only traces of carbon but contained all the other chemical elements originally present. Having been only moderately heated it retained its original cast form but approximated the chemical and physical properties of wrought iron. The shortcomings arose mainly from the fact that since carbon was removed through the surface, the process could not be commercially applied to moderately thick sections owing to the prohibitive annealing time. Moreover, a casting having both thick and thin parts naturally would be completely decarburized in the former while still retaining much carbon in the center of the heavier portions. If the process were continued to completion in the thick sections, trouble from oxidation and scaling of the thinner parts would be encountered. Furthermore, it was difficult to be sure that the castings were annealed clear through, since the interior is not available for inspection. Any castings not annealed through would be brittle owing to the remaining undecarburized core.

Hatfield in his "Cast Iron in the Light of Recent Research" says of this process as practiced in England: "Essentially, the materials used in Britain in the production of malleable castings, are high in sulphur, necessitating a somewhat lengthy anneal at a fairly high temperature with a view to annealing largely in decarburization. These remarks apply also to the practice in France, Switzerland, Belgium and Germany."

Production of "White Heart" Limited

The industry thus was limited to comparatively small tonnages and hence to crude methods. As practiced then, and still practiced in England, Germany and France, the product is used largely for harness parts and small and unimportant work. Melting is frequently done on a small scale either in crucibles or cupolas. The total volume of production is relatively insignificant in the iron production of Europe although there are said to be 126 white heart malleable foundries in Great Britain.

Reaumur's publication was productive of only the most meager commercial results from an American viewpoint. Boyden and his immediate successors attempted to anneal by decarburization. The metal made by the Philadelphia Hardware and Malleable Iron Works before the Civil war was "white heart", as was that of at least a number of its contemporaries. About 1861, however, the manufacture of this product in America practically ceased. A single jobbing manufacturer of white heart malleable continued operations until a few years ago, operating largely on European pig iron. At least one plow manufacturer continues to operate on the basis of European cupola practice and to turn out white heart malleable of high strength and low elongation.

Many of the stock phrases regarding malleable which have gone the rounds for many years originated with "white heart" metal. For instance, the fairly widespread belief that malleablization takes place from the surface in, that the material is not annealed clear through and that the material cannot be used in heavy sections because of the unannealed center, are among the common fallacies handed down from Reaumur's time. Even though the "white heart" or Reaumur's process never has possessed any tonnage significance in the United States, and has been practically discontinued for 60 years, its faults have been frequently assumed to apply to the American or "black heart" metal by those not conversant with the facts.

The art of making malleable castings, as that term is understood in America, was discovered probably unconsciously by Seth Boyden while attempting to practice Reaumur's method in Newark, N. J., in 1826.

Boyden was a manufacturer rather than a scientist. Probably for this reason no formal announcement of a new discovery was made. It is presumed that in attempting to duplicate European practice with American pig iron, which is low in sulphur and high in manganese, he inadvertently discovered an alloy which when heated to produce decarburization, graphitized instead. The product possessed all the properties of the best white heart metal and was more easily made and more uniform. Not realizing that he had discovered a new art, Boyden continued this work along the lines he found empirically most likely of success.

Boyden left a diary covering his experiments from July 4, 1826, to Sept. 1, 1832. It shows that he was attempting to duplicate Reaumur's process. Under date of Oct. 20, 1826, he writes: "I have a piece so good it will not harden any more than copper". Yet from his third ex-

Fig. 6—Statue of Seth Boyden, erected in the city park of Newark, N. J., by citizens in memory of the man who laid the foundation for the malleable industry in the United States

periment on there are allusions to graphitization. In the report on the third experiment he states, "Much blacker inside and not half so good". Again in Experiment No. 5 he refers to a piece "which had been done totally well before rendering dark in the middle". An entry on the eighth experiment is: "Quite gray; none of the above bend or are good for anything". In the ninth experiment he comments: "Hard iron melted in coal dust from the air received no change but in scoria and coal dust became soft gray iron. A piece of Sterling (grade of pig iron) without W (probably wrought iron) in soft gray state done (annealed) eight times remains gray and unmalleable".

Boyden had been unconsciously recording the first observation of the formation of temper carbon and its distinction from graphite. Being still convinced that he was striving to produce a steely decarburized iron he refers in Experiment No. 11 to the fact that "the iron was tough when broken and was rather too dark in color". Yet in the next experiment he writes, "Experiment in the foundry. Sterling the toughest but very dark. Sprues and Sterling dark and good". On Sept. 10, 1826, he notes that "some of the pieces were tough, gray and very good". On Oct. 20 of the same year he makes the peculiar observation that "the best piece I have ever seen....was pale blue in the middle".

For many years neither he nor his successors realized that decarburization was not essential to the process. He and his associates laid great stress on packing materials and their chemical effect upon the product.

Inasmuch as the graphitizing reaction discovered by Boyden forms the metallurgical basis of the present industry, its consideration in detail will be reserved for a later chapter. Black heart or American malleable cast iron bears no metallurgical relation to the European product and its history begins not with Reaumur but with Seth Boyden.

II

DEVELOPMENT OF MALLEABLE INDUSTRY IN THE UNITED STATES

SETH BOYDEN began business as an iron founder in 1820 at 26 Orange street, Newark, N. J. Being interested in malleable castings, he attempted to duplicate European practice at a time when metallurgy was practically unknown. After six years of continuous experiment he succeeded in producing malleable castings, but not of the kind he attempted to make.

Due presumably to the raw material available, he hit upon the practical operation of the graphitizing anneal and thus founded a new industry. Boyden operated the plant under his own name until 1835 when it became known as the Boston Malleable Cast Iron and Steel Co. The foundry continued under this management for two years, after which it was operated under various firm names by Daniel Condit, J. H. Barlow and others, becoming in 1907 the Barlow Foundry Co. This company occupied the original site until May, 1914, when it removed to another location and the birthplace of black heart malleable was razed.

Quite naturally the early development of the industry centered about its discoverer and its birthplace. At one time Newark had eight malleable foundries, and three of Boyden's brothers—Otis, Alexander and Frank—engaged in the malleable founder's art. Otis operated a foundry in Newark from 1835 until 1837, when it was absorbed by the Boston Malleable Cast Iron & Steel Co. Alexander and Frank engaged in the business in East Boston during the same interval, after which Alexander was employed by Frederick Fuller, of the Easton (Mass.) Iron Foundry, established in 1752. The business later came into the hands of Daniel Belcher and was continued by his descendents.

Two plants were started in Elizabethport about 1840 and in 1841 David Meeker began to manufacture malleable

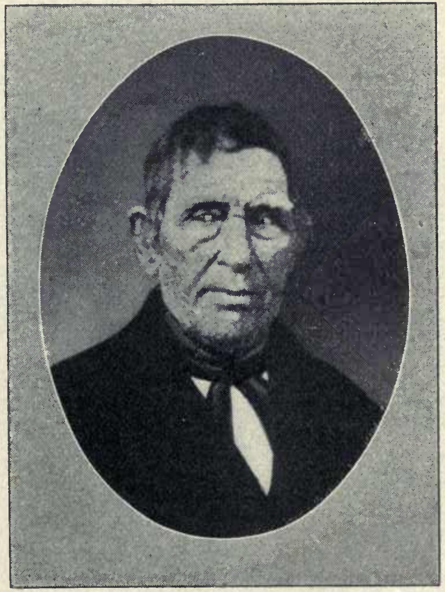


Fig. 7—Seth Boyden

Boyden's Successors

SETH BOYDEN, pioneer in the malleable iron industry in the United States, J. H. Barlow, his successor and William G. Morris, associate of Mr. Barlow, were prominent in the history of the early days of the industry in the United States. Since 1826, *when Boyden began the production of malleable castings, the Newark foundry has been operated under the following names:*

Seth Boyden	1826-1835
Boston Malleable Cast Iron & Steel Co.	1835-1837
Condit & Bolles	1837-1843
Daniel Condit	1843-1853
Condit & Barlow	1858-1862
Condit, Barlow & Shove.	1862-1866
Barlow & Shove	1866-1870
J. H. Barlow	1870-1879
J. H. Barlow & Condit.	1879-1882
Barlow, Condit & Morris	1882-1895
Morris & Barlow	1895-1899
A. E. Barlow	since 1899

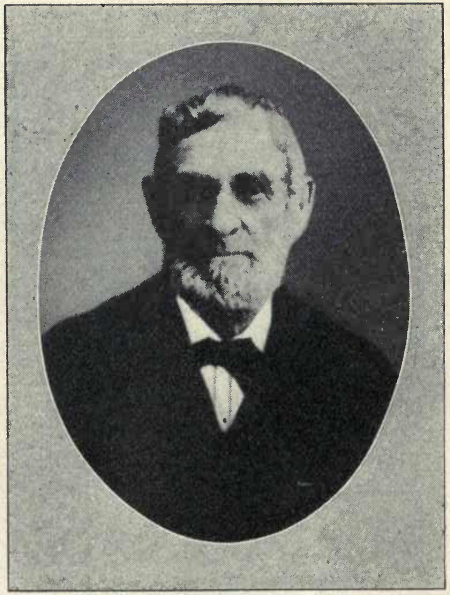


Fig. 8—J. H. Barlow, Boyden's successor

in the Hedenburgs Works. The New Jersey Malleable was founded at Newark in 1841.

The information regarding the activities of the Boyden brothers and their contemporaries and associates is derived from a paper presented before the Philadelphia Foundrymen's association by George F. Davis.

It would be exceedingly interesting to trace back to its beginnings the present, highly developed industry. Unfortunately written records of the early days survive, if at all, only in the account books and the minutes of stockholders' and directors' meetings of the older corporations. Such records are not open to public scrutiny and therefore it is difficult in sketching the early history of the industry to do full justice to all.

The writer has been unable to trace in complete detail the early history of the industry, other than through Boyden's activities. This may be due to the fact that these older plants did not survive or may be caused by inadequate search. It seems to be of common knowledge that during the first half of the nineteenth century, a number of persons entered into the business, the plants being mainly located in New England and New York, at least one as far west as Buffalo.

Thomas Devlin has informed the writer that when the Philadelphia Hardware & Malleable Iron Works, now the Thomas Devlin Mfg. Co., was founded in 1852, the company officials knew of the existence of the Westmoreland (N. Y.) Malleable Works, of a plant in Worcester, Mass., and also of the M. Greenwood Co., of Cincinnati, which was founded in or possibly before 1850 and later was taken over by James L. Haven.

In the early fifties, Isaac Johnson established a malleable foundry at Spuyten Duyvil. In 1872 he, together with J. H. Whittemore of Naugatuck and W. S. Nichols, a brother-in-law and representative of Walter Wood, organized the Hoosick Malleable Iron Works at Hoosick Falls, New York. Some years later, Johnson also organized the malleable plant bearing his name in Indianapolis, which in

1883 passed into the control of the group which later became the National Malleable Castings Co.

In the early eighties, the Walter Wood Mowing & Reaping Machine Co. absorbed the Hoosick Malleable Iron Works, enlarging the plant from time to time. The same organization under the style of the Walter Wood Harvester Co. started the business in St. Paul which, after a failure during the panic of 1893 and one or two changes of ownership, became the Northern Malleable Iron Co. under Frank J. Otis.

Much of the early development centered in New England, particularly in the state of Connecticut. Among the oldest malleable plants is what is now the Naugatuck works of the Eastern Malleable Iron Co. at Union City. Here the development work of J. H. Whittemore and B. B. Tuttle was done beginning in 1858. From that plant and that of the Bridgeport Malleable Iron Co. were recruited many of the executives who established the industry in the Middle West.

The Naugatuck and Bridgeport plants, with those at Troy, Wilmington and New Britain became the present Eastern Malleable Iron Co. At a later date the village of Hoosick Falls, N. Y., also sent westward a group of malleable iron foundrymen. G. H. Thompson went to Columbus, John Haswell to Marion, and later to Dayton, O. Sidney Horsley, superintendent of the Northern Malleable Iron Co., and others also graduated from Hoosick Falls.

In 1854 Duncan Forbes, a Scotchman who had previously resided in western New York, removed to Rockford, Ill., and with his son Alexander Duncan Forbes, established a gray iron foundry. In 1859 Forbes installed an annealing oven and intermittently produced cupola malleable castings in connection with the production of gray iron stoves which constituted the larger part of this business. In 1864 the gray iron portion of the business was definitely abandoned in favor of malleable castings alone.

Duncan Forbes, the first manufacturer of malleable castings west of Cincinnati, died in 1870. The business was continued and enlarged by others of his family. In 1890 the company was incorporated as the Rockford Malleable Iron Works and in 1907 removed to a new location in Rockford, where it continues to be operated by descendants of the original founder.

In 1866 Charles Newbold and Peter Loeb started a malleable and gray iron foundry in the east end of Dayton, O., which was incorporated as the Dayton Malleable Iron Co. in 1869. In 1872 the business was removed to its present location on West Third street, and from time to time the capital stock and plant equipment were increased.

In 1916 the plant of the Ironton Malleable Iron Co. was purchased, and has since been operated as the Ironton works of the Dayton Malleable Iron Co. In February, 1922, the Dayton Malleable also took over the foundry of the Timken Co. at Canton, Ohio.

In August, 1868, the Cleveland Malleable Iron Co. was incorporated and in 1869 Alfred A. Pope became interested in the business and immediately thereafter its president. In 1873 John C. Coonley, sometime of Louisville, and a number of men in the Cleveland company, started the Chicago Malleable Iron Co. The same organization, which in 1891 became the National Malleable Castings Co. acquired by purchase or construction, plants in Indianapolis, Toledo, O., and Cicero and East St. Louis, Ill., besides steel plants which are not of interest in the present connection.

A. A. Pope and J. H. Whittemore were leading factors in the early growth of the industry, the institutions over which they presided now being the two largest in the country. Many other manufacturers of malleable cast iron have honorable histories extending back into the sixties and seventies of the last century. The writer has not had the opportunity he could have wished to do full justice to the histories of some of these smaller companies.

The industry has the distinction of numbering on its rolls a president of the United States, Mr. Harding having been one of the original stockholders of the American Mal-

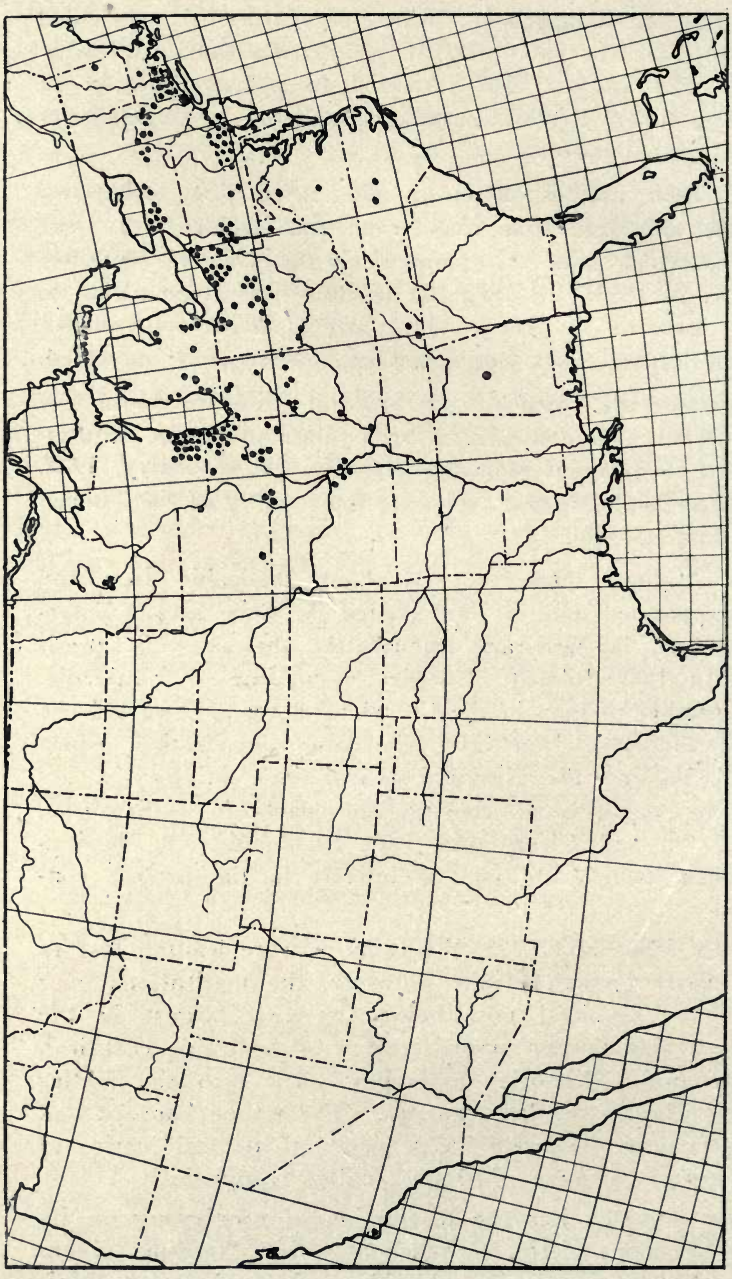


Fig. 9—Distribution of malleable iron foundries in the United States. The dots represent the location of malleable foundries according to data compiled for government use. The latest edition of *Penton's Foundry List* shows a total of 242 malleable foundries as compared with 211 indicated above

leable Castings Co., organized in 1905 under the leadership of Charles L. LaMarche.

In this as in other industries, the growth has been largely in accord with the survival of the fittest. Many plants have been started on a moderate scale especially at times of great industrial activity. Some of these failed to survive the first period of depression encountered; others, particularly in New England, continued a small but often prosperous existence, catering to a limited trade, usually in their immediate neighborhoods. A number of the organizations grew in size and influence, and by sound business and technical methods, coupled with an aggressive policy, attained position of prominence in their fields.

Another type of malleable foundry has sprung up in the history of the industry. This is the foundry which produces a given specialty not for the open market but as a department of an organization manufacturing a finished product. Many of these foundries also have branched out into jobbing work when not fully employed for their own requirements, but are primarily operated to furnish castings for the product made by the parent company. In this class are the malleable foundries of the General Electric Co., American Radiator Co., International Harvester Co. of America, Eberhard Mfg. Co., Link-Belt Co., and a number of others. These foundries, having a definitely established outlet for their product and the financial and administrative support of a well organized industry, usually have survived and grown successful. However, in at least one case a foundry of this character has been sold to a malleable founder in pereference to its continued operation by the consumer.

The organization of a special foundry is only possible where the requirements of the parent company run up to a sufficient tonnage to make possible operations on a large enough scale to warrant the best operating conditions and supervision. The malleable industry, involving more expensive equipment and greater technical skill than the gray iron industry, cannot well be operated in small units on account of excessive overhead. Therefore, unless an industry is large enough to operate quite an extensive foundry,

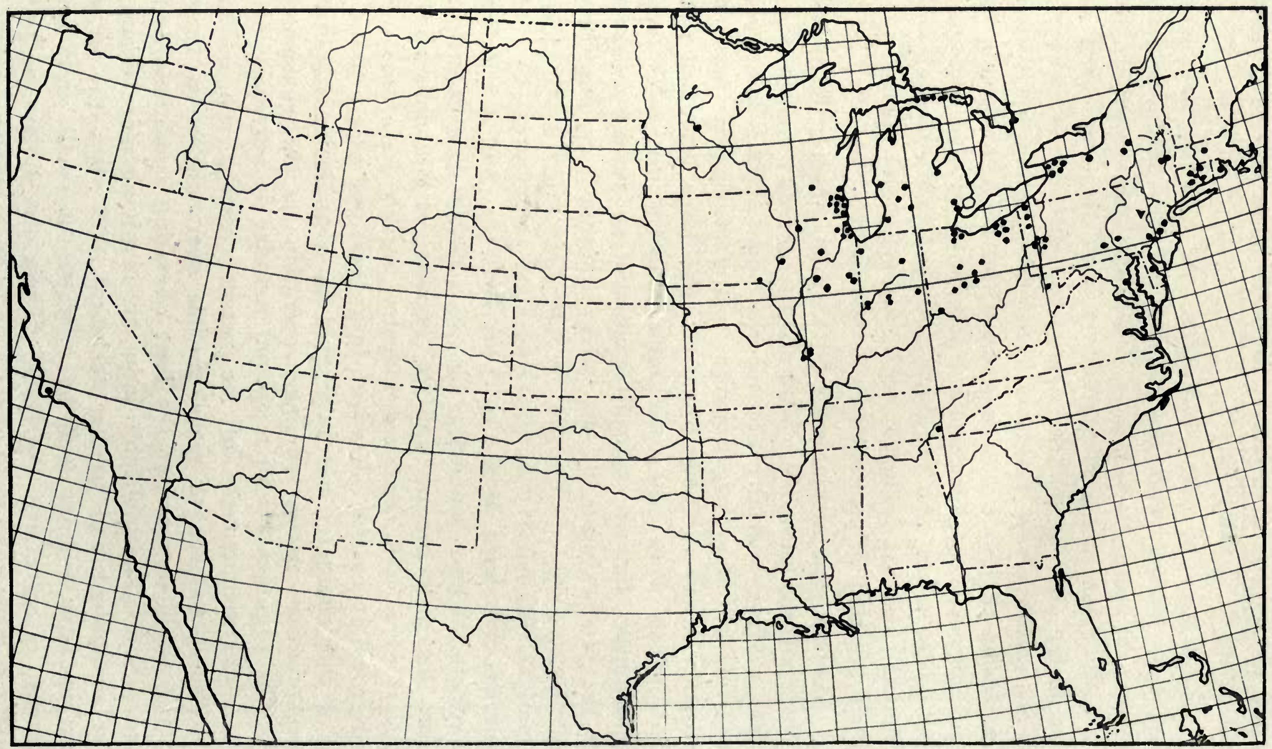


Fig. 10—Map showing location of principal sellers of malleable iron castings in the United States

castings of better quality usually can be obtained more cheaply by purchase from established jobbing foundries.

The present extent and distribution of the malleable industry is shown in Fig. 9. Each dot on this map represents the approximate location of a producer of malleable castings. The list is as complete as possible, having been compiled from the data of the American Malleable Castings association and from information gathered for the government during the war. There are a number of plants marked as producing malleable where there is reason to doubt whether they have actually done so. The most recent lists include between 20 and 30 more plants than are shown on the map. In part this may be due to incomplete returns, and to a less degree to new foundries of very small capacity. It is unlikely that any important plant has been omitted. It will be noted that the plants are largely in the territory north of the Ohio and east of the Mississippi rivers, their locations following closely the various divisions of the Pennsylvania, New York Central and New York, New Haven and Hartford lines, with an additional development near Milwaukee and in southern Michigan. These locations were largely determined by the fact that they are coincident with the important manufacturing districts of the country, present good shipping facilities and are conveniently near the sources of fuel and pig iron.

A more interesting compilation from the viewpoint of the user of malleable cast iron is the map shown in Fig. 10, showing the principal sellers of malleable cast iron. This has been prepared from the previous map by the elimination of foundries primarily operated as departments of larger industries producing finished products, as for example harness parts, pipe fittings, etc., and of foundries whose tonnage is not of sufficient magnitude to be an important consideration from the viewpoint of the consuming interests. It will be seen that the distribution is almost identical, although the number of plants has been considerably reduced.

Annual Production of Malleable

The plant capacity of the United States as of 1920 is estimated at 1,286,300 tons annually, divided by states as

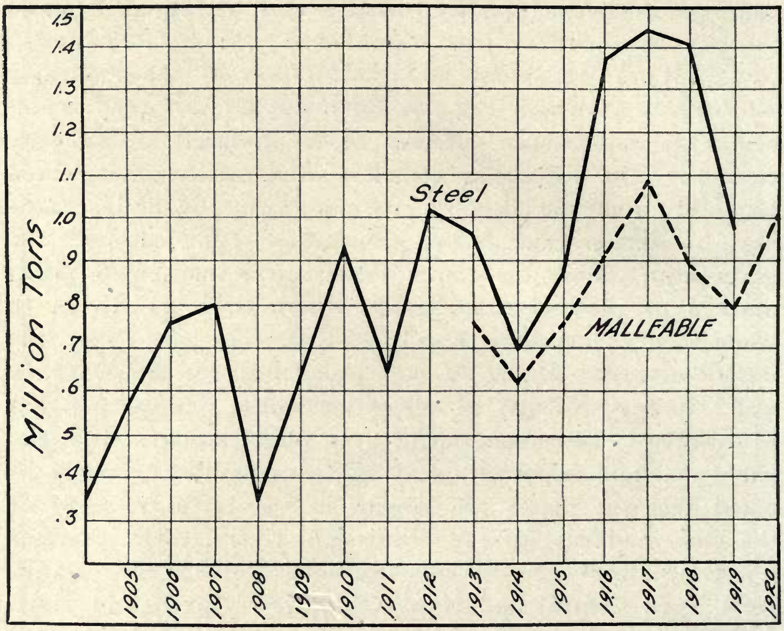


Fig. 11—Comparison of production of steel and malleable iron castings in the United States

The production of steel castings is charted from the statistics compiled by the American Iron and Steel institute. The production of malleable iron castings is carefully estimated on the basis of the known production of plants whose output constitutes the majority of the annual tonnage of the country. No definite figures ever have been compiled showing the actual production of malleable castings and in the absence of such information, it is believed that the above charted values are as accurate as any that can be obtained under existing circumstances.

follows: Illinois, 297,700; Ohio, 202,700; New York, 167,500; Pennsylvania, 133,100; Wisconsin, 116,600; Michigan, 108,400; Indiana, 88,300; Connecticut, 58,200; and all others, 113,800.

The most complete information at the writer's disposal indicates that there are between 176 and 204 manufacturers of malleable castings in the United States. In this list, however, are included a considerable number of manufacturers with whom the production of malleable castings is only incidental to other operations. Some of these produce malleable only intermittently or in small quantities, as their own needs require, and are included here in the interest of completeness rather than because of their importance to the jobbing trade. About 85 per cent of the tonnage of the country is produced by 76 manufacturers having a capacity in excess of 5000 tons annually each. Sixty-two and one-half per cent is produced by 33 owners having capacities over 10,000 tons per annum. No single manufacturer can be said to exercise anything approaching a monopoly, as the five largest interests together have only 28 per cent of the capacity of the country. Each of these five can produce 30,000 tons per annum or more. The eight additional manufacturers, having individual capacities from 20,000 to 30,000 tons, account for an additional 14.2 per cent.

Data as to the production of malleable castings in the United States go back only to 1913 when the American Malleable Castings association began the accumulation of statistics on this point. Fig. 11 shows the production of malleable castings by years since 1913, compared with the production of steel castings by years since 1904, as recorded by the American Iron and Steel institute. The production of malleable pig in 1913 was about 5½ times that in 1900. This would imply a production of only about 127,000 tons of malleable castings in that year.

It will be noticed that the annual production is considerably below the annual plant capacity. The recent figures on production of course are based on manufacturing operation in times of great industrial activity. Under these conditions, a deficit in production compared with capacity seems at first glance unlikely. This deficit is due to two causes; first the fact that the reported capacities are doubtless a little higher than the facts warrant and second that most of the malleable foundries had been unable to obtain either sufficient labor or fuel to permit the realization of their full production. In other words, plants apparently were built in excess of the available labor supply and no material increase in the country's maximum output of castings could be expected as a consequence of the erection of additional plants.

In view of the lack of productivity in all lines of manufacture before the 1921 depression, it is unlikely that the manpower of this or any other industry could be largely increased except by increasing the productivity of the individual employe. The only visible remedy seems to be an increase in tonnage per man by the introduction of every possible mechanical aid. A considerable improvement may be possible by some means tending toward a decreased loss of time by the individual worker, and an increase in his skill. Data based on conditions since the summer of 1921 are of course valueless on account of the very small production in all lines.

The commercial development of the industry was paralleled by steady progress in the technical details of malleable production. As has been stated earlier in the discussion, Boyden's discovery was not the result of a logical metallurgical development but was the accidental outgrowth of an attempt to practice a theoretically distinct art. When it is realized that all of this work was done at a time when even the chemical analysis of iron was an unusual thing and that Boyden and his successors blazed the way without any knowledge of variations in raw material and product, save what might be gathered by the crudest of inspection, we cannot but marvel at their courage and persistence in establishing the empirical basis for the present great industry. Boyden, however, having a truly technical mind, left behind complete notes of his experiments and the results attained. Some of his notes already have been quoted. He recognized the presence of carbon but only in the free state, believing white iron to contain none. He made many experiments with various packings and under different annealing conditions, finally concluding that red iron ore was the best material. He records the belief that the annealing temperature should be at least the melting point of silver. He considered the presence of silicon and sulphur but knew nothing of analysis. Under date of Jan. 23, 1829, he records observations as to the effect of additions of phosphorus, clay, lead, zinc, tin and antimony.

Boyden's brother, Alexander, seems to have been the earliest mystery monger in the trade, it being related by Davis, on the authority of Horace Spaulding, the last survivor of the Easton foundry, that Alexander had a little pump with which he squirted something into the stack and also that he used to throw some metal into the furnace, creating a great volume of smoke and doubtless an equally great awe in the mind of the spectator.

In 1872 Alfred E. Hammer, of the Malleable Iron Fittings Co., began to study the chemistry of black heart malleable at Branford, Conn. This company in 1864 had succeeded to the business of an earlier one, the Totoket Co. founded in 1854 for the purpose of practicing Boyden's method.

In 1875 Mr. Hammer had established a chemical laboratory which was, so far as he is aware, the first in connection with the malleable iron industry. Writing of this laboratory he says:

"I found that I was practically in an unknown country. For that reason, however, the work was not only interesting but positively exciting—so much so that I had a mattress laid in my laboratory and with the aid of an alarm clock, I was able to follow the then tedious chemical operations through the night without much loss of sleep."

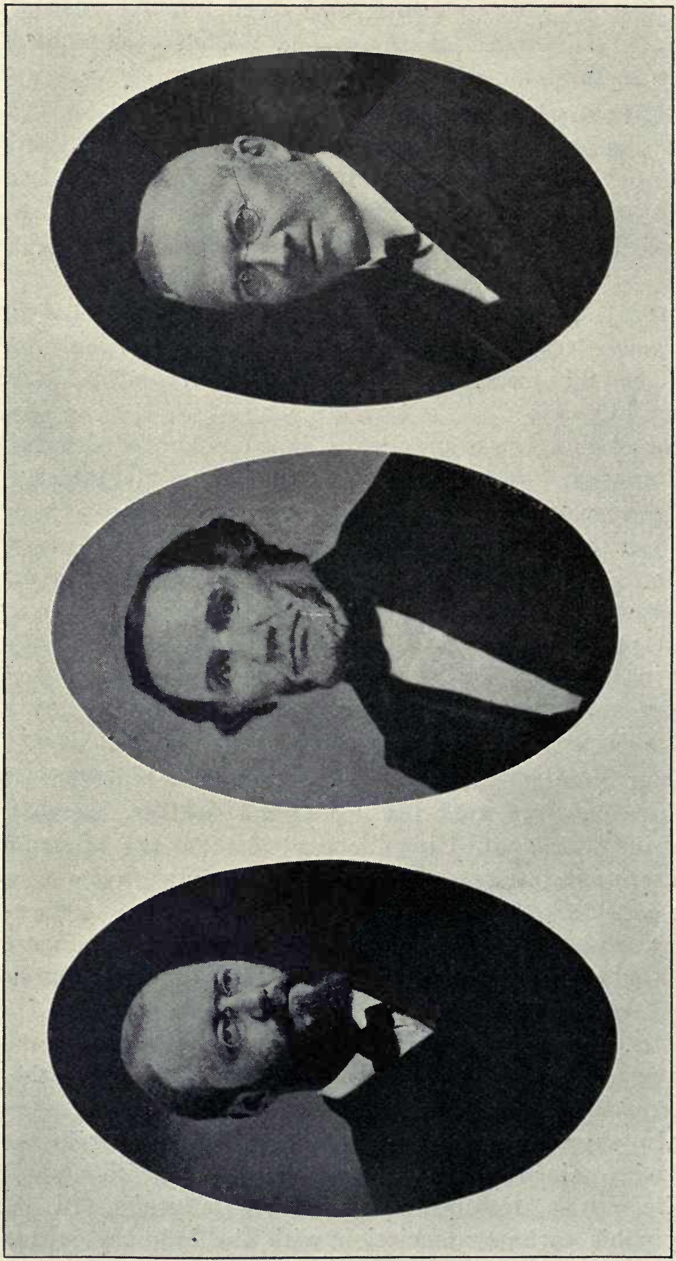
As a result of this work, he found it possible to lay down "a chemical ratio as between carbon and silicon, and manganese and sulphur," thus being the first one "to bring the malleable process down to a chemical proposition."

Among Hammer's difficulties, not the least was that at this period, pig iron was not made and sold by analysis. However, he soon applied his chemical ideas to the selection and mixing of irons, irrespective of brands and grades.

The work of this pioneer metallurgist seems to have escaped adequate recognition since his conclusions were thought to be too valuable trade secrets to warrant publication.

He certainly came to correct quantitative conclusions as to manganese and sulphur at a date long before the theoretical explanation was even thought of. His views as to carbon also seem to have been far in advance of later investigators who gained much greater general recognition.

While not a technically trained metallurgist, A. A. Pope from his earliest association with the industry strove by every means in his power to collect and interpret ex-



Walter Wood Duncan Forbes Thomas Devlin

Fig. 12—Familiar figures in the development of the malleable industry in the United States

perimental data bearing on the processes and products of his plants. These investigations were conducted by Emmerton, Benjamin and others and resulted in an accumulation of valuable data during the seventies and eighties.

It is interesting to note that especially with reference to manganese and sulphur, Mr. Pope's conclusions were very similar in application to those reached at about the same time by Mr. Hammer.

Among the most progressive of the malleable manufacturers was the late B. J. Walker, of Erie, Pa., who pursued a most liberal policy with regard to the exchange of information and did much to develop the industry.

In 1893 McConway & Torley established in Pittsburgh what is frequently said to have been the first laboratory in the malleable industry. It was under the direction of Dr. Richard Moldenke, who not long thereafter severed his connection with that company to become associated with another in the Pittsburgh district. H. E. Diller, now metallurgical editor of *The Foundry,* was associated with Doctor Moldenke at this time.

In the autumn of 1893, James Beckett, after a tour covering all of the malleable foundries then producing agricultural implement parts, found that none of them had established a chemical laboratory for works control. This statement does not apply necessarily to plants not engaging primarily in this specialty which were not visited by Mr. Beckett.

In 1894 the Wood Mowing & Reaping Machine Co., Hoosick, Falls, N. Y. employed Enrique Touceda as a consultant and established a well equipped laboratory.

In 1903 when the National Malleable Castings Co., established a works and experimental laboratory at Indianapolis, the author was unable to find by diligent search of the literature available any adequate information of a definite and quantitative character regarding the chemical fundamentals of the process. Therefore it was decided to disregard precedent and to establish a sound theoretical basis for works control, using the information accumulated by Mr. Pope as a nucleus. In this connection the quantitative effect of carbon, a *sine qua non* in the works control of the product, was worked out in 1904, the conclusion reached being apparently new to a number of the best informed malleable men with whom it was discussed at the time. A little later the effect, or rather lack of effect of manganese sulphide was also worked out. This offers the theoretical explanation of the practical observations of Mr. Hammer and Mr. Pope.

These facts were certainly discovered independently by other observers, including W. R. Bean now of the Eastern Malleable Iron Co. In the absence of contemporary publication it is impossible to state whether these discoveries preceded or followed the Indianapolis investigations. So far as the writer has been able to learn the Indianapolis laboratory was the first to successfully exercise complete works control on the basis of the total carbon content being the determining factor in the quality of the product.

During all of this time the results of none of these investigations became publicly available and therefore it is difficult to accurately chronicle the scientific development of the art. The organizations collecting scientific and research data of value did not feel it to be sound business policy to make public disclosures of their work. Regardless of whether or not this policy was fundamentally sound from the manufacturers' viewpoint, it certainly proved a handicap to the consumer, who remained in ignorance both of the theoretical principles and practical applications of the manufacture of malleable castings.

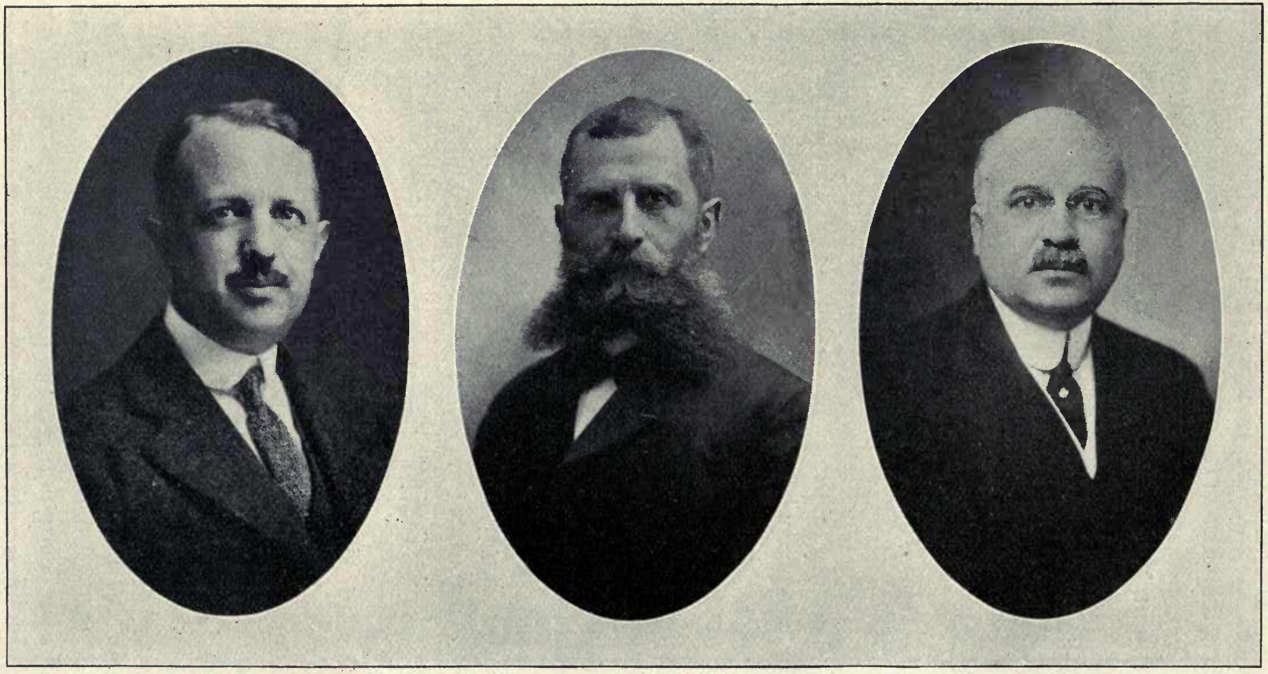
Having again severed his business connection and established himself as a consultant, Dr. Moldenke began to contribute voluminously to the technical press. Unfortunately the only sources of information open to him seem to have been the work in which he personally participated. Furthermore he was presumably handicapped by the confidential character of his relations with his clients and apparently felt constrained to speak only in somewhat general terms. Nevertheless he did yeoman service in striving for a better interchange of ideas and information, and also in advocating suitable technical control of the industry.

His services in this direction are probably of even greater importance than the actual informative value of his literary output. The earlier literature of the subject was derived directly or indirectly almost entirely from his publications.

There still persisted in the engineer's handbooks and in the technical press a mass of ill-supported conceptions largely predicated on a confusion with the white heart process. For example, great weight was attached to the oxidizing action of the packing and its effect on the properties of the product was unduly emphasized. Great differences also were supposed to exist between the heart and surface of the same casting. Similarly there was an impression that malleablizing proceeded from the surface inward and was complete at the surface before it had progressed far at the center. A corollary to this belief was that very thick castings could not be annealed clear through.

Since none of those who knew better felt called upon to publicly combat statements of this character, it is not surprising that the engineering public was left in ignorance and hence in distrust of the qualities of the material. Moreover it is not surprising that in the absence of guidance by those better informed, some of the less intelligent and progressive manufacturers did not clearly understand the principles of the process they practiced and therefore produced unsatisfactory castings.

A few of the larger producers maintained adequate laboratory facilities to investigate and control their methods. The smaller manufacturers, however, had to get on as best they could with their own resources until the American Malleable Castings association undertook as one of its activities to carry on extensive research work for the benefit of its members. Prof. Enrique Touceda, of Rensselaer Polytechnic institute, was employed as consulting engineer and since 1913 has labored unceasingly to instruct the members of the association in sound practice and correct fundamental principles. This work was largely confidential in character and added little to the user's knowledge but con-



W. R. Bean

Richard Moldenke

Enrique Touceda

Fig. 13—Three metallurgists who have been closely identified with the technical advancement of the industry

tributed immensely to his satisfaction in the use of the product.

At about this time, Oliver Storey published the results of some research work at the University of Wisconsin, dealing with the fundamentals of the graphitizing reaction. In the writer's opinion this was the first scientific American contribution to the literature of the metallurgy of malleable iron. The problem has been since investigated by Archer and White, Merica and by the writer. A few years earlier, Hatfield thoroughly investigated the less important subject of decarburization. The theoretical aspects of graphitization have been studied abroad rather thoroughly. In 1881 Forquignon published in the *Annals de Chemie et de Physique* a contribution dealing with his tests in the annealing of malleable iron and steel. Unfortunately the author has been unable to familiarize himself with this publication, which is said to have dealt very adequately with the subject.

In 1902 Charpy and Grenet published a study of the graphitization of white cast iron which covers the ground very fully and accurately, even in the light of present knowledge. This publication seems to be almost if not entirely unknown in this country. Howe, in the Transactions of the American Institute of Mining and Metallurgical Engineers in 1908, discussed critically and exhaustively the evidence then available bearing on graphitization. Hatfield in 1910 discussed the chemical physics of the precipitation of free carbon from iron carbon alloys in a paper before the Royal society. In 1911 Rueff and Goecke published a study of the solubility of carbon in iron and in the same year Ruer and Iljin discussed the stable system of iron carbon. Heyn summarized the contemporary knowledge of the iron carbon alloys at the New York congress of the International Society for Testing Materials in 1912. That these technical investigations have been of so little service to the American manufacturer seems a reflection upon the

A. A. POPE B. J. WALKER ALFRED E. HAMMER

Fig. 14—The names of these men are linked with the rise of the American malleable industry

American literature of the subject no less than on the industry as a whole.

Honda and Murakami in the Journal of the Iron and Steel Institute, of Great Britain, (1920) advanced the theory that graphitization does not take place directly but is a consequence of oxidation of carbon by CO_2 and the subsequent decomposition of CO formed with liberation of free carbon. In the light of his present knowledge, the author cannot agree with this conclusion; nevertheless it is a most interesting contribution to the theory of the subject.

The officers of the malleable association soon realized that while some of the work of its consulting engineer was properly of a confidential character, there existed a necessity for the publication of authoritative information regarding malleable cast iron. Accordingly the association encouraged participation in the programs of the technical societies by its consulting engineer and by others qualified to speak on the subject. It also established an educational committee to cooperate with institutions of learning and with engineering organizations in the dissemination of information regarding the product.

Through these various activities a fund of reliable information regarding the properties of a well made product is being made available to engineers. The cloud of mystery surrounding the manufacture of malleable castings is being penetrated and the conscientious manufacturer now can produce reliable metal by availing himself of the research facilities offered by the association.

The larger manufacturers have found it desirable to continue research departments under their own control for the investigation of their individual problems and for the prosecution of research in subjects beyond the scope of the investigations made by the association.

A further step forward in the industry was made when the American Society for Testing Materials began the development of a specification for malleable cast iron. The first specification was adopted in 1904 in a perfunctory manner and apparently was dictated by a single individual. This specification lay dormant for 11 years but later was actively studied and revised until 1919 when it assumed its present status.* All the requirements of the specification now in use have been given adequate attention by a well informed and competent group of men and are eminently calculated to safeguard the interests of the consumer without being an undue burden upon the producer. It may be assumed that such future revisions of this specification will be made as advancing knowledge and new requirements may warrant.

The necessities of the war also served as a great stimulus in this as in other industries. The limitations of labor and fuel and the exacting requirements of war material forced the attention of all manufacturers toward a closer study of their operations and better control of the product.

Probably the earliest application of malleable cast iron was in the manufacture of buckles and harness parts. This was a rather natural consequence resulting from white heart practice where only thin cross sections could be readily decarburized. Subsequently malleable castings for wagon and carriage parts were produced, and as the design of agricultural implements progressed malleable iron was the major material of construction. In fact, it almost can be said that this material made possible the production of agricultural implements at moderate prices. The use of chain belt in implement work and more especially the invention of the Ewart link started the manufacture of malleable chain belt as an important development in the industry.

The railroads also became important users of malleable in the form of couplers and smaller car details. For many years it was possible to divide the malleable industry of the country roughly between agricultural implement and railway material plants. Indeed, this classification still sur-

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Tentative changes were proposed at the 1922 meeting. See Chap. XIV.

vives in the malleable scrap market. Increasing train loads forced the abandonment of the malleable coupler for railway use about 20 years ago, although it survives on certain mine car and similar equipment.

There remained, however, a considerable tonnage of malleable car parts. Influenced partially by unfortunate experiences with foundries selling purely on a price basis, and partly by the introduction of the steel underframe to overcome difficulties encountered with wooden details, the master car builders restricted the use of malleable so that the production of railway malleable rather rapidly decreased.

Peculiarly enough, while malleable castings were viewed with disfavor by the car builders, practically all the standard draft gears were still made of malleable and largely continue to be made of that product. There is an obvious contradiction, for the draft gear not only is of vital importance but is subject to more violent stresses than any other car part. This is explained by the fact that in general the manufacturers of draft rigging dealt with competent foundries and secured a uniformly good product. By tests of their output they assured themselves against buying and reselling inferior materials. The agricultural implement trade meanwhile was largely withdrawn from the open market with the establishment of foundries of their own by the International Harvester Co. and others.

The manufacture of malleable pipe fittings also has become largely the business of plants producing the finished product instead of the castings. These developments and the changed industrial conditions of the last seven or eight years have very largely altered the selling field for malleable castings.

The handicap under which the railroads operated, involving curtailment of purchases, for a time reduced them to an almost negligible factor in the market, although journal boxes, car wedges, derailers, draft gears, rail anchors and many car parts now are made of malleable cast iron.

The automobile and allied industries entered the field at just about the time the railroad business began to wane, and are among the heaviest consumers of malleable castings. The applications are found in many vital details as in rear axles, spring shackles, and hubs, as well as in less critical parts such as lamp and wind shield brackets etc.

Another application is in some of the highest grade electrical starting equipment for automotive use.

Applications in truck and tractor design of similar character have been made. The use of malleable castings for kitchen ranges has also become standardized in the highest grades of this product. In hot water and steam heating systems radiators are assembled almost exclusively by the use of one of three types of malleable nipples, and malleable pipe fittings are standard.

During the war the industry was kept at high pitch by the exacting requirements of the allied governments. In addition to the obvious peacetime applications, such as railway equipment and automobile parts which were merely increased by war conditions, several entirely new uses were developed.

Among the applications in ordnance material were hand and rifle grenades, trench mortar shells and 75-millimeter shrapnel noses. The air service required fragmentation bombs of malleable castings and the tank service equipment and artillery tractors developed applications analogous to ordinary automotive equipment but involving greater difficulty in manufacture.

There is an extremely prevalent impression that the manufacture of woodworking and other cutting tools of malleable iron is a common commercial practice and that the resulting product masquerades as steel. Some material of this character must have been made in times gone by, although the writer in 18 years of rather intimate acquaintance with the product of the largest producer and a fair familiarity with the output of some of the other principal manufacturers has never seen any of this product. A well known consumer of malleable for other purposes states that hatchets continue to be made from malleable iron by at least two important producers.

One important manufacturer of vises is a large consumer of malleable and several concerns have made shear blades to which steel cutting edges are welded. This, with some business in the form of small hammers, and many wrenches, seems to be the extent of tool applications.

Just what the future may hold in store can hardly be foretold. The trend toward a critical study of the properties of all materials and comparison with the service requirements of engineering details without doubt will produce occasional adjustment of the present conventional designs.

The railroad business doubtless is destined to return and the automotive applications to increase. The opportunities for malleable for radiator nipples, pipe fittings, etc., where resistance to rust and to shocks is the determining factor, are great. Applications in the electromagnetic field also give promise of a bright future. This is equally true of agricultural appliances, although carriages, wagons and harness are permanently decreasing as the automotive applications increase. The shipbuilding field also holds considerable possibilities.

Foreign Production of Malleable

The production of malleable iron in the Dominion of Canada is of fair magnitude, there being 10 plants having in 1920 a production of about 30,000 tons in the aggregate.

In Europe the black heart industry seems to have been limited for many years to a single British producer, the Leys Malleable Castings Co., which began the manufacture of black heart malleable some time between 1878 and 1880, and the European factories of the International Harvester Co. and the American Radiator Co. It is possible that relatively recently other plants have started the manufacture of black heart malleables in England, more especially during the war period. It has been said that some ten or twelve plants now engage in that operation, but the author has so far been unable to obtain data as to tonnage which might serve as a check on the magnitude of the British industry. At the May 24, 1921, meeting of the British Iron Research association Professor Thomas Turner declared that the United States makes 10 times the number of malleable castings made in Great Britain.

Malleable Industry in Europe and Asia

The author's most recent information regarding the malleable production of continental Europe is derived from conversation with Raymond Gailly, of Gailly Freres, Charleville, France. According to M. Gailly at present there is no production of black heart malleable in France or Belgium. However, many small and medium sized plants for the production of the European type of product are being developed. In the larger plants, the mechanical equipment, especially for sand handling, is in accord with the most advanced practice.

Lower sulphur metal is becoming available, and an increasing interest in the American process is developing. Marcel Remy of Herstal, near Liege, Belgium, has been active in an attempt to organize joint action by French and Belgian foundries toward the study of the process, having in mind the introduction of the American product. M. Remy has submitted a report on malleable iron to an association of foundrymen at Liege which briefly summarizes the present state of the art.

Commander Kawahigashi of the Imperial Japanese navy advises that there is one malleable foundry in Japan operating on European principles and none making American malleable. It seems probable that this constitutes the extent of the malleable industry of Asia.

III

METALLOGRAPHY OF MALLEABLE IRON

ALL of the ferrous materials used commercially may be considered as alloys of iron and carbon. Their properties are determined primarily by the character of the individual constituents present. The possible entities or materials present in commercial iron and steel are as follows:

Ferrite—Carbon free iron.

Cementite—Iron carbide having the formula Fe_3C.

Austenite—A solid solution of iron carbide in iron, homogeneous in character and of indefinite carbon content.

Pearlite—A mechanical mixture composed of alternate layers of cementite and ferrite in such a proportion as to contain about 0.89 per cent carbon.

Martensite, troosite, sorbite, etc—Various intermediate products between austenite and pearlite.

Graphite—Free carbon in flat crystalline plates.

Temper carbon—Free carbon in an amorphous condition.

The common irons of commerce are all composed of various combinations of these ingredients, thus:

Wrought iron is nearly pure ferrite.

Cast and annealed steel is ferrite and pearlite.

Tool steel (0.90 per cent carbon) when annealed is practically pure pearlite.

Steels which have been hardened and tempered are martensite, troostite or sorbite with or without the presence of excess ferrite.

White cast iron is pearlite and cementite, as are also the very high carbon tool steels (over 0.90 per cent carbon) when annealed.

Gray cast iron is pearlite and graphite, usually containing also more or less ferrite and sometimes cementite, depending on the combined carbon content.

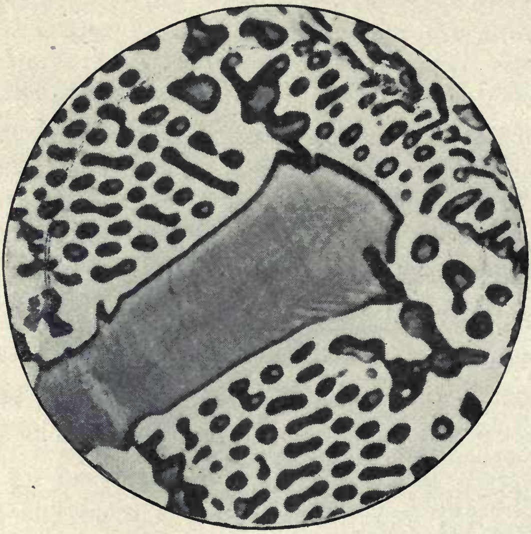

Fig. 15—Austenite and ledeburite in manganiferous white cast iron

Large gray areas, austenite; speckled white and gray areas, ledeburite, the eutectic of cementite and austenite

Etched with picric acid x 2000

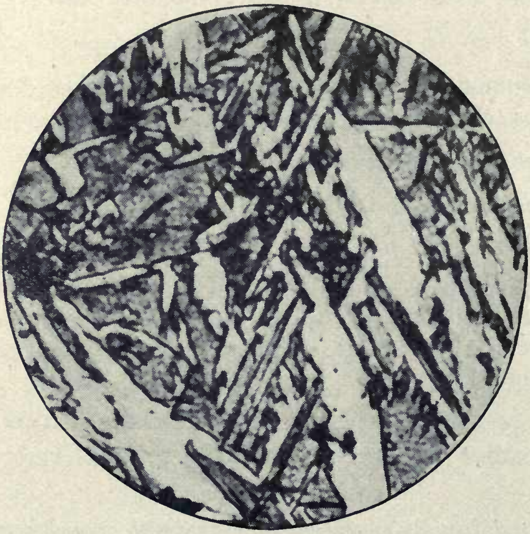

Fig. 16—Martensite in quenched white cast iron is shown by interlacing needle structure

Etched with picric acid x 2000

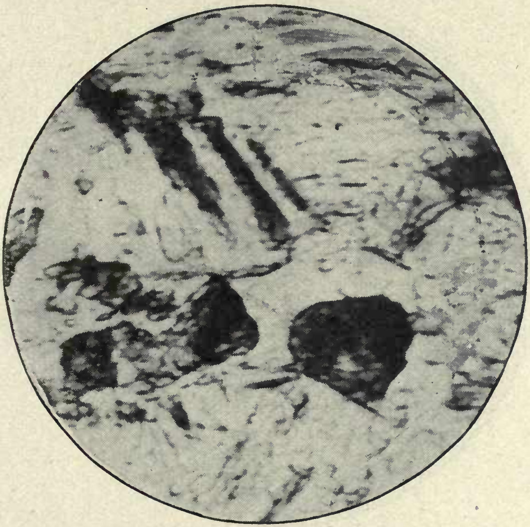

Fig. 17—Troostite in steel. The dark spots are troostite
Etched with nitric acid x 2000

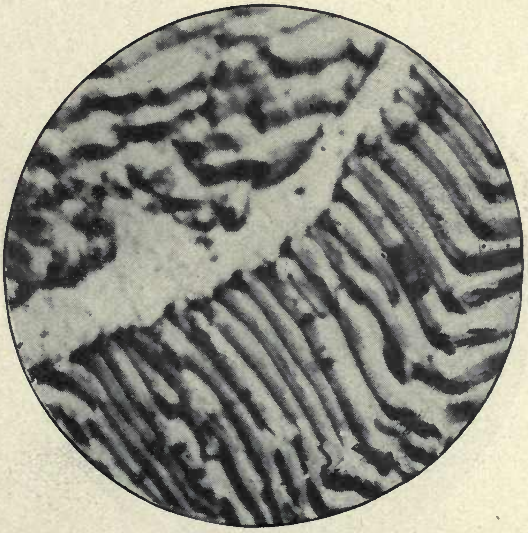

Fig. 18—Pearlite in incompletely annealed malleable
Alternate bands of ferrite and cementite are shown
Etched with picric acid x 2000

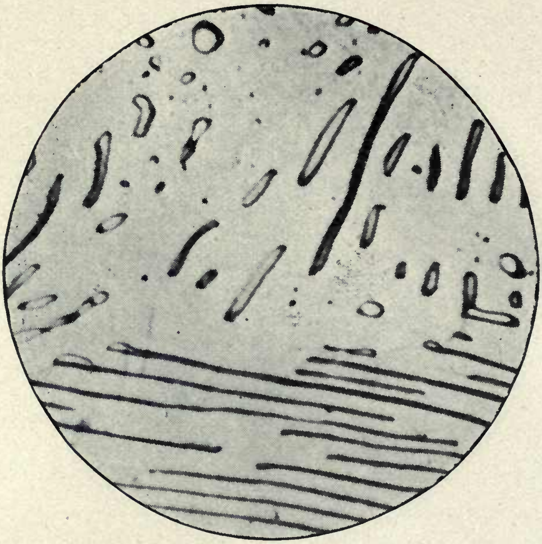

Fig. 19—Spheroidized pearlite

Lamina of cementite in a matrix of ferrite are shown, the lamina being in part changing to globules by surface tension

Etched with picric acid x 4000, but reduced one-half in reproduction

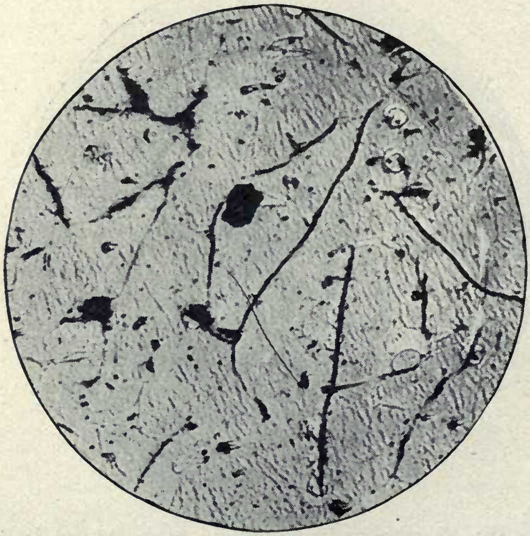

Fig. 20—Graphite in gray iron

Unetched x 200

Fig. 21—Soft gray cast iron

Black represents graphite flakes, the white areas surroundng the black are ferrite, the speckled areas are iron carbon phosphorus eutectic, and the gray areas pearlite

Etched with picric acid x 200

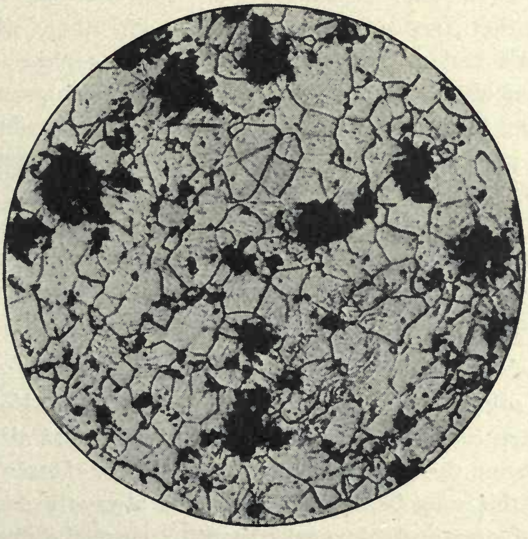

Fig. 22—Malleable cast iron

The black represents temper carbon nodules and the white ferrite x 200

Malleable cast iron is ferrite and temper carbon.

It will be noted that the latter product differs from all the others in containing only free carbon and free iron. Further it is the only material containing temper carbon and the only cast material containing ferrite and no pearlite or other form of combined carbon.

It owes its properties to this combination of constituents, and in turn it owes its metallographic composition to the peculiar circumstances under which it is produced. In this case, as in all others, the particular metallographic entities present are determined by the chemical composition and heat treatment of the alloy.

The particular substances which are stable at different temperatures and concentrations of carbon were first systematically recorded by Roberts-Austin. The Roberts-Austin diagram has since been modified in accord with later and more accurate quantitative observations, and in the light of new knowledge by many contributors.

It can be shown that there are two typically distinct series of alloys. In one, cementite and iron are the components present, either free or in solution in each other, while in the second free carbon enters to more or less replace the carbon of the cementite. On the basis of X-ray spectrograms, Jeffries and Archer have concluded that cementite itself cannot be dissolved in solid iron. Alexander has taken exception to this reasoning. Without wishing to attempt an expression of opinion as to the merits of the controversy in a field with which he is but slightly familiar the author is definitely sure that two distinct types of solid solutions exist—one of or in equilibrium with cementite and the other of or with carbon.

It has been clearly shown by Cesaro that molten cast iron or steel is a solution of cementite, Fe_3C, in iron, Fe_2. Volumes have been written to prove or to disprove the thesis that all graphite is derived from the decomposition of solid, or frozen cementite. However this may be, temper carbon is always a decomposition product of previously formed cementite, since the casting before anneal consists only of cementite and pearlite.

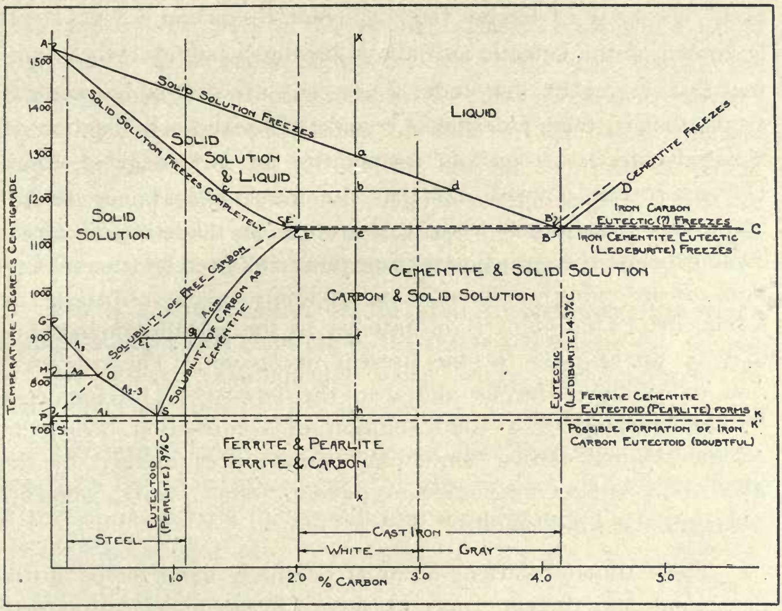

Fig. 23—Benedict's diagram recording the equilibrium conditions in terms of temperature and agraphic (non graphitic) carbon. It is based on Benedict's principle, somewhat modified

In this case, at least, we may base our conclusions on the conditions as outlined by the Benedicks in the form of a double diagram. Fig. 23 sums up the principles of Benedick's views with sufficient accuracy for the present purpose.

In this diagram the absissae or horizontal dimensions, represent carbon content in per cent, the ordinates or vertical dimensions represent temperatures in degrees centigrade. The conditions of equilibrium are then represented by various lines and fields on the diagram. Thus above ABD the metal is a homogeneous liquid. ABD marks the relation between carbon content and the beginning of freezing, while AEBC marks the relation of carbon content and completion of freezing. In the area AEB and DBC the metal consists of a mixture of homogeneous liquid and theoretically a homogeneous solid. In the former area the solid has all the properties usually associated with a solution except fluidity, hence the term 'solid solution.' The alloy of lowest freezing point B, carbon 4.3 per cent, is known as the eutectic and alloys having a higher carbon content than E, carbon just under 2 per cent, are said to be eutectiferous, that is, their freezing is completed by the solidification of a liquid eutectic at constant temperature of 1130 degrees, Cent. Davenport has pointed out that the massive character of cementite in commercial white cast iron is an evidence of supercooling below the eutectic freezing point followed by the separation of pro-eutectic cementite in addition to the cementite of ledeburite. This point is of interest to the metallographer, but may be disregarded for the present discussion. The solidification of noneutectiferous alloys to the left of E is completed by the freezing of a solid solution of composition dependent on the original carbon content at temperatures marked by the line AE. Below the freezing point, other rearrangements occur, in the solid metal.

These transformations occur at definitely fixed temperatures dependent on carbon concentration. These temperatures are known as thermal critical points, and four important distinct critical points have been studied, although more are believed to exist. A critical point is marked by the symbol A. The four important ones are distinguished from one another by suffixes, the points being named A_1, A_2, A_3 and Acm. *The numerals* represent their relative location as to temperature, A_1 being the lowest, A_3 the highest. Acm is not strongly marked thermally, but represents the solubility above A_1 of cementite contracted to *cm*. Critical points vary in position according as they are measured on a rising or falling temperature. A point determined on a falling temperature has the letter *r* preceding the suffix, while *c* designates a critical point determined on a rising temperature. Thus Ac_1 is the lowest critical point found on heating from room temperature, and Ar_1 the same point as determined in cooling. A *c* point is always located as high or higher than the same *r* point due to lag phenomena. The designations *c* and *r* originated as the initial letter of the French terms for heating and cooling. The A_1 point represents the temperature below which cementite becomes insoluble. The A_2 and A_3 points represent molecular changes within the iron not pertinent to our present discussion. These changes are called allotropic. Incidentally, however, the line *GOS* marks the minimum solubility of cementite in the solid solution or perhaps better the maximum solubility of iron in the solid solution. Alloys below and to the left of this line are mixtures of ferrite and saturated solid solutions. Alloys in the angle *GOSE* are homogeneous solid solutions and alloys below and to the right of *ES* are solid solutions mixed with cementite.

For a full discussion of the iron carbon diagram, which is impossible in this connection, the interested reader is referred to Dr. Howe's monumental work, "The Metallography of Steel and Cast Iron."

The exact location of some of the lines has been questioned on the basis of accuracy of observation. The solid lines of the figure indicate the equilibrium conditions in the metastable system Fe_3C—Fe.

Freezing of White Cast Iron

Confining attention to that area between the values carbon= 2.00 per cent and carbon=3.00 per cent, marked at the lower part of the diagram as the range for commercial white cast iron, it is found that molten iron begins to freeze when it reaches the temperature corresponding to the intersection of the line *A B* with the vertical line corresponding to its carbon content. Thus for a carbon content of 2.50 per cent indicated by the line *x-x* on the diagram, the freezing point is at *a*. The solid material is lower in carbon than the liquid material remaining, thus at a temperature *b* the alloy *x-x* has a solid phase of the carbon content *c* and a liquid phase of the carbon content *d*. At the temperature *e*, constant for all alloys of more than 2 per cent total carbon, the remaining liquid or eutectic freezes as an alloy containing 4.3 per cent carbon. The solid formed just before the eutectic freezes, contains about 2 per cent of combined carbon. In freezing, the eutectic breaks up into cementite and austenite containing 2 per cent combined carbon identical with the solid portion formed just before the freezing of the eutectic. This eutectic when frozen is known as ledeburite.

As the temperature decreases further, austenite is saturated with less than 2 per cent combined carbon, the solubility decreasing with the temperature as shown by the line *E S*. Thus when the alloy *x-x* is at the temperature *f* it consists of cementite and a decomposition product of austenite of a carbon content *g*. When the temperature falls to A_1 at the point *h* the solubility of cementite in iron becomes nil and the remaining solid solution then containing about 0.90 per cent carbon, is converted into pearlite consisting of a mixture of cementite and ferrite in such proportion as to give a carbon content of 0.90 per cent. It must be remembered that while these various transformations of the solid solution are going on, there exists also the cementite formed during freezing so that below A_1 the metal consists of cementite, pearlite (cementite + ferrite) and the socalled proeutectoid cementite separating along *Acm*. This is the actual course of events during the freezing of the ordinary white cast iron of the malleable industry.

The system has been described as metastable, in other words, it is permanent as regards its components, not because actual final equilibrium has been attained but because further rearrangement is impossible under the temperature conditions obtaining. If the iron be maintained sufficiently long at high temperature, either in cooling or by reheating, the cementite directly or indirectly will be converted into free carbon.

This reaction is due to the fact that at a given temperature carbon is less soluble when not combined with iron than in the form of Fe_3C. The equilibrium conditions in the stable system *Fe—C*, are approximately shown by the dotted lines. Ruef and Bowman have located the line *E′B′* at 1138 degrees Cent. ± 1 degree (about eight degrees above the eutectic freezing point of the metastable alloys). The solubility of free carbon, as distinguished from cementite is shown by the line *B′E′S′* although there is room for argument as to its intersection with the line of nil carbon content and with A_1 line. If the alloy marked *xx* be maintained at *f* a very long time, free carbon will precipitate and cementite dissolve until none of the latter remains and the system consists of free carbon and an alloy having an agraphitic (not free) carbon content *i*. If now cooling be very slow the carbon can be progressively precipitated with decreasing temperature until at, or about, A_1, no agraphitic carbon will remain. Archer maintains the solubility at A_1, to be about 0.7 per cent carbon and graphitization to be complete below that point only.

Recent work under the writer's supervision by Austin, Payne and Gorton since the preceding paragraphs were written has demonstrated the existence of a solid solution which we have named boydenite. It bears the same relation to the stable system which austenite, in its generic sense, bears to the metastable. Carbon has been shown to have a definite solubility as boydenite immediately above A_1, confirming Archer's views as to the existence of a eutectoid of carbon and iron. The relation of the carbon concentration of that eutectoid as now determined to that of pearlite is contradictory to Archer's opinion. The solubility of carbon in boydenite has been accurately determined and the probable locus of the A_{tm} line *E'S'* determined. The necessary revisions in the equilibrium diagram are shown in Fig. 24, which represents the best informa-

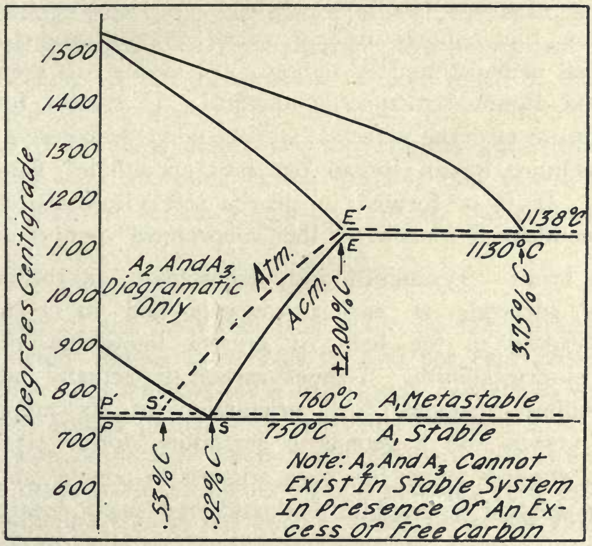

Fig. 24.—A further modification of Benedict's diagram indicating the results of recent research work

tion now at hand on the matter. The diagram also has been modified to take cognizance of the fact that the alloys are not binary but ternary containing carbon, silicon and iron. The liquidus indicated is derived from Gontermann's data interpreted in the light of additional experiment by Hird in the author's laboratory.

Graphite and Temper Carbon

Graphite and temper carbon are chemically identical and differ only in geometric form. Which one is formed depends only upon the temperature at which graphitization occurs. Iokiche has demonstrated by radiographic means that their crystalline and atomic structure is identical. If carbon forms at a temperature near the eutectic freezing point, hence in a nearly liquid medium, it can spread out into crystalline flakes of graphite. If it is formed in nearly solid iron at relatively low temperature it remains in the "amorphous" temper form.

The terms "crystalline" and "amorphous" in this connection are survivals of earlier concepts and in a measure are misleading in the light of present knowledge of what constitutes crystallinity. Temper carbon is actually possessed of crystalline structure, i. e. orientation of its atoms, but has not grown into a geometric crystalline form. It corresponds to graphite which has been crushed to powder and bears the same relation to graphite that powdered sugar does to rock candy.

The function of malleable metallurgy is to produce a graphite-free casting and then graphitize this at temperatures such that temper carbon results. The terms "graphitize" or "graphitization" apply to the separation of free carbon irrespective of its geometric form.

To this end the foundry must produce a white cast iron of such a composition as to be readily graphitized. The tendency to graphitization both during cooling and in annealing is affected greatly by the chemical composition of the product. Thus silicon and some of the rarer elements, notably aluminum, promote the formation of the stable system while sulphur, manganese, and some rarer metals retard the formation of the stable system. It can be seen that the properties of malleable iron depend largely on the total carbon present, because the more carbon is present the more will the ferrite matrix, of which the product is mainly composed, be interrupted by that element. Since the carbon possesses no strength, every temper carbon granule decreases by that much the strength of the product. In the early days much malleable was made high in carbon, owing to the advantage of a lower melting point with correspondingly greater fluidity. At times the carbon was so high, as compared with the silicon, that some graphite formed in freezing, making a bad matter worse, for obviously, a thin flake of carbon will do more damage than a spherical nodule of equal weight. From this practice resulted much of the "rotten" iron sold 10 years ago. Fig. 25 shows such a metal, in which "primary" graphite present in the original hard iron persists unaltered after annealing in the form of thin flakes. These are located between ferrite grains and cut up the structure badly.

Use of Silicon

Most of the malleable iron made by the better manufacturers today ranges from 2.30 to 2.70 per cent carbon before annealing. An average for a high grade product in castings of fair size would probably be between 2.40 and 2.50 per cent. Small work, especially where the highest strength is not needed, still is often made of higher carbon content, even up to 3 per cent, although this is not good practice from the viewpoint of the best physical properties. Since the size of the casting affects the rate of cooling it also affects the tendency to graphitize on freezing and hence the chemical composition required to prevent this occurrence.

Quite generally this tendency is held in check by controlling the silicon content. When little or no silicon is present, graphitization in the annealing process is retarded to a commercially prohibitive degree. When too much is present graphitization may be so much promoted as to take place during freezing. Most classes of work have a silicon content of from 0.60 to 0.80 per cent.

It is general practice and sound metallurgy to vary the silicon inversely with the carbon and for a given carbon, in-

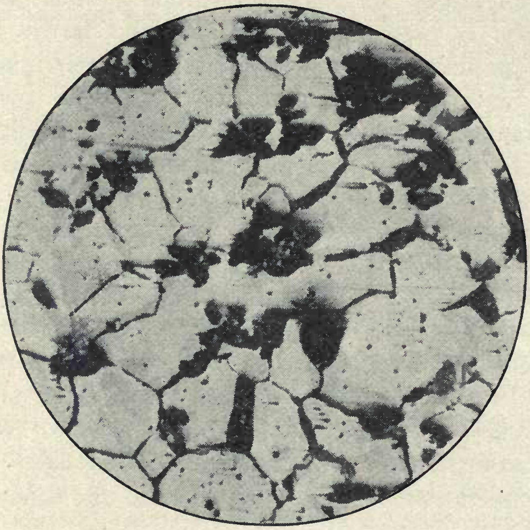

Fig. 25—Graphite crystals in malleable made from hard iron containing graphite

Black grains represent temper carbon; heavy black lines, graphite; thin black lines, grain boundaries; white, ferrite
Etched with alcoholic nitric acid x 100

versely with the cross section of the castings. The purpose of this practice is to select the silicon for a given carbon that the castings will be absolutely free from graphite.

For rather low carbons, say between 2.10 and 2.40 per cent, it may be good practice to let the silicon vary at nearly the same rate as the carbon. For instance, 2.40 carbon and 0.75 silicon metal has practically the same tendency to be graphitic in the casting or to mottle as 2.10 carbon and 1.05 per cent silicon. In higher ranges of carbon, say from 2.40 to 2.80 per cent the silicon may vary only three-fourths as fast as the carbon, 2.80 carbon and 0.45 silicon corresponding to 2.40 and 0.75 per cent silicon.

Extremely Low Silicon Undesirable

The reduction of silicon to values as low as 0.45 per cent is not usually good foundry practice because such iron is easily oxidized in melting and produces pin holes and similar difficulties due to the liberation of carbon monoxide while the metal

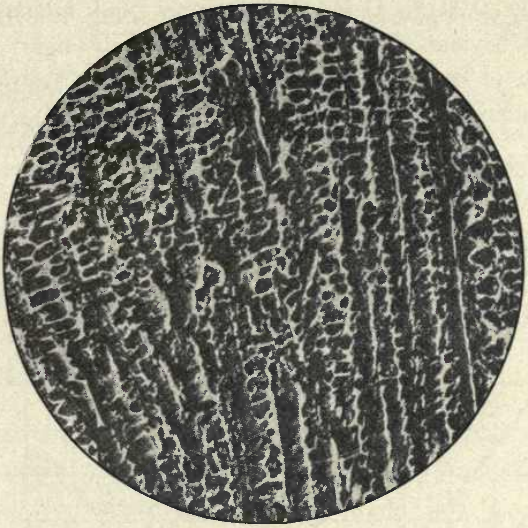

Fig. 26—Unannealed hard iron. The structure is always dendritic but varies slightly with the carbon content

White is cementite; gray is pearlite.
Etched with picric acid x 100

is freezing. A casting which would prove large enough to require the carbon and silicon referred to above probably could not be successfully made with less than 0.55 or 0.60 per cent silicon, thus setting a limit for maximum carbon distinct from consideration of strength. The maintenance of proper relationship between carbon, silicon and size of casting is usually possible only on the basis of foundry experience and constant attention to results; consequently these matters cannot be briefly and adequately dealt with in any terms of general application. From the consumers' viewpoint, any attempt to embody them in specifications would be the height of folly, because the practice of no two plants, in matters of casting temperature, sand preparation, etc., would be nearly enough alike to make any one specification generally applicable even on a single class of work.

The problem would be further complicated by variations in the size of castings. The figures previously given may be understood, to apply to fairly heavy castings and represent nearly minimum values of silicon for a given carbon. Light work may possibly run 0.20 to 0.30 silicon higher and unusually small work even beyond that. On such extremely light work the carbon also is occasionally well above 2.80, as previously explained, sometimes going over 3 per cent.

It is not necessary to lower the silicon for 3 per cent carbon far below that used at 2.80, partly because the tendency to mottle in very high carbon alloys is relatively little affected by the silicon. In alloys of this character the graphitization tendency is dependent mainly on the cooling rate. They should never be used in metal sections of any thickness since their

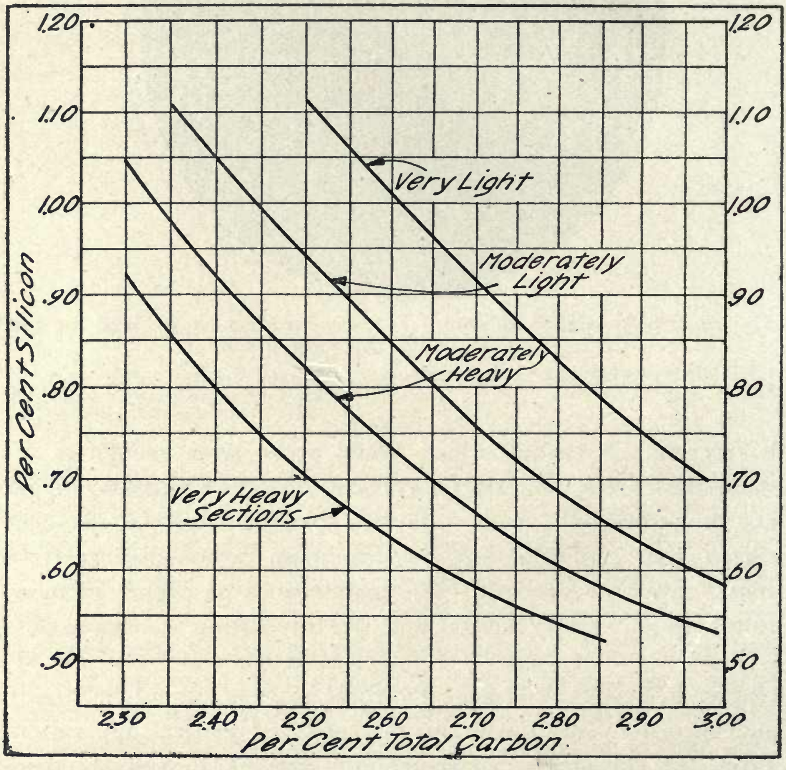

Fig. 27—Effect of silicon in relation to carbon on malleable. This graph is based on data from Thrasher's determinations

freedom from graphite is dependent primarily on their rapid cooling.

Sulphur and manganese have been referred to as opposing graphitization. These two elements unite to form manganese sulphide. This compound apparently has no effect on the formation of temper carbon. Accordingly, the absolute amounts of the two elements in the metal are unimportant provided they are in the proper proportion. It is found impracticable to follow the theoretical proportion of the two elements exactly, a slight excess in manganese always being necessary.

Effect of Manganese Sulphide

A low sulphur can be had only by very close selections of fuel and melting stock and is impossible of practical attainment except in electric furnace practice. The low manganese required for low sulphur also presents difficulty on account of the manganese content of the available ores. The presence of a moderate amount of manganese sulphide does no harm and is sometimes a manufacturing advantage. The user need therefore have no fear of sulphur. The only harm this element can do is to prevent complete graphitization in the anneal. A physical specification for tensile properties will protect the consumer adequately in this point and leave the foundryman to operate his process to the best advantage with the fuel and stock available.

The value for sulphur, .06 per cent maximum, written into the 1904 specifications of the American Society for Testing Materials, and abandoned at its first revision, is particularly ill founded in view of the fact that very little malleable is made in the air furnace which does not contain about that amount before annealing. During the anneal there always is an increase in sulphur ranging from 0.005 to 0.03 per cent. It therefore is practically impossible to produce from commercial raw material a product which would continuously pass this specification. The highest grade annealed product of commerce has from 0.065 per cent to 0.10 per cent sulphur, thus indicating the unsoundness of the 0.06 per cent limit.

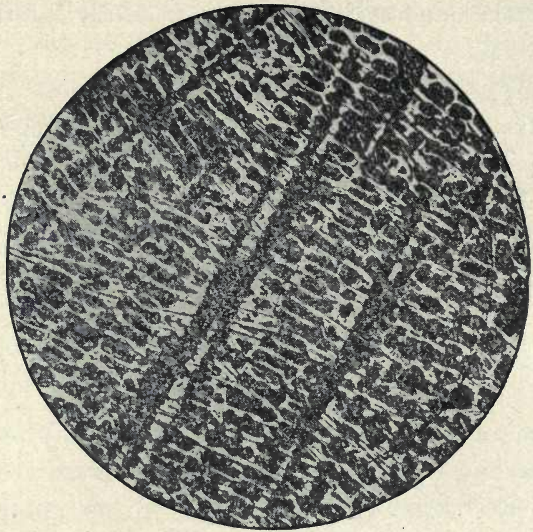

Fig. 28—Beginning of graphitization after one half hour at 1700 degrees Fahr.

Black represents temper carbon; white, cementite; gray, martensite to sorbitic mixed crystals. Etched with picric acid x 100

Fig. 29—Progress of graphitization after 1½ hours at 1700 degrees Fahr.

Black represents temper carbon; white, cementite; gray, martensite to sorbitic mixed crystals. Etched with picric acid x 100

Electric furnace metal can be produced as low as 0.01 per cent sulphur before annealing. The application of the desulphurizing process is controlled by one producer through the Kranz patents. No particular advantage has been found to result from these very low values as compared with slightly higher amounts and the triplex process usually is not operated to secure desulphurization to a point below 0.04 per cent.

Phosphorus also has been regarded with more fear than is warranted. In small amounts it has no effect on the product; for example, iron containing 0.05 and iron with 0.15 per cent phosphorus would have commercially identical properties.

When this element is increased to about 0.25 per cent it no longer is completely soluble in the ferrite of the finished product. It then has a direct effect on the properties of the metal. In this respect phosphorus differs from all the other common elements, in that its effect is not due to its action on the graphitizing process.

The exact point where phosphorus begins to exert a harmful effect depends to some extent on the heat treatment employed. Commercial melting stock and pig iron grading are such that the commercial product contains from 0.15 to 0.20 per cent of the element, usually about 0.18 or 0.19 per cent, which is amply safe.

The microstructure of the unannealed product is practically independent of chemical composition, unless the latter be strikingly abnormal. The structure is always dendritic, consisting of hard white cementite and a darker ground mass of more or less well developed pearlite, as shown in Fig. 26. Of course, there are minor differences of structure as between different samples, lower carbon iron containing relatively less cementite and higher carbon more. The coarseness or fineness of crystalline structure is dependent upon the rate of freezing. In very rapidly chilled metal it may happen that a mesh structure is substituted for the dendritic. This condition is unusual in castings.

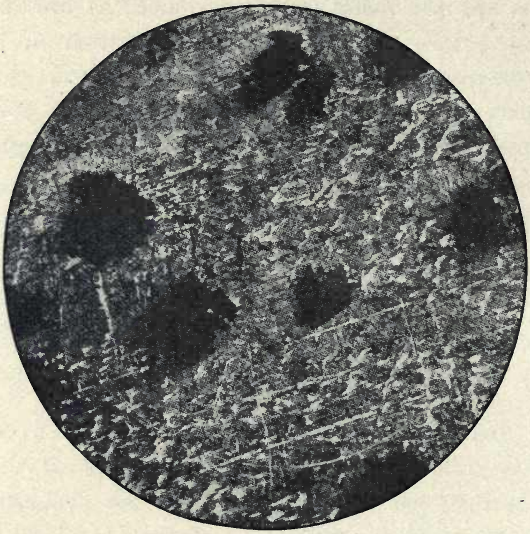

Fig. 30.—Progress of graphitizatoin after 3½ hours at 1700 degrees Fahr.

Black represents temper carbon; white, cementite; gray, martensite to sorbitic mixed crystals. Etched with picric acid x 100

Fig. 31—Equilibrium at 1700 degrees Fahr. after 70 hours

Black represents temper carbon; gray and white, martensitic mixed crystals Etched with picric acid x 100

Turning now to the second metallurgical step in the process, let us consider the changes taking place during graphitization in the so-called annealing of castings.

This process has for its object, not the elimination of carbon as many appear to believe, but the conversion of a metastable alloy containing Fe_3C and Fe into the stable system, consisting only of Fe and C. This reaction involves no changes of the ultimate chemical composition. All of the elements remain unaltered in quantity, the carbon only being converted from the combined to the free state, according to the reaction, $Fe_3C=3Fe+C$.

That a certain amount of carbon is oxidized is a mere incident in the process. The elimination of carbon is of practical significance but is not in any sense the purpose for which the annealing operation is conducted. In this theoretical discussion of the principles of malleable iron metallurgy this decarburization will be disregarded and only the essential graphitizing reaction will be considered.

In the early part of the chapter the conversion of the metastable into the stable system was touched upon and the mechanism of the change described. The equilibrium in the latter system is not as clearly understood as that of the former. This is due largely to the fact that steel and white cast iron furnish commercially important examples of the metastable system in which equilibrium frequently is attained. Consequently there was material ready to hand and also a commercial necessity for the study of the system.

Commercial Application

Malleable cast iron furnishes the only commercial application of material involving the attainment of equilibrium conditions in the stable system. Because the output of malleable is small compared with that of steel and also because the product was not always known and understood, even by the more progressive engineers, the theoretical aspects of the problems of malleable metallurgy received inadequate attention and the studies made in the laboratories of some of the universities lacked the advantage of contact with the commercial aspects of the problem.

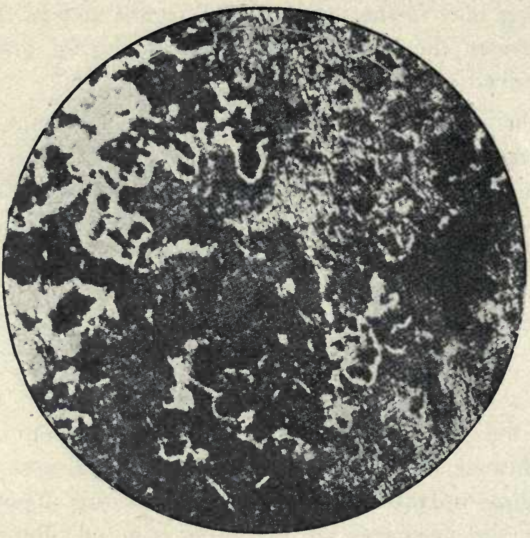

Fig. 32—Imperfect attainment of equilibrium below A_1 due to too short a time

Same as Fig. 31, followed by three hours at 1200 degrees Fahr. Black areas surrounded by white represent temper carbon; white, ferrite; gray, pearlite. Etched with picric acid x 100

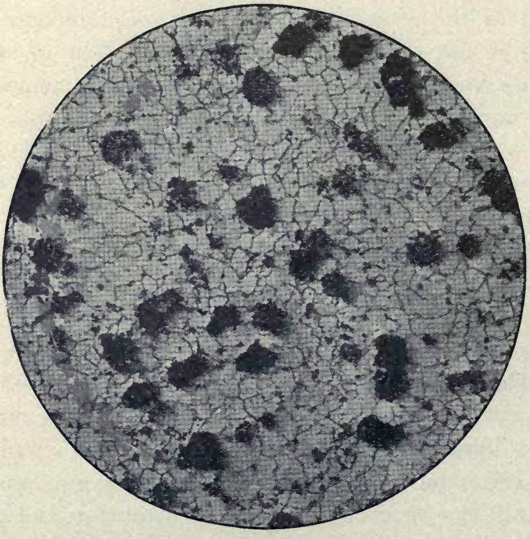

Fig. 33—Normal malleable iron, metastable equilibrium below A_1

Black represents temper carbon; white ferrite
Etched with alcoholic nitric acid x 100

Significant work leading toward the establishment of a correct equilibrium diagram for the system *Fe-C* was done by Storey at the University of Wisconsin, Archer and White at Michigan and Merica at the United States bureau of standards. Howe also gave adequate attention to the mechanism of graphitization in his "Metallography of Steel and Cast Iron."

It has been pointed out a number of times in this text that the conversion of cementite into free carbon results purely from the fact that the solubility of carbon in the stable system is less than in the metastable. That is, solid iron will dissolve less free carbon than carbon in the form of iron carbide.

When a white cast iron is maintained at a temperature higher than the lower critical point, Ac_1 (1350 to 1400 degrees Fahr.) free carbon is slowly formed and combined carbon is reduced to a corresponding degree. The rate at which this change takes place, while depending upon the chemical composition of the metal, is greater the higher the temperature. However for each temperature there is a definite value of combined carbon practically independent of the total carbon content, when the reaction ceases completely. These values of "combined" carbon, measuring the solubility of carbon as distinguished from iron carbide in solid iron, have for their locus the line $E'S'$ in Fig. 24.

The word "combined" is used in the preceding sentence in what may be a somewhat inaccurate sense. It is intended to differentiate free carbon from carbon which is not in the free state. Whether the combined carbon corresponding to the line $E'S'$ is actually combined with iron is very problematical. Quite possibly it is in solid solution and is not actually combined with iron.

Microstructure of Malleable

Fig. 26 shows the structure of a normal piece of hard iron as cooled in the mold. When white cast iron is raised to a temperature well above the Ac_1 point, say 1700 degrees Fahr., a decrease in cementite and an increase in the constituent forming the gray background, called "mix crystal" or solid solution, is observed. (See Fig. 28.) This results from the greater solubility of cementite at the higher temperature.

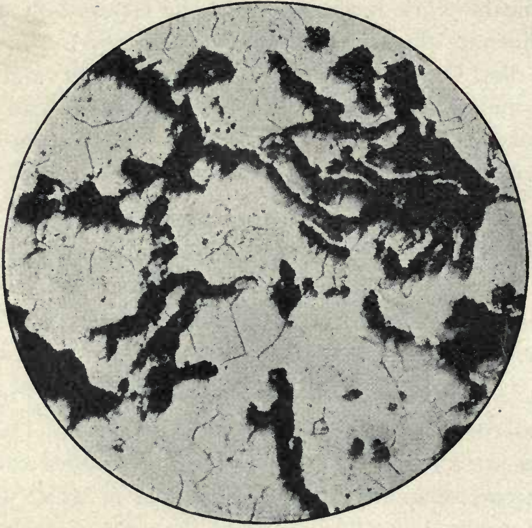

Fig. 34—Graphite crystals produced by annealing at 2100 degrees Fahr.
Black represents graphite; white, pearlite. Unetched x 100

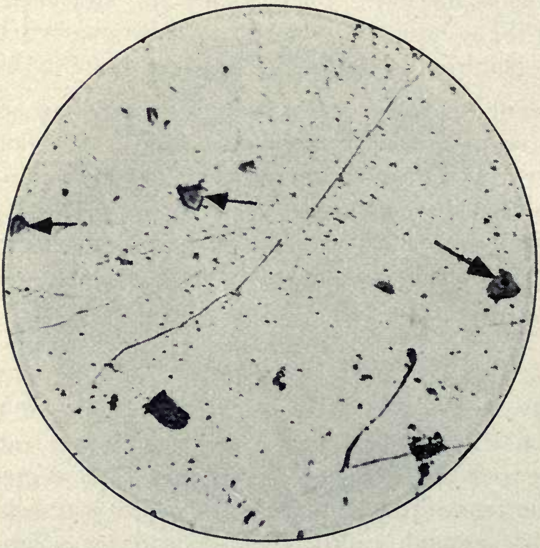

Fig. 35—Manganese sulphide in malleable cast iron. The arrows joint to MnS
Etched with picric acid x 500

As the heating at 1700 degrees is continued, temper carbon begins to form at the expense of cementite, as shown in Figs. 29 and following, and finally equilibrium is attained by the destruction of all cementite. The structure then consists of temper carbon and solid solution of carbon in iron, as shown in Fig. 31 and is incapable of further change as long as the temperature remains unchanged. The product then is still whitish in fracture and very brittle.

If the temperature is allowed to decrease the solubility of carbon grows less and more temper carbon will form if the material is held sufficiently long at the lower temperature. However, no ferrite will be formed at any temperature above the critical point. The ground mass above this point will remain a homogeneous solid solution, differing only in carbon concentration from that remaining at higher temperatures.

If the temperature is carried down to 1300 degrees, that is, below Ar_1, the carbon is completely insoluble, though equilibrium may not be reached unless the approach to this temperature is very slow. In case the time at 1300 degrees is not very long, a structure as shown in Fig. 32 will result, consisting of temper carbon surrounded by ferrite which in turn has a background of still incompletely decomposed mix crystal persisting from the higher temperature. At temperatures above the critical point, this ferrite separation does not occur, the structure strongly resembling Fig. 31, except as to detail in the metallic matrix.

Still further treatment at or slightly below Ar_1 will result in the complete graphitization of the product as shown in Fig. 32 which represents the structure of malleable cast iron. According to Archer's views as to the solubility of carbon at A_1 graphitization is always completed only by treatment below A_1 as outlined above. Graphitization is accomplished commercially by just such a heat treatment, that is, by heating first to a fairly high temperature for a considerable period and then cooling sufficiently slowly to a temperature below the lower critical point of the stable system.

The maximum temperatures and time chosen are largely a matter of individual judgment. The exact location of this line on the equilibrium diagram unfortunately has not been the subject of adequate research. Much remains to be done in mapping its course exactly. Our last knowledge is summarized in the revised diagram Fig. 24. Since there is no microscopic evidence of an iron carbon eutectoid it is somewhat doubtful whether A_{tm} should be interpreted as ending at S' or whether there is a sharp inflection at S', A_{tm} running nearly parallel to A_1 to or toward P'. The significance of A_2 and A_3 in the stable system has so far eluded experiment, and nothing final has been accomplished toward the location of S' as affected by variations in other elements than carbon.

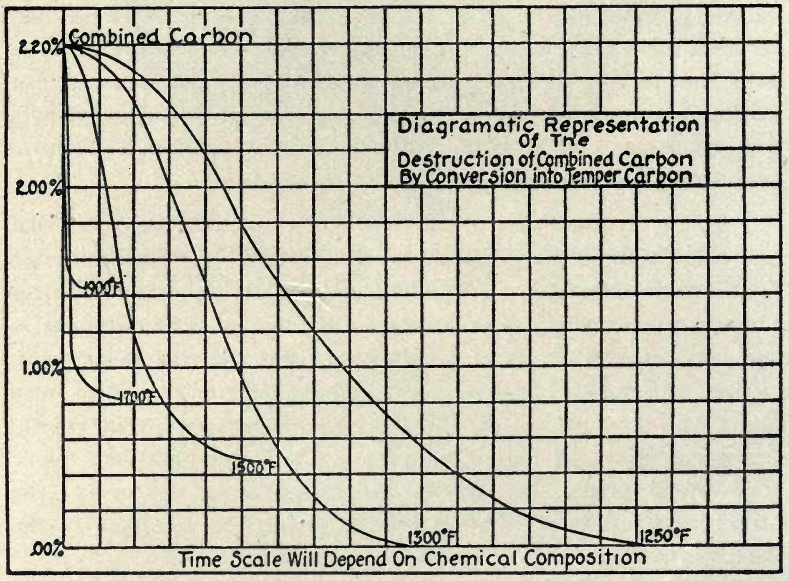

Fig. 36—Chart showing conversion of combined carbon into temper carbon

The graphs show the relation between the carbon remaining combined and the lapse of time at each of five temperatures. Note the increasing velocity and higher carbon content of the conclusion at high temperatures as compared with low.

These points are of very great academic interest, but from an operating viewpoint are inconsequential. No operating errors will be involved in considering the line to be straight and joining the two points mentioned.

Fig. 36 shows in diagrammatic form the decrease in combined carbon according to the time of exposure to various temperatures. It will be noted graphs are given for each of a number of temperatures. The horizontal or time ordinates have been plotted to scale; however, the values given for this dimension are suggestive only, since the rate of graphitization and hence the time to attain equilibrium at various temperatures is dependent on the chemical composition with respect to other elements in addition to carbon. The figure is given as an example of what may happen rather than for quantitative interpretation.

Speed is promoted by graphitizing the cementite at the highest possible temperature but to a certain extent at the expense of quality. Temper carbon differs from graphite only in form. It has been pointed out that these differences of geometric form are due to the temperature of the metal in which the free carbon is formed. Accordingly, the two forms, temper and graphitic, shade over into each other by infinitesimal degrees and the temper carbon formed at high temperatures may grow so coarse and flaky as to be almost graphitic. Fig. 34 shows the carbon produced by graphitization at 2100 degrees Fahr. far above any commercially possible temperature. It will be seen that this carbon is purely graphitic and bears no resemblance to the temper form. Also the matrix of malleable iron is not a continuous mass but consists of an assemblage of individual grains as shown in Fig. 33. The character and size of this grain structure is influenced by changes of heat treatment, introducing another viewpoint for the selection of annealing temperatures. Moreover, high temperature may cause operating difficulties due to the deformation of castings, destruction of pots and fusing of packing material. An attempt to reduce the annealing period too far by a rise in temperature therefore is usually inadvisable.

Commercial practice involves a maximum temperature of the castings of between 1500 and 1800 degrees Fahr. The time for maintaining the maximum temperature varies from 24 to

60 hours, or even longer, the longer periods properly accompanying lower temperatures. The commercial rates of cooling are variable, ranging from 5 to 12 degrees per hour.

In general the best practice is opposed to the highest temperatures, the minimum time of holding and the fastest cooling and favors a maximum temperature not far above 1600 degrees, a time not less than 40 hours near that temperature, and an average cooling rate certainly not faster than 10 degrees per hour; preferably less, more particularly near the critical point.

When properly heat treated, malleable cast iron contains no combined carbon except just under the surface. It is practically impossible to entirely eliminate these last traces of pearlite from the casting, but this ingredient can and should be reduced to the point where it is equivalent to not more than 0.15 per cent of combined carbon as referred to the total weight of the casting.

Approximately six years ago Thrasher published in graphic form the relation between carbon and silicon in white iron for constant tendencies to mottle. Based on the form of Thrasher's curves and known points near the middle of the range of composition for various classes of work, Fig. 27 has been prepared indicating the approximate relation between carbon and silicon for various classes of work, based on the tendency to primary graphitization only.

No attention has been given to the weakening effect of carbon which sets limiting values on that element nor on pouring temperatures or other variables which may affect graphitization. The data presumably apply to ordinary air furnace practice and doubtless are subject to a certain amount of modification according to other variables.

The more or less unavoidable oxidizing conditions in annealing remove some carbon from the surface. The extreme surface of malleable generally contains about 0.40 or 0.50 per cent combined carbon, while metal more than 0.1-inch below the surface is but little affected. Malleable castings sampled so as to include no material less than 1/8-inch below the surface will have nearly the ultimate composition of the original hard iron, except for the absence of combined and the presence of free carbon. If the sample is taken to include the entire cross section of metal the total carbon will vary with the thickness of the casting and will range from 0.40 per cent or even less up to the original carbon of the hard iron. In Fig. 37 the changes in carbon distribution during freezing of the hard iron and during its subsequent annealing are summarized in diagrammatic form. Time (estimated) is plotted as abscissae. At the top of the diagram the assumed temperature-time curve is plotted. At the bottom the relative weights of the various metallographic entities are recorded, the sum of course always being 100 per cent. Along the middle of the diagram the carbon concentration of the various homogeneous solutions (solid and liquid) is plotted for convenient reference.

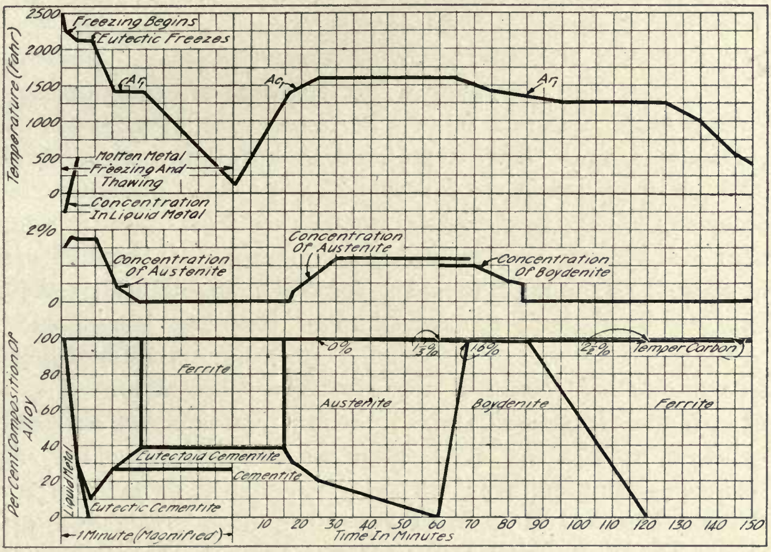

Fig. 37—Changes of metallographic composition during the freezing and annealing of white iron

IV

GENERAL MANUFACTURING AND PLANT

TODAY all malleable foundries in the United States and Canada operate upon the same general principles although, of course, the manner of execution of the individual operations varies with the ideas of the individual operator and the facilities at his disposal.

Physically the foundries of the country differ widely both in size and type of buildings. The range in capacity of plants is probably from 50,000 tons per year down to 1000 tons or less. If plants making malleable only as a side issue are included, the minimum capacity is considerably less than 1000 tons. The plants range from antiquated structures of brick with low wood roofs to modern brick, concrete and steel buildings.

A similar range exists in the facilities available in the form of mechanical equipment and, unfortunately, also in the personnel. It does not necessarily follow that the largest production is coupled with the best buildings, mechanism and talent although in this as in other industries, many things are possible for the large operator which are not available to the smaller. Large scale operations generally involve conditions better suited to the procurement of men and machinery of the highest order.

In a previous chapter there have been outlined the principles upon which malleable cast iron depends for its properties. It was there shown that the metal is the product of two distinct operations—the making of castings of white iron and the malleablizing of the castings by a subsequent graphitizing or annealing process. This divides the process into two distinct stages and, generally, the plants into two separate parts—the foundry and the annealing departments.

Centered around each of these major departments are others of a contributing character such as the stockyard, mason's department, flask shop, patternshop, coreroom, melting department, and chemical laboratory as foundry adjuncts

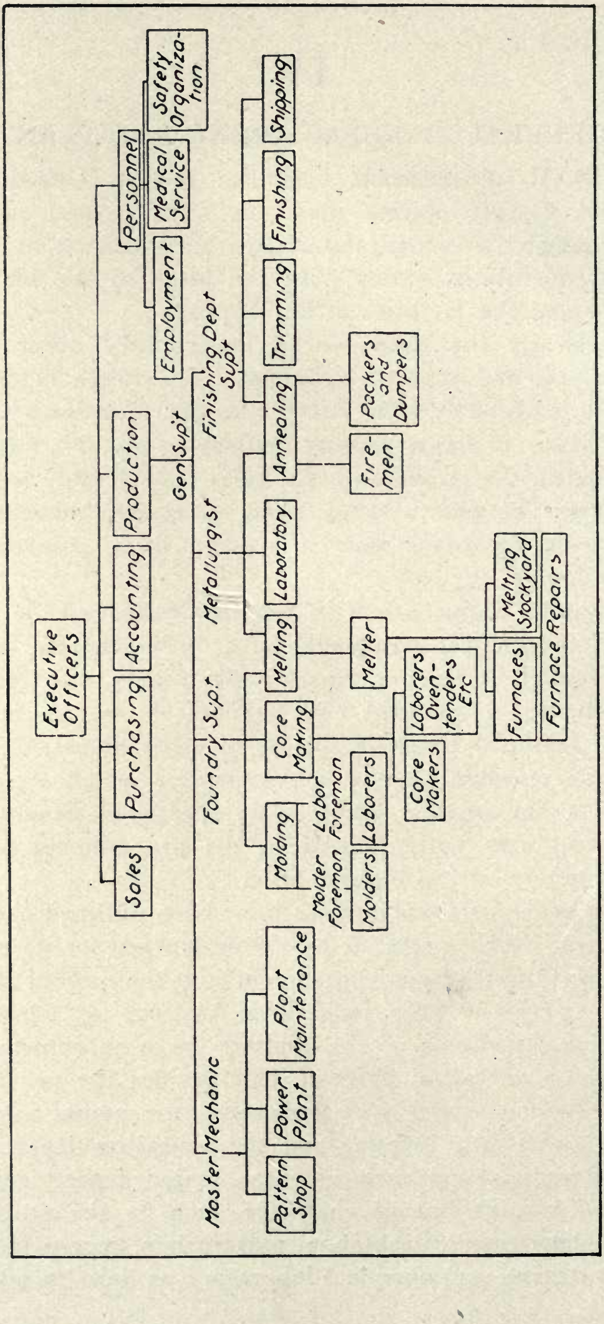

Fig. 38—Organization chart for malleable foundry

and cleaning, trimming, inspection and shipping departments, engineering and metallographic laboratories as adjuncts to annealing. Plant maintenance also requires the operation of a power station, machine shop, electrical department, etc. There are additional departments not directly of a manufacturing character, including those pertaining to sales, purchase, accounting, labor, costs, first aid and others.

The actual shop organization by which the departments are subdivided between groups of executives differs widely in different companies. Even the largest producer, operating seven malleable plants, finds it wise to use a somewhat different organization scheme in each of its foundries. Small plants usually are practically "one-man" shops. One executive, often the proprietor, exercises supervision over all works activities. The scheme is simple, but incapable of any very great growth.

A common method is to divide the duties among three major foremen or superintendents. One has charge of the foundry and is responsible for everything up to the delivery of hard castings to the trimming room; another converts these into the finished product; and the third is in charge of power plant, carpenter, machine and pattern shops, etc. Sometimes the last two are co ordinated under one head, making only a foundry and finishing department. A much more highly organized and efficient system is represented in the organization chart shown in Fig. 38, which is applicable only to a fairly large organization and incidentally is not exactly followed in any plant of which the writer has knowledge.

The raw material purchased by a malleable plant consists of pig iron and scrap as melting stock; coal, coke and sometimes oil, gas and electric power as fuel; molding and core sand for the foundry and refractories for the furnaces. In addition a wide variety of general supplies is used in more limited quantities.

In almost all plants the melting operation is executed in air furnaces which generally make two heats a day. In

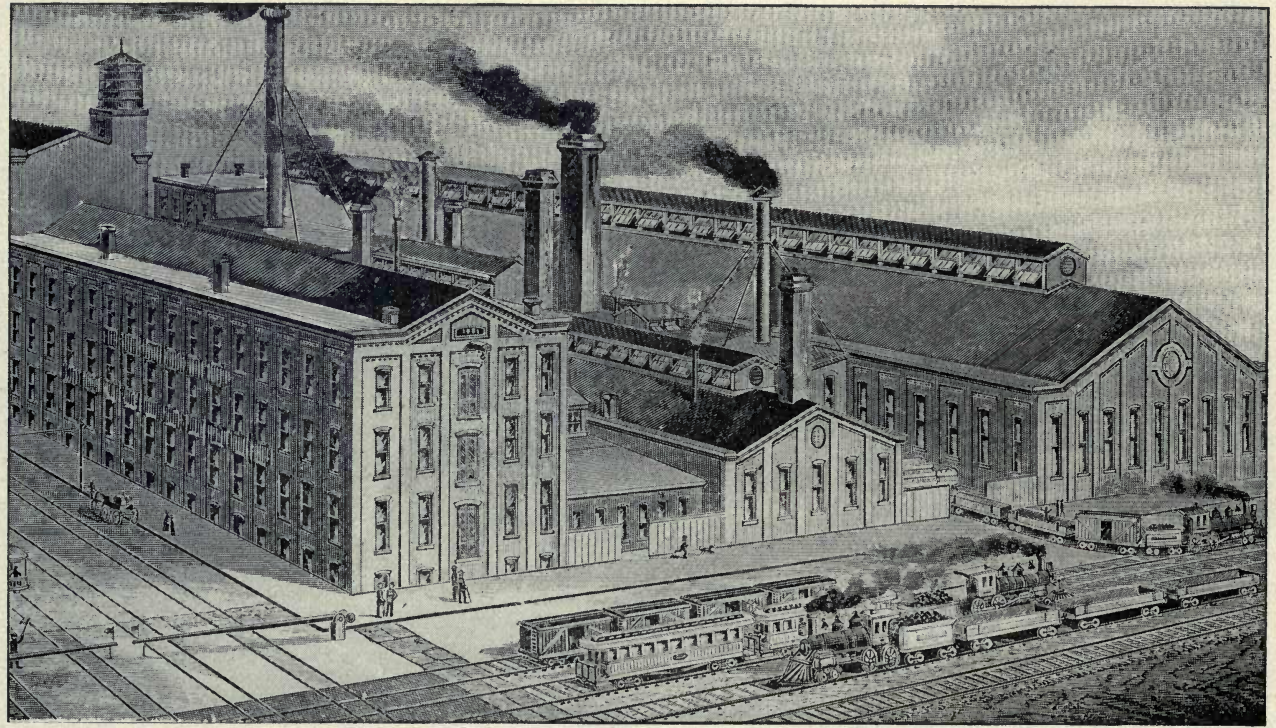

Fig. 39—A good example of the approved style of architecture for a malleable foundry built a generation ago

some plants only one heat is made and in a very few two or three heats every other day and none on the intervening day. The latter practice is a survival of a practice in vogue 15 or 20 years ago. Heats vary considerably in size. On a two-heat a-day basis, they vary in different plants from seven tons to 24 tons each; on a one-heat basis, from about 18 to 35 tons, and on a three-heat basis from five to 10 tons.

In a few plants the cupola is employed for melting but this practice is not recommended for important work. Open-hearth melting has been tried by a number of producers and while not well adapted except to continuous operation and large tonnages is in successful use in a limited number of plants. A few small furnaces each having a capacity of about five tons are said to have been tried. The charge in most successful open-hearth installations averages from 14 to 20 tons.

A single producer operates electric furnaces at two different plants. From 10 to 12 heats and even more when molds are available, are made in 24 hours, but the metal is delivered to different molders so that generally a given molder only pours off twice per shift. In these plants heats range from five to seven tons and from eight to fifteen tons in weight depending on furnace capacity. Six and twelve tons are the nominal furnace capacities.

Molding still is done by hand in many shops as it was in all plants 15 years ago. The patterns being small, many are mounted on a single gate. The pattern is provided with a match part and the mold made in a snap flask. Hand operated squeezers have been in use for many years, the air-operated devices apparently not having met with general favor, although used in some plants.

Recently the trend has been strongly toward patterns mounted on plates and vibrated by air when the cope is being lifted or the pattern drawn.

In many localities no labor now is available capable of commercially producing molds from other than plate patterns. Consequently this form of mounting which requires less skill of the molder than any other, is practically forced

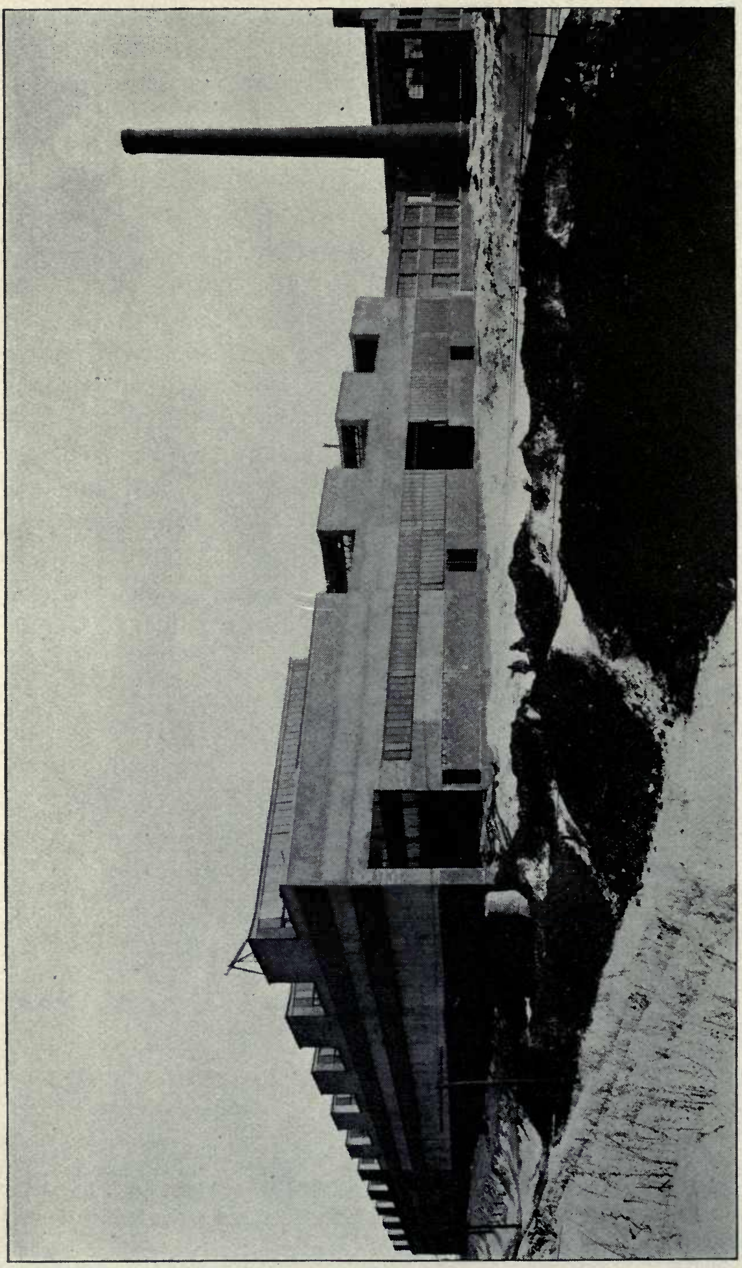

Fig 40—Exterior view of a large malleable plant built about 1917

on the industry. Nearly all of the more complicated mechanical devices have been tried, but so far they are not used extensively except for floor work, in which case various types of roll-over. roll-over drop and stripper plate machines are successfully employed.

As already stated the smaller molds are usually made in snap flasks. Sometimes, when there is danger of breaking out when pouring, the molds are strengthened with mold bands of strap iron. The use of jackets to prevent breakouts also is prevalent. The larger molds are made in box flasks, iron flasks being very common and desirable for use on machines.

All malleable castings are made in green sand except for cored holes. Since only relatively unskilled help is available, the use of three-part or other multiple-part flasks and loose pieces on patterns is practically impossible. Any pattern equipment which cannot be drawn straight out or rolled out on a flask hinge is incapable of quantity production under the conditions existing in most foundry centers.

Cores generally are made of local sharp or lake sands using rosin, oil or some of the wood sugars as binders. As a rule, the work is of such character that large and complex cores are not required.

A few foundries are beginning to prepare and deliver molding sand by mechanical means. One device for cutting sand on the floor is coming into fairly extended use, since human sand cutters are no longer available.

Molds are commonly set on the floor by hand, although at least two semi-automatic devices for removing molds have been tried, one of which offers prospects of successful operation.

No methods of molding, involving successive operations by a number of workers, have proved entirely successful thus far. Pouring is done either from hand ladles or from shank or "bull" ladles handled by two men, the former being more common. In cupola or air furnace practice molders catch directly from the stream as it flows from the furnace, the tap hole being only infrequently closed by a clay stopper or iron bar.

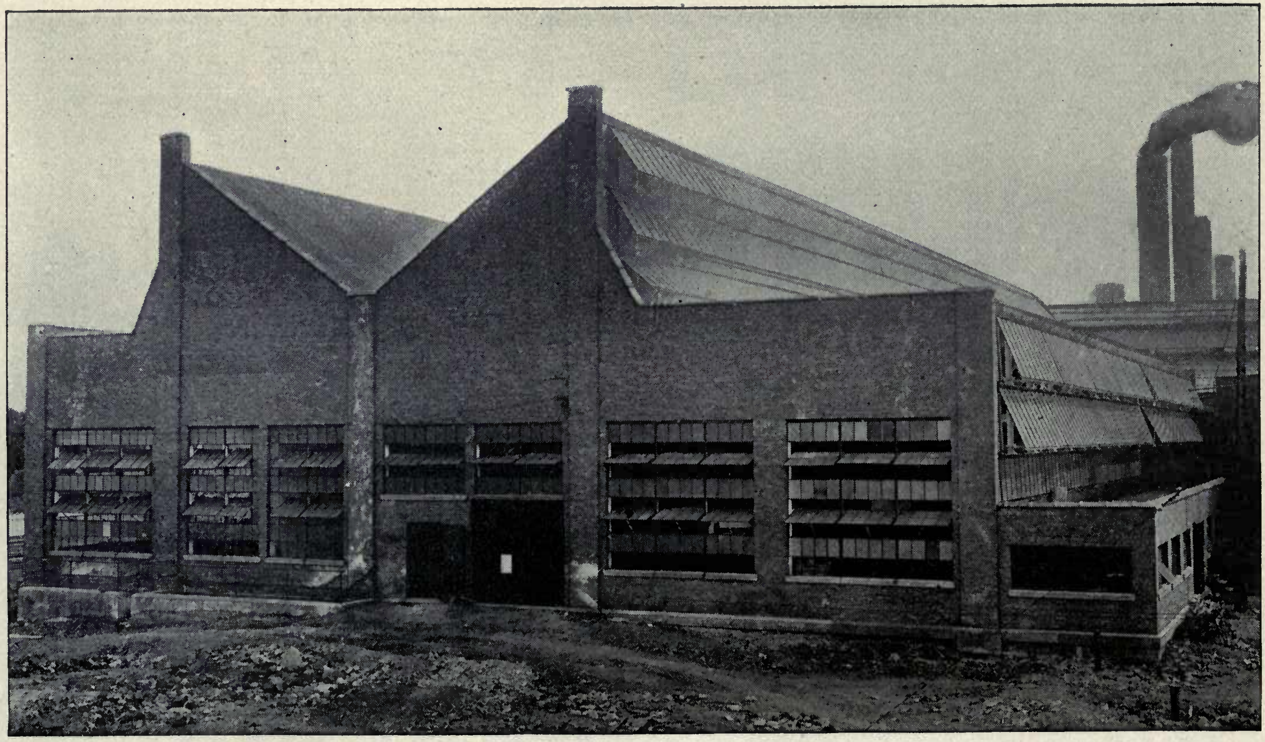

Fig. 41—Coreroom of a modern malleable plant showing roof construction designed to facilitate removal of fumes and gases and to afford good natural lighting

In electric furnace practice and sometimes also in open-hearth practice the heat is tapped into one or at most a few large crane ladles. Pouring is only rarely done from these ladles, the metal being transferred to hand ladles or shank ladles for pouring into the mold.

For relatively heavy work the metal is sometimes removed from air furnaces by ladles of 200 to 300-pounds capacity, mounted on two wheels and pushed and tilted by one laborer. These so-called "sulky" ladles can be used to pour work, but this is not often done.

The molds are shaken out by laborers who also remove large cores and break off the gates. This is easily possible because the white cast iron is extremely brittle; indeed great care must be exercised to avoid accidental breakage.

The castings are usually cleaned in tumbling barrels, although pickling or sand blasting is sometimes employed. The cleaned castings are inspected and gates and fins are trimmed off with light hammers. This department is referred to as the trimming room, from this operation.

Materials for Packing

The castings then go to the annealing department where they are packed into pots, either with or without packing, or occasionally stacked directly into muffle furnaces. If stacked in pots, the pots are usually introduced into the annealing ovens by mechanically operated trucks.

A great variety of materials is used as packing. The original process was thought to depend on the use of hematite ore for this purpose. Later on "squeezer" and "roll" scale from puddling mills came into use and great care was exercised to keep this rusty by the use of salamoniac solution. At present air furnace slag is the commonest material, although blast furnace slag, silicaquartz, ground brick and many other materials can be used. A refractory material in granular form to support the castings is the principal requirement. Also the access of flame to the castings

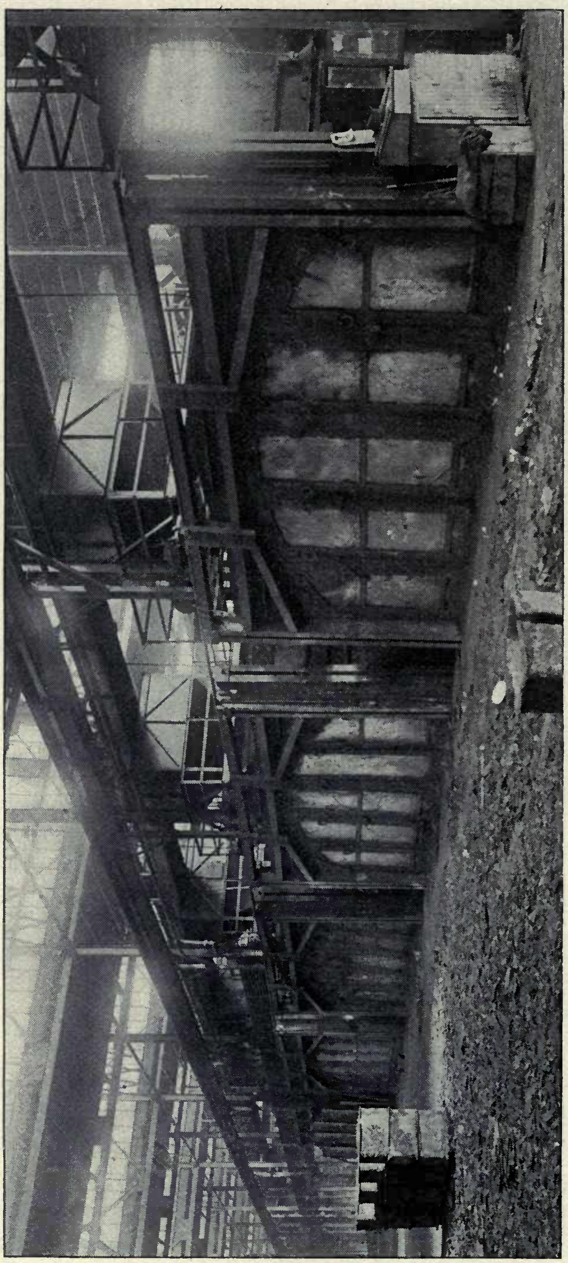

Fig. 42—Interior of the annealing department of a modern malleable foundry

The furnaces are charged by means of mechanically-operated trucks. Several stacks of annealing pots are shown at the left—The furnace doors sometimes are on hinges, or are handled by crane or by trucks must be prevented by using a fairly fine packing and by keeping the pots tightly luted with clay.

In general the pots are from 15 to 18 inches wide, 18 to 24 inches long and 12 to 14 inches high, being approximately rectangular in shape. In some cases the size of the work being annealed requires pots as large as 30 to 36 inches. Large pots usually are shallow (about 6 inches high) on account of their great weight. A larger number of pots are used to produce the desired height of stack. A few plants prefer circular pots on account of their freedom from distortion under heat. This advantage is offset by their being uneconomical of floor space in the ovens. The pots have neither tops nor bottoms, the bottom of a stack being made by a special casting. The stack of bottoms and pots thus forms a single large container.

Annealing

Annealing ovens vary greatly in size and hold from 50 to 350 pots arranged in stacks either three or four pots high. The largest type of furnace has inside floor area of about 625 square feet and a height of from 7 to 9 feet to the spring line of the arch. Such furnaces obviously hold enormous tonnages depending largely on how closely the pot space can be occupied by castings. Moderate sized ovens accommodate about 15 tons of castings, while the largest ovens when worked to full capacity can handle from two to four times as much. Some small commercial furnaces do not hold much over 5 tons.

Furnaces generally are heated with coal, fired by hand or by stoker or burned in pulverized form. Oil, producer gas, and natural gas have also been used to a limited degree.

Continuous furnaces of the tunnel kiln type, which are just coming into use, seem to promise great advantages, both economically and from the standpoint of control.

While the heat cycle for complete graphitization depends upon certain definite scientific facts and is fixed for a given class of material, in practice the cycle is also dependent upon the firing conditions, the circulation of gas in the furnace, weight of furnace contents, etc., since these affect the practical means for attaining the desired thermal cycle.

Theoretically the cycle can be reduced to about 100 hours under the conditions most favorable to rapid graphitization. However, the production of the highest grade of metal under operating conditions always necessitates a cycle of at least seven days even under conditions most favorable to speed. Cycles of 12 to 14 days are not uncommon with large furnaces.

Incidentally the consumer should be warned against a product made by any of the means which permit of cycles occupying only three or four days. Conditions can be arranged so as to produce merchantable work in that period; in fact, the writer has had practical experience with emergency annealing intended to turn out two charges a week from a given furnace, and actually doing so. However, the process is so tricky and the chance of inaccurate control so great that he is prepared to unqualifiedly condemn the practice. Furthermore when the process works exactly right the conditions are such as to preclude the use of sufficiently low carbon iron to produce a product of the highest quality.

The consumer should bear in mind that it is naturally to the manufacturer's interest to use the shortest practicable cycle on the score of fuel economy and decreased overhead for the use of furnaces. The producer therefore requires no outside stimulus to hurry this portion of his process and such a stimulus will only react against the purchaser. The conscientious manufacturer takes sufficient time at a cost to himself, in order to produce a high grade of work and should not be driven from this laudable position by the efforts of "stock chasers" whose only thought is of quantity and time.

When the work leaves the ovens it is separated from the packing, cleaned by rolling or sand blasting, subjected to any required machining or grinding operations, inspected and shipped. These operations are of a general character and are not especially characteristic of this particular industry. Some special operations will be discussed in detail later. The diagram in Fig. 43 summarizes the processes by which the raw material is transformed into the finished castings. It is evident that the process of manufacture is so complex that the cost of operating a malleable foundry is much greater than that of a gray iron shop. The first cost of a malleable plant of given capacity greatly exceeds that of a gray iron foundry of the same size.

The foundry buildings and operations are approximately identical in character and cost with those for gray iron, except that the cupola is a cheaper melting apparatus, usually in operation and in first cost than any of its competitors. When a gray iron casting passes the trimming room it is in a salable condition, except for some additional grinding. A malleable casting, however, still has to be packed, annealed, cleaned and straightened. In this process over half as much fuel is used, in many plants, as was used in the original melting. The overhead also is burdensome because the in-

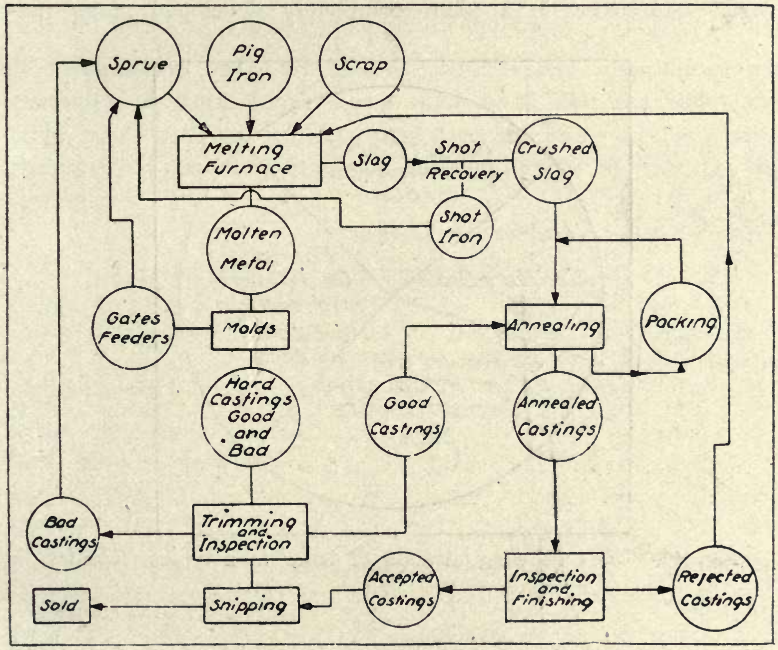

Fig 43—Chart showing cycle of principal operations in a malleable plant

vestment in annealing ovens is much greater per unit of capacity than the investment in melting equipment.

The division of labor between the several departments may be represented with some pretense at accuracy by the diagram shown in Fig. 44. To a certain extent the character of product manufactured alters the proportion shown. For example, a plant making small castings uses fewer laborers per molder than are employed in making heavy castings. Moreover, in a plant completely developed along mechanical lines, the ratio of unskilled to skilled men and of employes to product is greatly reduced.

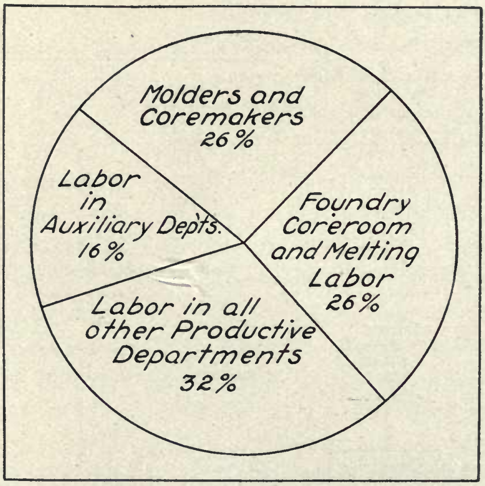

Fig. 44—Chart showing division of labor in a typical foundry

It has been estimated from data gathered for use of the fuel administration during the war that the country's plant capacity for malleable castings was about 1,000,000 tons per annum, and the labor requirements for operation at capacity were 20,000 molders and coremakers and 36,000 others. This is in the ratio of 1.8 employes other than coremakers and molders to 1 of the latter group. The writer's data indicate a ratio of about 2.2 to 1. Both sets of figures are based on estimates so that an exact agreement is impossible. The government estimate indicates further that the production of 1000 tons of malleable requires the employment of 56 men for one year, or roughly that a ton of malleable represents a labor expenditure of about 155 hours. In the writer's judgment the figure is probably low as an average throughout the country.

The amount of labor involved in the mere handling of material mechanically or manually in a foundry is seldom realized by those not conversant with the trade.

Conditions vary, of course, very widely, depending on character of work, plant layout and so on, but the following table may be regarded as suggestive at least of the labor consumed in handling material for production of one ton of castings:

Table I

MATERIAL HANDLED TO PRODUCE 1 TON OF CASTINGS

	Tons of material	No. of times handled	Total tons handled
Melting stock	2.2	3	6.6
Molten metal	2.0	3	6.0
Sprue	1.0	3	3.0
Slag	.1	6	.6
Castings	1.0	19	19.0
New molding sand	.35	2	.7
Used molding sand	5.0	5	25.0
Core materials	.25	10	2.5
Fuel	1.7	3	5.1
Cinders	.175	2	.35
Annealing pots	1.5	6	9.0
Packing	.5	5	2.5
Refractories	.15	6	.9
	15.925		81.25
Add 1/3 for handling supplies and equipment			27.08
			108.33

The items in the above table are based entirely upon estimates. The writer knows of no attempt to actually determine the several items. Also, evidently the expense of handling a ton of material can have no unit cost assigned, for the term "handling" may mean picking up the material and transporting it by a crane; picking it up to inspect, piece by piece, or the laborious operation of firing a ton of

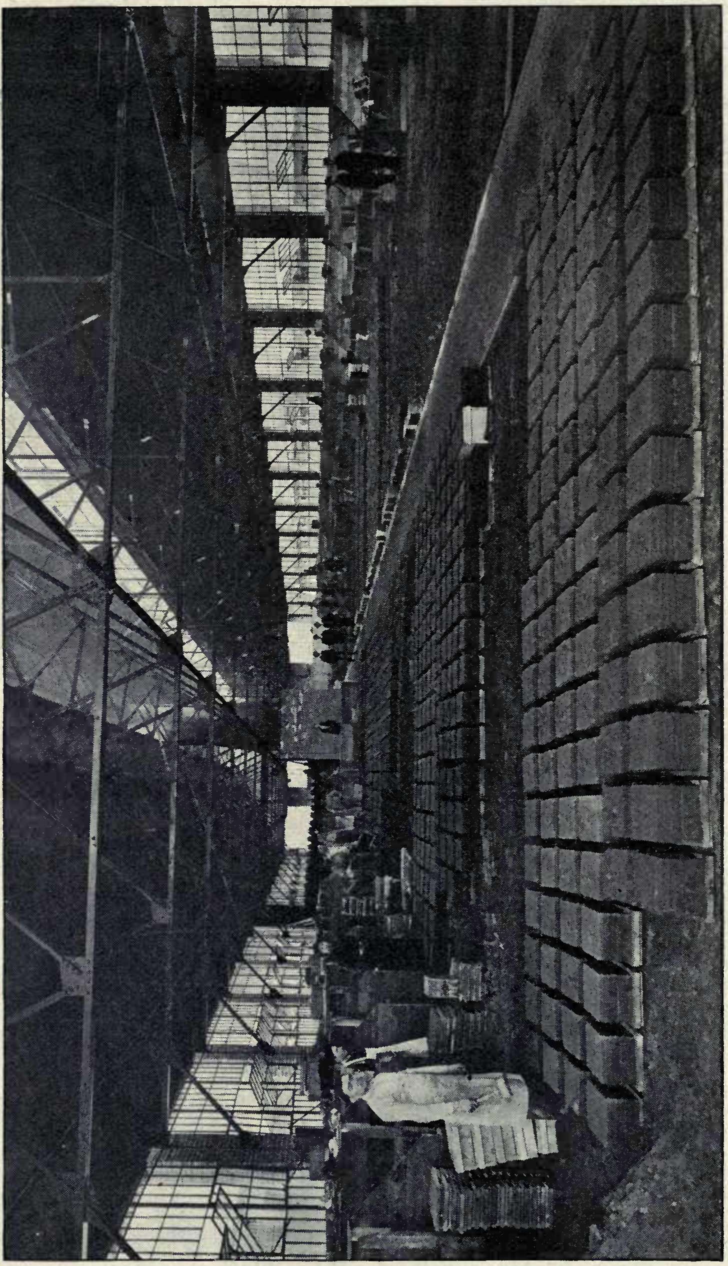

Fig. 45—Molding floor in a well organized American malleable foundry

coal in an air furnace, or wheeling a ton of sand a considerable distance by hand. The table is here presented primarily to show the importance of reducing the number of handlings each material undergoes and facilitating each by every available means.

The history of labor in the malleable industry has been that of labor in all similar work. In the early days the workers were practically native Americans, supplemented by thoroughly Americanized English, Irish, Germans and Scandinavians. Later the two latter groups increased considerably, and still later toward the end of the last century the influx of Balkan immigration began. The native American and the original foreign groups meanwhile drifted almost entirely out of the labor and molding groups, though a few remain principally in the coremakers' trade. Most of these men and their sons headed toward the machinists, carpenters and patternmakers' trades, or toward other employment of similar character but requiring less skill.

Type of Workmen Available

Meanwhile the Hungarians, Bohemians, Poles and Austrian-Slavs began as laborers and gradually worked upward through the various grades of skill, being supplanted in the lower grades by Italians and later by Bulgarians, Greeks and Russians, and still later by Turks and Armenians. In some few plants the negro long has been employed in all but the highest skilled trades and the northward migration of the southern negro farm laborer is rapidly enlarging this condition. Postwar developments meanwhile are making for the return of many former subjects of Austro-Hungary, Bulgaria and Russia to their native lands. He were a rash prophet who would attempt to discuss the net effect on the American labor market of this emigration, the European tendency toward immigration to America, the discontent of those who returned to Europe, the industrial stagnation of Austria and Russia, all in the light of the American immigration laws and shipping facilities. Natural clannishness of foreign races has produced a segregation of nationalties in different parts of the country. The lines of course are not rigidly drawn but the Scandinavian still persists in the northwest and to some degree in the St. Louis district. In the territory extending from St. Louis to Terre Haute the Armenian is relatively prevalent; the Russian and the Pole have settled in the Chicago district, as also the older class of Bohemians. The region around Indianapolis is manned by Greek, Bulgarian and Austrian-Slav foundry workers, while in northern Ohio Poles, Bohemians and Italians dominate. The latter element is very prevalent through the Pittsburgh district and through the Shenango and Mahoning valleys. New England and New York, being gateways to the interior, probably have a more mixed population than the Middle West.

Foundries of all kinds have been confronted with these conditions: First, a growing disinclination on the part of all labor to do foundry work; second, a trend toward less and less skilled and intelligent help; third, a more and more turbulent character of help from which the required force must be recruited. The trend toward negro labor represents a turn in the tide at least in the latter respect.

The industry is confronted with growing labor problems the solution of which requires the best efforts of its ablest executives. These efforts will have to continue for a long time to come in order that the decreasing productivity of labor may be prevented from being reflected in the product in the form of prohibitive rates.

The solution is in the utilization of mechanical aids to the utmost and in an enlightened labor policy.

Metallurgy of Malleable Is Complicated

Furthermore the malleable process is metallurgically more complicated than that of either gray iron or steel foundry practice, and the chemical range consistent with good results is smaller than in the former.

The most successful means of overcoming these handicaps in manufacturing cost is to operate upon a sufficiently large scale and on more or less specialized products in order to take advantage of those manufacturing economies associated with such production methods.

By inference the malleable industry is not well fitted for the manufacture of so-called short orders, that is, orders involving only a few pieces from a given pattern and small tonnages for a given consumer. It attains its greatest success when operating on orders of sufficient magnitude for each type of casting to warrant investment in the best possible pattern equipment and close study of each step in the manufacturing.

V

MELTING STOCK

THE raw materials of the malleable industry may be classified as melting stock, fuel and refractories. The remaining materials are not peculiar to the malleable industry and therefore are not important in the present discussion.

Regardless of what melting process is employed in making malleable, the melting stock is selected from the same general classes of material. Sprue, which includes the feeders, runners and defective castings produced incidentally to the plant operation, is seldom if ever sold and never is bought by a malleable foundry. Being a product of the foundryman's own plant, its composition and condition are known to him and the material requires no further description.

Malleable scrap is a material derived in part from the work condemned at the plant after annealing. Also it is an article of commerce in the form of scrap material consisting of worn out malleable parts. The scrap yard of a malleable foundry is shown in Fig. 46. Scrap has been somewhat roughly divided into "railroad malleable" and "agricultural malleable." The distinction is actually one based on size of castings rather than on the former use. "Automobile malleable" is regarded by some users as a legitimate subdivision but really does not differ materially from the railway malleable scrap from a metallurgical standpoint. Pipe fittings, often classed separately, could equally well be included with agricultural malleable scrap.

The composition of purchased malleable of course is entirely conjectural and there is therefore a limit beyond which its use introduces serious uncertainties as to composition of charge. It is safe to assume that railway and automobile malleable, before annealing had a carbon content

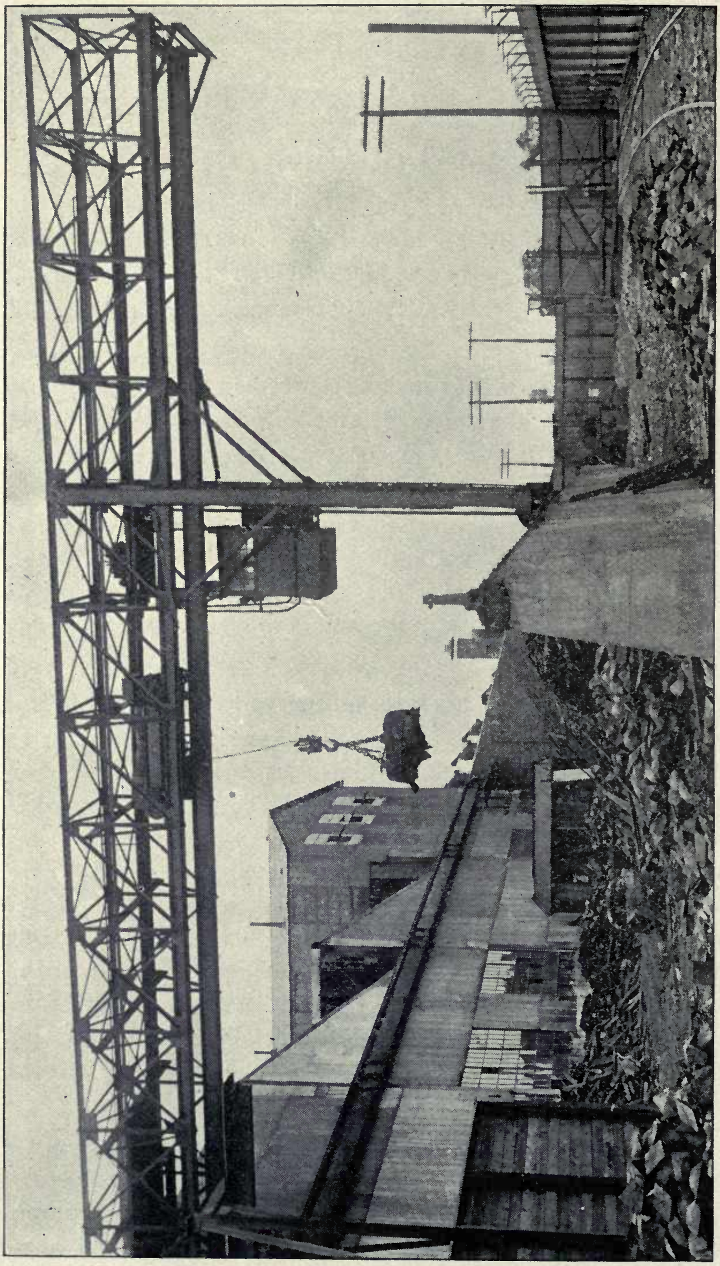

Fig. 46—The stock yard usually is served by a traveling crane

averaging about 2.50 per cent. No two pieces are alike in carbon, depending both on the original carbon and the degree of decarburization in the anneal, but the remaining carbon in work of these heavier classes is likely to be around 2.00 per cent or a little under. The silicon is likely to average around 0.70 per cent and in malleable scrap consisting of castings worn out in service the sulphur is from 0.06 to 0.10, the manganese 0.25 to 0.35 and the phosphorus from 0.16 to 0.20 per cent. In the case of agricultural and other light work, the initial carbon may have been considerably higher, but in view of the lightness of cross section this element may have been much reduced, possibly to 1 per cent and under. The silicon generally is somewhat higher than in the heavier materials, usually averaging about 85 per cent. The other elements are about as in railway malleable.

Malleable scrap is open to the objection that when used as a considerable percentage of the mix in air furnace or open-hearth practice, serious errors may be introduced in the chemical composition of the charge. This condition is aggravated if the malleable scrap includes gray iron scrap rich in carbon, silicon and phosphorus. It is a most reprehensible practice of a number of junk dealers either to purposely mix or to not properly separate the two materials, thus practically destroying the value of the malleable scrap to the malleable founder. This separation can be readily made only at the point of origin as the user has no commercially effective method of inspection. Equally harmful in the opposite direction is the admixture of steel.

Another source of trouble is the introduction of unknown amounts of rust into the charge when melting scrap that has been exposed to weather. Some scrap may contain 5 per cent or more of rust which of course is a dead loss in melting. It also forms a highly oxidizing slag which in turn strongly acts on the silicon and carbon causing unpredictable changes of composition in melting. The effects of this evil can be minimized by the use of clean scrap, which unfortunately cannot be purchased and by the purchase of scrap of such form that it presents little surface to rusting.

For this reason and because of the high labor cost of handling small scrap, agricultural material is not a satisfactory melting stock in air furnace or open-hearth malleable practice. Heavy malleable scrap stored out doors but not extremely heavily rusted usually behaves as though it contained about 1.75 per cent carbon and 0.47 per cent silicon. The presence of adulterations, except of high phosphorus material, is of less consequence in electric furnace melting than with air furnaces or open hearths. Malleable scrap is used not because it is a means of cheapening the metal but for the definite purpose of regulating the carbon content of the mix. Successful air furnace practice requires a charge averaging around 3 per cent in carbon, hence some low carbon stock must be used to mix with pig iron which is always of much higher percentage of carbon content.

Sprue is available in a quantity dependent on the foundry practice but not usually sufficient to bring down the carbon as far as necessary. Hence recourse is had to malleable or steel scrap. The use of scrap for the purpose of making up different amounts of sprue has been practiced for more than 30 years. The Chicago Malleable Iron Works has purchased scrap for air furnace charges on a commercial scale since 1885 and in 1888 the practice was well established. Possibly others adopted it still earlier.

Steel scrap is an article of commerce. What has been said of malleable regarding freedom from rust and from admixture of other forms of scrap applies equally well to steel. In addition there is a certain danger from the possible presence of alloy steels which may introduce entirely unexpected elements. A case in point is the high manganese steel used in frogs, switch points and cross overs and containing up to about 13 per cent manganese.

The carbon content of all steels is relatively low, ranging from around 0.90 to 1.00 per cent in some spring steels down to 0.25 or 0.30 per cent in castings. The silicon is always low and the manganese averages around 0.50 or 0.60

per cent. The sulphur and phosphorus values are always lower than in any other ingredient in the charge. Considering the fact that the material is always somewhat rusty it may be classed as pure iron in calculating a mix.

Heavy steel scrap is preferable to the lighter material as is the case with malleable scrap. Thin sheet, small clippings, rods, pipe and light structural material are particularly objectionable when rusty or burned.

Steel, as in the case of malleable scrap, is used to reduce the carbon content of the mix. Being lower in carbon a less percentage suffices for a given purpose; therefore there is less danger of introducing large errors of calculation in computing the mix or of large amounts of rust to complicate the reactions.

Steel is rarely used in making cupola or electric furnace malleable. Its general use was adopted more recently than that of malleable scrap, but the old records of the Indianapolis plant of the National Malleable Castings Co. show that for an extensive period, beginning in August, 1887, steel was regularly used in the mix, and that the practice continued as circumstances warranted. The author has no facts to indicate whether this practice was original with the late James Goodlet, then in charge there, or copied from some other plant.

Wrought iron, which chemically is merely an extremely low carbon steel, was used at the inception of the industry, Boyden referring to it in his notes. At a later date it was regarded as harmful and at present it is not available in sufficient quantity to possess interest.

Pig iron is the raw material which makes up the bulk of the tonnage from which malleable cast iron is made. In the days of the fathers of the industry charcoal iron was generally if not universally used. Then, as now, it was made from relatively low phosphorus ores. In the early days, before the Civil war, the references are mostly to irons smelted in New Jersey and Connecticut from eastern ores using charcoal from local forests. Boyden used such

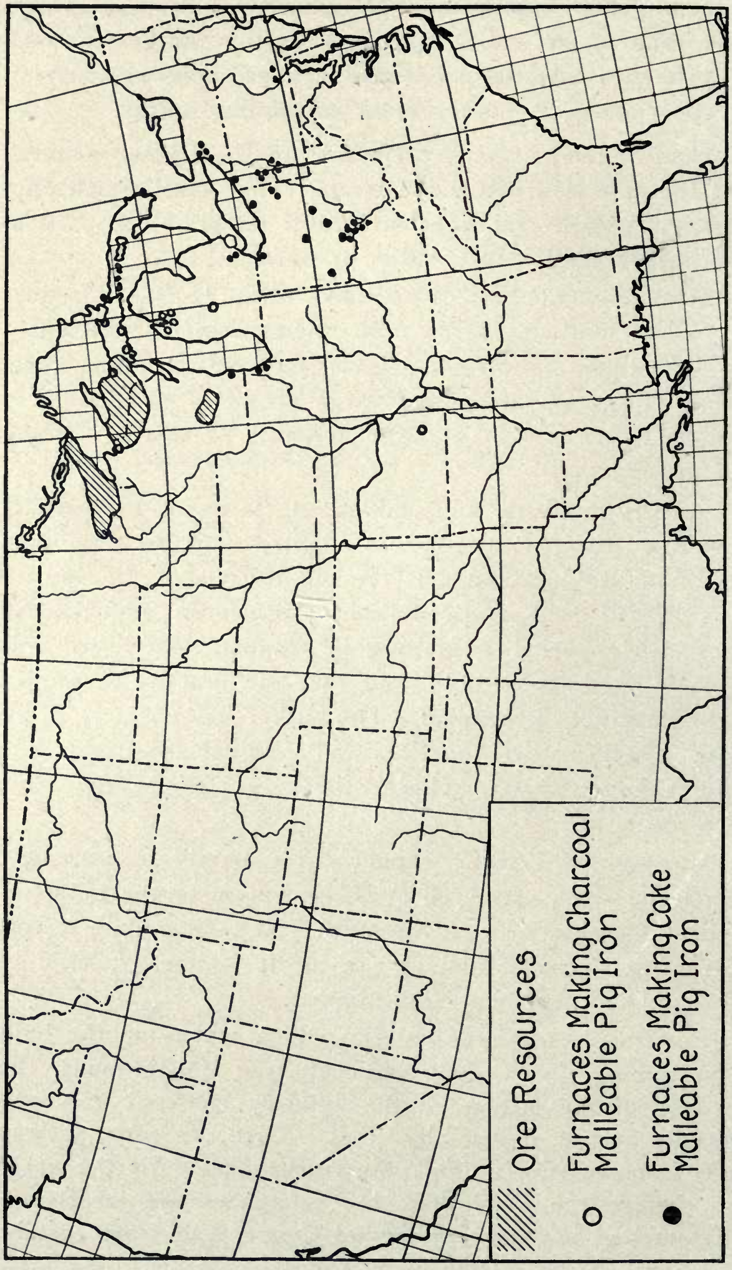

Fig. 47—Map showing location of principal ore fields, and coke and charcoal blast furnaces producing malleable pig iron

irons. Alfred Hammer used New Jersey coke and anthracite pig as early as 1878. In about 1885 there was a noticeable trend toward the use of coke-melted pig iron, first, as far as the author can judge, in the case of very soft pig iron. This was high in silicon, and was unusual in furnaces operating as cold as did the usual cold blast charcoal furnaces of the period.

The impression is quite general among the older foundrymen that, apart from differences of composition, there are differences in properties as between the products of different furnaces. Many also believe that it is preferable to use iron from several producers in each heat. It is not clear to the author upon what metallurgical considerations such differences could be based. Undoubtedly before the days of analyzed pig iron, these beliefs were based on sound reason; at present they would seem to be little more than prejudice as applying to malleable practice.

A similar situation is encountered in a somewhat general feeling that the use of malleable scrap is in some way connected with the substitution of coke for charcoal pig. It has been only relatively recently that interest in the control of the product by limiting the total carbon content became at all general. Dr. Moldenke in his book, "The Production of Malleable Castings" (1911), recommends for instance that the carbon be not below 2.75 per cent and may range up to 3 per cent. Presumably this represents the best general understanding of the time. While since 1906 certain manufacturers realized the relation between carbon and strength and acted on this knowledge, it is not surprising that in the days when the substitution of coke for charcoal iron began the mixes used never were based on considerations of carbon content.

With low silicon charcoal iron available it was easy to secure silicons low enough to produce a white fracture by the use of pig and sprue alone. Hot blast coke irons always contained enough silicon so that some material other than the available amount of sprue was required to reduce the

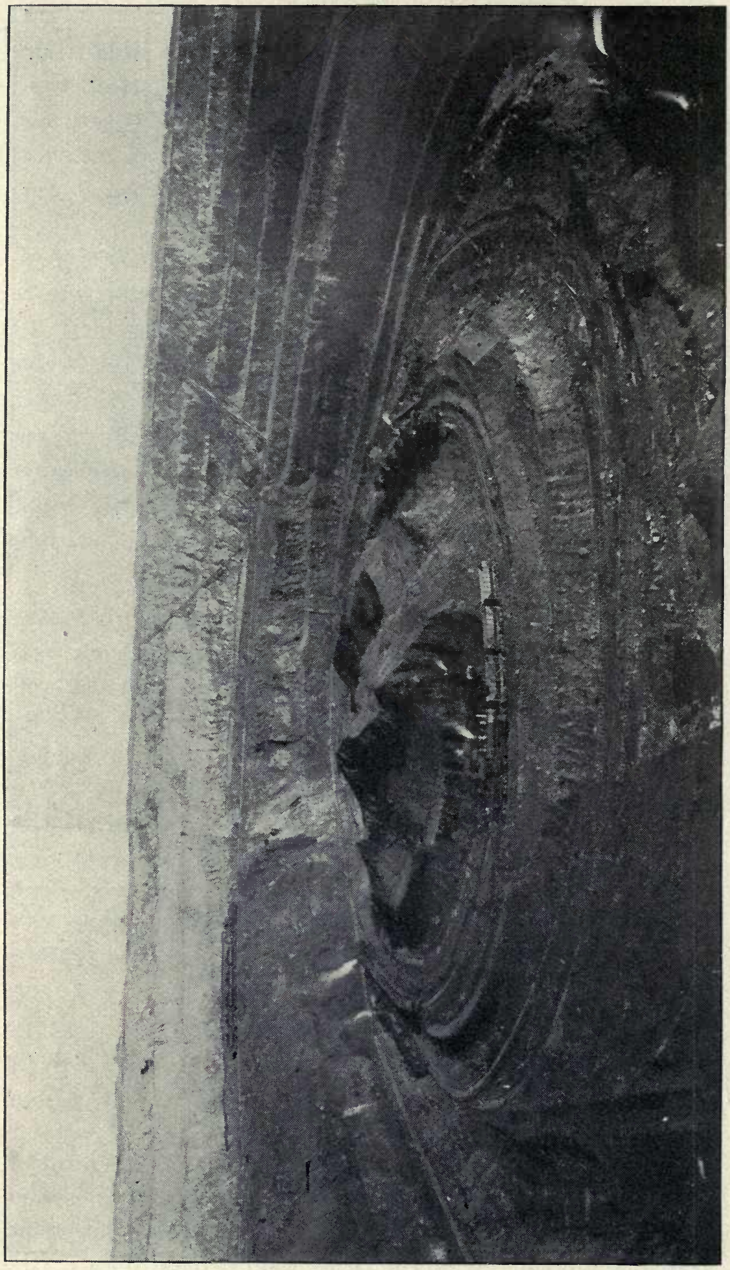

Fig. 48—An open pit iron ore mine on the Mesabi range. Ores in this district are suitable for making malleable pig

silicon content sufficiently to avoid "mottled" castings. The effect of this change of practice on carbon content was totally disregarded except by a very few observers.

The general observation that charcoal iron malleable could and should be made lower in silicon than malleable for the same purpose made from coke iron probably was true. However, it originated merely from the reduction in carbon which unconsciously accompanied the changed practice and not from the method of making the pig.

Where malleable was made from charcoal and coke iron of the same silicon content the former was somewhat the stronger, due to its somewhat lower carbon content, which in turn was due to lower furnace temperature.

In view of such former experiences great caution should be used in regarding as cause and effect phenomena without apparent logical connection.

The transition from charcoal to coke iron has extended over many years and is not yet complete. In the early ninety's coke iron was used very sparingly, but 10 years later the coke iron was far in the ascendant. At present comparatively few manufacturers continue the use of charcoal pig and they employ it only in limited quantity.

To the writer it has seemed that this retention of charcoal iron results either from sentiment pure and simple or from a superstitious belief that for some unexplained reason a modicum of charcoal pig imparts a mysterious virtue of unknown character to the resulting product. Being smelted at a lower temperature, charcoal iron differs from coke iron in being generally lower in carbon. On account of the low sulphur fuel, it is always lower in sulphur. Also the range of silicon values commonly available run lower in charcoal than in coke iron. Again, this is the result of the furnace temperature.

The lowest silicon charcoal pig irons commercially made contain less silicon than the lowest silicon grades of coke iron. Moreover, high silicon coke iron is more commonly obtainable than charcoal iron with the same con-

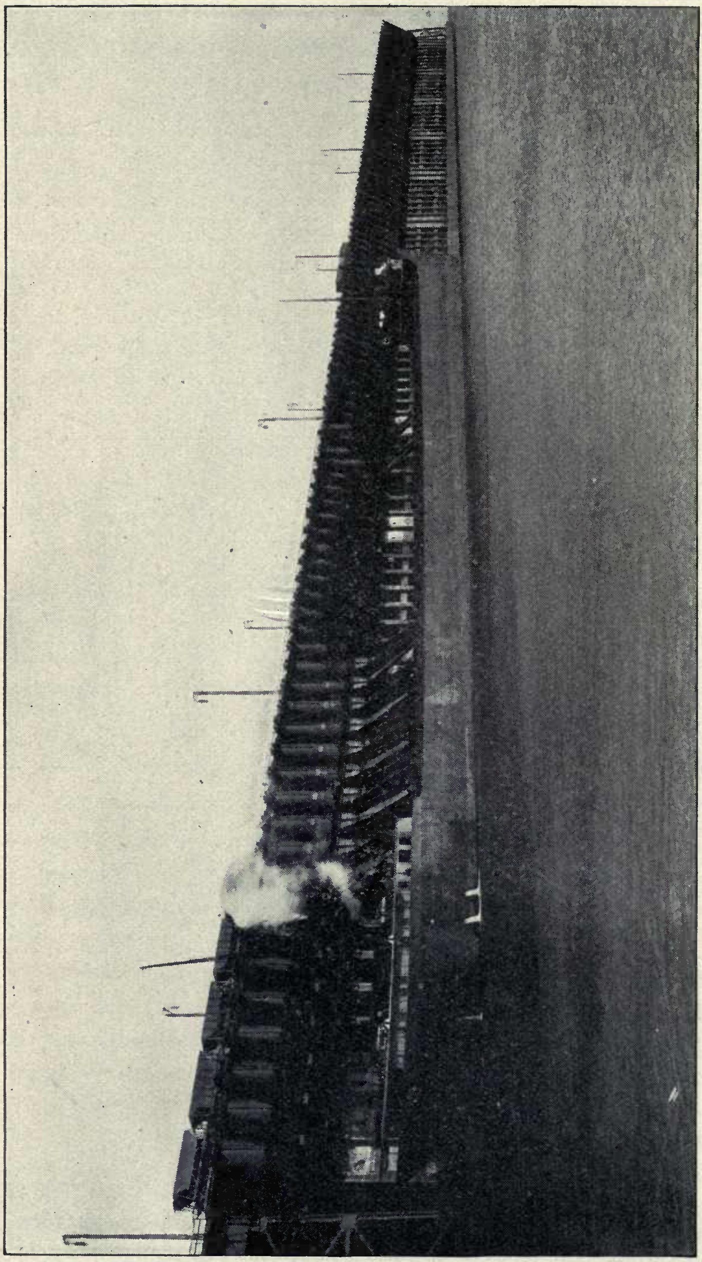

Fig. 49—An ore loading dock at one of the ports on Lake Superior

tent, in spite of the fact that the "Scotch" grades of charcoal pig have a high silicon content.

The writer has never been able to see any theoretical reason why charcoal iron should make a better product than coke iron, given a correct final composition. The late J. B. Johnson Jr., who dealt at length with the subject from the blast furnace viewpoint, ascribed the differences to the indirect effect of oxygen. For the best available opinions in this subject, the interested reader is referred to the published reports on Johnson's pioneer work on this subject in the *Transactions* of the American Institute of Mining and Metallurgical Engineers. In view of the radical alterations made in the raw material during the malleable process it is difficult to see how any differences, such as the form of crystallization of graphite in the pig iron, could survive the chemical and physical changes involved. The trade as a whole seems to look upon the matter in this light and from a tonnage viewpoint, charcoal iron is of little importance in the malleable industry.

The production of malleable cast iron requires the use of relatively low phosphorus ores, those of the Lake Superior region being the most available for the purpose. Consequently, many of the blast furnaces producing malleable pig are situated along the lake ports. The proximity to the Pennsylvania coal fields producing coking coals, has formed another area extending from Pittsburgh down the Ohio river and up the Mahoning and Shenango valleys. The charcoal furnaces are located near the ore fields in heavily wooded districts. The ore fields of Minnesota, Wisconsin and northern Michigan are shown in the form of a shaded area in Fig. 47. Immediately adjacent to this section are the principal charcoal furnace plants, shown on the map by open circles. The coke furnace plants are shown as solid circles. Most blast furnaces do not make pig iron for one purpose only, but the map is intended to include all important producers of this class of metal in considerable quantities. An open pit mine on the Mesabi range is shown in Fig. 48.

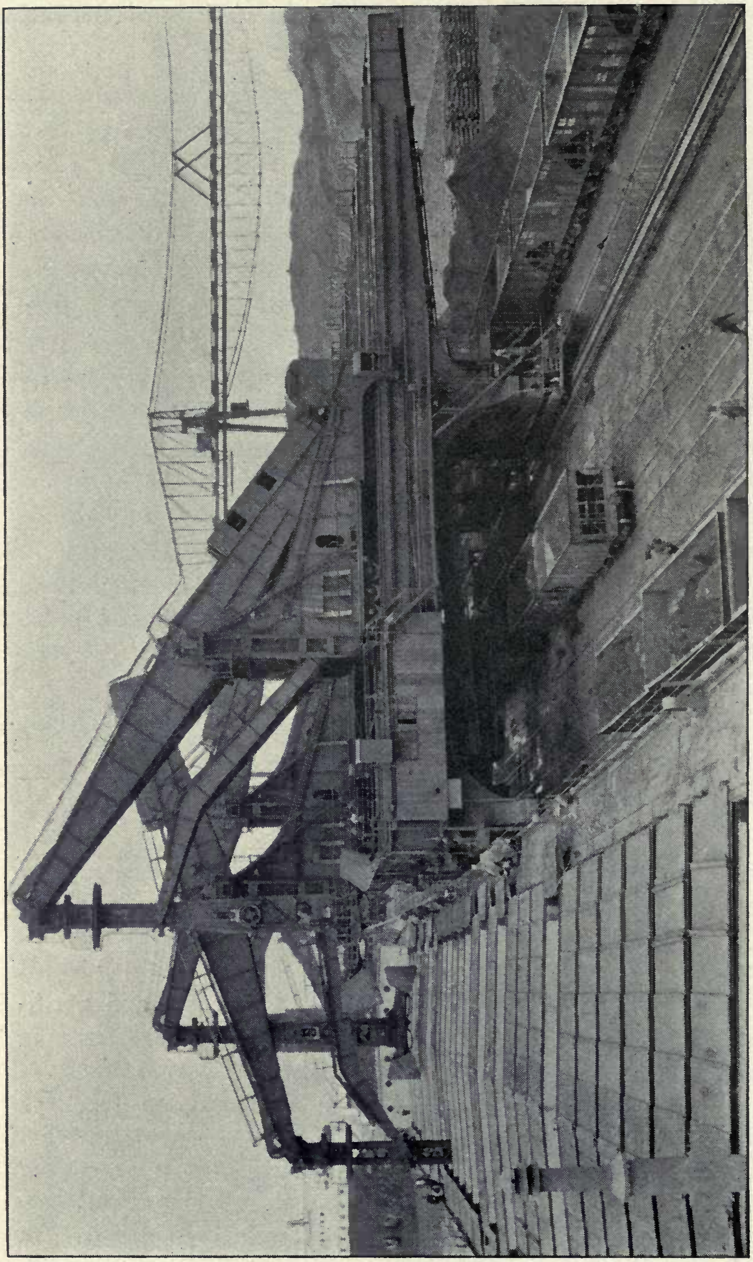

Fig. 50—An ore unloading dock at a Lake Erie port, where the ore is transferred from ore carrier to railroad car

The ores from which malleable pig iron is made have approximately the following composition:

	Per cent
Fe 51.5, present as Fe_2O_3	75.57
P .086, present as P_2O_5	.19
Mn. .40 to .70, present as MnO	.77*
SiO_2	9.50
Al_2O_3	2.75
CaO	.70
MgO	.50
H_2O, CO_2 and undetermined	10.02

*Average.

Malleable pig iron is sold with a guaranteed maximum of 0.05 per cent in sulphur, usually of either 0.19 or 0.20 per cent in phosphorus and is furnished with from about 1.00 to 2.00 per cent silicon, although higher values are sometimes required. The manganese varies from about 0.50 to about 0.90 per cent, the lower and higher values being encountered frequently. The average carbon content for the country is now and has been for at least 15 years close to 4.10 per cent, individual lots running normally from 3.85 to 4.40 per cent. The carbon content practically is fixed by the blast furnace temperature.

Pig iron may be either sand, chill or machine cast. The former carries with it a certain amount of sand fused into the surface. The chill and machine cast irons are free from this foreign matter, which fact presents a certain advantage both because nothing but iron is paid for and because less dirt is carried into the furnaces. The two latter classes, being rapidly cooled, contain more combined and less free carbon than the former, other things being equal. The melting point and, presumably, the latent heat of fusion are thereby decreased. It is claimed that a material fuel economy results. On all accounts the use of machine cast iron can present no disadvantages to compensate for the advantages outlined above and its greater uniformity of size and form.

Recently there has been a decided tendency toward changes in chemical composition of commercial pig iron. Up to 1914 the sulphur content, while guaranteed as 0.05, was nearly invariably under 0.03 in the Ohio and Illinois

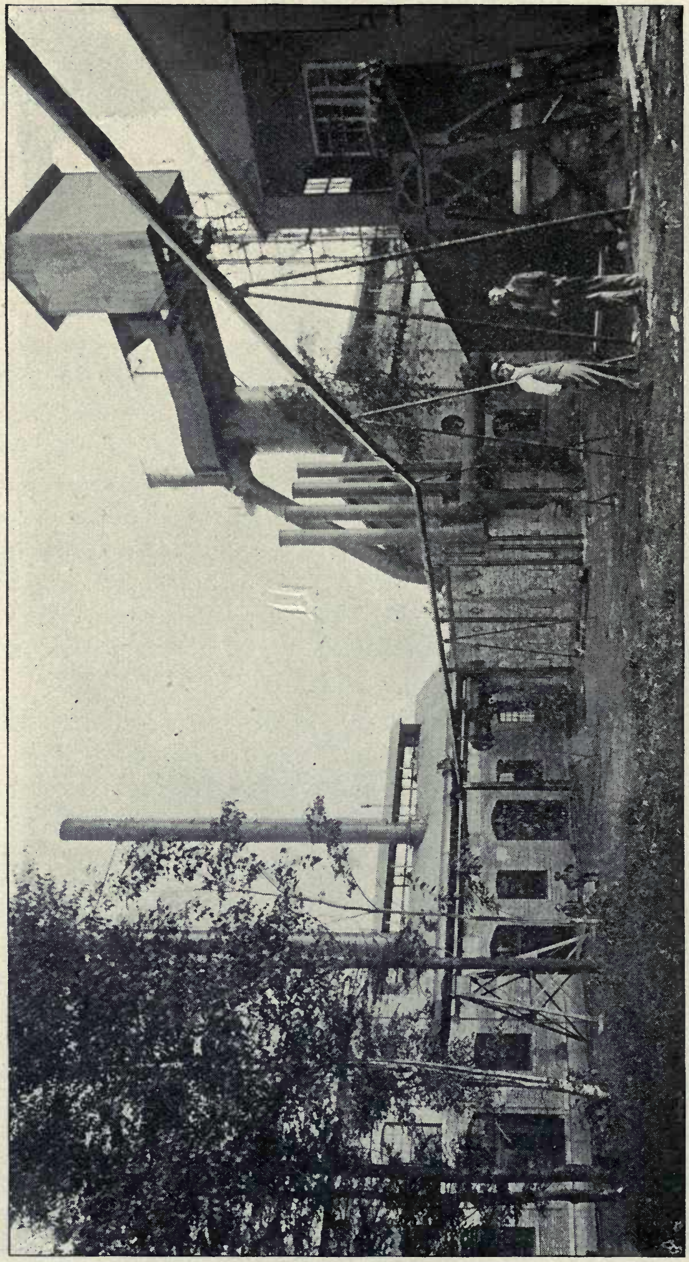

Fig. 51—A charcoal blast furnace in Michigan where malleable pig iron is made

irons. Since then fuel conditions have so far deteriorated the quality of coke available that at present sulphur is usually only a little under 0.05 per cent and occasionally exceeds that figure. Ten or 15 years ago iron often was sold with a maximum phosphorus of 0.16 per cent, no extra price being charged as compared with a 0.19 or 0.20 per cent maximum specification. The gradual increase in the ratio of phosphorus to iron in the product of the Mesabi ore fields has, however, forced an increase to the latter figures as a phosphorus maximum.

For about five or six years there has been a decided trend toward lower carbon malleable, brought about by the demand for increased quality of product. This results in lower percentages of pig iron in the mixes than formerly and therefore requires increasingly a higher silicon content to maintain the former silicon values in the product and in some cases raise them slightly. Accordingly the metal containing under 1.25 per cent silicon is now almost useless and most plants require some pig iron up to 2 per cent and possibly over in silicon. The average silicon content in all the pig iron consumed in the malleable industry is doubtless between 1.60 and 1.70 per cent.

There seems to be increasing difficulty in getting any low manganese pig. However, this stringency has been somewhat counteracted by the decreased amount of pig required and the increased sulphur content. Coke pig iron under 1 per cent in silicon and usually high in sulphur, is generally the product of an abnormal furnace condition, resulting in cold working and is not of a composition suitable to modern requirements.

High silicon pig, or blast furnace ferrosilicon is a metal usually running about 10 per cent in silicon. Its principal source is Jackson, O. The phosphorus, sulphur and carbon are kept low. The metal is used as a source of silicon when suitable pig is not available. In the electric furnace process, it may furnish most of the silicon of the cupola charge.

Ferromanganese is a blast furnace product made from manganese ores. It usually contains from 70 to 85 manganese and nearly 6 per cent carbon. Silicon, sulphur and

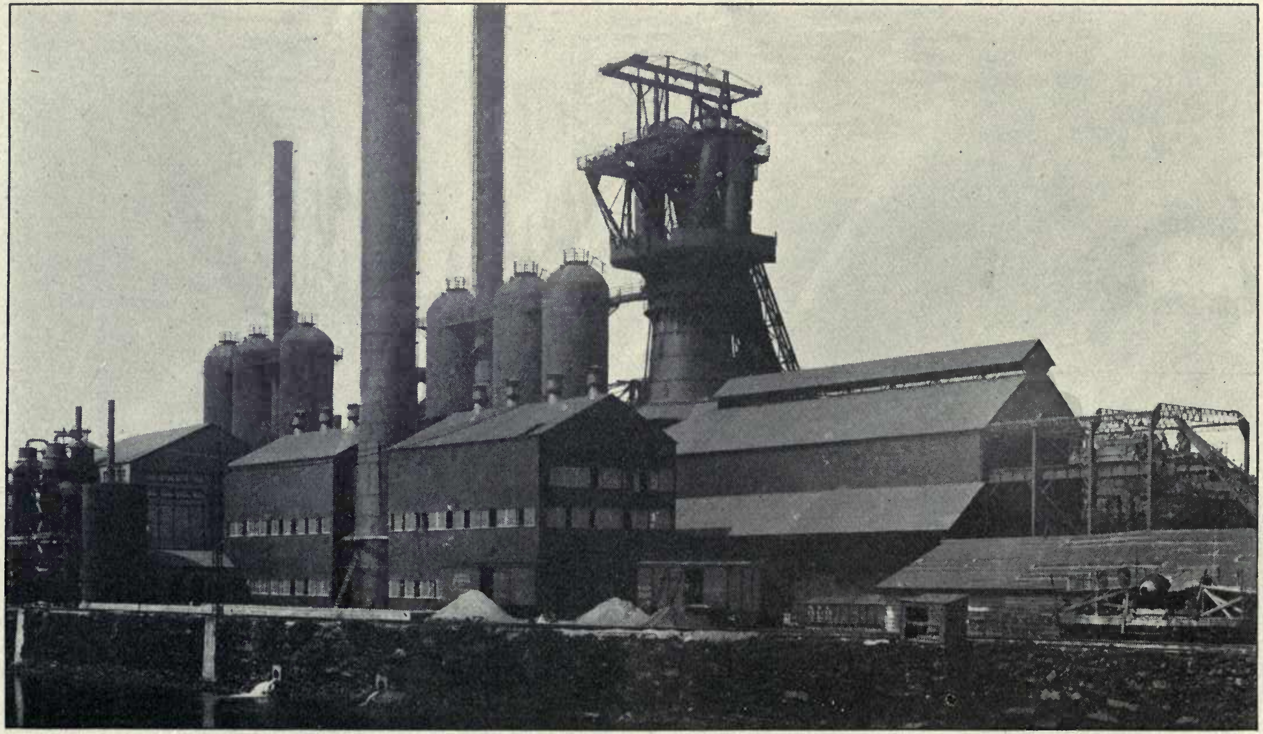

Fig. 52—A typical coke blast furnace in the Mahoning valley

phosphorus are low, iron being the principal element, other than manganese and carbon. Ferromanganese is used generally in the form of an addition to the molten metal to supply a deficiency in manganese.

Electric furnace ferrosilicon contains nominally 15, 50, 75 and 95 per cent silicon. The 50 per cent alloy, actually running from 48 to 54 per cent silicon, is most commonly used. In addition to silicon and iron the metal contains phosphorus, sulphur, aluminum and calcium. These elements are not usually present in important amounts.

Ferrosilicon, being readily oxidized, is not suitable for cupola use. When charged into an air furnace with the melting stock it must be protected from contact with furnace gases as far as possible. It is generally used as additions to the molten heat.

VI

FUEL AND REFRACTORIES

THUS far we have dealt with the raw material actually entering the product. There remain two other classes of raw materials which, although they form no part of the finished product, are used in such quantities and so affect the shop operation as to be of decided industrial importance. The first of these groups is fuel.

The fuels used in the malleable industry may be classified as melting fuel, annealing fuel and power plant fuel. The latter, although it may be used in large quantites, as in electric furnace plants, should be considered from the viewpoint of power plant practice rather than from a metallurgical angle. Melting fuels not only furnish heat but also very distinctly affect the composition of the resulting product. On the other hand, annealing fuels need be considered only from the standpoint of combustion.

The original source of almost all the heat used in melting and annealing malleable is coal, although it may be converted before use into coke, illuminating gas, water gas, or producers gas. Oil and natural gas are also industrially important in some localities and for some purposes.

Bituminous coal is very widely distributed throughout the country, as indicated in Fig. 53. Anthracite and lignite are not important metallurgical fuels and are therefore omitted from the map. Anthracite was formerly used as a cupola fuel and at an early date, possibly 1838 was used for annealing by Belcher. It is still used in at least one plant for this purpose.

Coal from practically any of the bituminous fields shown may be used for annealing, the choice generally being based on geographic and commercial considerations rather than on the properties of the fuel from any given field. Mine run fuel is generally used in annealing for hand firing. The criterion of quality is the absence of ash and water, these fac-

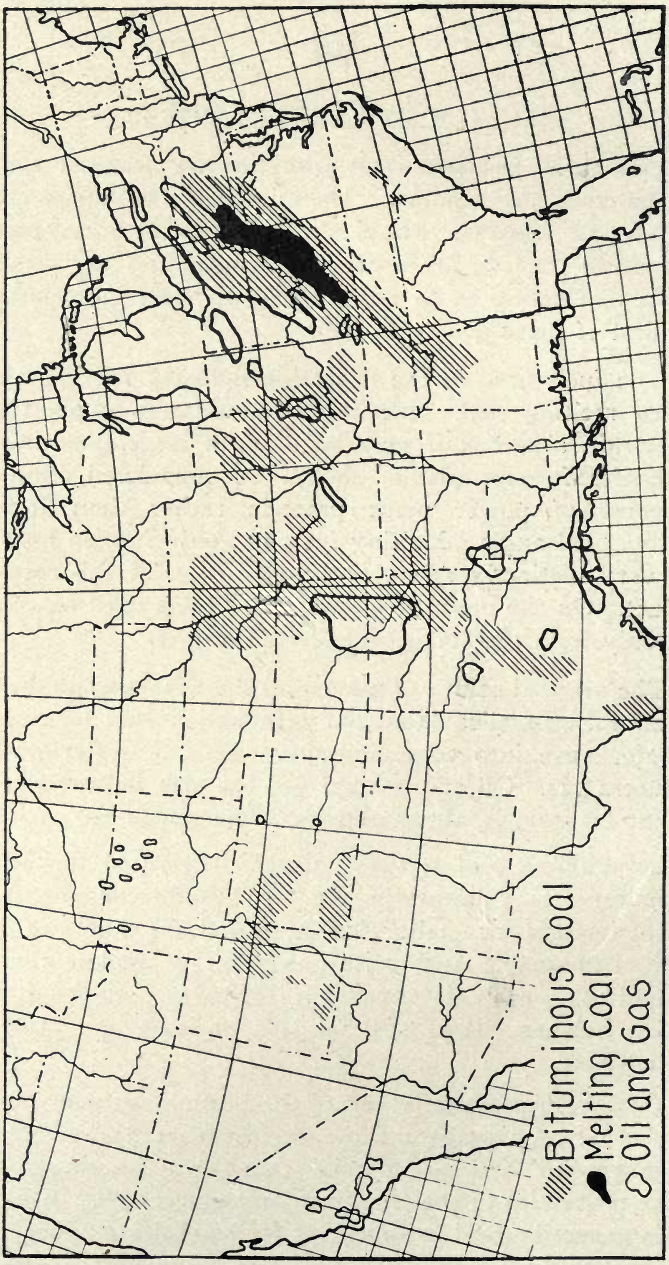

Fig. 53.—Map showing location of principal resources of metallurgical fuel in the United States

tors representing increased cost and operating trouble and not metallurgical suitability. A low ash fuel is sometimes preferred for use with pulverized fuel annealing equipment in order to avoid trouble from the ash settling in the furnaces and flues. The requirements of a crushing plant practically necessitate a fuel either quite dry as received or dried artificially before crushing.

Since lump coal is of no advantage, pulverized fuel plants buy the smaller commercial sizes of fuels. However, the selection of fuel for crushing in annealing practice is not well standardized. The author knows of two large and ably managed plants within a few miles of each other, both annealing with pulverized fuel. One buys a high ash local coal and removes about 10 to 12 per cent of water by drying before crushing, while the other obtains coal in the eastern fields hundred of miles distant which runs under 2 per cent in water and around 3 to 4 per cent in ash. The subject of coal for annealing is therefore easily dismissed with the statement that practically any local fuel can be employed, economical conditions alone governing the selection.

In the case of the melting coals conditions are quite different. Here, in addition to the purely economic problems, there enter many other considerations which narrow down the choice. Coal burned in the air furnace is expected to furnish heat units as economically as may be practicable, and must have certain other definite characteristics. It must burn with a long luminous flame of sufficient volume to entirely fill the air furnace. It must be so low in sulphur as not to prohibitively raise the content of that element in the metal.

Its character must be such that none of the constituents will melt and run to a tarry mass at the temperature of the fire. Its ash must be fairly low in amount and of such character as not to fuse together into clinkers at fire box temperatures. Its moisture content must be reasonably low in order to maintain good flame conditions.

These characteristics are found in coal from a very limited geographical area which is shown in black in Fig. 53.

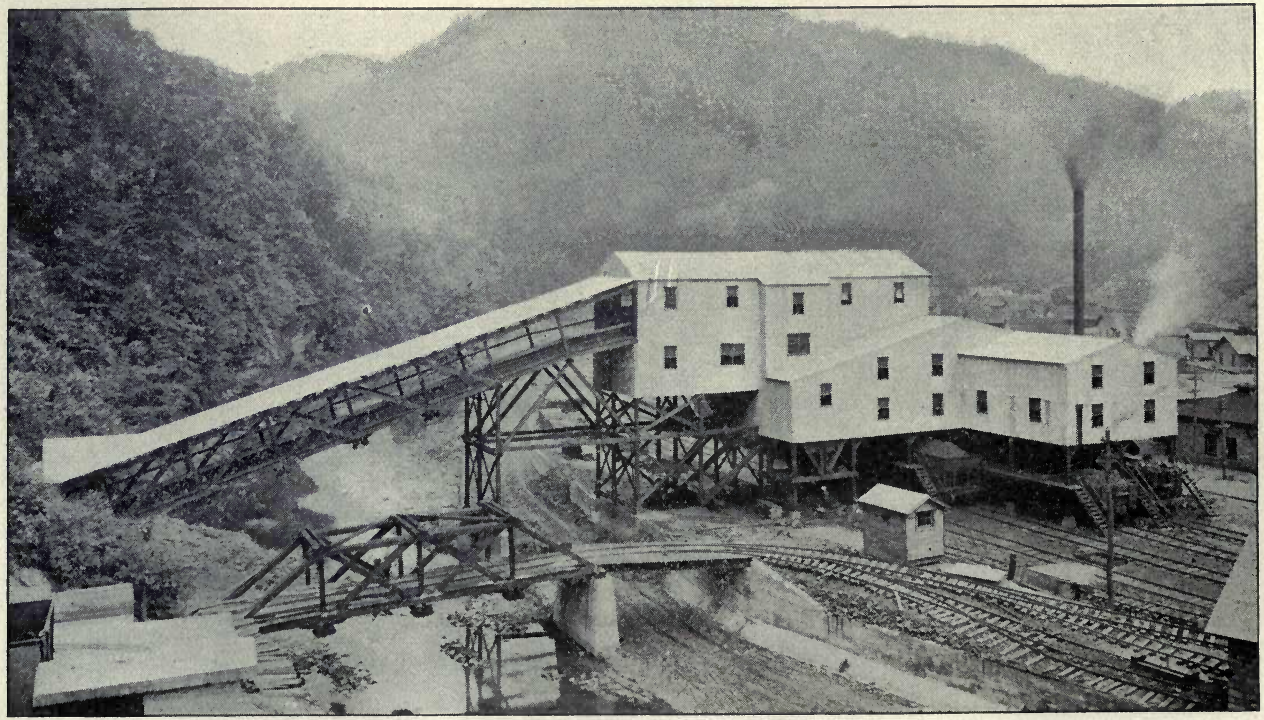

Fig. 54—A modern coal tipple in West Virginia

In the writer's experience the fuel varies even within this district, being in general better in the southern portion of the area.

No entirely satisfactory method of judging the quantity of a melting coal, except by actual test is available. This arises, in part, from the fact that the behavior of the fuel is dependent on the actual combustion conditions encountered which differ with different furnaces. The composition of a few good melting fuels is shown in Table II.

Table II

ANALYSES OF MELTING COALS

Origin	Pennsylvania	West Virginia	West Virginia	Kentucky
Sulphur	0.70	0.45	1.55	0.45
Moisture	0.62	0.76	1.34	1.10
Vol. Comb.	35.63	37.15	41.70	33.95
Fixed carbon	58.32	55.64	52.40	60.68
Ash	5.43	6.45	4.56	4.27
B.t.u. per pound....	13,902	13,434	14,058	14,276

There is a general preference for coal under 1 per cent sulphur, although the sulphur which the melt takes up depends not only on the sulphur content of the fuel but also on the form in which it is present. Some fuels, moderately high in sulphur, produce metal lower in sulphur than other fuels, much lower in that element. Many coals exist, even some in the Illinois, Indiana and central Kentucky fields which based on composition should work admirably. The expectation, however, is not borne out in practice.

What makes a long flame coal has never been definitely determined. The flaming coals are in general the coals best adapted to making illuminating gas. The flaming quality is associated with the distillation products of the fuel when heated in the fire box. The running of the coal is a phenomenon of the same character. The low moisture seems to be a necessary characteristic. Coals of this character artificially wetted behave differently from the naturally wetter Indiana-Illinois fuels.

The clinkering of the ash is largely a matter of chemical composition. Strictly speaking it depends on the com-

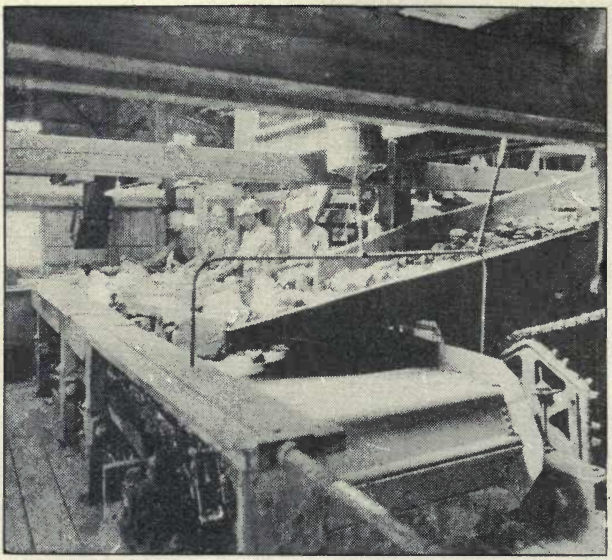

Fig. 55—Picking table in a coal tipple, showing facilities for removing slate, sulphur, etc., by hand.

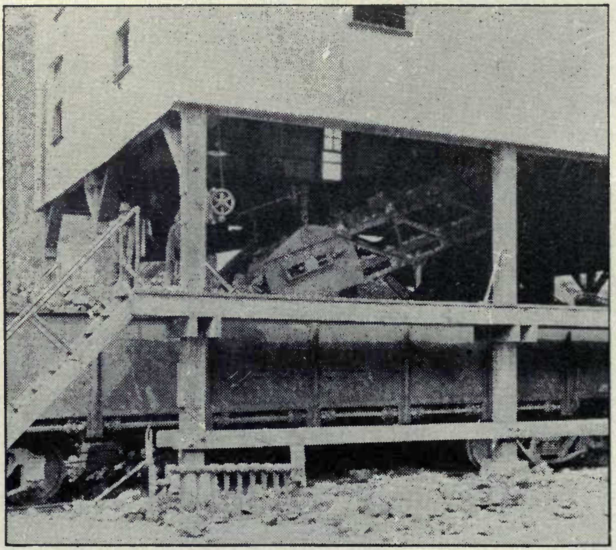

Fig. 56—Adjustable loading boom which places coal in car without breakage

pounds formed in the ash under the temperature and chemical conditions existing in the fuel bed. Therefore, analyses made on laboratory preparations of ash are not correct statements of what may happen in the fuel bed, but are of some value as indicating what may be expected. An ash of a very satisfactory fuel had the following composition:

	Per Cent
SiO_2	44.52
Al_2O_3	43.75
Fe_2O_3	1.32
CaO	5.72
MgO	1.05
Na_2O K_2O	3.64

The analysis is of a laboratory preparation of the ash. On the grates the Fe_2O_3 would be largely reduced to FeO.

The fusing point of the ash of eastern coals is 2400 to 2850 degrees Fahr. Above 2600 degrees Fahr. is preferable.

In general, the absence of iron oxide, alkalies and lime in the order given is considered a desideratum.

The ash and sulphur contents of coal are considerably affected by the method of preparation and in recent years mining conditions have been such as to make for a steady deterioration along these lines.

Air furnaces require a lump coal for their fuel but commercial practice varies as to the size of screen over which the coal should be passed before shipment. Some foundrymen desire coal not finer than that which will not pass a 4-inch mesh, while others tolerate all that will pass over a ¾-inch screen. The best practice probably is a little nearer the latter figure than the former—say about 1½-inch screened lump.

When fuel is to be burned in pulverized form in melting furnaces the quality of coal required is the same as for direct combustion on the grates, except that the smaller sizes of coal can be utilized.

A number of engineering concerns have developed highly specialized plants for grinding and pulverizing coal. The sequence of operations in all of them is substantially the

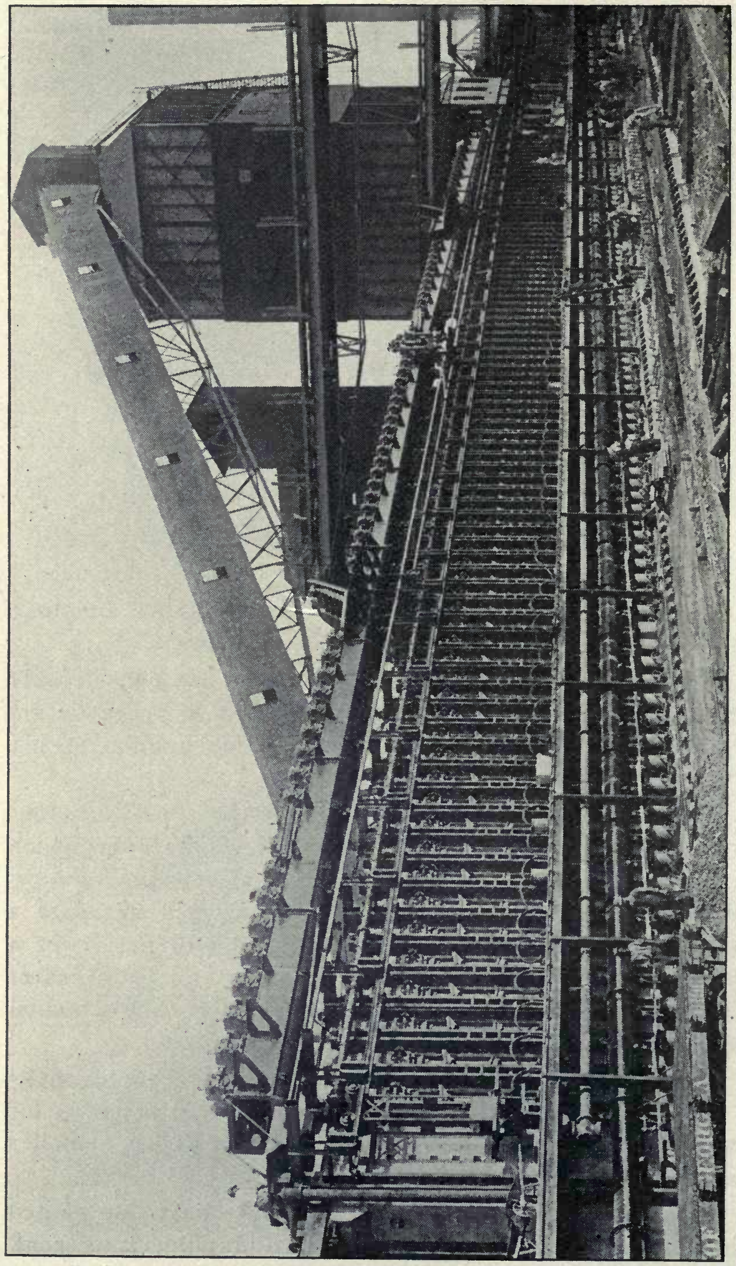

Fig. 57.—A modern by-product coke plant which is engaged in making foundry fuel

same. The coal, crushed to fairly small size or purchased after screening, passes through a device where it is dried by a current of warm air. A favorite method is to feed it in at one end of a rather long narrow cylinder rotating on its axis, which is slightly inclined to the horizontal. As the cylinder revolves the coal rolls over and over and travels toward and finally out of the lower end of the cylinder. A current of warm air passes through the cylinder, usually in the direction opposite the flow of coal.

From the end of the dryer the coal is automatically delivered to a grinder, one type of which consists of an arrangement like the "fly ball" or centrifugal governor of a steam engine. The weights are in the form of rollers which run against a surrounding ring when the mechanism is rotated. The fuel is ground to flour between these rollers and the ring, but if any hard lump such as a piece of scrap iron should fail to have been removed it merely crowds through between the roller and track and does no damage.

Means are usually provided for screening or otherwise separating insufficiently ground material and returning it to be reground. The product should be reground to pass a 100-mesh sieve and 75 per cent to pass a 200-mesh sieve. When ground to size it is transported by belt or screw conveyor to bins. A pulverizing plant is shown in Fig. 92.

In general it is well to store only limited quantities of ground coal owing to the fire hazards. Dried pulverized coal absorbs moisture readily, and sticks together and feeds to the burner in a lump condition if it has an opportunity to take up water before being used.

The transportation of coal dust by carrying it in a current of air is dangerous, the mixture being highly explosive. In the best installations the air and coal are mixed just as near the point of entry into the furnace as possible to minimize the danger.

Gas as a fuel is only an indirect application of the combustion of coal, indeed it might well be maintained that any use of coal for this purpose involves its gasification even though that process may be carried out in the fire box instead of in a separate apparatus.

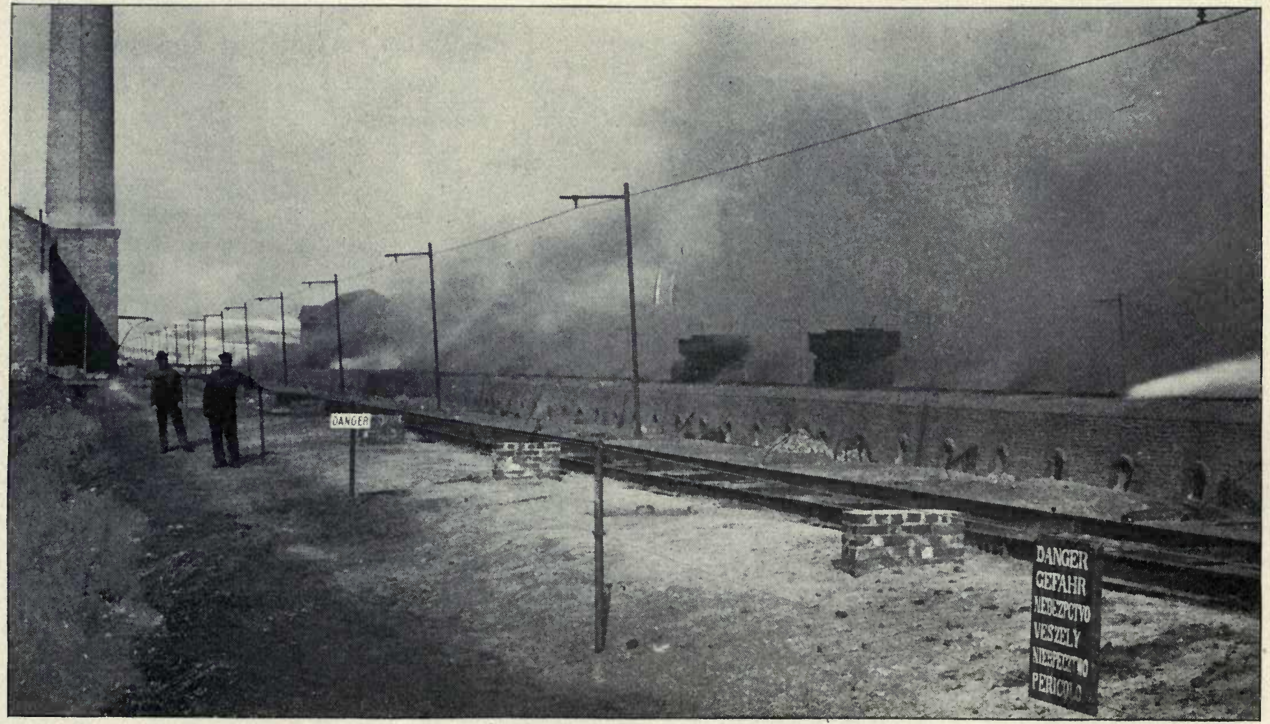

Fig. 58.—A typical scene at a beehive coke oven plant in the Connellsville region

Gas fuels are classified as illuminating gas or producer gas. The former is either a distillation product of coal, or a mixture of hydrogen, carbon monoxide and hydrocarbons, called water gas and made by the action of steam on red hot coke. Producer gas is a mixture of carbon monoxide and hydrogen.

Illuminating gas is too costly for extensive metallurgical operations. Its use is limited to crucible furnaces for brass melting, etc., and small core ovens. If the gas is a by-product in the manufacture of coke, it is commercially available and then only in the plant operating the coke ovens or in neighboring plants. If the gas is to be piped any distance it can generally be more profitably sold for public consumption for domestic requirements.

The operation of a gas producer is simple in principle. A gas producer is merely a firebox in which a deep bed of fuel is burned with a limited supply of air, the intention being to burn the carbon of the fuel to carbon monoxide.

Theoretically, the producer gas is air in which the oxygen has been converted to carbon monoxide and should contain about one-third carbon monoxide and two-thirds nitrogen. In practice the water from the combustion of the hydrogen of the fuel, the moisture of the fuel itself and the steam which is introduced with the air supply to avoid clinkering all react with carbon, liberating some hydrogen. Also the fuels rich in volatile matter distill off more or less hydrocarbon gases. Furthermore, if the fuel bed is allowed to get uneven permitting air to come through, some of the carbon monoxide is burned to dioxide. The latter constituent is more prevalent in producers blown with steam than in those blown with air alone.

As a general statement of the composition of commercial producer gas, the following figures are quoted from Wyer:

Table III

Composition of Producer Gas

	H	CH_4	C_2H_4	N	CO	O	CO_2
Gas from hard coal	20.0	..	..	49.5	25.0	0.5	5.0
Gas from soft coal	10.0	3.0	0.5	58.0	23.0	0.5	5.0
Gas from coke	10.0	..	..	56.0	29.0	0.5	4.5
Gas air blast	4.43	..	..	62.12	33.04	..	0.41
Gas same as above with air and steam blast	14.00	..	..	53.3	27.2	..	5.5

The CO_2 values are rather high, an attempt usually being made to hold CO_2 to 3 per cent.

It is obvious that the heat value of the gas from a pound of coal cannot be greater than the heat value of the original pound of fuel. The combustion of carbon to CO liberates $\frac{4450}{14500}$ or roughly 30 per cent of the heat of combustion of carbon to CO_2. This heat is transmitted to the incoming fuel and to the products of combustion as well as to the producer structure. It finally leaves the producer by radia-

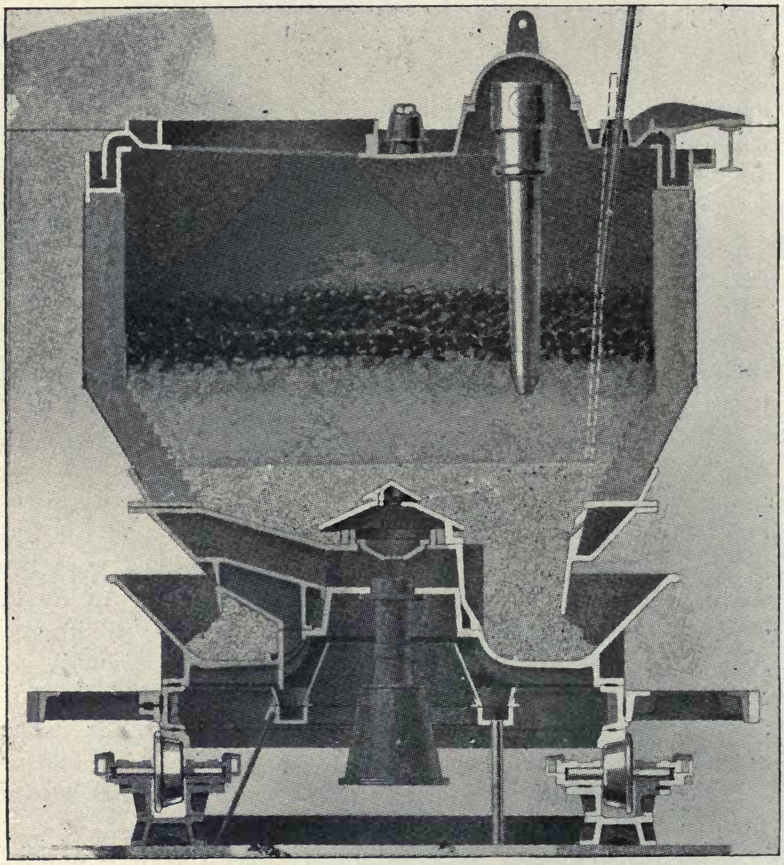

Fig. 59—Cross section of a modern gas producer

tion from the walls and also as the sensible heat of the gas. It therefore is of advantage, except in open hearth practice, to make the gas as near the furnace as possible to avoid the loss of heat units by cooling the gas stream in passing through long ducts.

Where the gas is to be widely distributed or burned in small accurately controlled burners a cleaned gas from which tar and heavy hydrocarbons have been removed is desirable.

As stated before, gasification adds nothing to the heat value of the fuel; it may, however, result in heat economy due to the better control and more economical combustion conditions possible with gas fuel as compared with solid fuels.

Producer gas being a fuel of rather low calorific power usually is burned with hot air. The use of cold air does not give sufficiently hot flames for melting operations; indeed the temperature may not be high enough to maintain combustion unless a warm or hot air supply is provided or the gas itself be fairly hot.

Producer gas usually is made from bituminous coal, although wood, peat, lignite, coke and anthracite can be used. The requirements for producer gas fuel in general are similar to those for air furnace fuel. The coal should be reasonably low in ash and the ash should not clinker. The coal must not soften or swell on heating and preferably should be low in moisture and high in volatile matter. Further, it should be fairly uniform in size and, for melting operations, low in sulphur. However, there are many bituminous coals giving good results in producers which do not work satisfactorily in the air furnace.

Coke is used as a metallurgical fuel in the malleable industry in cupola practice only. As everyone knows, it is gas or similar coal from which the volatile matter, including moisture, has been distilled in retorts, beehive ovens or by-product ovens. It contains all the ash in the coal from which it was made and is therefore from 50 to 100 per cent higher in ash than gas coals. The remainder of the coke is practically pure carbon. All coke contains sulphur and there is a general feeling in favor of foundry cokes containing less than 1 per cent of this element. Sulphur is

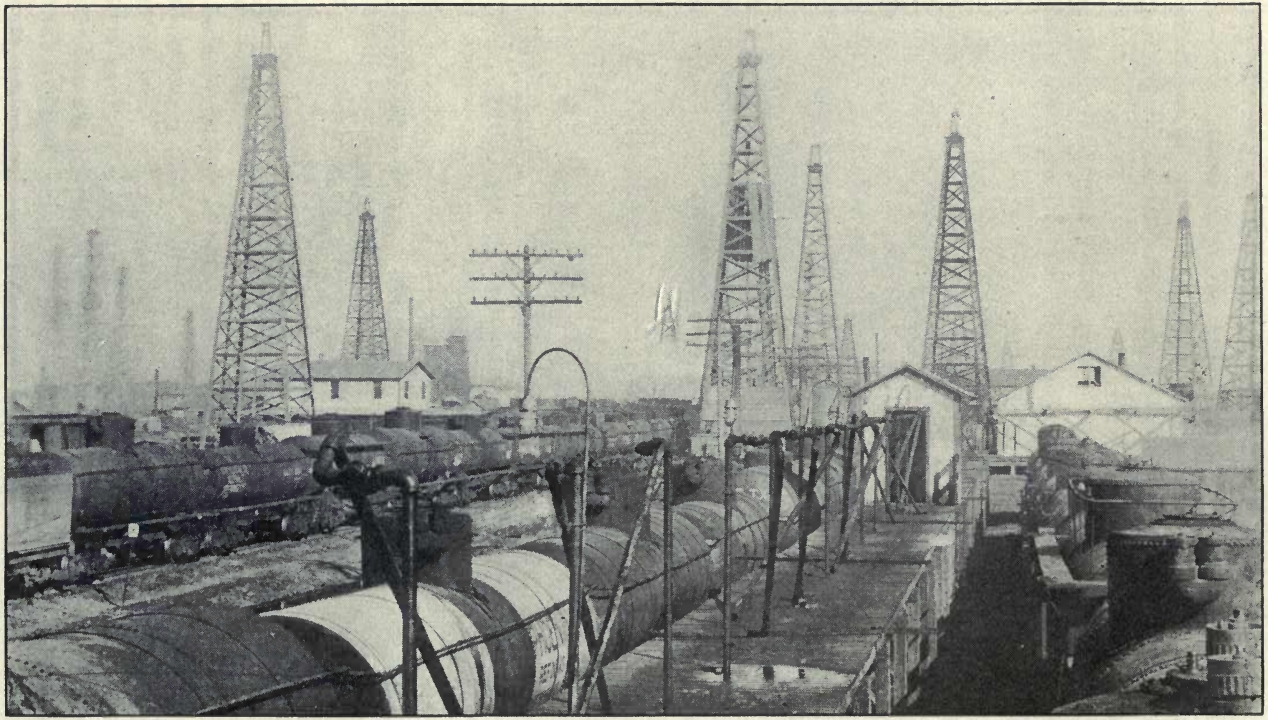

Fig. 60.—A scene in an important oil field in Oklahoma

taken up by the metal more readily in cupola practice than in the air furnace, owing to the fact that fuel and metal come into actual contact with each other. Moreover coke must not be too fine and must be fairly strong to make a suitable fuel. The ash should be as low as practicable and, if possible, siliceous in character, since it is easier to add basic materials to flux with the ash than to add acid materials.

The ash is similar in composition to that of coal and corresponds to low grade fire clay. Cupola fuel is not of great interest in this discussion, owing to the general abandonment of cupola malleable. In the case of electric furnace practice in which cupola metal is the raw material for the electric furnaces it is, of course, an important material.

Oil is found rather widely distributed throughout the country. Fig. 53 shows the oil areas, exclusive of oil shales. Oil has many advantages as a fuel, including cleanliness, relative freedom from sulphur, convenience of distribution and accuracy of control of combustion conditions.

Twenty or 30 years ago it was customary to burn local crude oils just as they came from the ground. The need for gasoline and lubricating oils has caused the abandonment of this practice and today the fuel oil used consists of the residue remaining after the distillation of the commercially important products. Nearly all the petroleum products are hydrocarbons of the methane series having the general formula—

$$C_rH_{2n + 2}$$

All have nearly the same heat value per pound, because n being a fairly large quantity, the atomic ratio of carbon to hydrogen is in all of them very nearly 1 to 2 corresponding to a ratio by weight of 6 to 1. The more volatile compounds such as gasoline, kerosene, etc., are the members of low molecular weight in which n is from 5 up.

Fuel oil has been applied to annealing furnaces very conveniently. It is a useful fuel in open-hearth practice and has been successfully used in that connection in the malleable industry. Under favorable circumstances it can sometimes compete for this purpose with producer gas and pulverized coal. Furthermore, it is easy to arrange open-hearths to permit the use of either oil or gas or oil or pulverized coal, which is a convenient arrangement.

Attempts have been made to burn fuel oil in air furnaces. No particular difficulty exists in actually doing the melting, but generally the process has not been either economically or metallurgically successful. J. P. Pero reports* what he regards as satisfactory results at an Illinois plant, but even there it is admitted that excessive oxidization losses were not overcome and the fuel cost was high. A plant in Michigan is said to have operated successfully with oil melting, even at a high unit cost for fuel. The details are not available to the writer.

Natural gas is actually the first member of the petroleum series methane CH_4, corresponding to $n=1$. It is found associated with petroleum. Its rapid exhaustion by wasteful use is one of the scandals of our economic system. It formerly was used for annealing.

There remain for consideration the raw materials which are grouped under the heading of refractories. These materials include molding sand, fire sand, fire clay, fire brick and, to a limited degree magnesite, magnesite brick, silica brick, dolomite, gannister and sandstone.

Molding sands are somewhat widely distributed in nature and consequently each plant generally uses a local sand. Molding sands are generally derived from granite which has weathered and are frequently found in glaciated areas. Molding sands differ among themselves and each purpose requires a sand of specific characteristics.

In the malleable foundry a sand is desired consisting of well rounded quartz grains, of nearly uniform and fairly small size, coated evenly with a moderate amount only of fairly plastic but also reasonably refractory clay. The actual size of grain and amount of clay desired will vary with the character of the work. The heavier castings require coarser and clayier sands than the lighter.

The uniformity of grain size and roundness of grain are desired in order to give the greatest possible opportunity for the gas to escape from the molds. If too much clay

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*Vol. XXVIII. p. 316, *Transactions*, American Foundrymen's association.

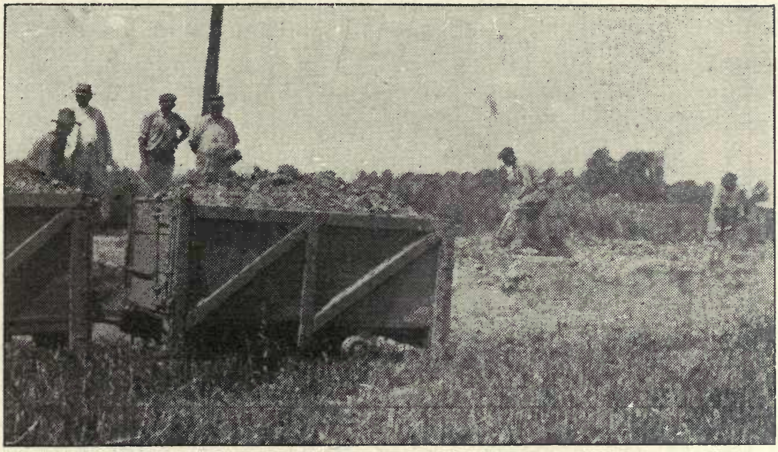

Fig. 61.—Operations in a molding sand pit

is present or if the sand consists of grains differing largely in size the clay or small silica grains partly obstruct what should be openings between the grains.

The clay is needed to hold the sand in place. The silica grain is very refractory, so that the refractoriness of the sand depends upon the property of the clay coating. If the clay contains lime or iron oxide the refractoriness is much decreased. Most sands contain vestiges of feldspar from

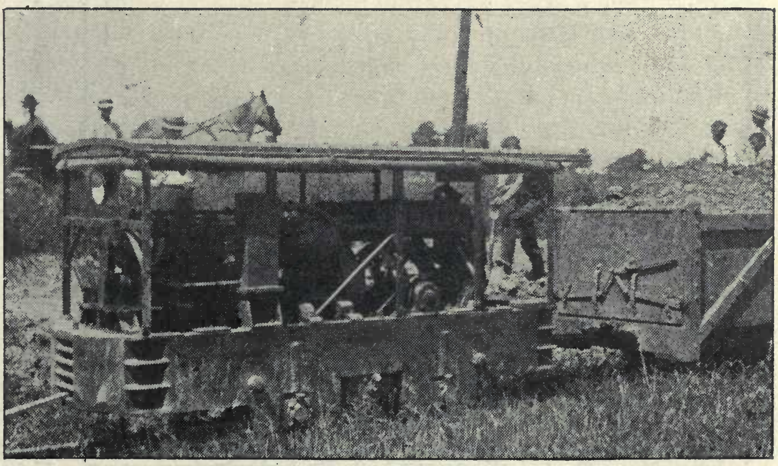

Fig. 62.—Hauling sand from a pit

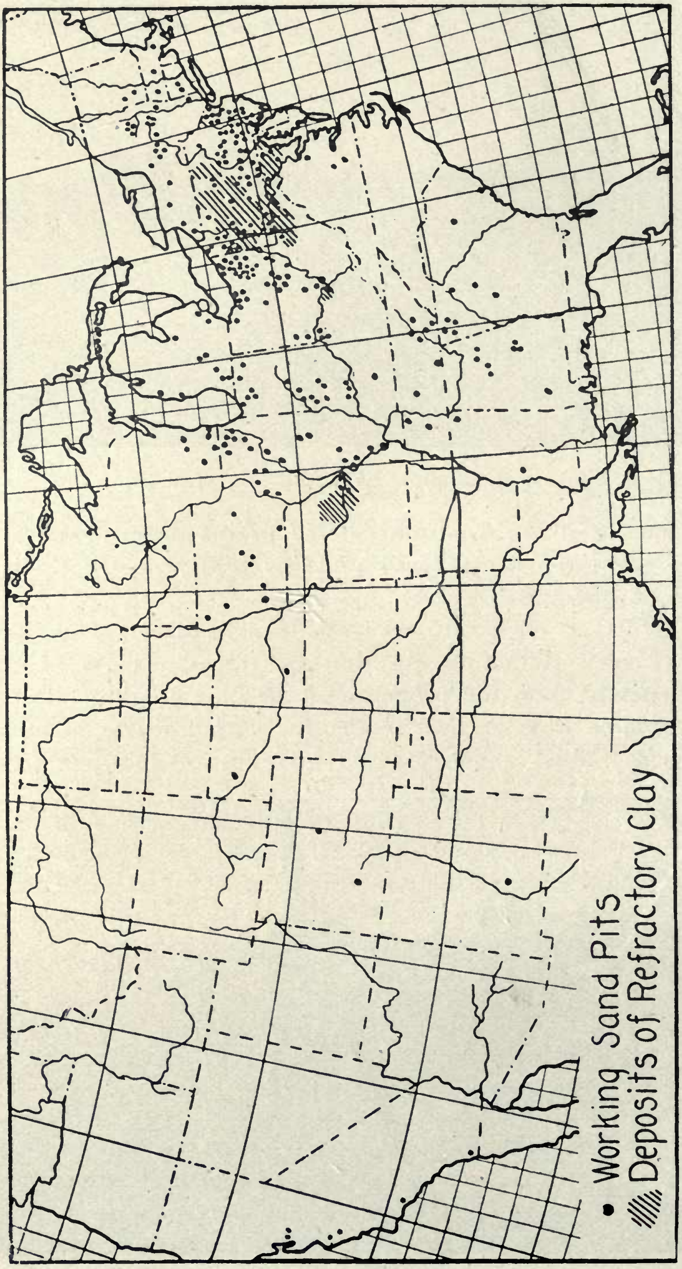

Fig. 63.—Map showing the principal sources of molding sand, fireclay and brick in the United States

the original granite and these sands are relatively easily fusible.

The analysis and screen test of sand does not furnish a good guide to its usefulness, as they are difficult to interpret.

The United States bureau of standards and the American Foundrymen's association have gathered extensive data which are available to the interested reader.

Tests for porosity, strength of bond, imperviousness and fusibility are more valuable, but a discussion of these properties and their relationships would be too technical to interest the general reader and in the present state of our knowledge would be largely speculative.

Frequently sand free of clay is wanted in coremaking, the binder furnishing all the cohesion desired and preventing cores growing too hard, due to the burning of the clay. For such purpose wind-blown lake or sea sands, nearly pure quartz, are generally used.

Fire sands are very pure silica sands usually in uniform rounded grains. They seldom contain over 2 per cent of impurities and are used for the bottoms of acid open-hearth and air furnaces. The presence of a small amount of basic material is required to cause the sand to sinter properly.

Sandstone is a naturally compacted mass of silica sand occasionally used in cupola and other furnace linings. Gannister is a siliceous sedimentary rock of highly refractory character used in furnace linings usually in crushed form.

Fire clays are refractory silicates of aluminum occurring in nature. They contain as impurities oxides of iron, calcium and the alkalies as well as some of the rarer metals.

The very pure and refractory flint clays possess little plasticity. Other varieties are more plastic and also more fusible. Fire clay is seldom used alone, being mixed with water and crushed fire brick or silica sand to form a material for patching furnace walls. Fig. 63 shows the location of the principal supplies of molding sand and high grade fire clay in the United States. Clay fire brick, made from fire clay usually at or near the source of clay, consist merely of mixtures of refractory and hard flint clays, ground fire

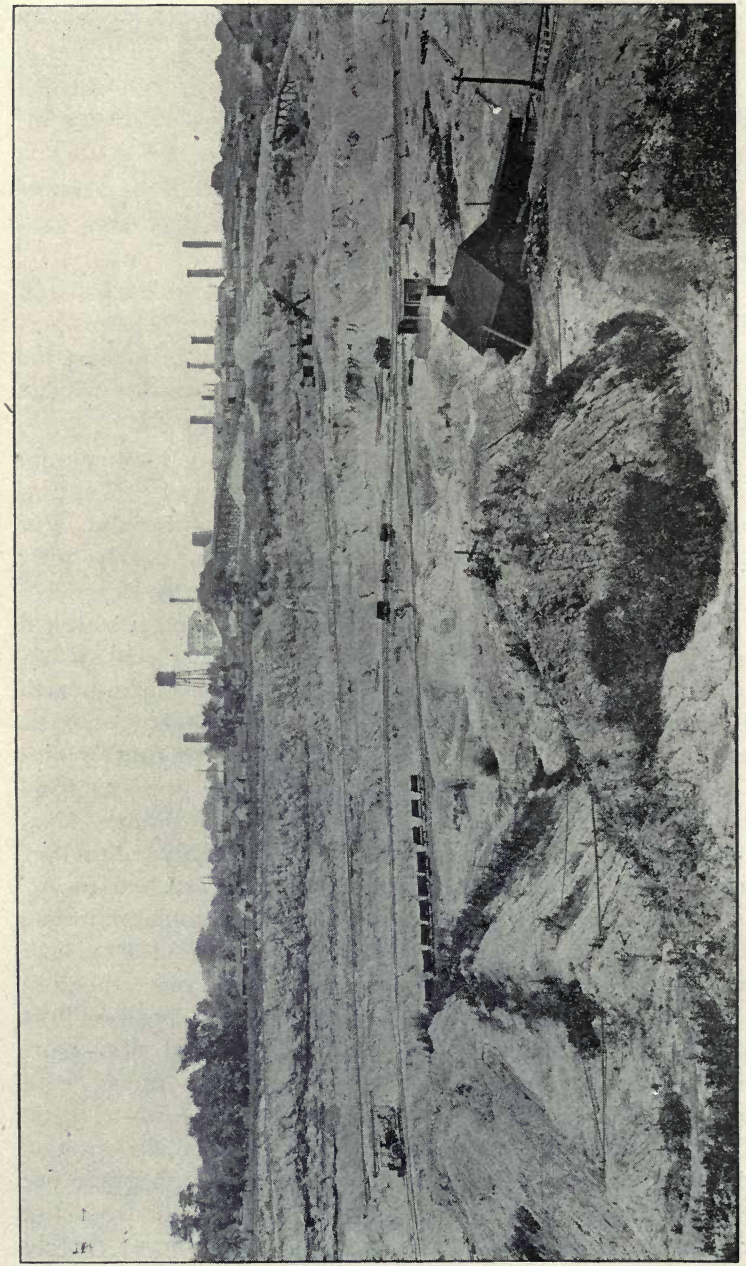

Fig. 64.—Open fireclay pit covering over 10 acres and with bed of clay from 25 to 40 feet thick

brick, ground gannister and a plastic fire clay formed into shapes and burned at high temperatures.

The manufacture of fire brick is one of the most important ceramic industries and cannot be more than casually referred to here. Brick differs in the material used, the fineness or coarseness of grind, the density to which the material is compressed and the temperature at which it is burned.

The material used largely determines the refractoriness or melting point. Fine grained, fairly dense and not too hard brick possess great strength. Coarse, open, lightly burned brick resists rapid changes of temperature. Fine, dense, hard burned brick resist penetration of slags, hence every use has special requirements. A noteworthy feature is that all clay brick shrink when first heated.

Fire Clay Refractories for Malleable Iron Works

The chief deposits of high grade flint fire clays are located in Pennsylvania, Kentucky and Missouri. These clays are formed from the weathering of feldspar and feldspathic rocks which have the formula K_2O, Al_2O_3 6 SiO_2. Pure kaolins should be Al_2O_3 $2SiO_2$, $2H_2O$, the potassium silicate having been dissolved. The flint fire clays approach this pure clay or kaolin in chemical composition except that they contain some iron oxide which gives the burnt product a yellow tint. They are a secondary or transported clay deposited in still water and are found in the carboniferous areas or coal measures.

Where the coal is thick the clay is generally thin, and when the coal thins out to almost nothing the clay thickens up to workable deposits eight to 20 feet in thickness.

These flint clays usually are mined in the Pennsylvania and Kentucky districts, also occasionally in Missouri, but the Missouri flint clays often lie in pockets. In certain districts, such as at Mexico, Missouri, extensive deposits are worked by stripping the overburden and then mining in an open pit.

The following chemical analysis of raw clay and burnt

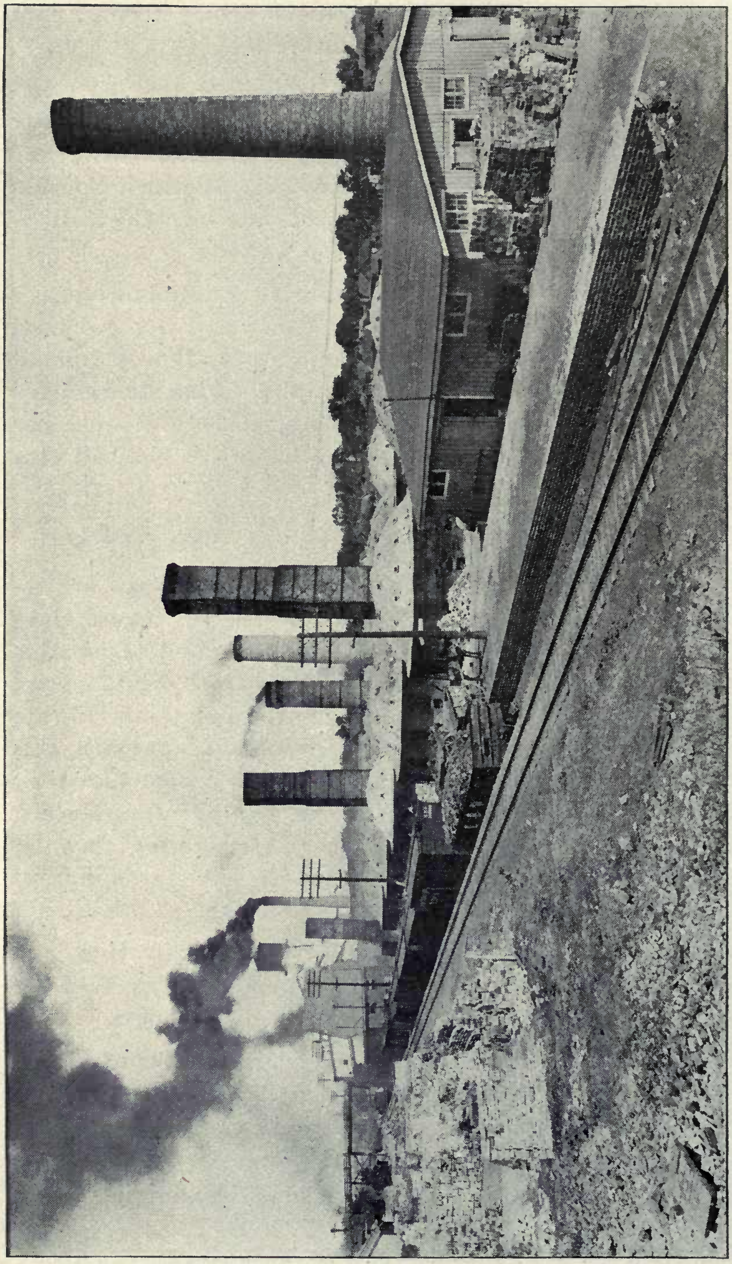

Fig. 65.—A plant in Missouri showing round, down-draft kilns, factory and stock sheds

bricks will illustrate typical compositions for malleable furnace work:

Table IV

Burnt Brick Analyses

	Pennsylvania	Missouri	Kentucky
SiO_2	53.05	55.29	54.41
Al_2O_3	41.16	40.18	36.20
Fe_2O_3	2.65	2.44	2.10
TiO_2	1.80	0.00	0.00
CaO	0.00	0.00	2.13
MgO	0.00	0.71	5.16
Alkalies	1.34	0.76	9.39
Fluxes	5.79	3.91	——
Cones	32-33	34	31

Raw Clay Analysis Missouri Flint Clays

	Per Cent
Loss on ignition	12.66
SiO_2	49.08
Al_2O_3	35.67
Fe_2O_3	1.28
CaO	0.00
MgO	0.63
Alkalies	0.68
Fluxing parts	2.59
Free silica	7.6

The clay is ground and screened in a dry pan in some plants while others put the raw clay in a wet pan and add excess water making the clay plastic and then introduce the correct per cent of coarse grog, chamotte or calcine. The latter is simply burnt clay crushed to coarse sizes to help take care of strains occurring in brick in malleable iron practice.

The clays are all pugged in a wet pan as this process develops the greatest placticity. This mud is carried to the molder who works up portions of it into long (soft mud) bricks and then throws them with great force into the molds which are bumped several times to cause the clay to fill the molds and give good sharp corners. These brick then are carefully dried on a steam-heated floor.

In a number of plants and for certain purposes brick instead of being molded as described are pressed hard before drying giving increased density.

When thoroughly dried the brick are trucked to kilns where they are set as shown, Fig. 67, leaving spaces for heat and draft. The kilns are down draft, fired with coal,

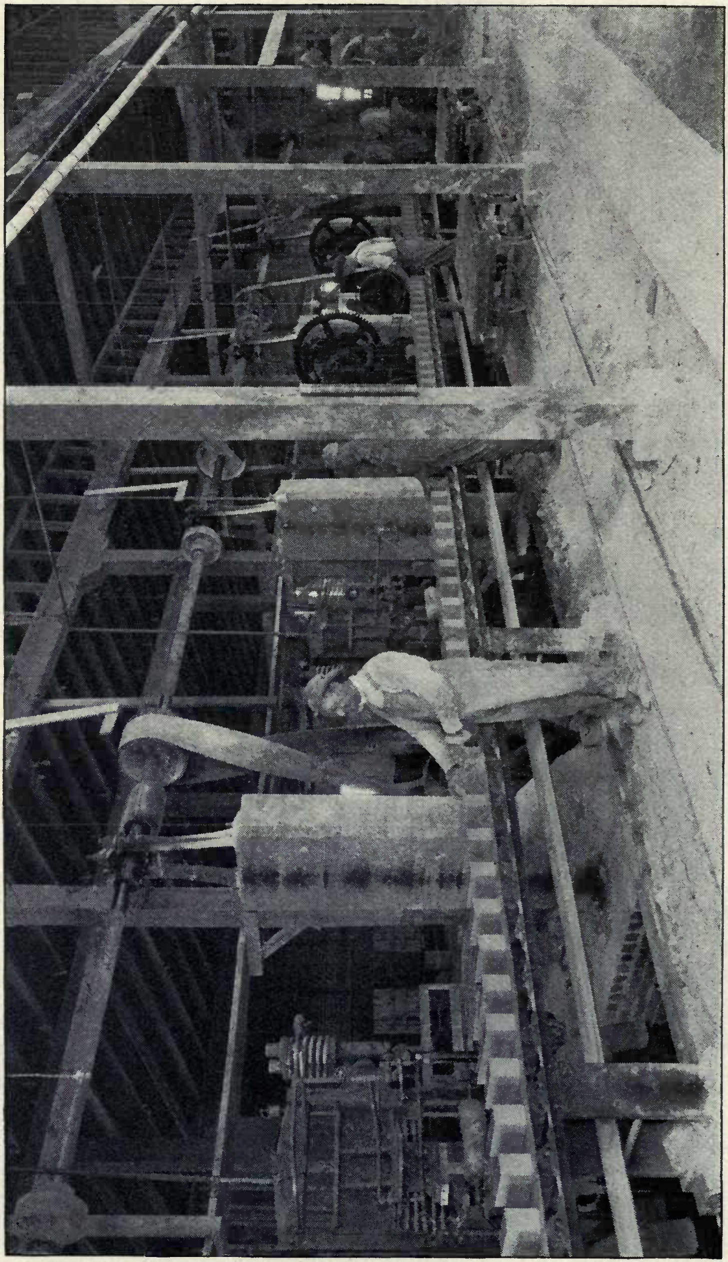

Fig. 66.—A repress room in a Missouri firebrick plant showing machines in which stiff mud firebrick are made

natural or producer gas, the gas being used more on continuous kilns.

Silica brick, used for very high temperatures, as in the roofs of open-hearth and electric furnaces, is a brick made like a clay brick in which the material is nearly all silica, using only enough clay to permit the brick to be burned to hold together. They are very hard, very dense, and possess an enormous coefficient of thermal expansion. They are strong, almost infusible, but will not withstand sudden temperature changes.

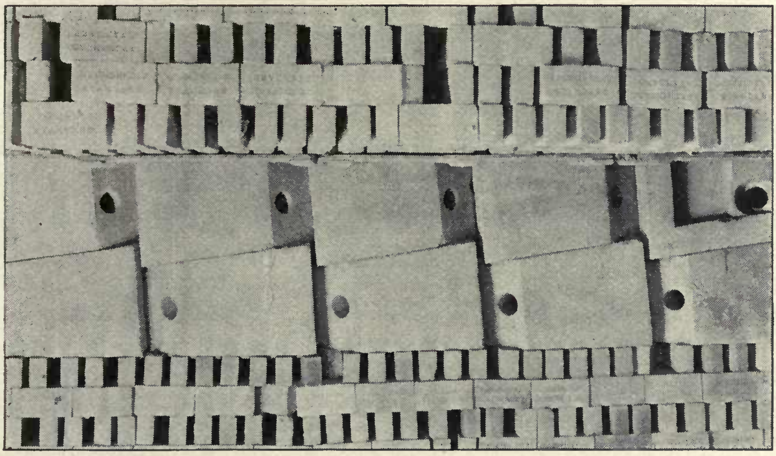

Fig. 67.—Firebrick and special fireclay shapes in a kiln ready to be burned

Magnesia consisting of MgO, obtained by heating the mineral magnesite, which is $MgCO_3$, to expel the carbon dioxide, is used both ground and as brick in basic furnace linings. In the malleable industry it is used only in electric furnaces. It is very refractory and resists basic slags. It conducts heat readily and must be backed up by a layer of clay brick if heat losses are to be made a minimum. It has relatively little strength.

Dolomite, a double carbonate of calcium and magnesium, is used in electric furnace bottoms. It is burned before use, resulting in a mixture of $CuO+MgO$ in the ratio of about 1.4 to 1.0. The commercial preparations may contain from 8 per cent to 25 per cent of other oxides, namely SiO_2, Al_2O_3, and Fe_2O_3. Some producers purposely add iron oxides (or silicates) feeling that the material then deteriorates less in storage and sinters better.

Chromite, zirkite, and bauxite, oxides of chromium, of zirconium, and of aluminum respectively, possess no commercial significance in the malleable industry, although they are well known refractories. Carborundum, silicon carbide, is another refractory which has not found application.

VII

AIR FURNACE MELTING

THE air furnace is the commonest device employed for melting malleable iron, having supplanted the cupola on the score of quality and the crucible furnaces of early days on the score of production and economy.

The air furnace is of the reverberatory type in which the metal, in the form of a fairly shallow bath, is melted by the flame from fuel burning in a firebox at one end of the hearth. The flame is drawn over the hearth by a stack at the opposite end from the firebox. In the earliest type, the stack was at one side with a charging door at the end opposite the firebox. The present arrangement is similar in character to that of a puddling furnace.

The early air furnaces were very small; some of the first are said by Davis on the authority of George Belcher to have had capacities of 800 or 1000 pounds, a 1500-pound charge being viewed with alarm. Modern furnaces have been continually growing in size, and now five-ton heats are unusual, capacities from 10 tons to 15 tons being most common in practice. Furnaces have been built and operated with capacities beyond 30 tons, but there are relatively few in use with capacities far above 20 tons.

Design Is Simple

The construction of an air furnace is relatively simple. Fig. 68 shows an air furnace in side elevation and cross section.

The furnace walls are of fire brick, usually 13 to 18 inches thick, supported and enclosed by cast iron side and end plates about 1 inch thick. The bottom or the hearth *A* is built of silica sand or more rarely paved with fire brick. Coal is burned in the firebox *B*, the air being forced through the fire by a blower discharging into the ash pit *C*; the ash pit doors *D* being kept closed. Air is also admitted through the tuyeres *E* to complete the combustion of the gas and flame coming over the front or fire bridge wall *F*. The roof of the

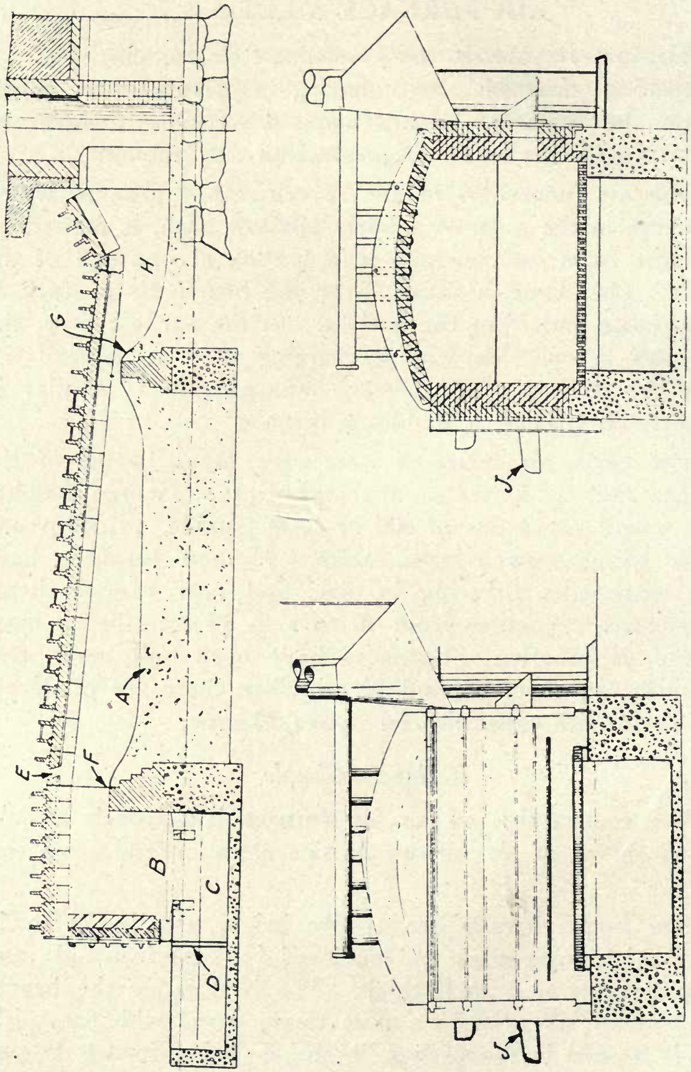

Fig. 68.—Sectional drawings showing construction of typical air furnace

furnace consists of a series of removable fire brick arches, or bungs, supported in cast iron frames. A sufficient number of these are removed to permit the introduction of the melting stock.

When charging the furnace, the sprue to be melted is introduced first in the form of a layer of fairly uniform thickness extending nearly the full length of the hearth. On this is placed malleable or steel scrap, the latter usually being kept well forward toward the front bridge wall. Pig iron is placed on top of this in two piles, one well forward, the other further back.

Most well designed furnaces are of such dimensions as to be nearly full to the roof when a heat of normal size is charged. Care therefore must be taken to leave an opportunity for the free passage of flame from *F* to the rear bridge wall.

The bungs are then put on and firing commenced. The iron soon begins to heat, naturally first at the top and in front. The firing is so conducted as not to cause much melting to occur until the lower part of the charge is well heated through to a good red.

Of the ingredients in the mix, sprue has the lowest melting point, pig iron next, then malleable scrap, and steel the highest. The melting points vary inversely as the combined carbon, although the conclusions are slightly complicated by the reabsorption or recombination of the carbon of malleable scrap below the melting point.

Through the courtesy of H. W. Highriter, the author has been furnished data as to the recombination of carbon in pig iron when heated under circumstances comparable with melting conditions. The data have been shown graphically in Fig. 69. Highriter observes a rapid increase in combined carbon at the expense of graphitic carbon above 2000 degrees Fahr. The author has calculated the temperature of the solidus for the observed combined carbon and plotted these temperatures in a dotted line. When this temperature falls below that of the specimen, incipient fusion has commenced. Melting is complete when the temperature reaches the liquidus which is dependent on the total carbon and calculated by Highriter as 2372 degrees Fahr. The metal by observation fused at 2362 degrees Fahr. It will be observed that the melting point referred to by the author is that where melting is begun, above this temperature presumably the graphite is rapidly destroyed by solution.

Moldenke many years ago published data as to the relation between combined carbon and melting point of cast iron and Dyer* refers to the same facts.

In interpreting the author's statements, and presumably Moldenke's and Dyer's, confusion between the beginning and completion of melting must be avoided.

If the firing is properly managed, it is not necessary to melt the steel, the molten pig iron dissolving the steel as it runs down before the steel actually melts. Some melters advocate introducing the steel only after the rest of the charge is melted.

The sprue melts fairly readily even under all the other material due to its high combined carbon content. As the iron melts the surface oxidizes so that there results both liquid iron and liquid iron oxide, probably Fe_2O_3. The latter floats on top of the former and reacts with the carbon, silicon, and manganese of the metal, oxidizing those to CO_2, CO, SiO_2 and MnO and being itself reduced to FeO almost or quite completely.

The oxides of manganese and iron combine with the silica to form an acid silicate which also dissolves some of the refractories in the furnace lining. The resulting slag soon covers the surface of the molten metal protecting it from further action of the furnace gases.

As pools of iron covered with slag form, a good melter will endeavor to roll unmelted pig iron and steel into these pools so as to bring the entire charge under the slag blanket as soon as possible, thus minimizing oxidation losses.

The flame conditions also are carefully regulated by attention to the dampers in the blast lines to the firebox and top blast tuyeres and by keeping the openings over the bridge walls and the channel or neck *H* to the stack of the right dimensions.

When the charge is all melted it is well mixed by rabbling with a skimmer bar. The slag is then skimmed off by raking

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*Iron Age, Nov. 17, 1921.

it out through the skim holes, the skimmer bar consisting of a 1-inch iron bar having a flat plate, say 5/8 x 3 x 9 inches affixed by its center to the end of the round bar. The other end of the bar is bent into a ring to form a handle.

Meanwhile the fire is being constantly worked with a poker to keep up active combustion. The heat has to be skimmed at intervals in order to make rapid heating possible and also to keep the final product fairly clean. One producer does not remove the slag, but drains it off after the metal has all been run out of the furnace.

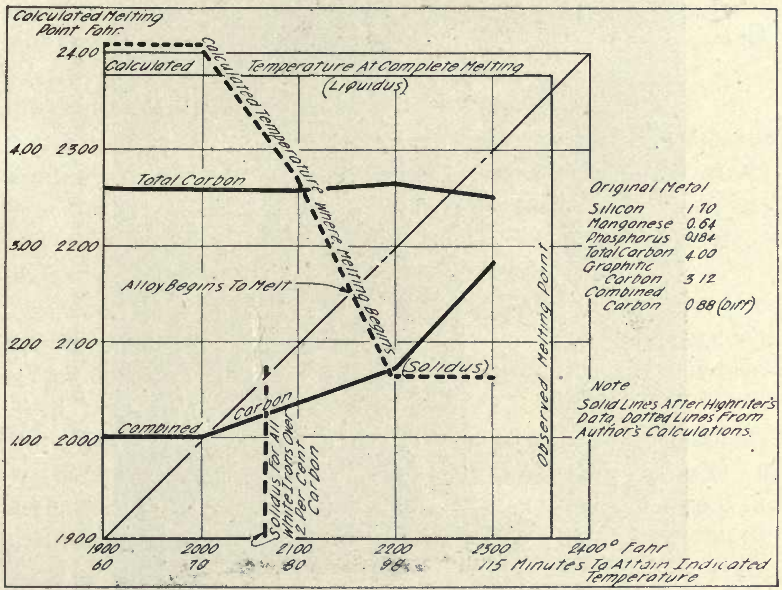


Fig. 69.—Graph showing recombination of carbon in pig iron

The progress of the heat is judged as to temperature and composition by the inspection of a freshly broken surface of a not too rapidly cooled sample and of the molten metal in the ladle. For satisfactory work a knowledge of the composition of previous heats also is necessary. In a few plants more or less complete preliminary analyses are attempted before tapping. This chemical practice is attended with a certain amount of un-

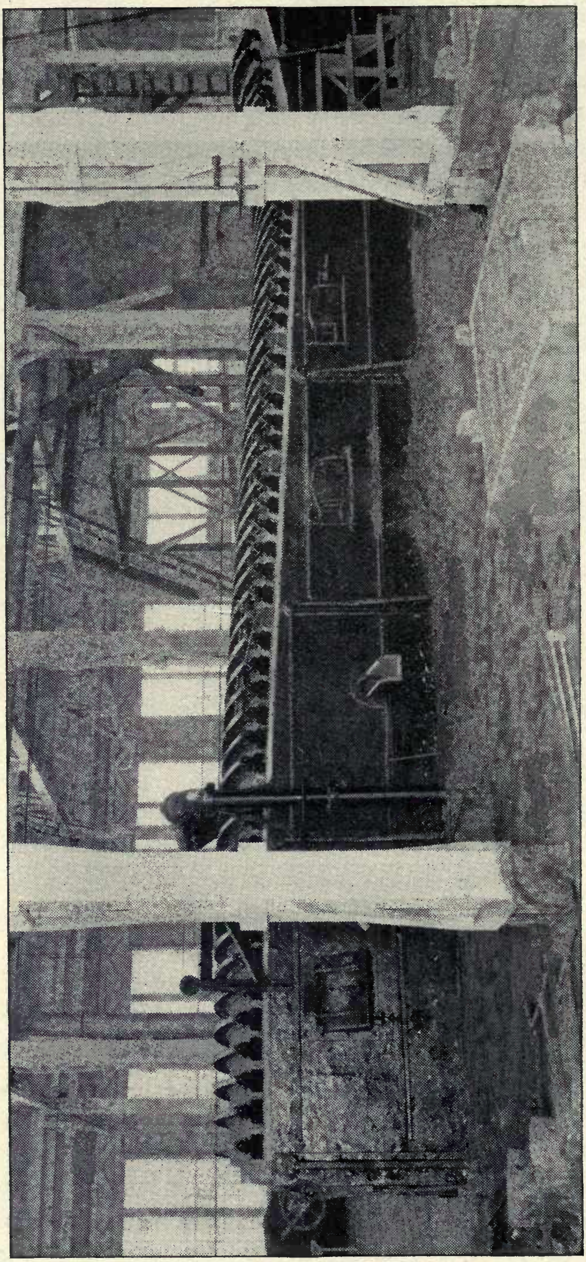


Fig. 70.—The roof of the modern air furnace is almost straight

certainty as to further changes of composition between sampling and tapping and is therefore less effective than the corresponding practice in electric melting. When the metal is hot and of proper composition the clap stopper in the tap hole *J* is cut through and the metal runs out in a stream into the molders' ladles.

In the early days of the art the profile of the furnace roof longitudinally was given very complex, almost fantastic curves. These usually had a sharp dip in the roof just beyond the front bridge, then a rise forming a sort of hump over the hearth, then a drop toward the rear bridge wall and then a rise directed toward the stacks.

Furnaces of the older type had sloping roofs but recently the tendency has been toward a nearly straight roof, lower at the rear bridge than at the front and sometimes rising again into the stack as a matter of convenience. A modern design is shown in Fig. 70.

The flame in flowing through the furnace obeys laws similar to those governing the flow of water in channels. These laws have been completely investigated by Crum-Grzimailo of Petrograd, (*Stahl und Eisen,* Dec. 7., and 11, 1911), who developed the mathematical formulae and coefficients applying to the problem in great detail. The discussion is much too technical in character to be even abstracted here beyond the statement that the laws are those which would apply to the flow of one fluid through another, if the two were not mixable and differed in density as does the hot flame and cold atmosphere.

This investigation coupled with a knowledge of combustion and temperature conditions to be expected forms the only logical basis for furnace design. In practice actual furnace design is generally based on modifications of previous designs. This is in many respects sound policy as tending to avoid erratic practices. On the other hand, there is a great tendency toward perpetuation of obsolete features inherent in such a process of evolution.

An inspection of the designs of many furnaces shows a wide variation on some apparently vital points. These differences, however, are not always as little justified as may appear on the surface for the viewpoint of different designers may not be the same.

Thus, for example, it is undoubtedly sound metallurgical practice to make but one heat a day on a furnace and make that a very large one, for the larger the capacity the greater is the melting economy, other things being equal. On the other hand, consideration must be given to the space required for molds, to the physical ability of the men to pour,

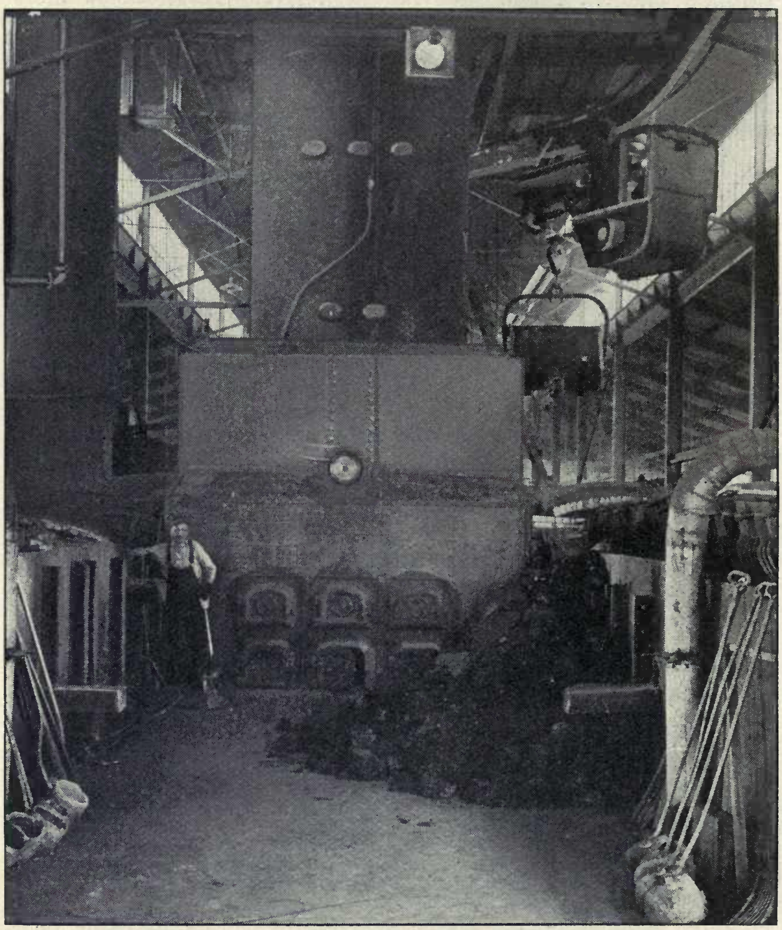


Fig. 71.—A waste heat boiler connected to two air furnaces. Note that coal for auxiliary firing is on hand

etc. Thus it is that this practice may not be feasible. If heats are required at given time intervals it may be more important to keep the time schedule correct than to get the maximum of economy, hence fuel consumption may be sacrificed to melting speed. Such a consideration also may limit the practicable size of heat. Also many furnaces are built in existing buildings, or under other conditions which handicap the designer by limiting him to certain dimensions from these causes.

A general idea of the usual dimensions of air furnaces can be gained from the following: The volume of the hearth, (the volume of the basin below the level of the skim holes) is directly dependent on the amount of metal to be melted and is not subject to any discretion. One pound of melted cast iron, together with its accompanying slag occupies about 5 cubic inches; therefore 10,000 cubic inches of hearth must be provided for each net ton of furnace capacity.

There are certain practical limits to the depth of molten metal in the hearth which can be successfully worked. Shallow baths presenting to the flame a large surface per unit weight of metal, heat easily and quickly but also oxidize easily and quickly. Extremely deep baths are difficult to heat, but the great weight per unit of surface favors the rapid transfer of heat from flame to metal per unit of hearth area.

Moreover, large capacities coupled with shallow baths may involve impracticable dimensions. Again, the bottom of the furnace must have sufficient slope to assure complete drainage to the tap hole. Even in unusually short furnaces this slope produces a difference in depth at the tap hole and rear bridge of perhaps 5 inches so that an average depth of less than 2½ inches is not workable in any event, because it necessitates a "feather edge" of metal next the bridge.

In practice the average depth of metal ranges from about 5 to 9 inches, the greater depths usually occurring in furnaces of the greater capacities. The depth at the tap hole may be from 2½ to 5 or 6 inches greater than the average depth depending largely on the furnace length. These depths correspond to hearth areas running from about 13½ square feet per ton down to less than 8 square feet per ton.

The requirements of firing, skimming, etc., as well as the maintenance of roof arches sets a maximum inside width of between 5 and 6 feet for air furnaces of the usual design, a few large furnaces of special design have a clear width of 7 feet. When the maximum width is reached the capacity of the furnace can be increased only by increasing the hearth length. Extremely shallow baths are impracticable when large capacities are desired because they necessitate long furnaces. For example, 20-ton furnaces with a hearth area of 13½ square feet per ton would be about 45 feet long between the bridge walls. Hearths from 14 to 27 feet long are in common use, and in a few unusually large furnaces they are several feet longer. A certain length of hearth is desirable because it insures a better contact of flames and charge. Excessive lengths cannot be had with small capacities as the furnace would be too narrow. The practicable length also depends on the fuel and firing conditions since a length which does not allow the flame to reach to the rear bridge wall is unworkable.

The firebox is almost of necessity of the same widths as the hearth. The grate area required depends on the rate of combustion of fuel desired and this in turn depends on the furnace capacity and on the relative importance of quick as against economical heating. Air furnace grates burn from 43 to 77 pounds of coal per hour depending on firing conditions. Values of from 67 to 77 pounds are more common than those near the lower limit.

Reported tests indicate that air furnaces use from slightly under 500 to about 1200 pounds of coal per ton of charge. These are extreme ranges, the usual commercial range being from 750 to 900 pounds per ton, depending largely on the size of the furnace. These figures give some indication of grate areas required under various conditions, having in mind also the fact that an attempt to melt rapidly is often uneconomical. It seems to be usual practice to provide from 2 to 2½ square feet of grate per ton of charge although a number of furnaces exceed this rate.

Many designers do not agree on the correct height of an air furnace roof. From 15 to 17 cubic feet per ton from hearth to roof are unavoidably necessary in order to accommodate the unmelted charge. This sets a minimum of height for any given hearth area per ton of charge.

Quantity of Air Varies

Almost invariably the roof slopes downward toward the rear bridge. The old humpback furnaces had a somewhat greater average height than the more modern straight-roofed furnaces. The average height of roof above the metal at the side walls is about 24 inches. A pound of ordinary melting coal requires about 12¼ pounds of air for combustion under usual operating conditions. The relative amount of air entering the furnace through the top blast tuyeres and through the grates varies in practice, but the average ratio seems to be about 28 to 100. Therefore a pound of coal requires about 10 pounds of air through the grates and 2¼ pounds of air through the top blast in ordinary operating practice.

The firebox is operated so that it produces a poor grade producer gas which is then burned with a sufficient amount of air for theoretical combustion. A typical gas leaving the firebox is composed of 1.2 per cent oxygen; 8.0 carbon dioxide; 12.1 carbon monoxide; and 78.7 per cent nitrogen. The gas leaving the stack contains 1.1 per cent oxygen; 12.7 carbon dioxide; 3.6 carbon monoxide; and 82.6 per cent nitrogen. The analyses take no account of the water from the combustion of the hydrogen of the fuel. The oxygen in this water and that used in the oxidation of silicon and manganese account for the relatively high value of the nitrogen. The flame gases also contain unburned hydrocarbons of unknown character and amount which escape sampling.

Any attempt to further reduce the carbon monoxide content by adding additional oxygen probably would result in a prohibitively high excess of oxygen in the gas, causing heavy oxidation during the melting process.

The mechanism of this oxidation has already been referred to as consisting of the oxidation of the iron to the Fe_2O_3 followed by the subsequent reduction of the Fe_2O_3 to FeO by the silicon, carbon and manganese of the bath. The amount of oxidation varies widely depending upon the furnace atmosphere and similar conditions. Over an extended period, however, it seems nearly constant for any successfully operating plant. The losses expressed in percentage of the total weight of original charge and in percentage of the amount of each element present are generally about as follows:

Table V

LOSSES OF ELEMENTS IN MELTING IN AIR FURNACE

	Total charge 100 per cent	Total amount of element 100 per cent
Carbon	0.62	15.8
Silicon	0.33	31.4
Manganese	0.26	48.1
Phosphorus	0.00	0.00
Sulphur	—0.01	—22.2
Iron	1.14	1.2
	2.37	

The results of the figures in the second column form an interesting comparison of the "oxidizability" of the different elements when melted in an acid furnace.

Oxygen Absorbed During Melting

A more interesting method of clearly showing the relative affinity for oxygen of the different metals is to calculate the oxygen combined with each one of the elements during melting. This calculation has been made using the preceding data and the results are shown in the table below. In the first column is shown the oxygen combined with each of the four oxidizable elements in terms of the weight of original charge and in the second column in terms of the weight of the oxidized element present in the charge.

Table VI

OXYGEN ABSORBED BY EACH OF THE OXIDIZABLE ELEMENTS DURING AIR FURNACE MELTING

	Total charge 100 per cent	Element present in original charge 100 per cent
Carbon	1.60	50
Silicon	0.38	36
Manganese	0.06	11
Iron	0.32	34
	2.36	

It will be seen that carbon combines much more greedily with oxygen than any other element, silicon coming next, manganese oxidizing much less readily and iron only slightly. Of course the results would differ with variations in gas composition and furnace lining.

It will be seen that the melting process oxidizes a total of 2.34 per cent of the original charge, and combines there with oxygen weighing 2.36 per cent of the original charge. There should thus result a weight of slag equal to 2.5 per cent of the metal charged and of gas equal to 2.2 per cent of the metal charged, were there no contamination from molten refractories. A typical sample of air furnace slag showed the following composition:

Analysis of Air Furnace Slag

	Per cent
FeO	28.80
Fe_2O_3	1.16
MnO	4.85
SiO_2 (etc)	50.42
Al_2O_3	14.77
	100.00

The metallic oxides aggregate 34.81 per cent of the weight of the slag. From the preceding tables, this corresponds to 13.8 per cent SiO_2. Therefore the above slag consists of a mixture of 58.70 per cent oxidation products and 41.30 per cent molten refractories and since the weight of slag oxidation products was computed to be 2.5 per cent of the weight of the charge the actual slag weight should be slightly more than 4.2 per cent of the original metal charged into the furnace. It is not assumed that these data are absolutely correct but they furnish a fair guide to what may be expected in practice.

Refractories Destroyed by Melting

Since every ton of iron melted destroys 34 pounds of refractories by melting, it is evident that frequent furnace repairs are necessary. The furnace parts most strongly exposed to heat usually are relined at intervals of from 10 to 20 heats. The roof over the hearth lasts usually from 16 to 24 heats and the sand bottom from 10 to 20 heats. In one instance the writer saw a furnace make 34 heats without relining, and

Fig.72

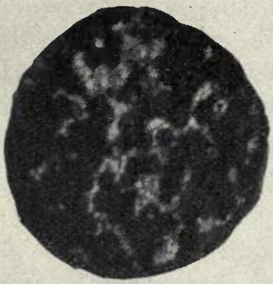


Fig.73

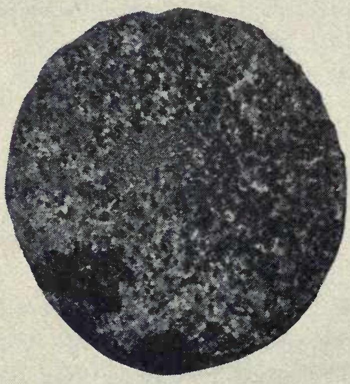


Fig.74

Fig. 72.—Gray sprue; characteristic of high carbon and silicon and sometimes of low pouring temperature (full size)

Fig. 73.—Gray sprue showing white patches; characteristic of less but still excessive carbon and silicon. Note "inverted chill," i.e. greater grayness near the surface than at center (full size)

Fig. 74.—Moderately mottled sprue; characteristic of carbon, silicon and temperature suited to small work (full size)

in another saw a bottom last 120 heats as a result of careful attention. However, this record is believed to be exceptional.

The charge going into the furnace can be computed by adding to the final composition wanted the expected melting losses and then arranging a mixture from the available melting stock conforming to these requirements. The process is one

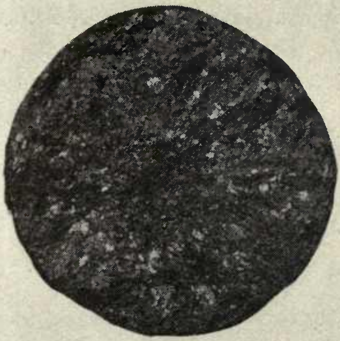


Fig. 75

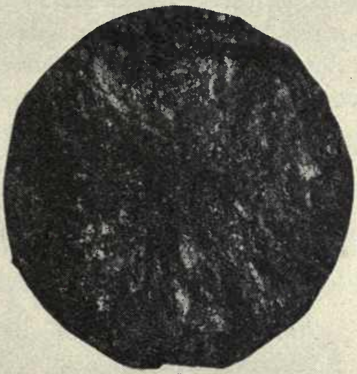


Fig. 76

Fig. 77

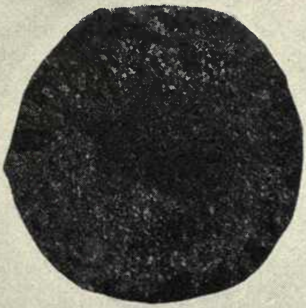


Fig. 78

Fig. 75.—Normal sprue for metal of the higher carbon ranges of specification metal in average work. Note leaf-shaped bright crystal facets radiating from center (full size)

Fig. 76.—Similar to Fig. 74 but lower in carbon. Note decrease in leaf-shaped crystals (full size)

Fig. 77.—Similar to Fig. 76 but quite low carbon. Note finely granular fracture from which the leaf-shaped crystal has almost disappeared (full size)

Fig. 78.—"High" iron, i.e. metal low in carbon, silicon and manganese; fracture granular throughout and edge showing blowholes (full size)

of simple arithmetic and the great mystery made of the matter by the older melters was not justified.

However, the skill of the melter is important in maintaining furnace conditions so that the oxidation losses are uniform and as small as practicable. The appearance of the flame in the furnace, the eddy currents in the bath and the appearance of the slag, whether viscous or liquid, indicate to the skillful melter what is going on in the furnace. Similarly the color and fluidity of the metal and the appearance of the fracture after cooling permit of close inferences regarding its composition.

Interpreting Appearance of Fracture

Among the more obvious indications of the fracture are the presence of graphitic areas or mottles indicative of too high a silicon or carbon or both, larger leafy crystals radiating from the center indicating moderately high carbons decreasing to very fine granular structures as the carbon falls to near 2 per cent. There also is the rim of fine blow holes and the spray of oxidizing iron arising from the surface of the metal in cases of "burnt" heats very low in silicon.

The actual conditions are not even capable of illustration photographically since some of the fractures do not show up clearly except by looking at them in light falling in various directions.

It can be shown that by far the largest part of the oxidation losses, occurring in practice, is complete, when the metal is melted down and ready to skim.

From the time the iron is all melted, before skimming, until the moment of tapping no marked changes of composition occur as to carbon and manganese although the silicon will decrease perhaps 0.1 per cent during the removal of the first slag. This presupposes a properly operated furnace.

Composition May Vary During Heat

Samples taken from the last of a heat frequently show a considerably lower carbon, silicon and manganese content than those taken at the first of the heat. However, this is due, not to a progressive oxidation which would have affected the entire heat to that extent had it been left in the furnace, but to the effect of oxidation on the very thin layer of metal left in the furnace as the last metal is being withdrawn. Only a small weight of metal is of a composition different from the bulk of the heat. A feature that frequently is misunderstood is the elimination of graphite. Often it is supposed that the fact that the longer the heat is left in the furnace the lower the graphite is due to oxidation of carbon and silicon. As a matter of fact the elimination of graphite is largely a function of the pouring temperature and time, and metal will show progressively clearer fractures during the progress of the pouring of a heat without any accompanying change of ultimate chemical composition. Fig. 79 shows such a condition.

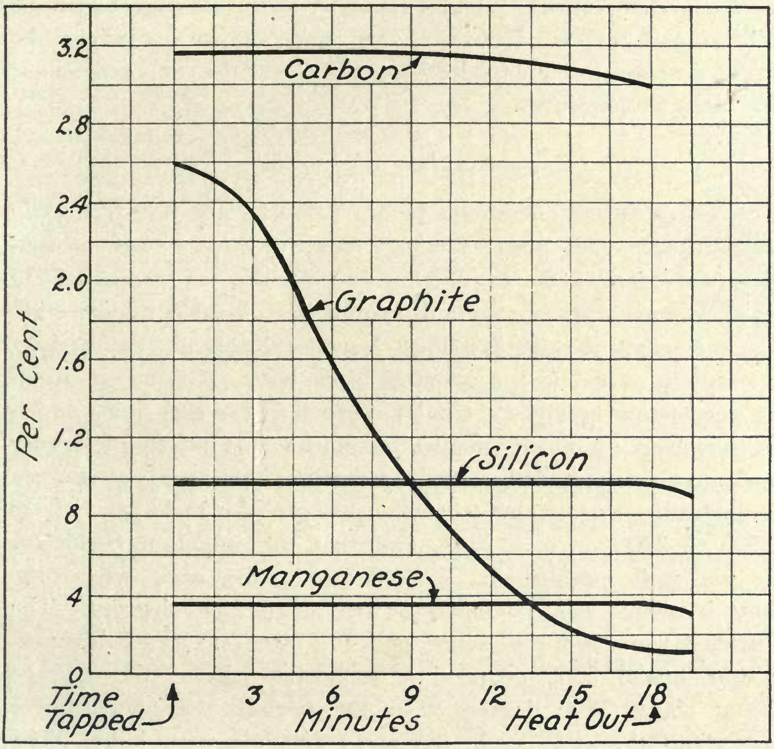


Fig. 79.—Changes of metal after tapping

In this figure the composition of the metal with respect to total carbon, graphitic carbon, silicon and manganese is shown for samples in the form of 1½-inch sand-cooled cylinders poured at intervals of three minutes each while the heat was running out of the furnace. It should be said in explanation that this was not a normal malleable iron heat but one for a special class of work requiring great perfection of surface on castings on thin sections, hence the high values of silicon and carbon. However, the curve shows strikingly the rapid decrease in combined carbon as the metal is exposed longer to high temperatures.

Temperature of Furnace

Temperature conditions in air furnaces are not accurately established. The metal flowing from the spout has a temperature from 2100 to 2500 degrees Fahr, as measured by radiation pyrometers. Such determinations involve a correction for coefficient of radiation since clean metal does not radiate heat as rapidly as would a theoretical black body. The use of optical pyrometers involves a similar correction for emissivity which is however of much smaller magnitude. Optical pyrometer measurements coupled with observations of metal at known temperatures suggest that true values are probably more nearly from 2500 to 2700 degrees Fahr. and that the radiation coefficient is not well established. The flame in the neck when the heat is melted has a temperature of about 2500 degrees. The furnace roof and the flame under it seem to reach temperatures up to 3000 degrees or somewhat higher, the average being about 2800 degrees. In the firebox the temperatures are about the same as in the neck, 2500 degrees, Fahr. The latter figures are probably more accurate than those on the flowing metal since black body conditions are more nearly approached. They are if anything somewhat low.

The following heat balance gives a general idea of fuel consumption in an air furnace. Since there is considerable variation in furnace practice the correction of heat values for the actual temperature of fuel and air entering the furnace was believed an unnecessary refinement.

While based only on estimates, this balance gives a fairly comprehensive idea of what becomes of the heat delivered

Table VII

HEAT BALANCE OF A TYPICAL AIR FURNACE

	B.t.u. per ton charged	B.t.u. per ton charged
Heat value coal burned	11,200,000	
Heat from oxidation of charge	219,400	
Heat of formation of basic silicates	30,000	
Total	11,449,400	
Latent and sensible heat of metal	....	878,940
Sensible heat of flue gas	....	6,112,000
Loss to incomplete combustion of C to CO only	....	1,232,000
Evaporation of water in coal	....	10,000
Heat value of unburned combustible in ash	....	37,335
Sensible heat of slag	....	42,000
Latent heat of slag (est.)	....	30,000
Sensible heat of furnace structure	....	600,000
Radiation conduction and unaccounted for	....	2,507,125
Totals	11,449,400	11,449,400

to the melting furnace. The values may be summarized on a percentage basis shown in Table VIII.

This indicates clearly that the larger part of the waste is in the sensible heat of the flue gas. This heat occasionally is recovered by the use of waste heat boilers which generate steam with the heat of the gases leaving the furnaces. The difficulties encountered are largely of a steam engineering character and arise from the intermittent supply of heat available.

Prof. Touceda in a paper before the American Foundrymen's Association in 1920, has given tentative suggestions for the utilization of waste heat from air furnaces. These suggestions are for various double hearth furnaces in which the waste heat from one hearth is used to preheat the charge in

Table VIII

HEAT BALANCE IN TERMS OF HEAT VALUE OF COAL FIRED

	Per cent		Per cent
Heat value of coal fired	100	Heat in metal	7.81
Heat from reactions in furnace	2.2	Heat in flue gas	54.70
		Heat in slag	0.64
		Incomplete combustion	11.30
		Heating furnace walls	5.35
		Radiation and conduction	22.40
Total input	102.2	Total output	102.20

the other. The mechanical means are somewhat complicated involving movable hearths and also somewhat continuous operation. From a thermal viewpoint, however, they are most interesting.

Reference has been made to the use of forced draft in air furnaces. The air supply is usually at low pressure, about 4 ounces per square inch, although a few plants use pressures of a pound. In such cases the furnaces must be equipped with doors at the fire hole and skim holes. At least one important producer operates on natural draft alone, using no blowers and consequently no top blast. This particular plant depends on extremely high stacks. Many air furnace stacks are from 45 to 85 feet high, and have internal diameters from 24 to 48 inches. The lack of agreement is unaccountable except on the basis of poor design. Nearly all air furnace stacks have capacities far beyond their actual requirements.

It has been stated in the general discussion of fuels that both oil and pulverized coal fuel have been tried in air furnace practice. As far as the author knows, the use of oil never has been generally satisfactory, owing to difficulties in maintaining the proper furnace atmosphere, free from excess of air or CO_2.

The chemical changes in melting depend entirely upon the temperature and composition of gas in contact with the metal. The use of producer gas entailed similar difficulties and was never commercially adopted, except of course in open-hearth practice. Similar difficulties have been encountered in the use of pulverized coal but have been successfully overcome, at least by a few combustion engineers.

A successful equipment of this character is shown in Fig. 80 and consists of a hopper containing the pulverized fuel provided with screw conveyors for feeding a stream of coal into the current of air from the blower shown in the lower right hand corner of the picture. The ends of the conveyor shafts are shown under the numbers 1-2-3-4-5 painted on the hopper.

The current of air loaded with coal dust enters the furnace through three burners in the head wall of the fire box, which is blocked up; and through two burners through the roof at the point where the top blast usually enters. By proper manipulation of the relative supply of coal and air to these several burners, proper control may be maintained and satisfactory working insured. The entire problem is merely the design of a burner capable of so feeding the fuel into the air as to maintain uniform combustion conditions with coal and air supply capable of regulation through a fairly wide range.

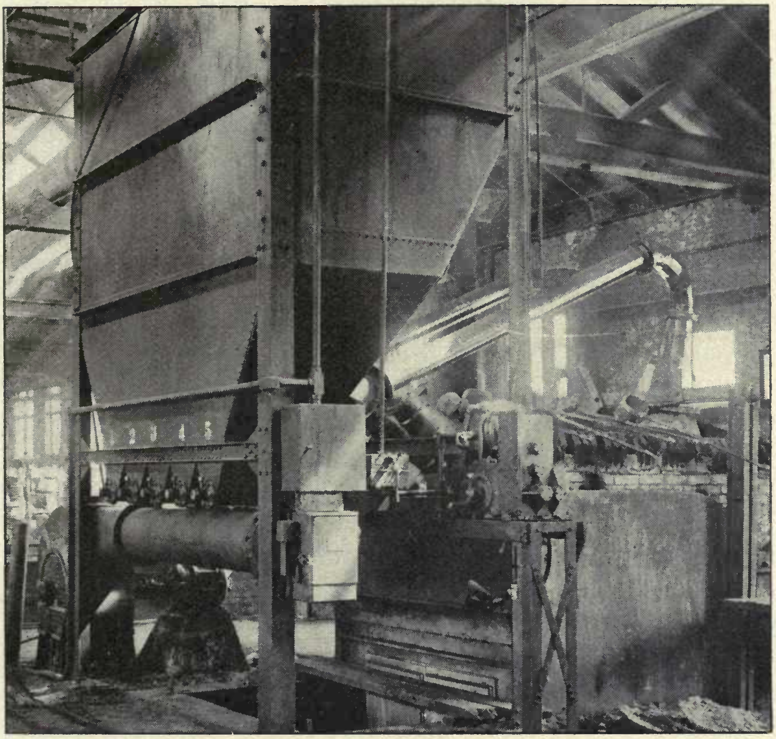


Fig. 80.—A powdered coal attachment for an air furnace

Such a set of burners operated to duplicate furnace atmospheres corresponding to the best air furnace practice will produce results superior in control and economy to results under hand firing. The improvement results primarily from the constancy of ratio of coal to air throughout the heat, thus avoiding the losses due to alternately incomplete combustion and excess air which occur even with the best hand firing when the average condition is perfectly controlled.

Table IX

CHEMICAL CHANGES IN AIR FURNACE

	Raw material					Product	By-products		
	Metal charged pounds	Coal	Air	Refractories	Total	Molten metal	Slag	Flue gas	Cinders
Fe.	1901.3	....	.....	...	....	1878.5	22.8	.....	...
C	62.0	609.0	.....	...	671.0	49.6	...	617.0	4.4
Si	21.6	....	.....	...	21.6	15.0	6.6	.....	...
Mn	11.0	....	.....	...	11.0	5.8	5.2	.....	...
S	0.9	5.0	.....	...	5.9	1.1	1.2	2.0	1.6
P	3.2	....	.....	...	3.2	3.2	...	.....	...
Clay	...	....	.....	34.0	34.0	....	34.0	.....	...
O	...	....	1918.0	...	1918.0	....	15.0	1903.0	...
N	...	....	7243.0	...	7243.0	....	...	7243.0	...
H	...	39.0	.....	...	39.0	....	...	39.0	...
Ash	...	21.0	.....	...	21.0	....	...	.....	21.0
Water	...	14.0	.....	...	14.0	....	...	14.0	...
Total.	2000.0 lbs.	688.0	9161.0	34.0	11,883.0	1953.2	84.8	9818.0	27.0

The author has seen the results of many tests on this type of equipment but it is doubtful whether data have yet been accumulated which warrant a definite conclusion as to economy of operation due to pulverized fuel.

The tests which he has seen seem to indicate that the requirements as to furnace atmosphere are such that no direct saving on coal is practicable. The economies may rather be expected to result from decreased labor and refractory costs, and greater independence in using poor coal.

The data at hand point also to a lower and much more constant loss by oxidation of the several metals than is normal to ordinary air furnace practice, but insufficient experience is available to be sure whether this condition always exists.

As a skeleton outline of the metallurgy involved in the operation of an air furnace the outline of the chemical changes shown in Table IX may be interesting. The summary is typical only and does not necessarily apply exactly to any given case.

The summary is based on the weights of each material and each element entering into the reactions for one net ton of charge.

Air furnaces usually are operated by a crew of either two or three men exclusive of those doing the charging, bringing in fuel and stock, etc. The majority of air furnaces make a heat in 20 to 30 minutes per ton plus about one half hour if the furnace is hot to begin with, or plus one and one half hours if the furnace is cold at the start of the melting operations.

Large furnaces melt faster, per ton, than small ones, but large heats still take longer to make. It is said that one plant, using oil fuel made heats around 30 tons in three and one half or four hours, although the writer is not prepared to vouch for this statement. Another plant making heats of this size with coal runs 16 to 18 hours to a heat, it is said.

In most plants skimming begins when the heat is well melted which will be from one and one half to two hours before the heat is ready. In a plant where instead of skimming the slag is tapped out after the iron is poured it is claimed that no loss of time or fuel is incurred due to this method. The operation is on fairly large furnaces. In spite of the obvious desirability of this operation, if practicable, it has not been adopted elsewhere. The author does not know whether or not this conservatism is justified. The feeling seems to be one of suspicion as to the general economy and practicability of the operation.

VIII

ELECTRIC FURNACE MELTING

PRACTICALLY the only radical change in melting practice which has been introduced into the malleable industry in the last half century is the use of electric furnaces. So far only one producer operates under this method, which is protected by patents covering the conditions necessary to commercial success.

In electric operation, increased accuracy of chemical control is made possible and the success of the melting operation is largely independent of variations in quality of stock and fuel and of blast and similar conditions. The belief that electric melting is adopted because it permits the manufacture of alloys of compositions unattainable in the air furnace is not founded on fact. While it is possible, for example, to make iron as low as .017 per cent in sulphur, if desired, there is no engineering advantage in such an operation.

Electric melting as practiced today is conducted by the triplex process, developed by W. G. Kranz, which, as the name indicates, is conducted in three distinct stages. This process supplements the advantages of the electric furnace with the use of a cupola and a bessemer converter to assist the electric furnace in operations to which it is not so well suited. The rationale of the process is as follows:

The electric furnace alone is suitable for melting or heating metal with slight contact with air or any other substance except the furnace lining and slag. Therefore, it is suited rather to keep the composition of its contents unaltered than to make changes in composition.

Chemical changes occur therein only as a consequence of the addition of various alloys of slag-making ingredients and the effect of such additions can be quantitatively controlled. The changes of chemical composition easiest of attainment in the electric furnace are increases in silicon, manganese, or phosphorus and decreases in sulphur and oxygen. Carbon can be added or removed, or silicon removed with greater difficulty but the removal of phosphorus is not practicable under the usual operating conditions in malleable melting.

Whereas the electric furnace is an expensive source of heat energy, the cupola is the cheapest known method for merely melting cast iron, composition being no object. Cupola melting always removes at least part of the silicon and manganese and adds sulphur, leaving the phosphorus unaltered. The carbon content is nearly independent of the mix used depending only on the condition of the fuel bed. The carbon content always is relatively high.

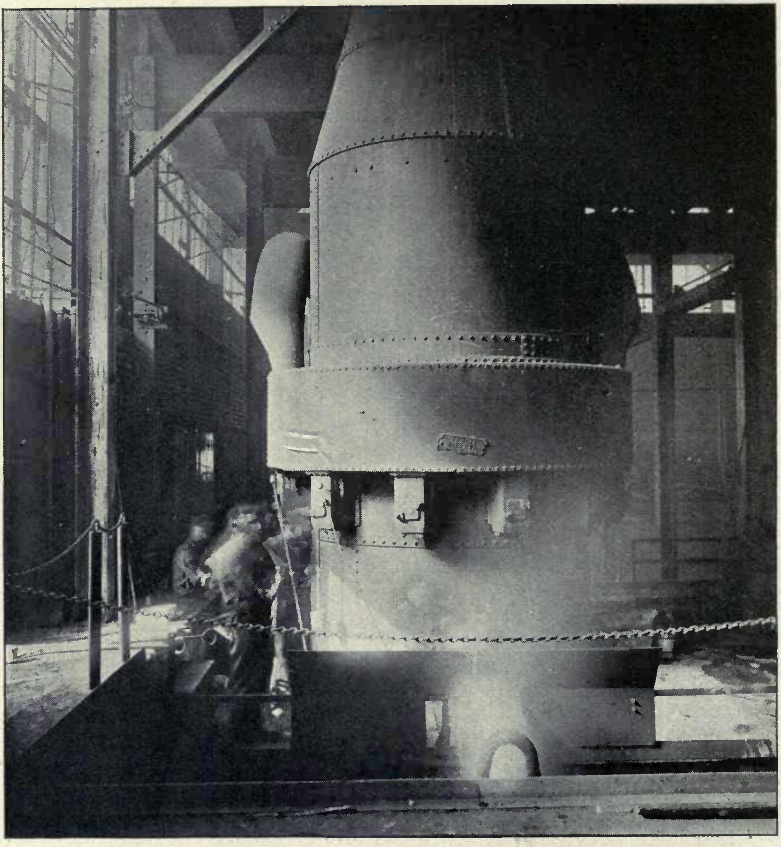


Fig. 81.—Cupola producing molten iron—The starting point of the Kranz triplex process

The bessemer converter furnishes an easy and economical way to remove all carbon silicon and manganese from iron but adds a great deal of oxygen.

The three units form an ideal team, each possessing good qualities to supplement the weak points of its mates. The cupola furnishes cheaply a supply of liquid iron of high and approximately constant carbon content which readily can be controlled as to its maximum silicon, manganese and phosphorus content, but may have high sulphur from the fuel. Carbon, silicon and manganese can be removed from this metal in the bessemer converter, although oxygen may be added. By taking the proper relative amounts of cupola and bessemer metal a mixture can be produced having a carbon content close to any desired value, and which also is below any desired fixed values in silicon, manganese and phosphorus. However, it contains an indefinite and relatively large amount of sulphur and oxygen.

This molten mixture can be given its final heating in the electric furnace without too great expense, and by the use of suitable slags the sulphur and oxygen can be removed without any effect on the silicon, manganese, or phosphorus. Guided by the analysis of the molten charge, silicon and manganese can be added to adjust these values as desired and a product made without prohibitive cost, adjusted to chemical specifications on each of the five common elements and freed from oxygen.

These are the steps in the Kranz process, which since passing through the experimental stage in 1913-1914 has produced many thousands of tons of malleable cast iron in two plants of the largest producer of malleable in the world. The process as outlined comprises melting in the cupola; decarburizing in the converter; heating, desulphurizing and deoxidizing and raising the manganese and silicon in the electric furnace; and, if desired, adding sulphur in the ladle. For still greater uniformity it was once suggested that the cupola and converter metal be stored in a mixer prior to its introduction into the electric furnace, but practice has proved that this step is not necessary.

It has been found that a product varying from dead soft steel to gray iron, and including alloy steels can be made by this process at the will of the operator. If dephosphorization is desired, for example in steel-making, an extra step is required in the electric furnace, involving the formation of a dephosphorizing slag and its removal before proceeding with the desulphurizing and deoxidizing.

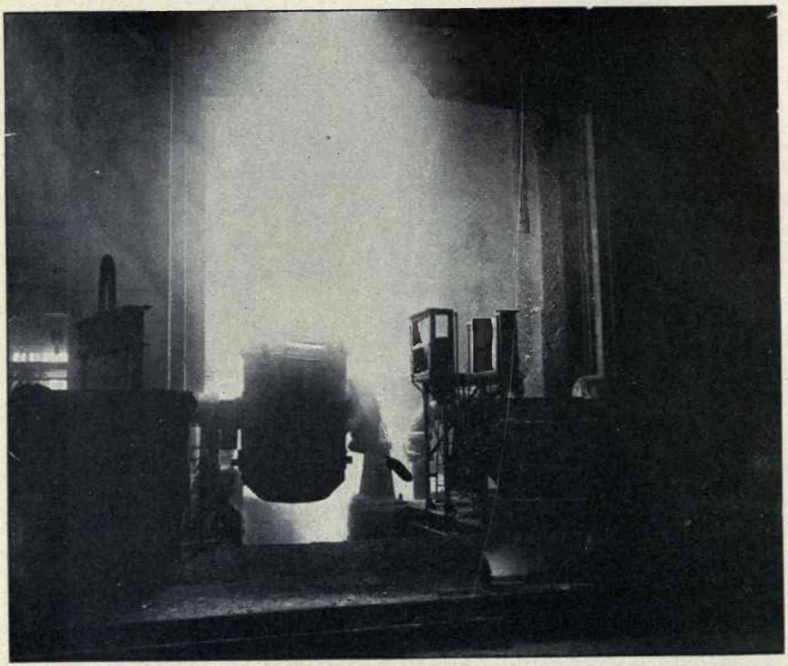


Fig. 82.—Two-ton side-blow converter producing liquid steel from cupola metal in triplex process

Metallurgy of Triplex Process

It may be well to consider the individual steps involved in greater metallurgical detail. In general, the melting stock consists of sprue and malleable scrap and high silicon pig iron. The mix is calculated only to be close to the desired value in silicon content. The manganese automatically remains low and with a little care the phosphorus can be kept below about 0.19 per cent, which is all that is required.

It is intended that the cupola metal shall run slightly under 1 per cent silicon. Too low a value causes trouble from gumming up the cupola taphole and spout and the ladle. The maximum is determined by the metal to be made. The composition of the metal leaving the cupola under ordinary working conditions is approximately as follows: Carbon, 3.10; silicon, 0.80 to 0.95; manganese, 0.12 to 0.19; sulphur, 0.09 and up, and phosphorus, 0.14 to 0.19 per cent. The dimensions of the cupola are such as to allow the unit to run continuously to produce the metal required by the electric furnaces. Interruptions and intermissions are undesirable because they affect the temperature of the fuel bed and consequently the carbon content.

The ratio of iron to coke in the cupola may average 7 to 1, varying somewhat with operating conditions. Two cupolas are provided and are used alternately to permit repairs.

The converter easily reduces the molten metal to a composition about as follows: Carbon, 0.20 and under; silicon, trace; manganese, trace; sulphur, 0.12 and up; and phosphorus, 0.17 per cent and up. A considerable oxidation of iron also occurs, which together with the mechanical loss in the form of fine drops amounts to from 8 to 15 per cent of the converter charge. If a carbon content of say 2.60 per cent is desired, cupola and converter metal in the ratio of 240 to 50 will be required and the mixture will have a composition as follows: Carbon, 2.60; silicon, 0.66 to 0.78; manganese, 0.10 to 0.16; sulphur, .095 and up; and phosphorus 0.14 to 0.19 per cent.

Since each furnace heat is handled as a unit, it will be seen that the converter charge is dependent on the capacity of the electric furnace and the carbon content of the cupola metal. In the illustration chosen the converter must deliver 50/290 or about 17 per cent of the capacity of the electric for each blow. The metal introduced must exceed this amount by the expected oxidation and mechanical losses.

The electric furnaces actually in use have a rated capacity of six and 15 tons, respectively so that when working at capacity the converter would have to deliver 1.02 and 2.35 tons respectively.

The electric furnaces used are of the Heroult type, operating on 3-phase, alternating current. The 6-ton units consume

800 kilovolt-amperes of power at 80 to 100 volts and the 15-ton units from 18,000 to 22,000 kilovolt-amperes at from 90 to 110 volts.

Handling Charge in Furnace

The internal diameter of the larger units is approximately 10 feet. In all cases the bottoms are dolomite and the lining of the side walls magnesite. The molten metal is introduced into the furnace, the arc formed, and a lime slag made on the surface. The slag-making ingredients are lime, fluorspar and coke; in amounts determined by the working conditions and not by weight. About 150 pounds of lime and coke and 100 pounds of fluorspar may be used in a 12-ton heat, the active ingredient of the resulting slag being calcium carbide, CaC_2. The actual amounts of slag-making ingredients are however not determined by weight but by the appearance of the slag and the operating conditions of the furnace. This carbide reacts energetically with any metallic oxides present. For instance

$$3\ FeO + CaC_2 = CaO + 3\ Fe + 2\ CO$$

No appreciable amounts of CaC_2 are formed until the oxygen is practically completely eliminated. At that stage the elimination of sulphur begins, the products being CaS and carbon, which dissolves in the metal. This process can not be conducted under any but a reducing condition for CaS is easily oxidized to CaO, the sulphur unfortunately not burning to SO_2 but dissolving in the iron. This introduces certain difficulties in lowering the silicon content. For example silicon is easily and almost quantitatively oxidized by ore, the reaction presumably being

$$Si + 2\ Fe_2O_3 = SiO_2 + 4\ FeO$$

Unfortunately the FeO of the resulting slag immediately reacts as follows:

$$FeO + CaS = FeS + CaO$$

and the desulphurizing must be recommenced. The removal of silicon can be conducted in this way, but it is a cause of difficulty in the maintenance of the desired slag.

Fortunately the high carbon alloys occurring in malleable practice do not take up carbon from the carbide slags used to any appreciable extent, nor does the CaC_2 reduce a considerable amount of silicon from any calcium silicates which may be present.

A sample is taken for analysis after the metal is thoroughly mixed in the furnace and should show a correct amount of carbon and phosphorus, and a deficiency in silicon and manganese. These latter two elements are added as ferrosilicon, ferromanganese, spiegel or similar alloys. Carbon can be added as pig, cupola iron, or in very hot heats as coke or can be reduced by steel additions. Silicon can be removed with ore as previously described but it is not intended that this be done in regular practice. The removal of phospohrus from malleable heats is so expensive that it is cheaper to scrap such heats than to attempt to correct them.

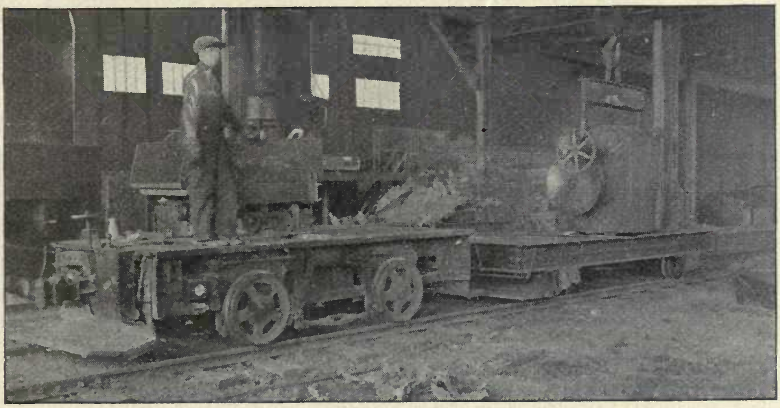


Fig. 83.—Transfer train consisting of electric motor car and trailer with crane ladle. This equipment is used in carrying cupola and converter metal to the electric furnaces

Temperature Limited by Operations

The temperature to which electric metal can be heated depends only on the refractories used and in commercial practice is from 2600 to 3000 degrees Fahr. The figures are by radiation pyrometer and in the writer's judgment are likely to be lower than the correct values. More recent data by optical pyrometer show temperatures from 2900 degrees to 3000 degrees Fahr. It appears therefore that the figures around 2600 degrees arose from an improper correction for coefficient of radiation. The relative merits of the two systems of pyrometry have been discussed in connection with air furnace melting. It is customary to take a heat away in one or two large ladles and to proceed immediately with another heat. The advantages of the process already have been pointed out and all point back to accuracy of control. The most serious limitation is the expensive first cost of the melting installation, which places it beyond the reach of the small producer. Furthermore the process is not suited to intermittent operation involving the banking of cupolas and filling of electric furnaces with coke. To obtain successful results a 24-hour day during the working week is necessary. Counting 1½ hours per heat or 16 heats per day and allowing for some loss of time for repairs between heats, and bearing in mind possible reductions in economy where very small units are used, a simple calculation will indicate that successful operation can be had only in plants of fair capacity.

The two plants now in operation are equipped with three small and two large furnaces, respectively, and are intended to operate on large tonnages. Furthermore, the crane service required for the handling of hot metal, etc., almost precludes the introduction of hot melting into any but an especially built plant, thus further limiting its general introduction.

All this is in addition to the limitations to the general use of the process due to its control through patent protection. Furnace repairs are relatively much less frequent in electric furnaces than in air furnaces. The bottom is taken care of after each heat. The magnesia side walls and silica roof each last from 120 to 240 heats, while the basic bottom, being repaired after each heat, lasts indefinitely.

The cost of heat in the electric furnace is high, but on the other hand the utilization of heat reaches an extremely high efficiency owing to the elimination of the losses in fuel-fired furnaces arising from the escape of the hot products of combustion. The current is on about one hour for each heat.

Charging, tapping and patching consume up to 45 minutes of time. Cupolas are intended to run a week on each lining but usually are repaired at 24 to 72-hour intervals.

The converters are of the side-blown type of a capacity suited to the Heroult furnace they serve and are lined with ganister. Converter bottoms last about a week, and the tops nearly indefinitely.

It will be instructive to follow quantitatively the chemical changes occurring. The following analysis is typical of the slag produced by the cupola.

	Per cent
SiO_2	52.90
Al_2O_3	12.80
FeO	5.10
Fe_2O_3	.00
MnO	2.60
CaO	21.30
MgO	3.70
S	0.20
Undetermined and error	1.40
	100.00

This is practically a mixture of molten refractory and limestone, little oxidation of the metal having occurred under the strongly reducing conditions of the cupola.

Assuming that the cupola charge consists of 10 per cent silicon pig, sprue and malleable scrap, the two latter averaging 0.70 silicon, in order to have a mixture at 1.10 silicon the mix will contain 4.3 per cent pig iron and, for example, 40 per cent sprue and 55.7 per cent malleable scrap. The average analysis of such a mixture figures out carbon, 2.68; silicon, 1.10; manganese, 0.27; sulphur, 0 55 and phosphorus, 0.177 per cent. This metal, when melted and leaving the cupola has a composition of carbon, 3.10; silicon, 0.85; manganese, 0.15; sulphur, 0.09 and phosphorus, 0.177 per cent. This change of composition coupled with the previously given slag analysis amounts to a net loss by oxidation of 0.166 per cent of the total weight charged.

The oxidation of silicon, manganese and iron is nearly balanced by the gain in sulphur and carbon from the fuel. In practice there is a loss of noticeable magnitude due to mechanical causes. By calculation the slag corresponds to 5.8 per cent of the weight of the charge; 16 84 per cent is derived from oxidation of the metal; 25 per cent from the limestone added as a flux; and the balance from the fusion of the furnace lining, coke ash, impurities in stone, etc. Assuming the limestone to have been 90 per cent $CaCO_3$, the weight of the limestone added was about 50 per cent of the slag weight or 2.9 per cent of the weight of metal charged. The limestone lost to the flue gas an amount of CO_2 equal to 11 per cent of the slag weight.

When the cupola metal is blown in the converter it becomes a steel containing, for example: Carbon, 0.10; sulphur, 0.095; and phosphorus, 0.187 per cent. The slag formed has a composition of which the following is typical:

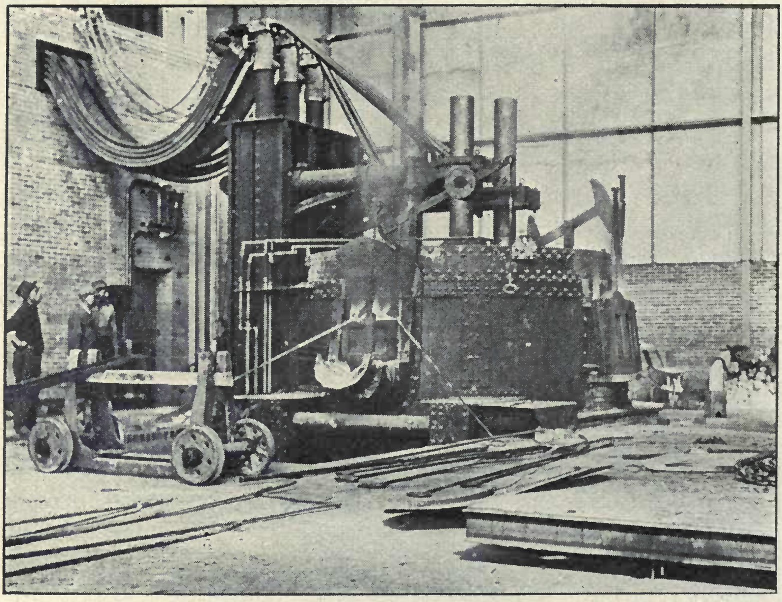


Fig. 84.—Heroult electric furnace in which cupola and converter metal is charged for final step in triplex process

	Per cent
SiO_2	57.50
Al_2O_3	1.43
FeO	34.41
Fe_2O_3	1.45
MnO	3.80
CaO	0.25
MgO	0.34
Error and undetermined	0.82
	100.00

A loss in weight of 5.36 per cent of the weight charged into the converter is indicated. In practice a larger loss is noted due to mechanical losses and to considerable amounts of iron oxide which escape as fume and are not taken into account in the analysis.

The slag is equivalent in weight to 4.86 per cent of the metal charged. Of this slag 50.08 per cent is an oxidation product of the metal and 49.92 per cent is fused refractory.

In the electric furnace no oxidation takes place, the only elements affected being sulphur and oxygen which leave the metal to become calcium sulphide and carbon monoxide, respectively. The former remains in the slag, while the latter escapes as a gas. Therefore the slag in the electric furnace is not in any material degree derived from the elements in the iron, but depends for its quantity and largely for its composition on the slag forming additions used. These are lime (CaO) fluorspar (CaF_2) and coke. The supposition is that the coke and lime form calcium carbide which removes both sulphur and carbon.

However the slags never are nearly pure mixtures of CaC_2 and CaF_2. Typical slag obtained under conditions which would possibly have destroyed any CaC_2 by the action of the atmospheric moisture had a composition as follows:

	Per cent
SiO_2	29.80
Al_2O_3	2.85
FeO	0.50
Fe_2O_3	nil
MnO	0.18
CaF_2	0.70
CaO	44.51
MgO	7.55
CaS	7.20
Undetermined	6.71
	100.00

From the behavior of the slag it seems reasonable that most of the lime is combined with silica and that there is but little free CaO as $Ca(OH)_2$ either normally present or derived from the decomposition of carbides. Possibly the CaO from these sources may run to 5 per cent or similar undetermined amounts.

Possibly the MnO shown is MnS floating up from the metal, in which case the CaS would be reduced and CaO increased to allow for the S combined with Mn. The fluorine apparently is largely eliminated in the furnace. Data as to slag quantities are uninteresting as having no connection with the metallurgical principles. The additions may amount in the aggregate to perhaps 1 or 1.5 per cent of the weight of the metal.

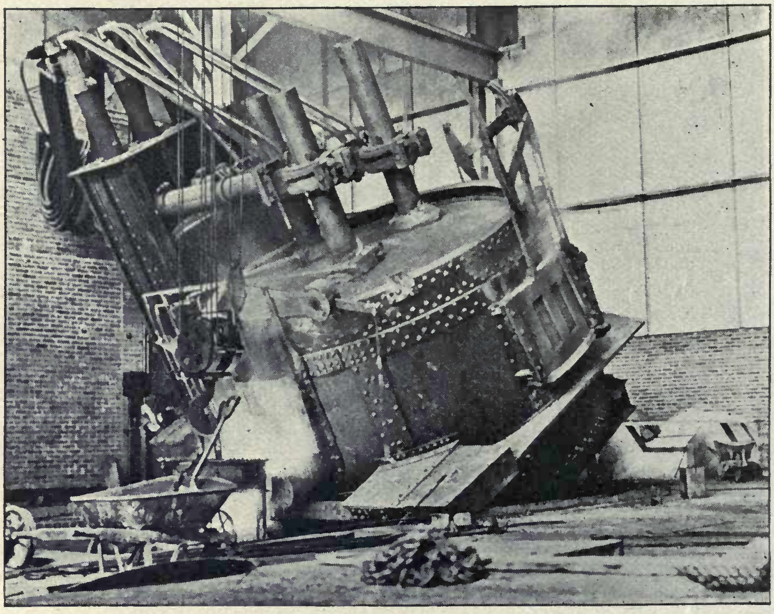


Fig. 85.—Heroult furnace tilted for pouring

Metallurgy of the Slag

Assuming a desulphurization of .07 per cent, the slag composition referred to and excluding sulphur from the coke amounts to around 44 pounds of slag per ton of metal. Of the slag the SiO_2 Al_2O_3 and MgO are primarily derived from the furnace lining. Those comprise 40.2 per cent of the entire slag. Therefore for each ton of metal 17.6 pounds of refractory are melted and 26.4 pounds of slag is formed from lime, fluorspar and carbon and from the metal itself. Of the ingredients from the metal the principal item in weight is 1.4

Table X

BALANCE SHEET FOR DISTRIBUTION OF METALLOIDS IN ELECTRIC FURNACE PRACTICE

In pounds per ton of cupola charge

	In cupola charge	From cupola coke	From converter air	Total
C	53.6	8.3	...	61.9
Si	22.0	...	...	22.0
Mn	5.4	...	...	5.4
P	3.54	...	...	3.54
S	1.10	0.7	...	1.80
O	...	...	0.60*	0.60
Fe	1914.36	...	...	1914.36

	In final product	In cupola slag	In converter slag	In converter gas	In electric furnace slag	To electric furnace atmosphere
C	51.90	...	...	10.0	0.00*	...
Si	14.17	5.0	2.83	...	0.00*	...
Mn	2.46	2.4	0.50	...	0.04	...
P	3.54	...	...	...	0.00*	...
S	0.08	...	...	...	1.00	...
O	...	...*	...*	...*	...*	0.60
Fe	1904.84	4.8	4.60	...	0.12	...

*Includes only those amounts at some stage alloyed with the molten metal.

pounds of sulphur, the MnO and FeO being only about 0.3 pounds per ton. Deducting these two, the slag has 24.7 pounds of material per ton of metal derived from the slag-forming additions. All of these figures mentioned are to be considered as suggestive only. A balance sheet of the elements concerned in the triplex process is shown in Table X. It must be understood, however, that the process has not been quantitatively investigated to the point where all the reactions are clearly worked out. The figures in the balance sheet for oxygen are merely estimates. The sulphur data are not based on a complete series of tests, but are in accord with current practice. The table neglects oxygen in original metal and final product. Ferromanganese and ferrosilicon are not supposed to be added. If charged into the electric, these alloy quantitatively with the charge.

Heat Balance of Triplex Process

A heat balance for the triplex process is extremely interesting as giving an insight into the character of heat losses re-

Table XI

GENERAL HEAT BALANCE OF TRIPLEX PROCESS

Cupola

	B.t.u.	B.t.u.
Heat value fuel	3,718,000	
Total heat, metal		1,692,000
Sensible heat, slag		63,800
Sensible heat, flue gas		180,000
Heat value of Fe, CO in flue gas		744,000
Radiation and unaccounted for		1,038,200
Total output		3,718,000
Converter		
Total heat of metal charged	282,000	
Heat of combustion of C, Si, Mn	93,400	
Total input	375,400	
Total heat, metal		292,800
Sensible heat, slag		10,900
Sensible heat, gas and undetermined		71,700
Total output		375,400
Electric Furnace		
Total heat metal charged	1,690,800	
Heat equivalent of electric input	564,200	
Total input	2,255,000	
Total heat, metal		1,865,000
Sensible heat, slag		23,000
Radiation and undetermined		367,000
Total output		2,255,000

maining. Unfortunately the results of complete tests of the process including all the factors involved are not available. Also the heat of formation of some of the compounds entering into the reaction, more particularly in the electric furnace are not known. In the absence of this information the following balance has been built up on estimates from other sources of the composition of gas leaving the cupola and converter, and of the temperature of the cupola gas, and of the metal at various stages. Also the heat of formation of the slag has not been considered a source of energy nor has allowance been made for the latent heat of fusion of slags and refractories.

The presence of oxygen in the metal, at various stages has not been followed quantitatively so that no account of the thermal effect of the formation and reduction of FeO can be taken. The latter items are included among the undetermined

Table XII

HEAT BALANCE OF UNITS IN TRIPLEX PROCESS

	B.t.u.	B.t.u.
Heat value of coke	3,718,000	
Heat value of current	564,200	
Heat combination of Fe Si, Mn and C	93,400	
Total heat input	4,375,600	
Incomplete combustion in cupola		744,000
Sensible heat, slag		63,800
Sensible heat, flue gas		180,000
Radiation and undetermined		1,038,200
Total cupola loss		2,026,000
Sensible heat, converter slag		10,900
Sensible heat, gas and undetermined		71,700
Total converter loss		82,600
Ladle loss by radiation (preheated ladle)		12,000
Sensible heat, slag		23,000
Radiation and undetermined		367,000
		402,000
Total heat, metal		1,865,000
Total output		4,375,600

losses at the various stages of the process. However, the balance in Table XI, based on one ton of metal charged into the cupola and on temperatures above atmospheric may be regarded as indicative of the major items.

The cupola utilizes 45.5 per cent of the heat of the fuel. The converter delivers 77.7 per cent of the total heat supplied, using 11.5 per cent of the heat of combustion of the elements burned in further heating the metal. The ladle loss in transferring the metal, not shown above, amounts to less than 1 per cent. The electric furnace delivers in the metal 82.7 per cent of all the heat furnished it, using 30.9 per cent of the thermal equivalent of the electric input in heating the metal.

Heat Balance in Per Cent

A summary of the heat balance based on the process as a whole appears in Table XII. The tabulation may be condensed somewhat further and expressed in percentages of the total heat supplied by fuel and power as follows:

	—Per cent—	
Heat of combustion fuel	86.5	
Heat equivalent of power	13.5	
Heat of combustion of elements in converter	2.2	
Heat loss in cupola		47.3
Heat loss in converter		1.9
Heat loss in ladle		0.3
Heat loss in electric furnace		9.1
Total heat metal		43.6
Totals	102.2	102.2

The figures show the relatively very great thermal efficiency of the process as compared with air furnace or open-hearth melting. A heat made from cold stock in the electric furnace would show a still higher thermal efficiency, approximating that of the electric furnace alone. This would not, however, correspond to a greater economic efficiency in view of the greater cost of a heat unit as electric energy than as coke.

From the viewpoint of fuel consumption a vast consideration of the electric furnace is not complete without pointing out that a consumption of 2½ pounds of coal per kilowatt-hour is an extremely economical figure, attainable only in unusually large turbine-driven plants.

There would be superimposed on this further transformer and line losses so that the electric furnace may get from 4 per cent to 8 per cent of the energy of the boiler fuel as electric energy.

This consideration, coupled with the high overhead for the power plant, accounts for the great cost of heat energy derived from electric power as compared with that of an equal amount of heat energy potentially present in the fuel.

IX

CUPOLA AND OPEN-HEARTH MELTING

IN ADDITION to air and electric furnace melting, which was discussed in Chapters VII and VIII, there are two commercial methods of melting malleable. That which employs the cupola can be dismissed with a few words, since its use for producing specification metal has been prohibited by the specifications of the American Society for Testing Materials since their first revision.

The objections to cupola metal are based on lack of uniformity of product and lack of control. Because of construction of the cupola and its method of operation, no large amount of liquid iron is accumulated at one time; therefore there is no assurance that successive taps will be even nearly the same in composition unless the charge consists of only one material, which manifestly is impracticable.

These variations are of no consequence in the general run of gray iron castings, but in malleable practice with its much reduced practicable range of composition they are prohibitive, especially for large work. Furthermore, since the cupola runs continuously for several hours there is no means of judging the fitness of the iron for its intended purpose either by analysis or fracture before it is poured.

Control of Metal Limited

Even when the best possible uniformity is secured the cupola process has limitations of control which render it unsuitable in the production of a general run of malleable castings. The molten iron runs down through a mass of incandescent coke, meeting in the spaces between the coke a stream of gas, originally air, but converted by the fuel into a mixture of carbon dioxide, carbon monoxide and nitrogen.

Under any given operating condition, especially as to temperature, a definite equilibrium exists which determines the composition of the products of combustion in contact with incan-

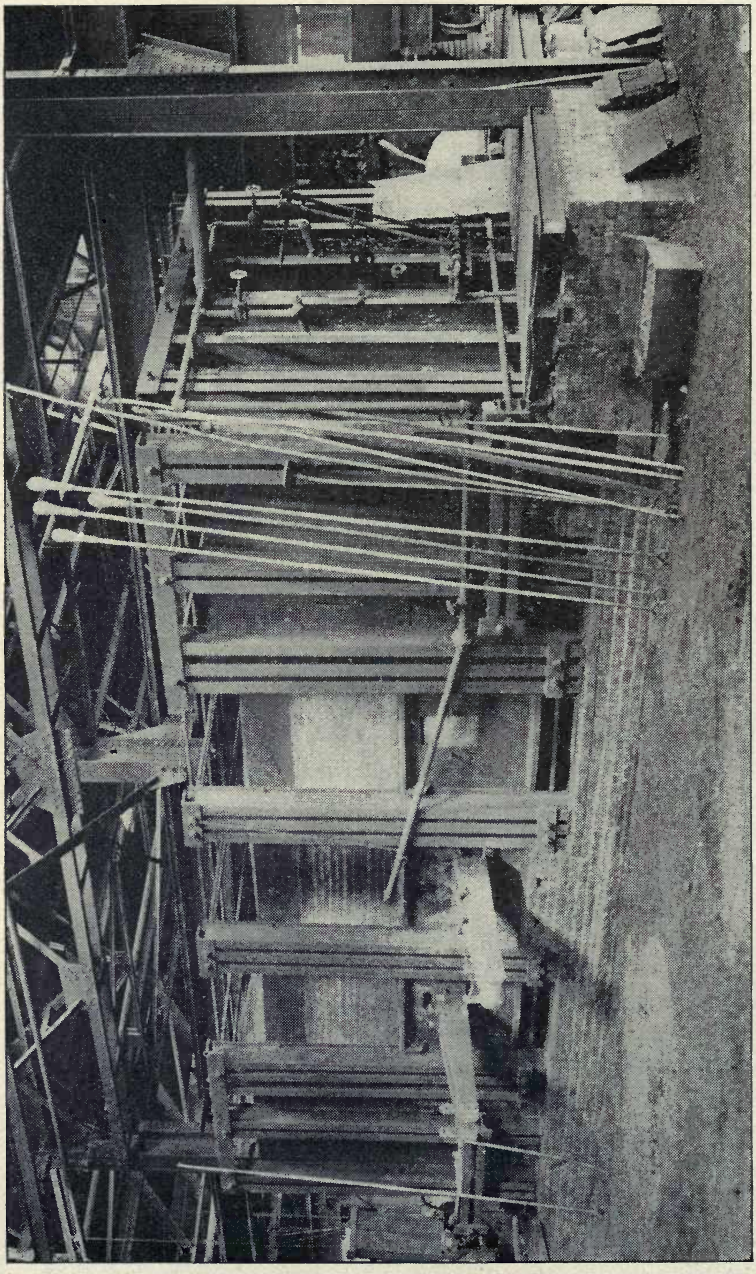


Fig. 86—Pouring side of open-hearth furnace for malleable iron

descent carbon at that temperature. The descending liquid iron thus passes into a zone in which temperature and gas composition are adapted to equilibrium with molten iron of only one specific carbon content and capable of adding or removing carbon easily if the metal comes down lower or higher than this value in equilibrium with the gas phase. Therefore a cupola produces metal of a carbon content almost independent of that of the charge and dependent solely on the combustion conditions.

The possible range of working conditions is such as to produce metal containing from about 2.70 to 3.25 per cent carbon—a value too high for the production of a high class product except in small work. The sulphur content of cupola metal also is invariably high in view of the intimate contact of molten metal and fuel.

Some cupola metal made for extremely small work thus is converted into white heart malleable, possibly without the full understanding of the operator, and the work is annealed by decarbonization of the thin sections and not by graphitization.

The surviving successful application of the cupola process to black heart malleable is in the manufacture of pipe fittings where the product usually does not have the greatest possible strength.

The metallurgy of cupola melting has been considered in Chapter VII in connection with the triplex process. However, a higher fuel ratio is common in ordinary cupola melting than in the triplex process because the iron must leave the cupola at a higher temperature in order to run into molds than if it is to be handled only by a crane ladle.

A ratio of metal to fuel of between 4 to 1 and 6 to 1 may represent operating practice, and this represents the one great advantage of the cupola—cheapness both of construction and operation, the utilization of heat being about two or two and one-half times as efficient as in the air furnace.

Open-hearth melting, especially when large tonnages and continuous operation are involved, should be a desirable method of operation. That its practice is confined to relatively few

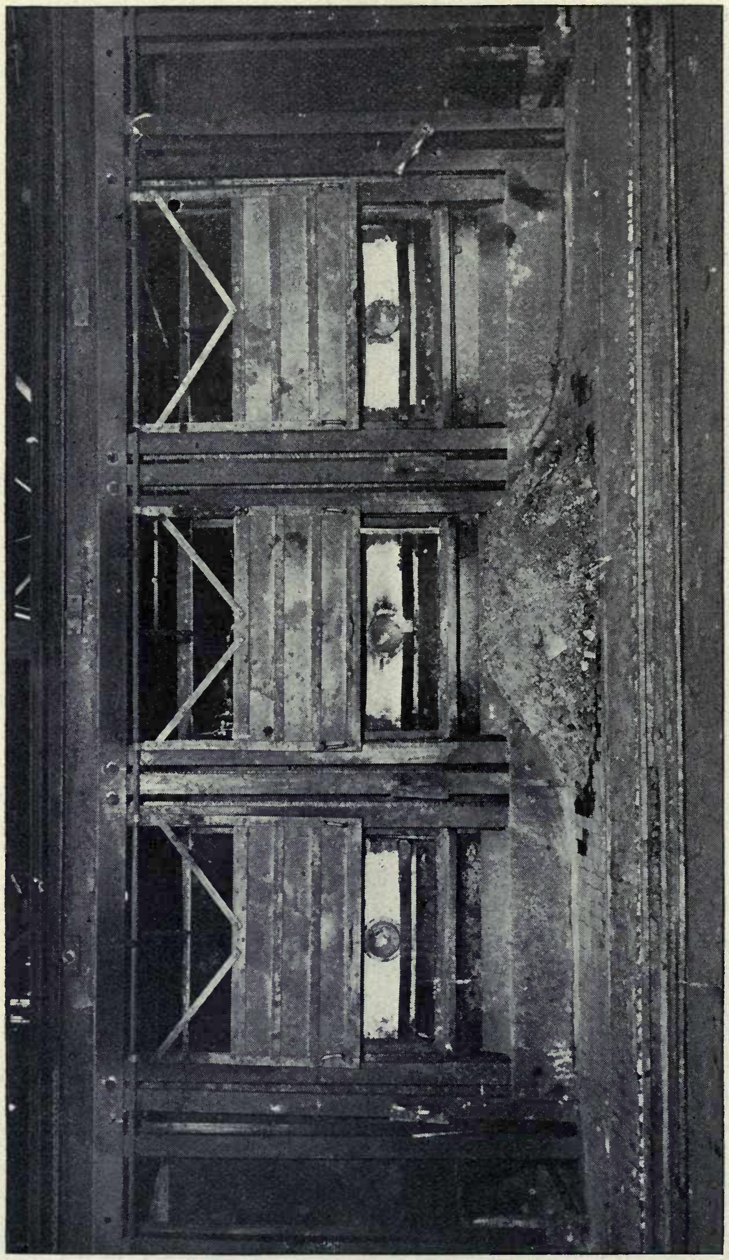


Fig. 87—Charging side of open hearth in malleable plant

plants may be due to the conservatism of the industry and to the tonnage limitation.

In general, the open-hearth furnaces used in the malleable industry are similar in construction to those used in steel making and in size represent the lower limits of capacity used in that industry. Some experimental heats have been made in basic furnaces but acid-lined furnaces apparently are used for commercial operation.

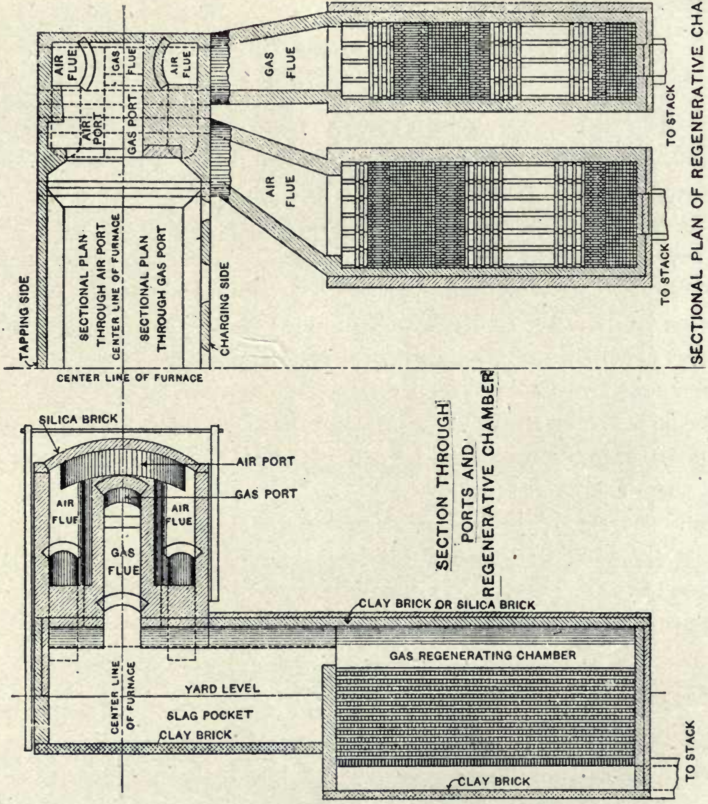
The melting operation is similar in principle to air furnace melting, except in the application of the heat.

Furnaces ranging in capacity from 5 to 20 tons have been used, the larger units being preferred when practicable. The furnace roofs are of silica brick and the bottoms of silica sand. The regenerative system upon which the operation depends is so well known as hardly to require description. The products of combustion leaving the hearth pass through checkers of fire brick and impart their heat to these brick. When the brick is thoroughly heated the direction of gas passage is reversed, the air being drawn into the furnace through the previously heated checkers. The products of combustion pass out through checkers at the opposite end of the furnace. When producer gas is used it also is preheated. The incoming air gradually cools the hot set of checker work while the products of combustion heat the checker at the outlet end when the latter grow hot the direction of passage is again reversed, this operation being continued.

Using Heat of Flue Gases

The period of reversal depends upon the heat capacity of the checker work and in ordinary design a reversal every 15 to 30 minutes may be contemplated. The object is to utilize the sensible heat of the flue gases. The gases leaving the iron cannot impart heat thereto unless their temperature is above that of the metal. However, their heat can be imparted to the furnace content by using it to preheat the air and sometimes the fuel used before the combustion begins. In this way a higher furnace temperature and lower heat loss are maintained.

The heat loss depends upon the temperature of the out-


SECTIONAL PLAN OF REGENERATIVE CHAMBERS
TAPPING SIDE
AIR FLUE
AIR PORT
GAS FLUE
GAS PORT
AIR FLUE
SECTIONAL PLAN THROUGH AIR PORT
CENTER LINE OF FURNACE
SECTIONAL PLAN THROUGH GAS PORT
CHARGING SIDE
GAS FLUE
AIR FLUE
TO STACK
TO STACK
CENTER LINE OF FURNACE
SECTION THROUGH PORTS AND REGENERATIVE CHAMBER
SILICA BRICK
AIR PORT
GAS PORT
AIR FLUE
GAS FLUE
AIR FLUE
CLAY BRICK OR SILICA BRICK
GAS REGENERATING CHAMBER
YARD LEVEL
SLAG POCKET
CLAY BRICK
CENTER LINE OF FURNACE
CLAY BRICK
TO STACK

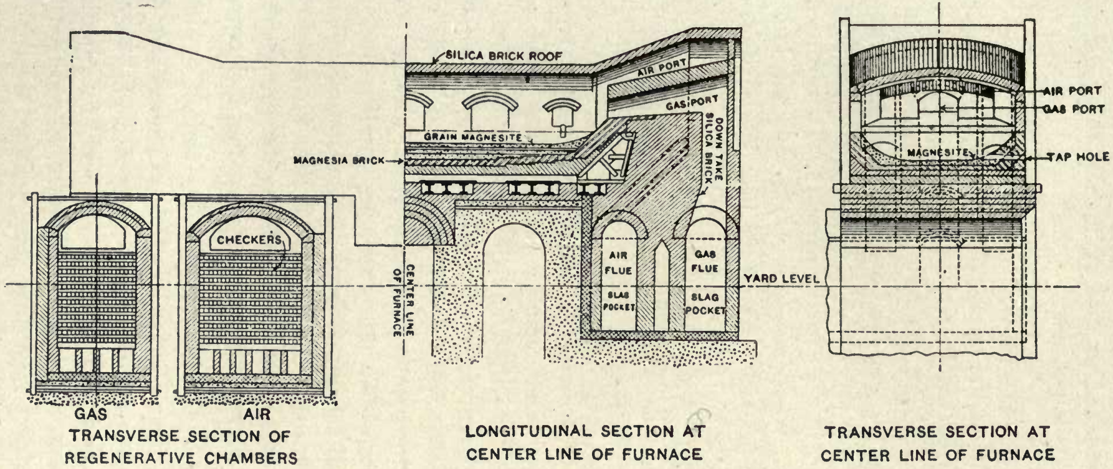


Fig. 88—Design of a modern, stationary open-hearth steel furnace.

Open-hearth furnaces for malleable melting usually range from 5 to 20 tons in capacity and are similar to those used in the steel industry, as illustrated above. The drawing shows the arrangement of the hearth, the air and gas ports, flues, regenerative chambers, slag pockets, etc. Within the past few years in the steel industry much attention has been given to the design of ports, and as a result several changes have been introduced which have appreciably increased the efficiency of combustion. The blow-torch principle has been applied to open hearths, with the result that ignition of the gas takes place promptly after the air and gas unite, and the flame becomes effective nearer the ports than heretofore. Unusually good operating records have been made with the new furnaces. It is believed that thus far, the blow-torch principle has not been applied to open hearths producing malleable.

going gases and this in turn upon the volume of the regenerator chambers and the period of reversals. In theory the outgoing temperature might be reduced to that of the incoming air and gas but this is practically impossible.

Campbell states that open-hearth steel furnaces should be capable of operation without the stack gases attaining a red heat. However, this result is not often attained. Assuming this red heat to be 900 degrees and the gas composition to be the same as in air furnace melting the sensible heat of the out-going gases is only 9/25 of that of the air furnace, counting from 0 degree Fahr. as a basis (which is not strictly correct). Therefore the heat value saved in the regenerators is 17/25 of that lost in the stack in air furnace practice. Using the heat loss in sensible heat of gases, leaving the air furnace as 7800 B.t.u. per pound of coal, and counting again from 0 degrees Fahr., the heat saved per pound of coal would be 5304 B.t.u. or over one-third the heat value of the fuel.

Quoting Campbell in *Manufacture and Properties of Structural Steel*, for a given sized chamber the escaping gases are a certain number of degrees hotter than the gases that go into it. If this difference is 300 degrees, then if the entering gas is 400 degrees, the escaping gases will be 700 degrees, and if the entering gases are 700 degrees the outgoing gases will be 1000 degrees. It will be seen that this reasoning implies that no change of economy results from changes of temperature in producer gas passing from the producer to the furnace. If no heat is lost in the gas while passing from the producer to the regenerator a loss corresponding to this saving is incurred in the outlet gases.

Since open-hearth furnaces are much less common in the malleable industry than air furnaces, correspondingly less is known of their design and operation. For general information on open-hearth operation the interested reader is referred to the literature of the subject regarding steel melting.

By kindness of Messrs. Lanihan and Fulton; the writer has been given access to a certain amount of data accumulated in the successful operation of open-hearth furnaces by the Fort

Pitt Malleable Iron Co., Pittsburgh. Much of what follows is based on that practice supplemented where necessary by conclusions drawn from other sources.

Malleable melting in the open hearth differs metallurgically in one essential respect from steel melting. The steel maker operates to greatly reduce the carbon and silicon content of the bath by oxidation. In malleable practice this oxidation must be kept down as much as practicable to insure control and reduce melting losses. Therefore the furnace atmosphere is subject to the same limitations as to composition as in air furnace practice. In view of the fact that this oxidation is actually kept down to about the same limits as in air furnace practice it seems reasonable in the absence of direct figures to assume that the CO, CO_2, O and N in the products of combustion should be about the same as is given in Chapter VI. An essential difference, however, will be the presence of a greater proportion of steam or water, since these furnaces are operated on natural gas and oil.

In the chapter on air furnace melting, the flue gas analysis was given as oxygen, 1.1; carbon dioxide, 12.7; carbon monoxide, 3.6; and nitrogen, 82.6 per cent. Assuming the gas in the present case to have this composition and assuming that the formula of the petroleum is $C_n H_{2n+2}$ the ratio of C to H in the fuel will vary from 3 to 1 to 6 to 1, depending on the molecular weight of the hydrocarbon being burned. We can calculate the flue gas per pounds of fuel closely.

Assuming a ratio of C to H of 5 3/4 (which probably is a little high but will compensate for the inaccuracy introduced by neglecting the carbon burned from the metal) we may conclude that one pound of fuel will require nearly 17.1 pounds of air for combustion, yielding 18.1 pounds of gas made up of the following amounts of the several constituents:

	Pounds
O	.152
CO_2	2.430
CO	.436
H_2O	1.322
N	13.76

If a gas analysis were made, the water would not be found, being condensed to a liquid in sampling for analysis. The composition by volume apparently would be:

	Per cent
O	0.8
CO_2	9.7
CO	2.8
N	86.7
Total	100.0

In the absence of actual analyses this may be taken as representing a near approach to the combustion conditions to be expected using oil fuel. The differences using gas fuel are probably insignificant as compared with the probable inaccuracies in some of the assumptions made.

The chemical changes occurring in the bath are identical in character and similar in magnitude to those occurring in the air furnace.

The oxidation losses in open-hearth melting have been investigated, in the light of the changes of composition during the process as determined at the Fort Pitt foundry. Typical results are given both in per cent of the original charge and in per cent of the original amount of the element present:

Loss in Open-Hearth Melting

	Total charge 100 per cent	Amount of element 100 per cent
C	0.49	16.9
Si	0.29	22.9
Mn	0.154	40.5
P	0.00	0.0
S	—.004	—10.00
Fe	1.58	1.6
Total	2.51	

It will be noted that the oxidizing conditions are similar to those encountered in air furnace practice and described under that heading. The gain in sulphur and loss of carbon, silicon and manganese are less in open-hearth practice than in air furnace practice. However the oxidation of iron is sufficiently greater to keep the net loss at nearly the same figure as in air furnaces.

These conditions can be further followed by a consideration of the composition of open-hearth slag. A representative sample of this material had the following analysis:

	Per cent
FeO	37.6
Fe_2O_3	2.7
MnO	3.87
SiO_2	51.30
Al_2O_3	1.95
Undetermined	2.58
	100.00

The greater oxidation of iron as compared with manganese is evident. The decrease in Al_2O_3 also is apparent, since the refractory lining is largely silica instead of largely alumina as in fire brick structures. The silicon entering the slag from the metal corresponds to 12.1 per cent of the weight of the slag. Therefore, the slag consists of 56.27 per cent compounds derived from the oxidation of the charge and 43.73 per cent melted refractories.

Comparing the iron content of the slag with the iron oxidized we find that apparently about 101 pounds of slag, or 5.05 per cent of the weight of the metal are formed per ton charged and hence by calculation 44 pounds of refractories or 2.2 per cent are melted per ton of metal charged. These figures again are similar in order of magnitude to those determined by more exhaustive study on air furnaces.

Heat Balance Based on Assumed Data

The heat balance of an open hearth can be calculated readily from a knowledge of the reactions occurring. Unfortunately we have not a complete record of tests involving all the factors to be considered. From the preceding assumptions and the fact that the average natural gas consumption of the furnace in question was about 8200 cubic feet per ton when regularly operated, the balance in Table XIII may be considered as an approximation, no claim to precision being warranted by the character of the data.

Expressing results in per cent of the heat value of fuel used and summarizing a little further the data may be expressed as in the summary in Table XIII.

In comparison with air furnace practice it will be noted that a general increase in economy is shown, 10.22 per cent of the heat of the fuel being effective instead of 7.81 per cent. The waste in sensible heat of flue gas and the loss due to incomplete combustion are decreased because, being gaseous or liquid, the fuel is all consumed and because hydrogen is present. Since the furnace constantly is kept hot, there is no perceptible heat loss due to sensible heat of furnace wall. However, there is a large loss due to the need of keeping some heat on the furnace during idle periods.

Table XIII

HEAT BALANCE OF OPEN-HEARTH FURNACE

	B.t.u.	B.t.u.
Heat value of fuel	8,514,000	
Heat value of metal oxidized	294,000	
Heat formation of silicates (estimated)	36,000	
Total heat input	8,844,000	
Latent heat of fusion and sensible heat of metal		879,000
Sensible heat of flue gas		3,007,000
Loss due to uncomplete combustion of C to CO only		545,000
Sensible heat slag		51,000
Latent heat fusion slag estimated		36,000
Radiation conduction and stand by losses		4,326,000
Total heat output		8,844,000

Summary of Heat Balance of Open-Hearth Furnace

	Per cent	Per cent
Heat value of fuel	100.00	
Heat reactions in bath	3.86	
Totals	103.86	
Heat in metal		10.22
Heat in flue gas		35.33
Heat in slag		1.02
Incomplete combustion		6.41
Radiation and standby losses		50.88
		103.86

This loss, increasing with the idle time, makes 24-hour a day operation highly desirable. With such operation it seems that possibly 25 per cent of the present fuel could be saved. Radiation and conduction losses would still exist but stand by and sensible heat losses would be eliminated. Under such conditions an economy of about 14 per cent in the use of fuel might be reached as against about 8 per cent in air furnace practice in 24 hour operation.

Open-hearth furnace heats range in size from 14 to 20 tons or more, preferably at least two heats a day being made on a furnace. Fuel in the plant in question is natural gas or oil. The gas consumption varies from 8200 to 9100 cubic feet per ton.

Oil fuel runs from 43 to 62 gallons per ton. In both cases the results depend on whether or not the furnace operates continuously or intermittently and on the condition of the furnace.

For heats from 15 to 18 tons in size about 5 to 5½ hours are consumed in melting; 20-ton heats take around six hours.

The efficiency of design is largely dependent on the checker arrangement with its corresponding effect on the utilization of waste heat. Unlike an air furnace, the open hearth requires rather infrequent but very extensive repairs. Furnace bottoms and banks are of course continuously watched and patched between heats. One furnace operated two years and two months, making 1282 heats with no repairs except cleaning the checkers and changing doors. The same furnace has since made 2051 heats with one cleaning of the checkers, a new roof, front, back and bridgewalls, an unusual record.

On the other hand, another furnace, running on one heat a day and frequently cooled ran only 200 heats before extensive repairs were required, showing the extreme destruction from unequal expansion in heating and cooling of the brick.

The labor to operate an open hearth consists of either three or two and one half men per furnace. Charging is not included in this labor. The work of charging into a furnace through doors is prohibitively heavy and charging machines are almost a necessity.

No data as to the use of pulverized coal or producer gas are available for malleable melting, although both of these fuels are used in steelmaking with great success.

X

ANNEALING PRACTICE

THUS far in the discussion of malleable foundry practice the various methods of producing molten white cast iron have been considered. The next step is converting the hard iron casting into the malleable casting of commerce.

Unfortunately this process still is most widely known as annealing instead of the better terms, heat treating, graphitizing, or converting. It is the intention to describe mainly the practical execution of the process in this chapter.

The process primarily is only an effect of time and temperature, and not a chemical one in the sense of a change of composition. Therefore a general consideration of the subject should begin with the viewpoint of the general methods of application of temperature to the product, leaving for later discussion the practical limitations of temperature and time and the incidental change of chemical composition involved.

The practice of annealing as originally developed contemplated packing the castings in a chemically active packing material in cast iron containers and transferring them into an oven where the desired heat treatment was executed. This method of operation still is used conveniently, although it is now thoroughly recognized that the use of packing is by no means an essential in the process. In addition to its control over the chemical changes occurring in the product by oxidation, the packing has the important function of supporting the casting while hot.

Packing Supports Castings

Commercial annealing contemplates the attainment of maximum temperatures of from 1500 to 1850 degrees Fahr. and the maintenance of such temperatures for days at a time. Obviously iron at this temperature will be fairly soft and a casting of any intricacy would be irretrievably ruined by sagging if not supported. Except in such special cases as may arise where the design of the part is such as to be practically self supporting, some method therefore must be adopted for preventing the distortion of the casting either under its own weight or under the weight of the castings in the pots above it.

A second function of packing, in its present application is to hinder rather than to accelerate oxidation. If a casting be exposed directly to the products of combustion of the fuel at these high temperatures it will come out badly scaled and possibly ruined for the purpose intended. There are few better means of protecting the casting from furnace gases than enclosing it in a fine inert packing.

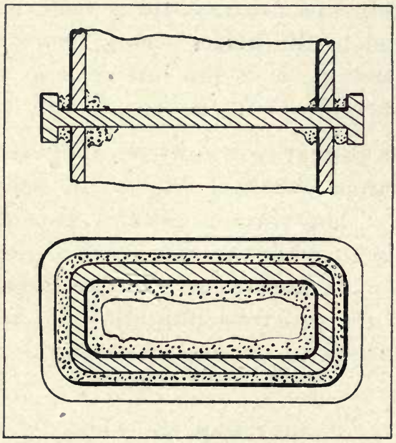


Fig. 89.—Separator plate designed to eliminate use of packing with annealing pots

How Castings Are Packed

The process of packing is carried out in malleable annealing as follows. First a bottom which is practically a heavy cast iron bench with legs 4 or 6 inches high is set on the floor. On this is set a pot which is an approximately rectangular or round frame, usually about 12 inches deep.

The size and form of pot depends largely on the work handled and to some extent on the whim of the annealer.

Unusually large pots fill the space in the furnace more completely than smaller pots but heat slowly and rather unevenly due to the low conductivity of the packing material. Round pots do not distort as much due to the sagging of the contents as do those with flat sides. However, they heat more slowly and do not utilize the furnace capacity as efficiently as the latter. Furthermore in most places the pots are handled by hand so that too great weight must be avoided. The pots must be about 1 inch thick to have a commercial life and hence extremely large pots can not be made as deep as smaller ones. Also when large they are not easily stacked very high and therefore a waste of oven capacity may result.

The writer has seen rectangular pots as large as 30 x 36 inches inside used where the character of the castings made this size unavoidable. Round pots frequently are 24 to 30 inches inside diameter. Rectangular pots running from about 14 x 18 inches to 16 x 24 inches inside are common.

Where the work is of such character as to stack solidly together, a pot of the smaller size or only a little larger will give a stack as heavy as can be readily moved or uniformly heated. In thin, sprawly work larger sizes may be unavoidable. The pots are made of white cast iron either like that in the castings or of a cheap cupola iron high in sulphur and low in manganese which will not graphitize.

Method of Packing Pots

After the pot has been placed upon the stool, the first step is to put in a layer of packing from one to three inches thick. On this are shoveled or packed sufficient castings to nearly fill the pot. Small castings, for example link belt parts, are shoveled in. Large castings usually are set in regularly to conserve space, care being taken to fill the spaces remaining inside or between large castings with smaller ones as far as practicable. As much packing is shoveled in from time to time as can be made to run down into the spaces still remaining. Extremely complicated work must be placed carefully so that it may be perfectly supported at all points. This sometimes necessitates the use of special plates and other supporting devices designed particularly for the part in question.

Factors Affecting Heights of Stack

When the first pot is nearly full a second one is set on it and the packing continued as before. The building up is continued until the stack of pots is from 3½ to 6 or 7 feet high above the top of the stool depending on the height of furnace and the ideas of the annealer. Care is taken that the top pot be finished with several inches of packing into which no castings project and usually the top is covered with a plate or with fire clay, or both. A reasonable height must be attained to secure economy of space. On the other hand, stacks of excessive height are not only difficult to heat uniformly but are subject to careless packing since the packer must stand on a stool and pack in an inconvenient position. High stacks also are easily upset in handling. The writer favors a stack four pots high where the individual pots are 12 to 15 inches deep, thus making a maximum height of stack of 60 inches above the top of the stool.

In any event, after the packing is complete and before the cover is put on, the stack of pots is rapped with a heavy hammer or otherwise jarred to settle the packing solidly. It is easy to leave 20 to 30 per cent of voids due to careless packing. This not only reduces the capacity but permits the ingress of furnace gases and also lets the charge settle, usually unevenly. The result is badly warped castings, scaly iron and possibly some completely burned castings in the top pots where the packing has sunk away.

The life of an annealing pot depends somewhat upon its composition, but more largely upon the furnace atmosphere to which it is exposed. Pots which crack from internal stresses do so in the first or at least in an early exposure in the furnace. Thereafter failure is by oxidation of the surface, which depends on the thickness of the pot, temperature of the furnace, time the pot is in the furnace, and combustion conditions. A life of from only 10 to 12 passes is frequent, but the average probably lies between 15 and 25 passes. Under favorable conditions a pot may survive from 30 to 50 trips through the furnace.

Pots are made either of the same metal used for castings or of white cast iron from a cupola operated for that purpose. In the latter case the mix is usually such as to produce a sulphur-manganese ratio which nearly prevents graphitization. This is an advantage as reducing the growth of pots in use.

The heating of an annealing furnace is invariably from the top down. This causes the top of a stack of pots to heat first. It is customary to counteract this tendency by packing the light work in the bottom and the heavy work in the top so that the greatest thermal capacity is nearest the source of heat.

The packing of castings is a fairly expensive operation involving considerable skill which if slighted is productive of bad work and loss of castings.

Various schemes have been suggested for working in empty pots to avoid packing. These take the general form of a set of plates between the several pots so that the matrial in the bottom pot does not have to carry the entire weight of metal above. Such methods were employed successfully for many years but require careful exclusion of air.

J. H. Fryer recently introduced a design of separator plate as shown in Fig. 89 which by its flanged construction permits the making of a good clay seal. While particularly important in pots where packing is not used, this sealing also is required in the usual practice.

The pots prepared by any of these methods are introduced into annealing ovens, which are merely fire brick chambers capable of being heated to the desired temperature. Some idea of the dimensions of these ovens has already been given in the general description of a malleable foundry. Ovens may hold from 25 to 100 stacks of pots, neither extreme being common. Nearly all ovens are deeper than they

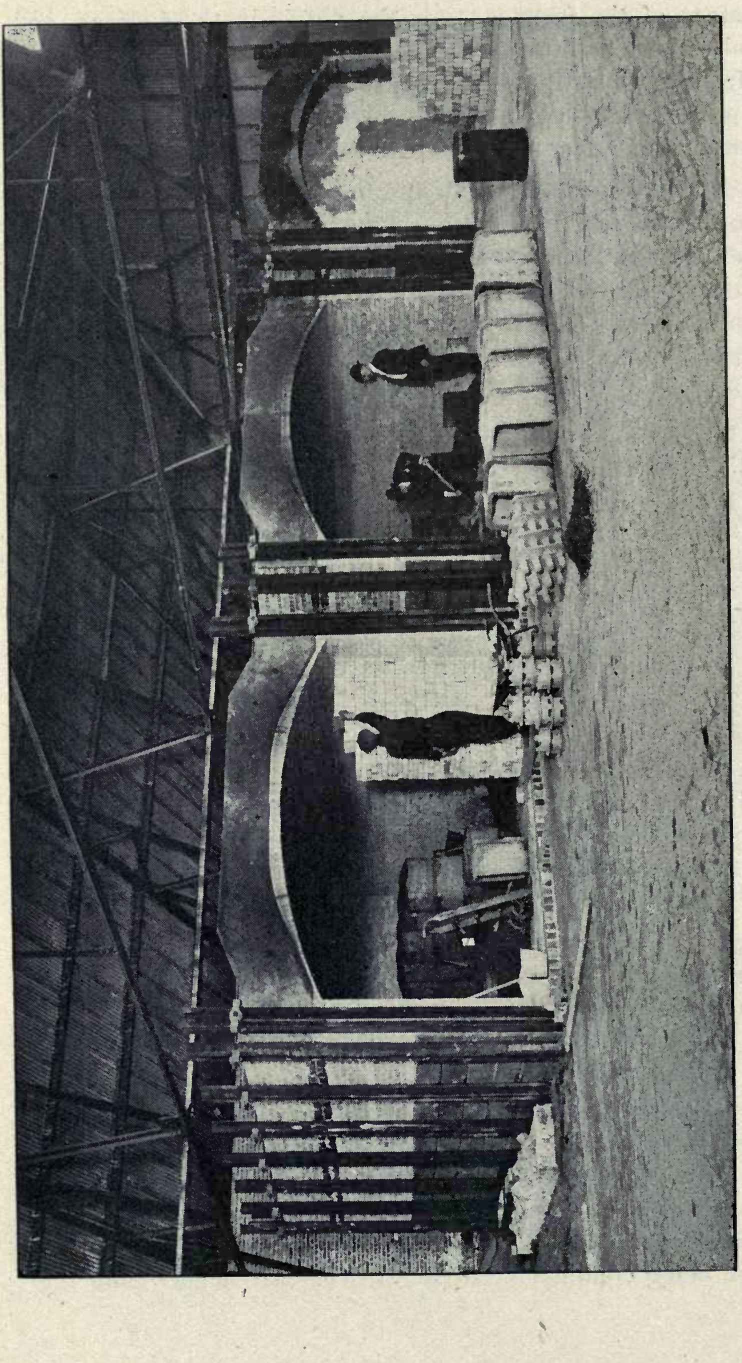


Fig. 90.—A view of the annealing department in a modern malleable castings plant

are wide, and the flame usually travels from back to front. A number of exceptions exist more particularly in pulverized fuel or oil-fired furnaces. The older ovens, and particularly the smaller units frequently were built in sets of two to eight ovens. In this way the loss of heat through the side walls and the waste of floor space was minimized. Heavy walls about 32 inches thick sometimes were employed to serve as heat insulators. More recently, with the advent of various types of heat insulating brick the actual wall thickness has been reduced.

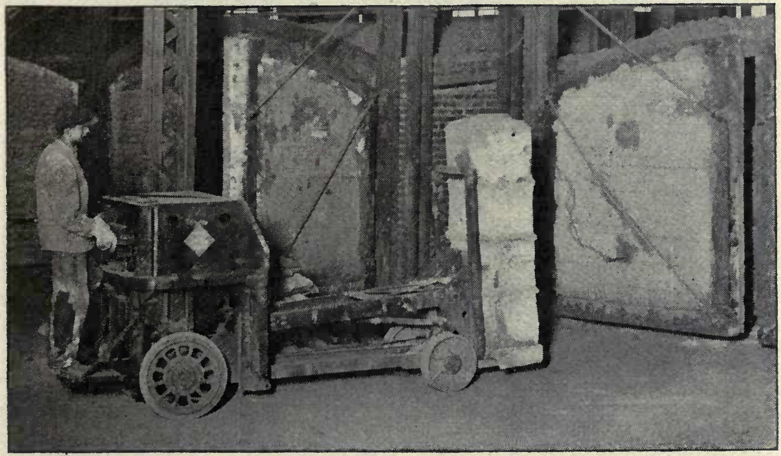


Fig. 91.—Charging trucks facilitate the handling of pots to and from the annealing furnaces

Many designers laid great stress on heating the annealing furnace floors by elaborate systems of checkers or flues through which the waste heat of the furnace passed. Other designers preferred to use only the necessary flues to carry off the flame from the furnace.

Large Ovens More Economical

Large ovens are economical of fuel as they present relatively little wall surface per unit of metal content. However, they usually are harder to heat uniformly, and therefore require greater skill in design. A number of engineers feel that wide arches are expensive to maintain. The relative importance of these factors in the mind of the designer usually influences the construction chosen in any given case. It is not likely that any wide difference in performance is to be expected from the possible variations in furnace dimensions. Economy usually dictates the use of a local coal for annealing fuel. The firebox design generally is extremely simple, consisting merely of an area fenced off in a back corner of the furnace by two walls a little higher than the stack of pots used. The grates, within this area, are fired through the rear wall. Occasionally, instead of providing an inside firebox, the firebox is built outside the furnace against the rear wall and communicates with the furnace chamber through a fire hole, which is like a window through a wall.

Various stoking devices, including automatic coal feeds, shaking grates, etc., have been used, but none of these seems to have commended itself sufficiently to gain a firm foothold in the industry. Possibly the explanation is that the firing operation in annealing does not require as careful control as in melting.

It is desirable both in the interest of economy and in order to avoid rapid burning of the annealing pots that an excess of air be prevented from entering the furnace. However with well packed pots the process will be operative, though uneconomical, if this precaution is neglected. Thus there has been little incentive to control annealing firing as closely as the melting operation where the making of good iron is impossible with poorly controlled fires.

Many producers of whom B. J. Walker is considered the pioneer, have experimented with pulverized fuel in annealing and a good measure of success has attended their efforts. The arrangements employed are of the same character as in air furnace firing, although the problem is slightly less difficult.

The standard design of annealing oven contemplates the introduction of the pots at the front of the furnace. The opening is closed by doors, usually made in sections which are equivalent to a front wall.

At an early date attempts were made to render the process approximately continuous. Seth Boyden built a "shoving" furnace of which G. H. Kingsland of the Wilmington Malleable Iron Works writes as follows:

"The furnace was torn down under my direction. The pots were 12 inches high and 10 inches wide each way, with a bottom just like a box without a cover. These were placed on rollers, pots being pushed in at one end and shoved out at the other. I believe the furnace held 30 of these boxes, five wide and six deep. One row of five was shoved out each working day and a row of five pushed in. The furnace was about 2 feet high at the crown of the arch, with flues under

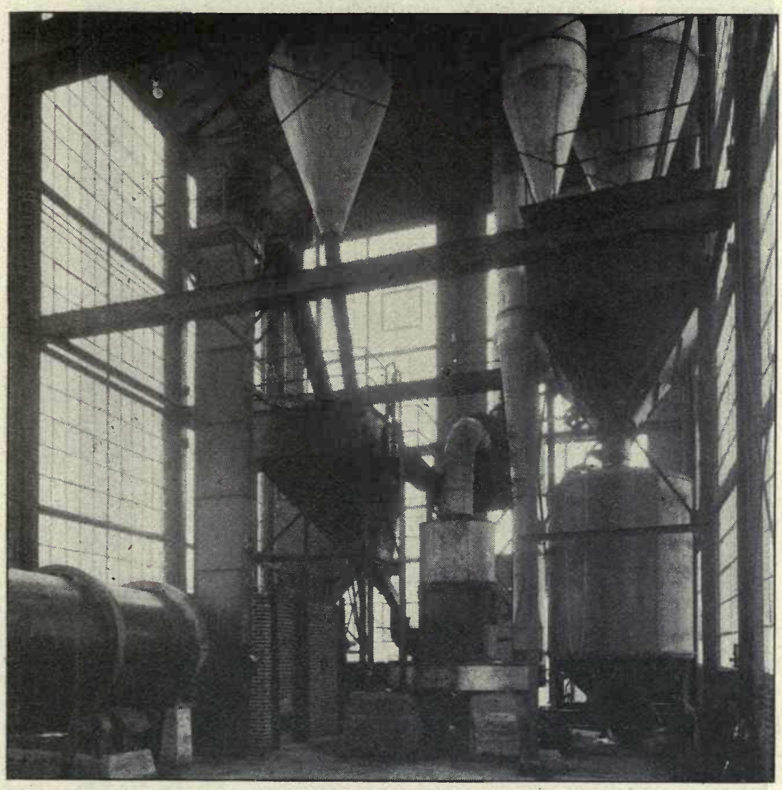


Fig. 92.—The interior of the powdered coal mill of a modern malleable plant. The horizontal cylinder at the left is the dryer

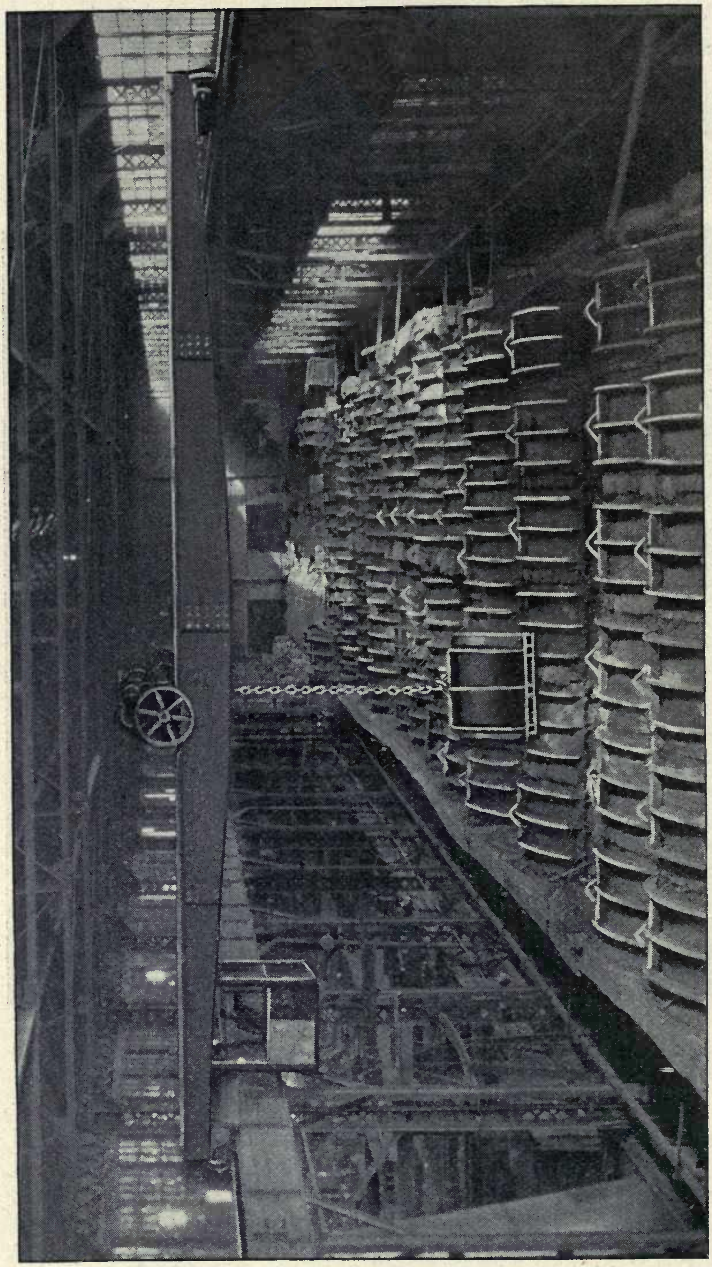


Fig. 93.—While most of the plants in the United States employ annealing furnaces similar to those shown in Fig. 90, a few plants use the pit type illustrated above.

the floor and in the side walls running to a stack about 25 feet away through a vitrified pipe. The Barlow people later charged the entire furnace at one time instead of at the rate of five pots daily."

Limitations of Removable Roof

In order to permit the loading of annealing furnaces by cranes the design is sometimes modified by forming the roof of removable arch-shaped sections, like the bungs in an air furnace. In this case no doors are required and the furnace is usually submerged in the ground almost to the spring line of the arch.

The heat insulation of the side walls in such furnaces is unusually good but heat losses through the roof are large since the limits of weight prevent the use of a roof of sufficient thickness. Moreover, the construction involves a great number of joints in the roof which are difficult to seal. The width of furnaces of this type is restricted because of the prohibitive weight of long roof sections. Therefore the design is along the lines of a relatively long and narrow unit, as compared with the nearly square floor plan of the ordinary furnace.

It is important that the furnace structure be protected from the effect of moisture if water is present in the soil in which the furnace is set. A story regarding a battery of furnaces built near a river subject to spring floods is well known in the mallealble industry. To the astonishment of their builder, these furnaces became miniature lakes when the back water from the first flood rose to a level higher than the furnace floor.

The practice thus far described involves the use of pots either with or without packing. Since pots and packing are expensive, efforts have been made to dispense with containers, muffle annealing being the outgrowth of these attempts.

Muffle-type Furnaces

Muffle furnaces—not "muffled" as frequently pronounced and even spelled—are constructed so that the flame from the fire box or burner does not come in contact with

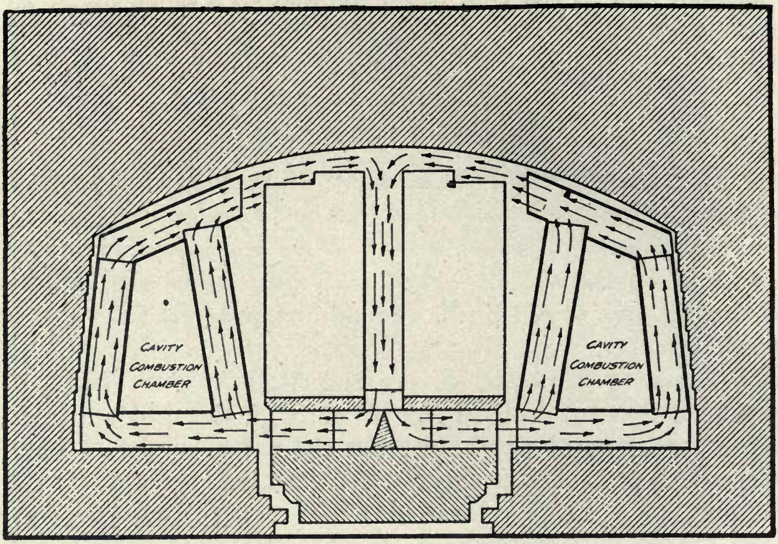


Fig. 94.—Diagram showing the distribution of heat in a continuous-type annealing furnace

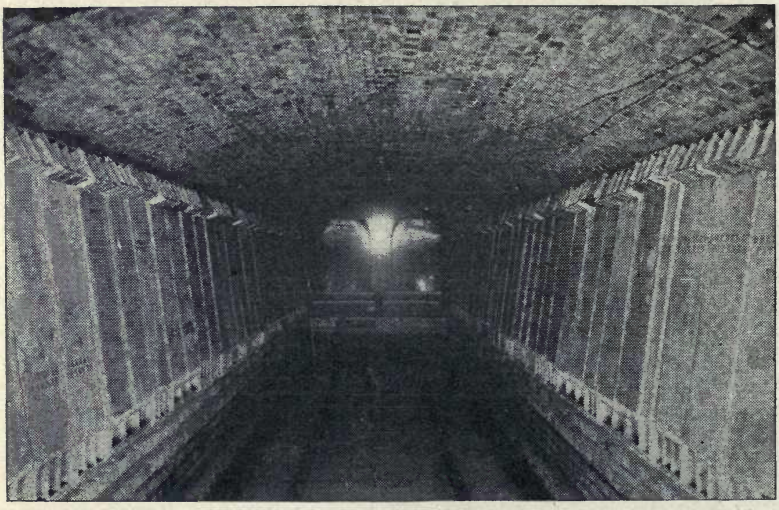


Fig. 95.—Interior of continuous-type annealing furnace looking toward the entrance end

the castings to be annealed. In their general design muffle furnaces represent the usual oven with the addition of a separate interior chamber or chambers. As usual, the flame enters the oven but instead of filling the entire space it merely passes through the spaces between the interior chambers or muffles and the walls, floor and roof. The muffles are built as thin as possible usually 4½ inches thick, in the interest of low thermal capacity and good heat conductivity. The castings to be annealed, which must be of a character not to distort easily when hot, are stacked in the muffles, the front of the muffles bricked up and the oven proper closed with the usual doors. The heat treatment is identical with that in the ordinary annealing furnace.

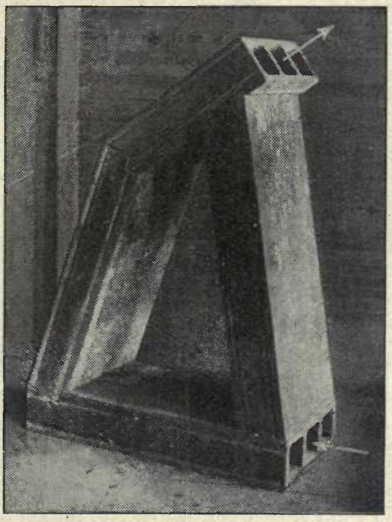


Fig. 96.—Single section of combustion chamber of continuous-type annealing furnace

At the conclusion of the treatment the castings are removed by hand; consequently the furnace cannot be "pulled" until the contents are well cooled. Therefore the output of the furnace is decreased by the time taken for cooling to

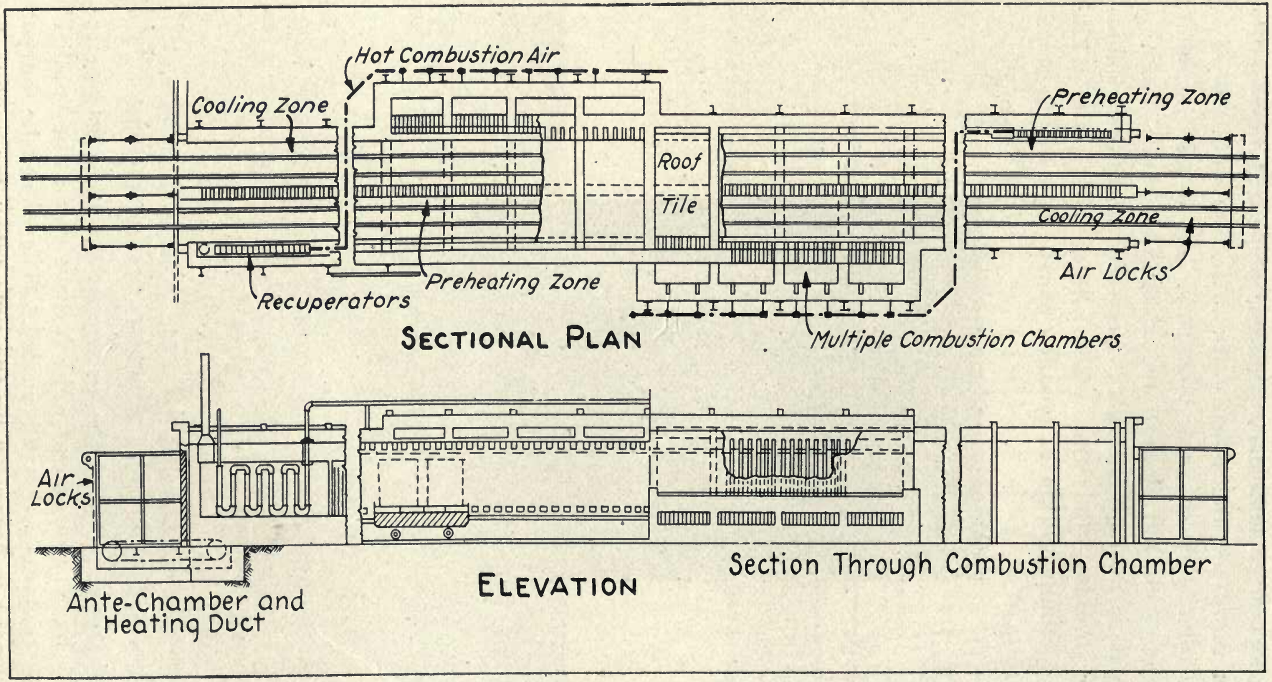


Fig. 97.—A sectional plan and elevation of a double-chamber, car-type tunnel kiln for annealing malleable iron castings. The firing zones are diagonally opposite each other

this temperature as compared with the time to cool sufficiently to pull pots mechanically. The thermal efficiency also is decreased since the heat must be transmitted to the castings through the intervening brick wall. On the other hand, the cost of pots and packing and the cost for heating pots and packing are saved.

In view of the fact that the efficiency of annealing furnaces is largely determined by the heat insulation of the walls and roofs and is consequently widely different in different plants, it is difficult to speak with assurance as to the relative economy of muffle and pot furnaces. The general impression toward muffle-type furnaces seems to be favorable. Reliable tests can only be made by weighing coal and iron on a series of runs in each of two furnaces of identical exterior construction, one loaded with pots the other having a muffle built within it.

The coal consumption for annealing varies greatly in commercial practice. Plants of good reputation burn around 1000 pounds of coal per ton of iron annealed, although with well-built furnaces and particularly with pulverized fuel much better records should be obtained. A quantitative idea of the heat values involved may be obtained from Table XIV, which is based on the theoretical heat requirements of the various reactions involved.

These figures are for the minimum possible use of fuel, making no allowance for incomplete or other imperfect combustion conditions, radiation from furnace walls, heat carried out by convection currents of cold air when the furnace is supposed to be cooling slowly, conduction of heat into the ground, etc. All of these losses exist and are of large magnitude. The aggregate of all losses is what makes up the difference between the theoretical coal consumption of 274 pounds per ton and the actual commercial figures of 600 pounds to 1000 pounds per ton.

Another way of approximating the radiation and similar losses is by considering the fact that an annealing furnace of ordinary construction will cool from 1500 to 1300 degrees

Table XIV

Heat Requirements of Annealing Furnaces

Available Heat of Fuel

	B.t.u.	B.t.u.
Heat value per pound coal		12,500
Flue gas from 1 pound coal theoretical combustion conditions:		
3.8 pound CO_2		
0.4 pound H_2O		
13.2 pound N		
17.4 Total		
Total sensible and latent heat in flue gas from 1 pound coal at 1100 degrees above atmosphere	5,000	
Total heat in cinders from 1 pound coal, sensible heat and heat of combustion of unburned fuel	160	
Maximum available heat per pound of coal (12,500-5,160)	7,340	
Total	12,500	12,500

Thermal Capacity Oven and Charge

	B.t.u.	B.t.u.
Total heat 1 ton castings at 1650 degrees above atmosphere		389,400
Total heat in 1½ tons pots and 1125 pounds packing at above temperature		955,350
Total heat wall, floor and roof 3900 pounds brick per ton charge raised average of 1200 degrees Fahr.		624,000
Total sensible heat furnace contents per 1 ton casting (of this 19.8 per cent only is in castings)		1,968,750

Heat from Chemical Reactions

	B.t.u.	B.t.u.
Heat from decarburization 1 ton castings ½ per cent or 10 pounds carbon burned to CO_2		142,200
Heat absorbed by reaction (10 pounds carbon) $6\ FeO + 5C = CO_2 + 4\ CO + 6\ Fe$		136,360
Heat evolved by decarburizing per ton of castings		5,840*
Heat absorbed by graphitization of 2 per cent carbon per ton castings. Reaction $Fe_3C = 3\ Fe + C$		53,640
Heat required to maintain chemical reaction per 1 ton of castings		47,800

Resume Based on 1 Ton Product

	B.t.u.	B.t.u.
Sensible heat castings	389,400	
Heat of reaction	47,800	
Useful heat	437,200	
Sensible heat furnaces, pots and packing	1,579,350	
Total heat	2,016,550	

Total heat required in oven at 7340 B.t.u. per pound of coal = 274 pounds coal per ton.

*Exact decarburizing reactions unknown. Assumption made on basis of known composition of resulting gases.

Fahr. in from 25 to 50 hours, depending mainly on the size of furnace and the heat insulating ability of the walls.

The area of walls and roof of an annealing furnace totals about 35 to 40 square feet per ton of capacity. With the foregoing figures it can be calculated that about 239,000 B.t.u. per ton of castings must be radiated to cool the furnace 200 degrees. This at the rate in round numbers of 6800 B.t.u. per square foot of oven surface (average furnace temperature 1400 degrees Fahr.) which in turn is at a rate of between 136 and 272 B.t.u. per square foot per hour.

Table XV

DISPOSITION OF HEAT IN ANNEALING FURNACE

Total heat in 900 *pounds coal at* 12,500 *B.t.u.* = 11,250,000 *B.t.u. per ton of castings* = 100 *per cent*

	B.t.u.	Per cent
Heat for chemical reaction in 1 ton of castings ..	47,800	0.52
Sensible heat in 1 ton of castings	389,400	3.46
Sensible heat in pots and packing	955,350	8.48
Sensible heat in furnace structure	624,000	5.54
Radiation and conduction, furnace structure	750,000	6.66
Sensible and latent heat flue gas (theoretical combustion)	4,500.000	40.00
Heat loss in cinders and air leakage	144,000	1.24
Sensible heat, excess air. error and unaccounted for (excess temperature, etc.)	3,839.450	34.10
Total	11,250,000	100.00

Assuming that 1400 degrees is the approximate mean inside temperature while the furnaces is under fire, the oven loses heat by radiation and conduction at the rate of between 5000 and 10,000 B.t.u. per hour per ton of contents.

Therefore with poor insulation the heat lost per ton from these sources will be 10,000 B.t.u. per hour that the furnace is fired, or 80,000 to 1,200,000 B.t.u. which figure may be halved by good insulation. This is equivalent to from 55 to 165 pounds of coal per ton, an amount insufficient to account for all the coal frequently used. The remaining losses presumably are due to intake of cold air, excess air for complete combustion, excess temperature of outgoing air, etc., and other similar losses to be determined only as the result of experimental investigation.

An idea of the heat balance may be obtained from Table XV, which is based on an assumed coal consumption of 900 pounds per ton of castings with only fair insulating and combustion conditions. The last item of the table is equivalent to a little less than 50 per cent excess air.

It will be noted from the table that only about ½ per cent of the heat of the fuel is expended usefully in the chemical changes, which are the purpose of the annealing operation, 0.01 per cent in producing the accompanying change in volume and only 3½ per cent additional in heating the castings themselves to the requisite temperature for the reaction to take place.

Obviously the thermal efficiency of the process is extremely low, due to the great heat capacity of the oven and its contents and to the great amount of heat which is carried out by the avoidably large mass of gas at fairly high temperature. If the alternate heating and cooling of the furnace structure could be avoided, if the furnace gases could leave the chamber at temperatures lower than that of the pots at their maximum and if the sensible heat of the pots after anneal could be transmitted to other pots just heating, greater economy could be effected. Attempts to do this have been shaped in various continuous annealing processes using tunnel-shaped kilns.

The Dressler-type kiln originally designed for use in annealing sheets and also for use in the ceramic industries is just entering the field. Only 3 of these have so far been constructed and, owing to business conditions only one has operated for a considerable continuous period of time. The principle of operation is that the heat treatment is accomplished by passing the furnace charge, on cars, slowly through a long tunnel of relatively small cross section. The tunnels are about 300 feet long and the cars of castings or pots pass through in the time required for one annealing cycle.

Any given part of the tunnel remains constantly at one temperature. The temperature varies along the length of the furnace to correspond to the changes in temperature which may be desired as the castings pass through the operation. Special forms of heating units have been developed using oil, gas or pulverized coal which are conducive to efficient circulation of the hot furnace atmosphere without necessarily contaminating it by admitting the flame itself.

Heaters Installed for High Temperatures

The heaters are installed where the highest temperatures are required and the products of combustion, leaving them at a temperature low enough to make the further transfer of heat to pots at their highest temperature impossible, pass on and are further used to begin the heating of pots just entering the furnace and to preheat the air for combustion.

Further details of construction involve the use of air locks to permit the work to enter and leave the kiln without admitting air, the mechanical means of moving cars through the furnace, etc. In the absence of any operating data on such kilns in malleable practice the effect on fuel saving can only be surmised. The principal sources of fuel economy which may be expected in a continuously operated kiln are the following:

First, the fact that the furnace structure is neither heated nor cooled results in a saving on the basis of our previous figures of 624,000 B.t.u. per net ton. Second, the fact that since the flue gases and also the product being annealed impart much of their heat to the incoming material, the loss in sensible heat of flue gases and of pot packing and so on should be considerably reduced. Third, the furnaces now in use being oil or gas fired, should permit of more economical use of fuel than can be had in furnaces fired with coal. Fourth, it should be possible to reduce air leakage in a kiln of this type far below what could be done in the case of a furnace through which the products of combustion are forced to pass.

Offsetting these economies the long slender furnace presents a somewhat greater surface per ton of content so that radiation losses would increase considering an equal degree of heat insulation in the tunnel furnace and in an oven. In practice this loss is largely counteracted by efficient heat insulation on the walls and roof of the structure.

On the basis of entirely arbitrary assumptions as to exit temperatures, flue gas composition, etc., the writer has calculated that it might be possible to anneal a ton of castings in a kiln of this type with the expenditure of about 2,100,000 B.t.u. It must be clearly understood that these figures are speculative only, and in no sense founded upon experimental results.

At the time this is written only one furnace of this type has been operated sufficiently long to be considered beyond the experimental stage. The best information at the author's disposal is that in the furnace in question about four million B.t.u.'s were required for annealing a ton of product.

As in the case of electric melting furnace equipment it must be remembered that the entire plant layout must be adapted to the use of the continuous kiln and suitable provisions be made for the transportation of trucks and the mechanical handling of material in connection therewith. Also as in the case of the electric furnace a very considerable first cost is involved as compared with the simpler units. Again as in the case of the electric melting operation one of the hoped for advantages from the use of the more elaborate method is a better control of the product, in this case arising from the greater uniformity of the heat cycle to be expected in a tunnel kiln operation as compared with the operation of a furnace which has temperatures varying widely, not only from time to time, but also from place to place in the furnace. Touceda has designed annealing furnaces of the usual form in which attempts are made to carry the elimination of heat losses as far as practicable. He has also suggested a furnace heated by fuel in which the temperature once reached would be maintained electrically by nearly automatic means. Such a furnace if practicable would be very interesting. At least one concern is attempting to introduce an electrically heated furnace. This, however, is decidedly in the experimental stage. So much for the practical execution of the annealing operation.

Controlling Annealing Temperatures

In any annealing operation pyrometric control will be required. Thermocouples are somewhat frequently introduced in nichrome or ceramic tubes through the furnace wall or roof. The practice has the advantage of a quick response to changes of firing conditions and is the only one possible in the continuous furnace. However, it does not give any data as to the temperature of the metal itself and accordingly it is advantageous to have one or more couples actually within the pot. The interior of a good sized pot may lag 15 or 20 hours behind the furnace temperature. The lag is less the more solidly the pot is filled with iron and more the greater the per cent of packing. These figures apply when the furnace temperature is known and uniform. If the space into which the couple penetrates is filled with flame then the flame temperatures, varying as they may several hundred degrees in a quarter of an hour or less, are absolutely meaningless. Theoretically it may be possible to mount a couple in a protection having the same temperature lag as an average pot.

Many satisfactory pyrometric equipments are on the market. Provision for automatic recording is virtually essential. The writer's preference is for potentiometer recorders. He further prefers a tape record to a disk record. In large plants multiple point recorders are convenient. Noble element couples seem commercially undesirable at the temperatures involved, both on account of expense and the low electromotive force. In oxidizing atmospheres, couples of the chromel type have a good life but neither these nor platinum will survive reducing conditions. Iron-constantan is perhaps most satisfactory under those conditions.

For data on the construction, operation, and characteristics of various types of pyrometric equipment reference is suggested to *Technologic Paper* 170 of the United States bureau of standards, "Pyrometric Practice" by Foote, Fairchild & Harrison.

A very brief exposition of principles must here suffice.

Any thermocouple sets up at its terminals a difference of potential, or millivoltage, depending upon the difference in temperature existing at the junction of the two dissimilar wires and the temperature where these wires are joined to the copper of the instrument or distributing system. To know the temperature of the hot end we must know that of the cold end. We may read this with a thermometer or else keep it constant either by burying the cold end in the ground, circulating around it water at constant temperature or introducing it into a thermostat kept at a controlled temperature above that of the room by electric heaters automatically switched on and off to maintain a fixed temperature. Boiling water, kept supplied to replace evaporation may be used.

There are also electric devices for compensating for "cold end temperature."

The thermocouple electromotive force is measured by a millivoltmeter which however actually measures the current set up by the electromotive force through the assured constant resistance of the instrument and external circuit. Since current is the quotient of electromotive force divided by resistance the readings may be affected just as much by changes of resistance as by changes of electromotive force. Such changes are counteracted by making the resistance of the instrument high as related to that of the thermocouple and leads. Accidental changes of resistance external to the apparatus may be small or even negligible fractions of the total. Such high resistance instruments are difficult to make rugged. Another course is to use low resistance instruments and take pains to keep the total resistance constant. This is possible but troublesome. All indicating instruments depend for their accuracy on some torsion member, springs or suspension exactly retaining its elastic properties unaltered.

The only available means for directly measuring an electromotive force is to oppose it to another variable and constantly known potential using a galvanometer only to indicate, by the absence of any current when the two are exactly equal. The apparatus for doing this is called a potentiometer. Its use is usually slightly less convenient than that of a millivoltmeter but avoids all errors except those due to variations in temperature of the cold ends. This can also be electrically compensated. The potentiometer also can be built with a more open scale than a millivoltmeter nor need the scale begin at zero, so that the scale length available can be used for only that range of temperature of interest in the process, say 1000 degrees to 2000 degrees Fahr. Either type of apparatus can be made autographic. Although this is slightly more complex for the potentiometer type this system has the advantage that the motion of the pointer is rectilinear and not a circular arc as in the galvanometer type instruments.

XI

PRINCIPLES OF ANNEALING

ALTHOUGH the general principles of graphitization and decarburization as applied to annealing and the commercial methods of applying heat treatment to castings have been considered in preceding chapters, it may be well to correlate the scientific principles and commercial equipment with a view to providing a more definite practical understanding of the art of annealing.

It has been repeatedly stated in the chapters of this book that annealing consists primarily of the conversion of the metastable system Fe-Fe_3C into the stable system Fe-C. This involves no change of chemical composition and is not the effect of any chemical action on the iron by packing, furnace gas or other substances. The only chemical reaction involved takes place within the iron carbide or cementite of the iron and involves only the chemical elements present within the iron, in unaltered amount before and after the reaction:

$$Fe_3C = 3\,Fe + C$$

The reaction involves the absorption of heat (8940 small calories per gram molecule) and hence the reaction will continue only if heat be supplied. Recent published articles have cast grave doubt on the heat of formation of Fe_3C. Different observers do not even agree on whether it is positive or negative.

In Chap. III a detailed discussion of the acceleration of the reaction with increasing temperature was given and it was pointed out that the reaction is necessarily incomplete at all temperatures above the lower critical point of the final alloy. The best and most recent data available to the writer has been summarized in Fig. 24 in Chapter III and point to a solubility of free carbon at A_1, considerably less than the eutectoid ratio of the metastable system. Below A_1 the solubility apparently becomes negligibly small but still existant. No evidence of a eutectoid of C and Fe as a metallographic entity has been found.

Metallurgically the purpose of the annealing treatment is to cause the iron to traverse such a temperature cycle as will completely and most expeditiously transform it into ferrite and temper carbon, having due regard to the resultant grain structure of the ferrite. The actual heat cycle required to accomplish this result depends upon the chemical composition and previous thermal history of the product annealed.

The control of the annealing oven to produce a given cycle is further influenced by the design of the furnace, the uniformity of temperature throughout, rate of heating, etc. Therefore the art of annealing cannot be taught adequately in a chapter of a book. At most the general principles may be outlined, it being understood that in practice the operations are shaped toward the desired end in accordance with the skill and experience of the annealer.

It already has been shown that the graphitization of cementite occurs more rapidly the higher the temperature and that the rate of this reaction decreases as the reaction approaches its end point. Consequently at first glance, it would seem advantageous to conduct the process in the beginning at the highest possible temperature. However, there are practical and theoretical objections to this procedure. The practical objections in order of importance are as follows:

1. The extreme warping or distortion of castings when softened by the high temperature.
2. The sintering or fusion of any available packing material from the same cause.
3. The wear and tear on the fire brick of the oven.
4. The decreased service obtained from annealing pots.
5. The increased fuel cost of attaining extremely high temperatures.

The theoretical reasons are even more important, being:

1. The large flaky character of the free carbon crystallizing out at the higher temperatures.
2. The poor ferrite structure set up under these circumstances.

Accordingly the metallurgist must determine for himself where the best balance between speed and quality may lie, having regard to the alloys with which he has to work. Opinions vary somewhat but the advantageous maximum of temperature of castings, as distinguished from furnace atmosphere or wall temperature, lies between 1500 and 1700 degrees Fahr. While graphitization can be initiated at temperatures far below 1500 degrees, the reaction at these lower temperatures is prohibitively slow without any compensating advantages. Few packings can be found which will withstand temperatures in excess of those occurring when heating castings to above 1700 degrees Fahr. Moreover, the effect on grain structure begins to make itself felt at this temperature.

The reaction at 1800 or 1900 degrees Fahr, is not sufficiently faster to warrant incurring the increasing difficulties which present themselves above 1700 degrees. Many malleable operators feel that the extra time required to anneal at temperatures not exceeding 1600 degrees is well spent.

A safe maximum temperature having been determined for the particular product under consideration, the annealer first directs his attention to attaining this temperature as rapidly as possible consistent with a reasonable uniformity of temperature throughout the oven. It is here that oven design influences the economy and quality of the annealing operations.

It is unavoidable that those pots nearest the source of heat will heat more rapidly than the rest. However, if a furnace is designed to permit the rapid and free circulation of flame, the differences of temperature will be far less than where such circulation is hindered to some extent.

All commercial furnaces have the heat supplied above the pots and all well designed furnaces have a sufficient height of roof to permit the flame to reach freely to the tops of the farthest pots. The author has never heard any annealer question the reason for introducing the heat at the top, all seeming to take this arrangement for granted. However, there is a good scientific reason for this design. The heating of the furnace contents is accomplished mainly by the vertical gas currents in the spaces between the several stacks of pots and to a minor extent by conduction downward through the pot and contents. If two of the vertical passages between the pots are at different temperatures, a gas current will be set up rising in the hotter and descending in the colder of the two. Therefore, if the hot

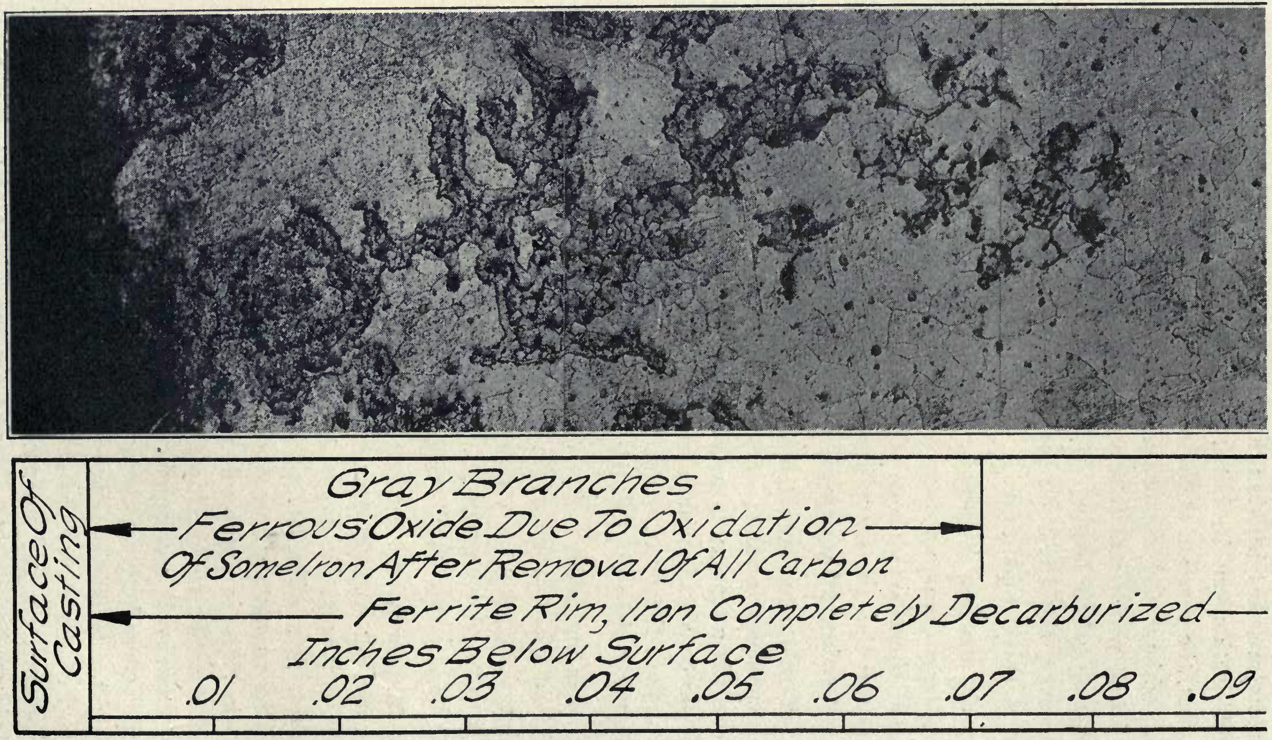


Fig. 98—Rim of a casting containing most of the usual defects due to annealing. Etched with picric acid, magnified 100 diameters and subsequently reduced one-third on engraving

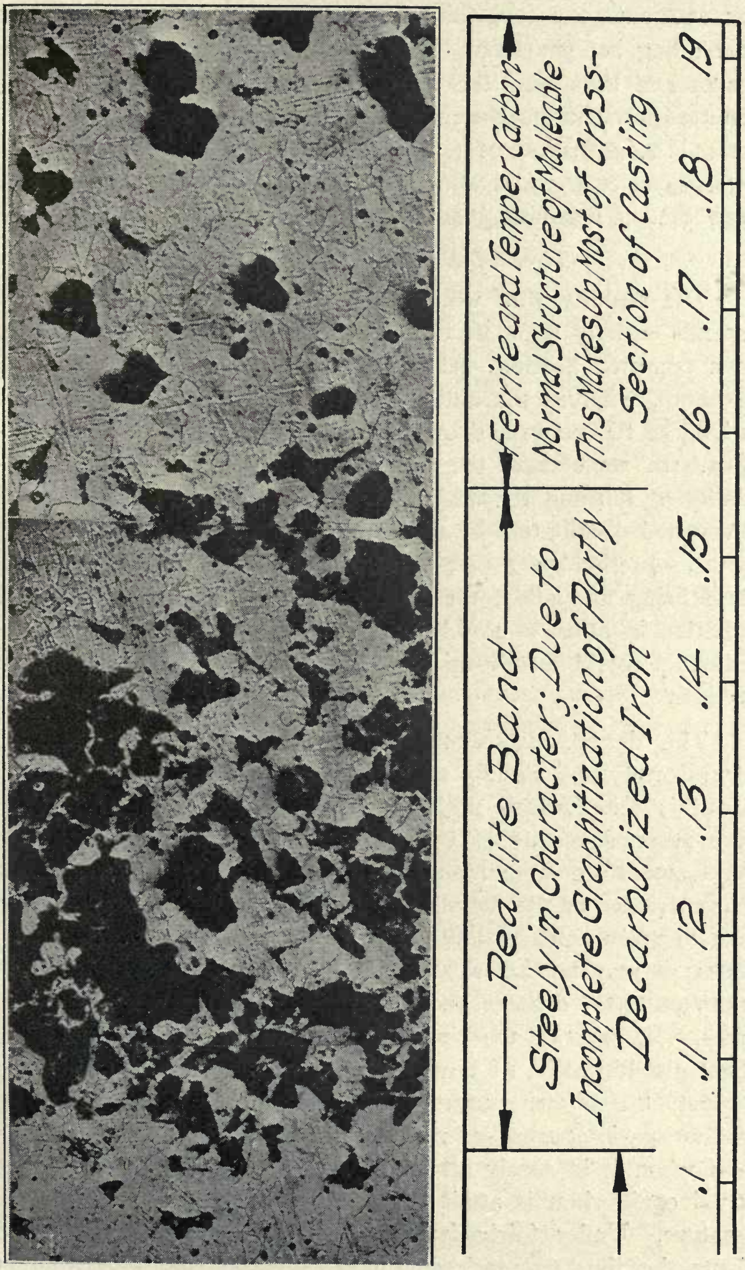


Fig. 98 (continued)—This portion of the micrograph adjoins that shown on page 216 at the right gas enters at the top, this circulation will tend to divert the descending hot gas from the hotter passages toward the colder spaces and thus heat the latter more rapidly. Were the heat admitted at the bottom the circulation described would cause an increase in the difference of temperature between the hot and cold passages since the ascending current in the hotter space would draw the hot incoming gases with it.

Time of Heating Varies Widely

The rapidity with which an oven can be heated uniformly depends entirely upon its construction. A number of observers have recorded heating cycles with pulverized fuel as short as 18 hours, whereas the author frequently has witnessed periods as long as 100 hours and over, usually under adverse fuel conditions. In some cases the increased time is due to the impossibility of burning the coal rapidly, while in others the rate of downward distribution of the heat in the furnace is the limiting factor. In the latter case it sometimes is necessary almost to cease firing and allow the heat to equalize by conduction and radiation in order to avoid overheating the top pots. This procedure is sound metallurgically but necessarily involves a waste of time.

The desired maximum temperature having been reached as uniformly and rapidly as possible, the next step is to maintain this temperature until the reactions within the castings have attained a state of equilibrium. This time depends upon the temperature chosen and upon the chemical and structural characteristics of the metal. In experimental determinations the time to reach actual equilibrium is long. Under favorable conditions it may be 20 or 30 hours at 1900 degrees, 100 to 150 hours at 1500 degrees and several hundred hours at 1400 degrees. In practice the times are materially shorter because a slight graphitization of cementite may be relied upon in cooling through the higher ranges of temperature and also because equilibrium is approached more rapidly during the earlier stages than when it is nearly attained. Indeed it might be said that actual equilibrium is attained only in infinite time at any temperature. Under fairly favorable conditions in well conducted plants the time to reach equilibrium within commercial limits may be roughly as follows: 1700 degrees, 25 hours; 1500, 50 hours, and 1450, 80 hours or possibly 50 per cent more under less favorable conditions.

These general relationships already have been indicated in graphic form in Fig. 36 in Chap. III. The time required is approximately inversely proportional to the temperature above A_1 for alloys high in carbon or silicon the time required is less than for those lower in these elements. The presence of excessive manganese or sulphur, or of some of the more unusual elements may prolong the time considerably. Also it is believed that the rate of freezing and possible other variables in the previous thermal history of the metal have an effect upon the rate of graphitization.

The combined carbon content at equilibrium is greater the higher the temperature, therefore the iron is not completely annealed at the expiration of the required time at the maximum temperature chosen. The carbon content, or solubility of carbon, as dependent on temperature has been definitely determined for metal containing about 1 per cent silicon. The relation is shown in Fig. 24. Therefore the anneal will not be complete unless the reaction is allowed to progress to equilibrium at or just under Ar_1. The Ar_1 point in commercial iron probably is between 1340 and 1375 degrees Fahr.

Approach Temperature Slowly

One way to accomplish the desired result would be to drop the temperature quickly from the maximum to just under Ar_1 when the reaction at the former temperature is complete and to maintain that temperature below Ar_1 as long as may be required to re-establish equilibrium at the lower temperature. This operation will readily yield perfectly annealed material but is difficult to execute in practice except possibly in tunnel furnaces. Under commercial conditions, equilibrium can be attained more readily just under Ar_1, by approaching this slowly from above at a rate permitting the graphitization to just keep pace with the falling temperature than by a quick drop and a long wait to establish equilibrium. Rates of cooling between four and 10 degrees per hour usually are desired and most operators prefer to cool more and more slowly as the temperature drops.

To make sure of attaining equilibrium a number of annealers wisely attempt to hold a constant temperature just under Ar_1 for some time. Nothing is gained by additional slow cooling after the reaction at Ar_1 is complete.

In many plants the cooling rate is determined by the heat radiation of the furnace. In these cases the annealer merely seals the furnace at the high temperature and lets it take care of itself. Fortunately, since the rate of cooling decreases as the temperature of the oven falls, a well insulated furnace cooling naturally will fall in temperature at a steadily decreasing rate, as the metallurgical theory required. Therefore the results of this practice often are much better than might be expected. Difficulties begin to arise when the cooling is accelerated by some unforeseen or unknown cause and the illogical operator is no longer able to account for his results.

It will be noticed that a complete annealing cycle may be subdivided into five distinct intervals as follows: Heating to maximum temperature, maintaining maximum temperature till equilibrium is attained in graphitization of cementite, cooling to critical point, holding just under the critical point, and further cooling to permit handling.

The first and last periods have no metallurgical significance and can be accelerated as much as is convenient. However, the second and the combination of the third and fourth, are determined by the product being manufactured and cannot be reduced below definite minimum values. The minimum cycle is divided as follows: Heating to 1600 degrees, 30 hours; holding at 1600 degrees 45 hours; cooling to Ar_1 and holding there, 35 hours; and cooling to handle, 5 hours. The total is 115 hours, which would make a six-day annealing cycle as an absolute minimum, the time above 115 hours being spent in charging and pulling. However, few plants are able to insure success in so short a cycle and seven days may be considered as the commercial minimum. Cycles of nine days and more are not uncommon with large furnaces in order to secure the best results.

The minimum annealing time is fixed by natural laws which cannot be changed to suit the wishes of the manufacturer or the consumer. Any attempt on the part of the user to hurry the producer is misguided. The response to such pressure will be in inverse ratio to the conscientiousness and intelligence of the particular manufacturer concerned. It would seem that self interest will drive the malleable founder to adopt the shortest workable annealing cycle in order to avoid the investment in additional ovens and their fuel supply. Nevertheless the author has known many purchasers of malleable who seemed to regard the operation of a long cycle as an arbitrary wish of the manufacturer imposed upon his customer without any adequate reason.

For many years the larger producing interests have been approached from time to time by frequently sincere but always poorly informed inventors claiming either to much reduce annealing time or sometimes to do away with annealing entirely. As a rule, those in the former class expect to accomplish results by changes either in furnace design, methods of heating, etc., or by some unusual and often secret packing. Being an atomic rearrangement within the metal itself, the annealing reaction cannot be accelerated or retarded by the material surrounding the casting.

The laws governing graphitization have been investigated by a number of entirely competent experimenters and depend on clearly known chemical fundamentals. The design of heat treating furnaces also is well understood. Changes in furnace design could only reduce the annealing time by accelerating the time of heating, since as already explained, the times and temperatures during the rest of the cycle are fixed by the metal being annealed. All of these patented or secret annealing methods therefore are foredoomed to failure.

It is conceivable, although improbable, that someone will discover an alloy with a carbon content, similar to that now used, of such a character that graphitization will be suppressed at temperatures above 1600 degrees Fahr. but which will graphitize easily or even spontaneously at lower temperatures. Such an invention would accelerate or eliminate the present annealing process. Since the alloys of iron with most of the reasonably common elements are constantly being investigated and no indications have been found of any elements with properties producing the complex effect here described in any degree, it seems most unlikely that any greatly accelerated annealing method for producing black heart malleable will be found.

Therefore producers and consumers should admit the necessity of adequate time for annealing and conduct their several operations in accordance. The author is still waiting to hear from a most enthusiastic engineer who, three months before this was written, offered to demonstrate the manufacturer's ignorance of annealing principles by taking home a sample of hard iron in the evening, annealing it over night and returning it completely annealed the next day.

Other incidental changes are produced in the metal while graphitization is going on. The clearest evidence that these changes are only incidental is the fact that the process of graphitization can be carried on perfectly without any gain or loss of weight. To prove this, an accurately weighed specimen of hard iron can be enclosed in a tube of difficultly fusible glass, the air displaced by hydrogen, the hydrogen pumped out to a fairly low pressure and the tube then sealed, so that the metal can be annealed surrounded by nothing but a trace of a reducing gas. Samples of 10 or 12 grams weight annealed in such a tube in accordance with the heat cycle of commercial practice, are unaltered in weight to 1/10 milligram. In other words, the weight remains constant to 1/1000 of 1 per cent.

Migration of Carbon

However, under commercial conditions the castings always are in an atmosphere having oxidizing possibilities. This atmosphere may be the atmospheric air remaining in the spaces not otherwise occupied or it may be the products of combustion or gases arising from reactions with packing materials. Therefore there always is a tendency toward burning out the surface carbon. The mechanism of the removal is interesting. Only the carbon in the outer layer of molecules can combine directly with any oxygen in the surrounding gas. Therefore unless either the gas can penetrate the solid metal or the carbon can migrate to the surface, decarburization would be limited to the infinitesimally small amount produced by burning out the carbon one molecule deep.

At one time it was generally believed that the gas penetrates but the migratory action certainly exists and is probably the major method by which carbon and oxygen are brought together. Carbon exists in iron at any temperature above *Ac*$_3$ in part, as a solid solution of a definite saturation value at any given temperature. If the carbon concentration is locally lowered below saturation, diffusion will enrich this area at the expense of the more highly carburized areas. So long as cementite, or undissolved iron carbide remains, the deficit will

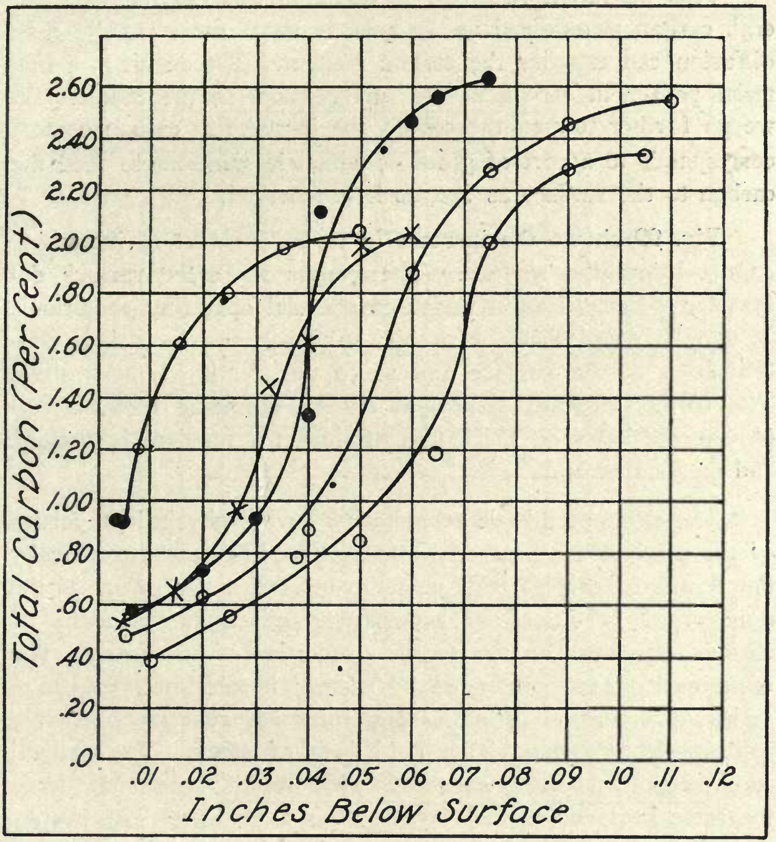


Fig. 99—Increase in carbon content at increasing depths below the surface of malleable cast iron

be made up by solution of additional amounts of this element in such a quantity as to maintain the solid solution in a saturated state.

This migration requires considerable time so that in general, carbon is oxidized at the surface much more rapidly than diffusion can equalize the carbon content. The result is a material poorer in carbon at the surface than in the center. As we go further toward the center, the increase in carbon content corresponds to a sort of gradient which is sufficient to feed the carbon to the surface as fast as it is removed.

Fig. 99 shows the increase in carbon content at increasing depths below the surface. The graphs represent various degrees of decarburization under commercial operating conditions. It will be noted that the graphs vary both as to carbon concentration at the surface and as to the depth of penetration. The former depends somewhat on the oxidizing medium employed, the latter on the length of time, the medium is applied, and on its activity.

The effect of this decarburization on the physical properties of the product are relatively small. Fig. 100 shows graphically the results of careful tests made to determine the effect of the removal of 1/16 inch of carburized surface in specimens of various diameters on the tensile properties of the metal. The experiments were conducted by casting tensile specimens to a series of diameters, grinding one specimen of each size truly cylindrical, removing about 1/16 inch of stock. The ground specimens then were annealed with rough specimens from the same heat and turned to size after annealing. The graphs show the amount by which the properties of the specimen ground before annealing exceeds the corresponding properties of the turned specimens.

The experiment was conducted in this form to eliminate variations due to cooling rate and original rough surface which variables are included in the data given in the chapter on tensile strength.

The tests were conducted on one lot of metal, all annealed together. Therefore they correspond to one set of decarburizing conditions only. Since decarburization varies, as the annealing conditions vary, another series of investigations was made to determine the changes in properties in iron of initially similar composition by variable decarburization.

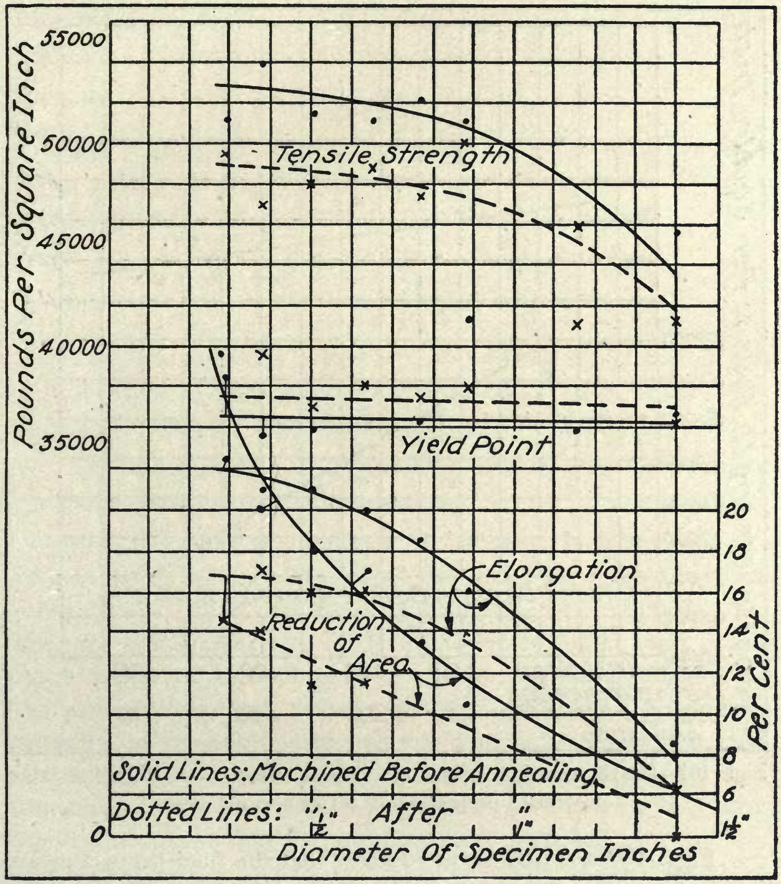


Fig. 100—Graph showing effect of removing 1/16 inch decarburized surface in specimens of various diameters on the tensile properties of the metal

Results of 50 Tests

In Fig. 101 have been plotted the results of some 50 such tests on iron having from 2.40 to 2.60 per cent carbon, 0.70 to 0.80 per cent silicon before anneal, which correlate the tensile properties with the carbon content after annealing. The graph is plotted from average values. Individual tests depart considerably from the average since small differences of carbon content in the hard iron affect the results much more than much larger variations in this element due to decarburization.

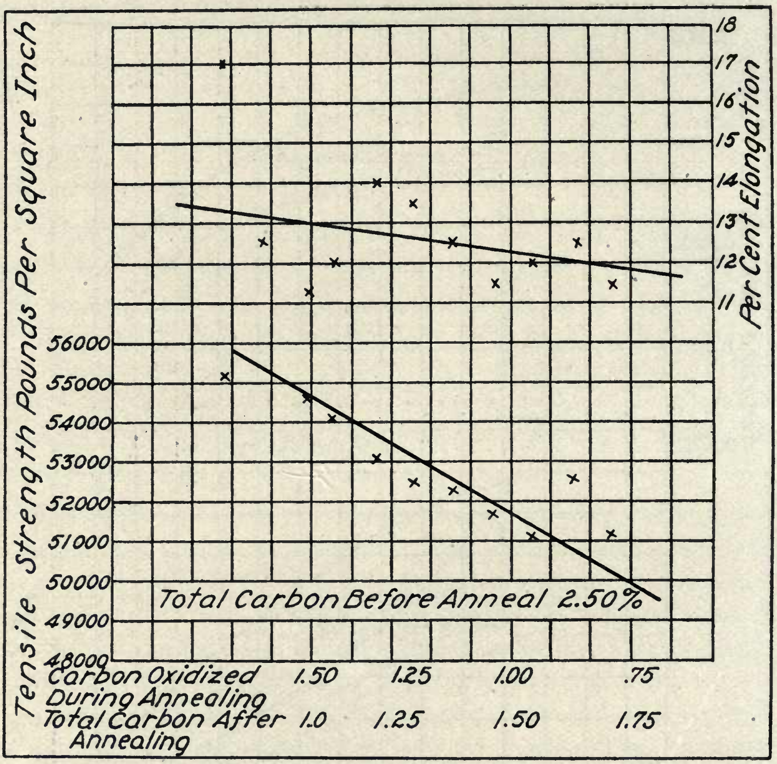


Fig. 101—Graph showing effect of varying degrees of decarburization on tensile properties of malleable cast iron

Figs. 100 and 101 serve to show that the final properties are relatively little affected by the decarburization process. Being measured on surface metal the elongation probably depends only in the carbon content near the surface and but little on the depth of decarburization. The tensile properties are somewhat more consistently affected by decarburization.

Decarburization is controlled in practice by the character of the packing material. Perhaps it would be more accurate to say that the results in practice depend on the packing used, there being but little available information with regard to the action of packing.

The commercial packings depend for their activity chemically on the reduction of ferric oxide, Fe_2O_3 to FeO, ferrous oxide. It is not to be understood that they actually liberate oxygen on heating as for instance potassium chlorate does.

Four Possible Reactions

The process is a chemical reaction in which the oxygen never appears as such but merely combines with carbon. Four reactions are possible, depending upon the circumstances:

$$
\begin{aligned}
3\,Fe_2O_3 + Fe_3C &= 2\,Fe_3O_4 + CO + 3\,Fe \\
6\,Fe_2O_3 + Fe_3C &= 4\,Fe_3O_4 + CO_2 + 3\,Fe \\
Fe_3O_4 + Fe_3C &= 3\,FeO + CO + 3\,Fe \\
2\,Fe_3O_4 + Fe_3C &= 6\,FeO + CO_2 + 3\,Fe
\end{aligned}
$$

The two reactions $FeO+Fe_3C=Fe+CO+3Fe$ and $2\,FeO+Fe_3C=2Fe+CO_2+3Fe$ are theoretically possible but occur only under unusual circumstances, if at all.

The reaction $3FeO+5CO=Fe_3C+4CO_2$ can probably occur under certain unusual conditions.

The fact that the analysis of packings is expressed as a rule in terms of the Fe_2O_3 FeO, SiO_2 and possibly Al_2O_3 and other oxides has given rise to the unfortunate conception that they are mixtures of two oxides of iron with other inert oxides. As a matter of fact all packings in use, as distinguished from the raw packing, have become complex silicates. The practical annealer unconsciously acts on this knowledge where he limits his additions of roll scale, or other raw material to small amounts at any one time, for a packing containing any large amount of free oxides is not a workable material.

The raw material from which packing is built up usually is roll scale or squeezer scale from rolling mills, pot scale (the oxide from the outer surface of the annealing pots after they are drawn from the furnace) or air furnace slag. Iron ore was once used but probably is now obsolete. Table XVI shows the composition in the usual terms, of these several materials.

It should be understood, however, that only the first three are actually oxides. Ore is nearly pure ferric oxide contam-

Table XVI

COMPOSITION OF TYPICAL PACKINGS

	FeO	Fe_2O_3	MnO	SiO_2	Al_2O_3
Ore	.00	91.43		8.57	
Pot scale	37.10	53.11		9.79	
Roll Scale	61.47	31.99		6.54	
Squeezer scale	69.74	9.34	.80	14.95	5.17
Slag	28.80	1.16	4.85	50.42	14.77

inated somewhat with silica minerals. Pot scale is a more or less impure magnetic oxide, Fe_3O_4 contaminated by sand adhering to the pots. Roll scale is magnetic and ferrous oxide originally nearly pure, but contaminated in gathering it up and shipping. Squeezer scale is a mixture of basic silicates of iron and manganese with some iron oxides, mainly ferrous oxide dissolved in bibasic ferrous silicates. Slag is a neutral silicate contaminated with fused brick, etc.

Some typical analyses of packings as actually used are shown in Table XVII both in terms of the usual proximate analysis and in terms of the compounds apparently present.

It will be seen that the packings contain little free oxide and are mainly silicates. The ferrous silicates are incapable of reduction to metallic iron under the usual annealing conditions so that the oxygen for oxidizing the carbon is derived primarily from the reduction of Fe_2O_3 to FeO although the ferrous oxide of pot and roll scale may enter into the reaction.

The relative amounts of carbon monoxide and carbon dioxide formed depend on the temperature and the packing used. With the materials and temperature of commercial practice the ratio is fairly constant; approximately 12½ per cent of the carbon being burned to CO_2 the remainder to CO.

The principal reaction involved, assuming Fe_2O_3 as the active medium, corresponds to the equation:

$$9\ Fe_2O_3 + 8\ Fe_3C = 18\ FeO + 7\ CO + CO_2 + 24\ Fe$$

The actual mechanism of the decarburizing reaction forms an interesting though complex problem in physical chemistry. The oxidation of the carbon in the iron and reduction of the packing are accomplished by the gas surrounding both. To be operative, a system must be chosen so that at the temperature and pressure in the annealing pot the gas phase present is such that the reactions

$$Fe_3C + CO_2 = 2\ CO + 3\ Fe$$
$$Fe_2O_3 + CO + = 2\ FeO + CO_2$$
$$FeO + CO = Fe + CO_2$$

can all proceed from left to right. In other words the system must be one in which a ratio of CO to CO_2 can be maintained which will at the same time oxidize Fe_3C, reduce Fe_2O_3, and reduce FeO.

If the relative concentration of CO and CO_2 be such that the first reaction ceases or reverses no decarburization will occur. If the reaction is initiated it would soon cease, due to the conversion of all available CO_2 to CO, unless the second reaction continuously reconverted CO to CO_2. If the last reaction reversed, the iron of the casting would be oxidized in addition to the carbon in the consequent scaling . Only some of the more usual reactions have been considered there being a

Table XVII

ANALYSES OF PACKINGS

Source	Pot scale	Roll scale	Squeezer scale	Slag
Fe	4.04	6.88	.....	.....
FeO	54.36	57.33	58.49	38.25
Fe_2O_3	9.04	5.97	3.14	1.03
MnO	....	.....	1.50	3.03
SiO_2	21.02	26.16	24.92	43.60
Al_2O_3 and undetermined	11.54	9.66	11.95	14.09

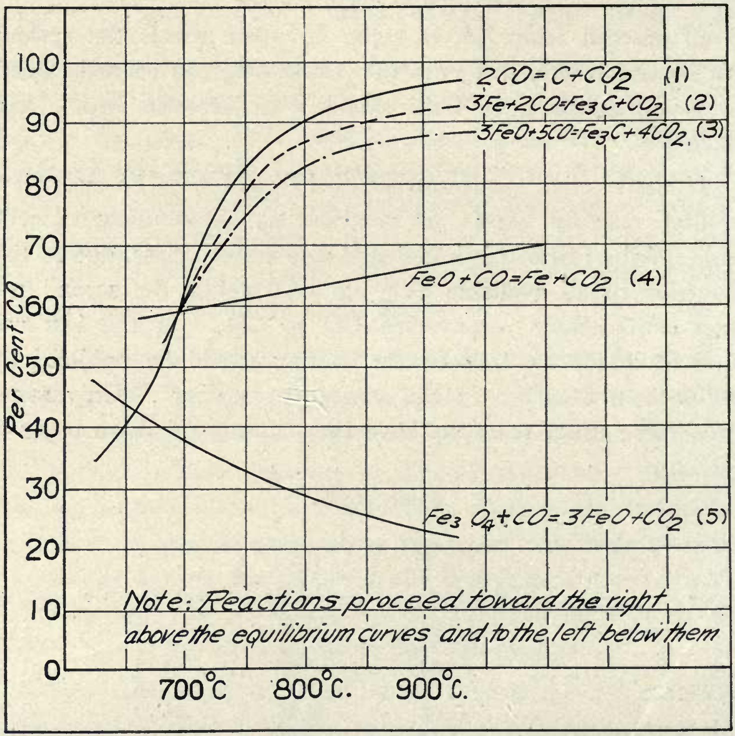
Proximate Composition of Above

Per cent

Fe	4.04	6.88	.....	.....
FeO	23.40	31.34	21.00	12.60
Fe_2O_3	....	5.97	.....	1.00
$(FeO)_2\ SiO_2$	40.90	.....	56.90	.....
$(Fe_2O_3)_2\ (SiO_2)_3$	14.10	.....	5.40	.....
$(FeO)_3\ (SiO_2)_2$	....	27.91	.....	.....
$FeO\ SiO_2$	....	.....	.....	45.20
$Fe_2O_3\ (SiO_2)_3$	....	.....	.....	5.40
Various inert silicates by difference	17.56	27.90	16.70	35.80

number of others possible between the components of such a system.

Scientific investigations of the subject matter involved would be based on determination of the composition of the gas phase in equilibrium with the several oxides of iron and carbon concerned and a location as to temperature and concentration corresponding to the reactions proceeding in the desired directions. The subject has been but imperfectly studied, the available information being mainly due to Schenks' summary "Physical Chemistry of the Metals." Matsubara, in a paper presented before the American Institute of Mining and Metallurgical Engineers, February, 1921, amplifies and checks Schenks' data, particularly with respect to the reactions into which the cementite enters in the presence of CO and CO_2.



Note: Reactions proceed toward the right above the equilibrium curves and to the left below them

Fig. 102—Equilibrium curves illustrating the reactions between carbon, iron and oxygen, after the data of Matsubara

Fig. 102 is drawn from Matsubara's paper, based on his own results as well as those of Boucourd, Bauer, Schenk and others. It represents the percentage of CO in a mixture of CO and CO_2 for various temperatures at which the several reactions will proceed equally rapidly in both directions—or at which they will cease and equilibrium will be established. The graphs are plotted for a pressure of one atmosphere as the sum of the partial pressures of CO and CO_2. For other pressures the equilibria can be calculated from the equilibrium constants of the several reactions. Letting P be the pressure exerted by CO and CO_2, X the amount of CO in the mixture of these gases and K_1, K_2 and K_3 the equilibrium constants for equations 1, 2 and 3, respectively, then

$$K_1 = \frac{X^2}{1-X} P$$

$$K_2 = \frac{X^2}{1-X} P$$

$$K_3 = \frac{X^5}{(1-X)^4} P$$

K_1 K_2 and K_3 can be calculated from Fig. 102 for any given temperature and hence the change produced in X by changes of pressure at that temperature can be calculated and a diagram similar to Fig. 102 constructed for other pressures.

Reaction (4) and (5) are independent of pressure. Unfortunately nothing is known as to the locus of the curves corresponding to (4) and (5) for the silicates forming commercial packings. The interpretation of the equilibrium diagram to determine what reactions occur is as follows:

On areas below (3) cementite is oxidized to FeO and CO; in areas above (4) FeO is reduced to Fe with the formation of CO_2, hence in any region below (3) and above (4), FeO will oxidize the carbon of cementite. Such regions exist only above 700 degrees Cent., therefore the reaction cannot be maintained at lower temperatures. That the lines (1), (2), (3) and (4) should intersect at one point is curious, and indicates that at that temperature, pressure and composition, C, Fe, FeO and Fe_3C or any two or more of these radicals can exist together in equilibrium. Almost any question as to the course of the annealing reaction or the behavior of packings could be answered by the construction of such diagrams for the particular packing material. Many conclusions as to the reactions of the pure elements and their oxides and carbides will present themselves on further study of the diagrams.

XII

PATTERNMAKING AND MOLDING

IN MANY respects, patternmaking and molding practice in malleable plants does not differ from that in other branches of the foundry industry. The various devices adopted for repetitive work in gray iron or brass also are found in use in the malleable shop. Indeed, since the producers of malleable engage largely in the manufacture of small and moderate sized parts in large numbers the development perhaps is further advanced than in gray iron practice. However, there are certain vital differences between patternmaking and molding for malleable cast iron as distinguished from the same operations in the gray iron trade. These differences arise from the metallurgical properties of the two materials.

The two essential distinctions between white iron and gray iron lies in the melting point and shrinkage of the two metals. Gray iron castings of moderate size are made of metal containing, for example, 3.25 per cent carbon, 2.00 silicon and 0.50 phosphorus as compared with the composition of white cast iron which approximates 2.50 per cent carbon, 0.75 silicon and 0.19 phosphorus. The equilibrium diagram for the iron carbon alloys shows that all alloys above 2 per cent in carbon finish freezing at the same temperature—1130 degrees Cent. or 2066 degrees Fahr. It shows further that the point where freezing begins varies with the carbon, decreasing nearly uniformly from 1550 to 1130 degrees Cent. as the carbon increases from nothing to 4.3 per cent.

Leaving the other elements out of consideration, the white iron should begin to freeze at roughly 1310 degrees Cent. or 2390 degrees Fahr. and the gray iron at 1220 degrees Cent. or 2250 degrees Fahr.

Thus gray iron will be completely liquid at a temperature 140 degrees Fahr. lower than that at which white cast iron has begun to solidify and the range of partial solidification or pastiness is larger by that amount in white cast iron than in gray iron.

The presence of silicon still further accentuates this point. According to Gontermann's data, metal of the composition assumed for gray iron should begin to freeze at about 1200 degrees Cent. or 2190 degrees Fahr. and be completely frozen at 1140 degrees Cent. or 2080 degrees Fahr., whereas white cast iron should begin to freeze at 1330 degrees Cent. or 2420 degrees Fahr. and finish the process at 1170 degrees Cent. or 2140 degrees Fahr.

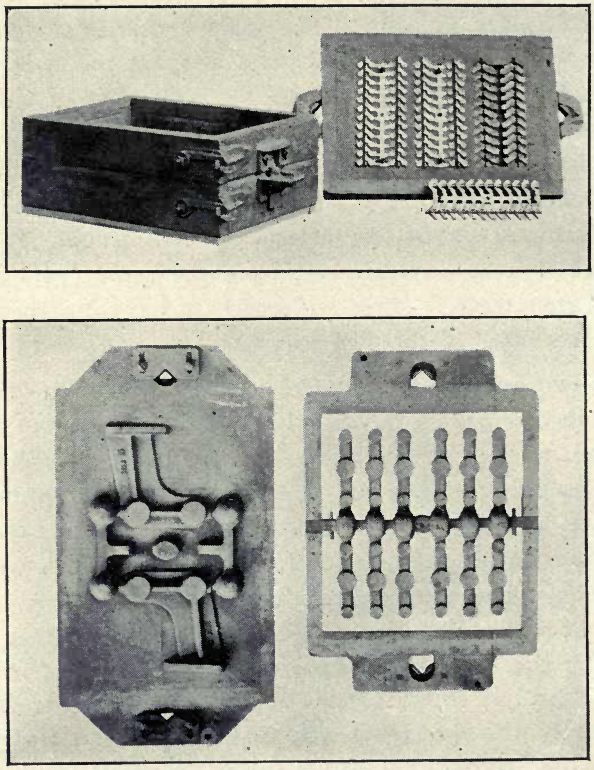


Fig. 103—(Above) Two gates of metal patterns in match part; (below) Pattern mounted on match plate and gated pattern mounted on vibrator frame

The data are not exactly in accord with those based on carbon alone, due to minor differences in the observations on which the data were based. The point to be clearly brought out is the higher point of incipient freezing and longer partially frozen range for white cast iron than for gray iron. The presence of phosphorus in larger amount in the latter still further accentuates the difference, although the writer has no available data on the freezing conditions in the system Fe-Si-P-C.

The data given show clearly that white cast iron must be poured at a much higher temperature than gray iron, since the latter will be liquid at a temperature perhaps 230 degrees Fahr. below that where the former has begun to set. Furthermore, it is quite possible that the fluidity of white iron when at a temperature say 100 degrees Fahr. above its freezing point is materially less than that of gray iron at the same temperature above its freezing point.

Within the author's knowledge data on this point are lacking. A further corollary of the difference in freezing conditions is that other things being equal there will be more shrinks or porous areas in white than in gray iron castings. This arises from the longer freezing range of the former corresponding to a larger fluid contraction of the still liquid alloy between the time and temperature of incipient and complete solidification. The consequence of this increased fluid contraction is that as the temperature of complete freezing is approached there no longer remains a sufficient volume of liquid to fill the voids in the previously formed solid skeleton.

Therefore, in the last freezing areas, voids remain between the dendritic crystals of the first frozen solid.

The shorter the freezing range the less of this contraction can occur. It has been shown by Cesaro that liquid iron is a solution of cementite in iron and Wust and Peterson have demonstrated that all such alloys freeze as cementite and austenite. However, in the temperature interval just under freezing the higher silicon and carbon metals graphitize by the conversion of cementite into iron and carbon.

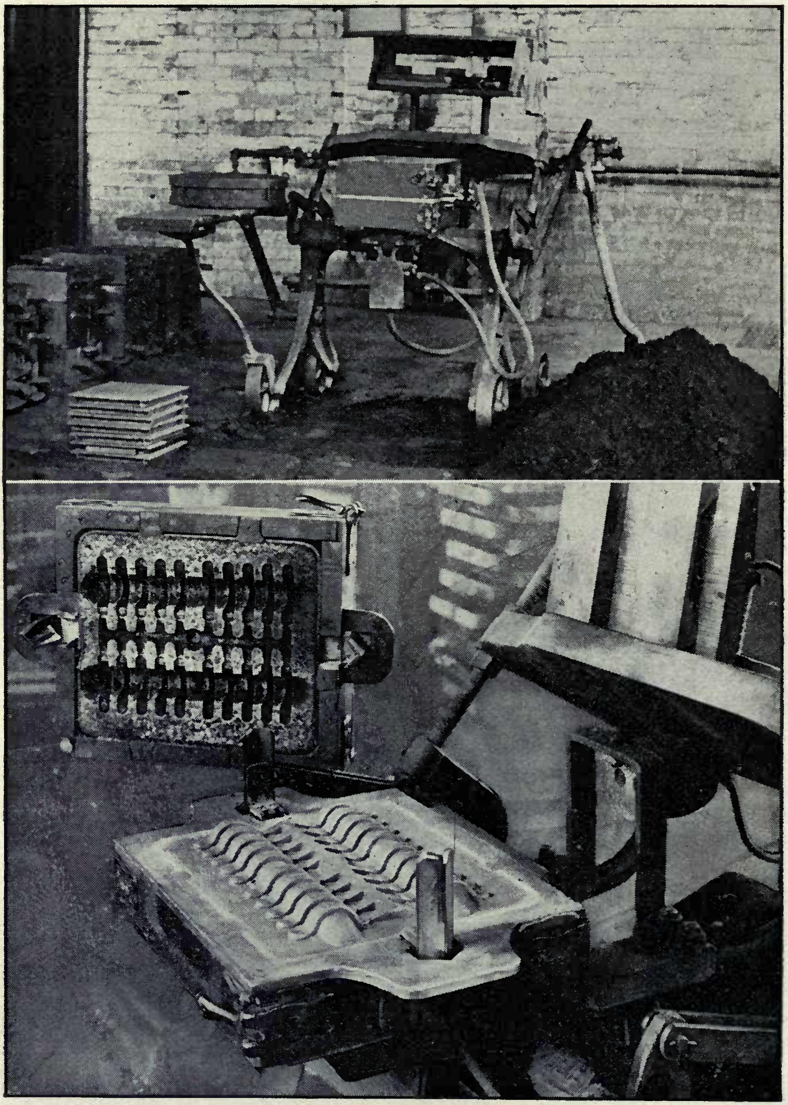


Fig. 104—Hand operated squeezer-type molding machine and (below) mold and pattern equipment in position on machine. Heavier machines operated by air also are used in the industry

The iron resulting from this reaction occupies almost the same volume as the original cementite. The total volume therefore is increased almost by the volume of carbon liberated. As a consequence there is a tendency to expansion at these higher temperatures. A number of observers especially Turner have recorded actual increase in linear dimensions while the metal was cooling and therefore contracting, just under the freezing point.

The expansion due to graphitization is important in two respects. It causes the casting to be only about 1 per cent smaller in linear dimensions (3 per cent by volume) than the pattern instead of double these values for white iron, and also tends to fill up in part the voids left by fluid contraction.

The difference in pattern equipment and molding methods in the malleable as compared with gray iron industries is due to the necessity for providing against the following differences in the properties of the two metals.

1. The higher melting point and lower fluidity of white iron.

2. Its greater tendency to internal shrinkage due to fluid contraction.

3. Its greater shrinkage from pattern size.

It will be noticed that the noun "shrinkage" has two distinct but related meanings to foundrymen. One refers to the reduction in the overall dimensions of the casting as compared with the pattern and the other to the production of porosities due to voids left by the contraction of the fluid metal.

A distinction based on the words "solid contraction" and "fluid contraction" seems desirable but has not gained favor among foundrymen. Accordingly one must be constantly on the alert to avoid confusion due to the indiscriminate use of the term "shrinkage."

Speaking first of this property in the sense of solid contraction, the fact that the shrinkage of white iron is about ¼-inch

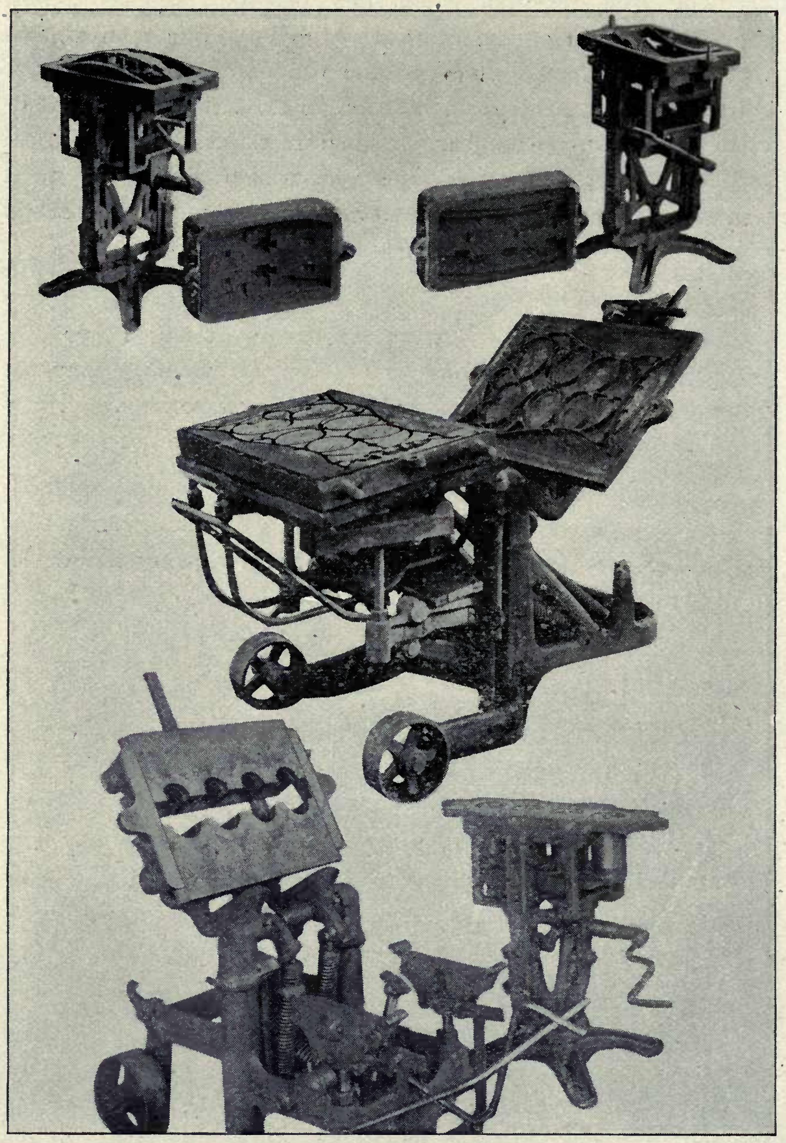


Fig. 105—Stripper and roll-over molding machines

(Top) Plain stripper plate molding machine and equipment for cope and drag. (Center) Roll-over machine for drag. The cope is rammed up from a plain plate. (Bottom) Stripper plate machine for cope and a roll-over machine for the drag.

per foot instead of ⅛-inch per foot as in gray iron does not cause any difficulty in patternmaking, except that a proper allowance must be made by using a "double" or ¼-inch shrink rule in laying out the work in case the casting is to be used hard. This shrink rule is merely a rule graduated in feet and inches and fractions of inches—usually sixteenths—in which the distance marked as one foot is 12.25 inches. A casting from this pattern will come from the mold about true to size.

Experiment has shown that the solid contraction of white cast iron (metastable carbon iron alloys) is substantially the same irrespective of composition. The contraction in cooling from solidification to room temperature is graphically shown in Fig. 106.

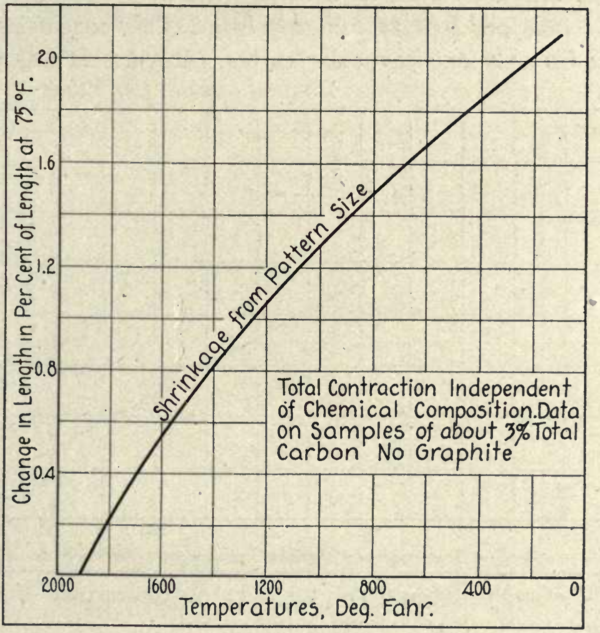


Fig. 106.—Curve showing contraction in cooling from solidification to room temperature

On annealing the casting expands due to the fact that temper carbon and ferrite occupy a considerably greater volume than the cementite from which they are formed. The increase in volume and in linear dimensions, depends primarily on the original total carbon and to a less degree on the heat treatment by which the graphitization is attained and possibly on other more obscure circumstances.

Some conclusion as to the changes of dimensions produced by graphitization can be formed from the following density data: Ferrite 7.90, cementite 7.438, carbon 2.30 to 2.70.

Dimensions Determined by Trial

The expansion in annealing is usually assumed to be one-half the original contraction making the net "shrinkage" allowance ⅛ inch per foot as for gray iron. This conclusion can be correct for only one particular carbon content. It was probably fairly accurate in the days when high carbon iron was prevalent.

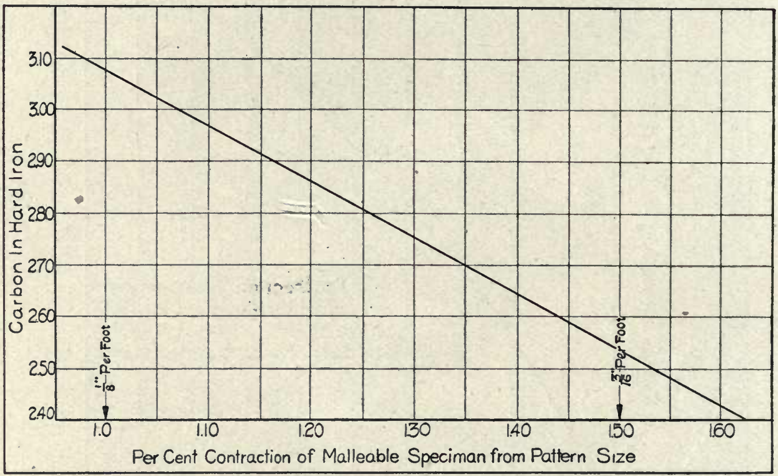


Fig. 107—Graph showing the per cent of contraction of malleable from pattern size

W. L. Woody has given the writer data obtained in a study of over 1000 heats from which test specimens were cast from a pattern 12 inches long, the specimens being micrometered after annealing. The results are shown graphically in Fig. 107. The percentage of net shrinkage of unconstrained specimens can be read from this graph.

The author has determined the density of hard iron and malleable cast iron made therefrom for various carbon contents.

The data are shown in Fig. 108 calculations as to change of dimensions in annealing from these changes in density yield results apparently in error in the direction of too much expansion in anneal, i.e. to too small a shrinkage allowance.

In determining pattern dimensions consideration must also be given to the fact that, due to rapping, the molds always are larger than the pattern, except on "stripper plate" equipment.

On vibrator plates this "rappage" will be small and uniform, in bench and floor molding by hand it will be variable and may be large.

Very small parts may actually require a negative "shrinkage allowance" "the rappage" exceeding the solid contraction.

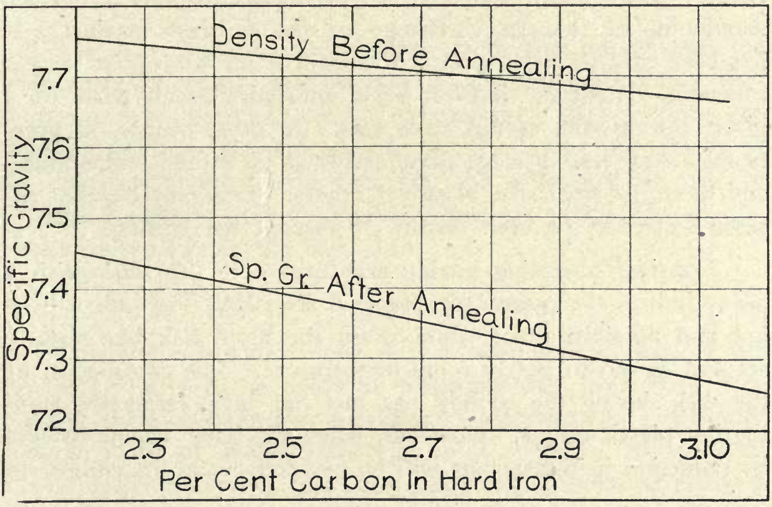


Fig. 108—Graphs showing relation of annealing upon the density of the metal

Further it may happen that in irregular and intricate castings some parts constrain others when freezing and leave shrinkage strains. The relief of these strains during the annealing may cause unexpected changes of form.

Therefore it often is necessary to arrive at the pattern size for important dimensions by actual trial and even then the castings will come true to size only so long as temperature of

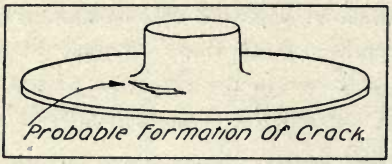


Fig. 109—Casting with thin disk and thick hub, showing probable point of rupture

pouring, chemical composition, and sometimes even the solidity of sand and cores are maintained exactly constant.

The heavy solid contraction of the white cast iron also imposes a number of difficulties which would not be clear to the reader were he to consider the problem altogether from the standpoint of the net shrinkage of the finished product. It has been said that the total contraction of all white cast iron is constant. However, it is at least unusual that all parts of a given casting cool at the same rate. In other words, in practically every casting some parts arrive at their final temperature, and therefore final size, ahead of others. This may develop excessive stresses or even distort or disrupt the casting.

Consider a casting having the form of a thin disk with a heavy hub at the center, as shown in Fig. 109. The hub will be hot and possibly almost fluid when the light disk has already set and cooled to nearly room temperature. The contraction of the disk during the cooling has met but little resistance from the hot plastic center. However, when the latter begins to cool its reduction in dimensions will be resisted by its attachment to

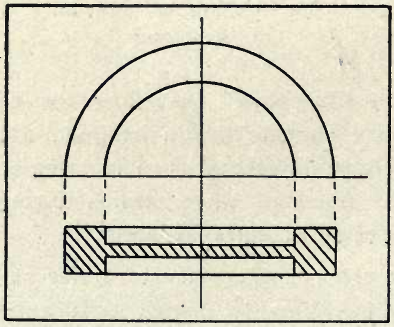


Fig. 110—Type of casting with thin disk center and thick rim

the solid thin flange. Sometimes this attachment will be so secure as to permanently stretch the pasty mass within. If this cannot occur the flange may be torn loose from the hub at one or more places or may even be entirely detached.

In the reverse case of a thin plate surrounded by a thick rim, as shown in Fig. 110, the contraction of the rim would be opposed by the previously solidified center, either crushing the center or producing a radial tear in the rim. Generally the point of failure is at or near the hottest part of the casting where the strength is the least. Occasionally no external defect results due to the welding up of such defects by molten metal from the center. Then the consequence is a pipe or other void.

The magnitude of the stresses from this source may be enormous, depending only on how rigidly the last cooling portions are held by their solid surroundings. In gray iron the difficulty is less pronounced due to the lower magnitude of the contraction and to the fact that the solid portions can be deformed slightly without breaking, whereas practically no distortion is possible in the hard iron.

Effect on Design of Castings

The practical application of this reasoning is that, in the design of parts to be made of malleable cast iron great care must be used to avoid such forms and proportions as will rigidly connect parts of widely different cross section. All sections should merge uniformly into each other, avoiding abrupt changes of thickness. Fairly thin ribs intended to rigidly brace heavier sections, spoked wheels with hubs heavier than the rim and in general any design in which unequal rates of cooling can set up opposing stresses should be avoided. If such designs are successfully executed by the foundryman it is only by methods of gating or chilling calculated to accelerate the cooling of the heavier sections and retard that of the lighter. This calls for the exercise of great skill and judgment and may produce prohibitively higher losses with a corresponding increase in cost.

We may now consider the shrinkage produced by fluid contraction and resulting in porous material in the areas freezing last. It is impossible to suppress these so called shrinks in any casting. Their formation is inseparably connected with selective freezing over a temperature interval and hence always occur in every casting.

Depending on particular conditions, these shrinks may be widely distributed in insignificant amount at any one place, or they may be concentrated in one spot, aggregating a considerable volume. A casting freezing at a nearly uniform rate throughout, due to equality of section, etc., and freezing almost as rapidly as the iron enters the mold may have the porosity so uniformly distributed and so nearly filled up from the ladle during pouring as to be practically sound. On the other hand, a casting having a heavy cross section in some one place which is fluid long after pouring ceases will show a great shrink, especially if the heavy section is high up in the mold.

Fig. 111—Dendrite (about half size) from shrink in hard iron ingot 8 inches in diameter by 20 inches high which was poured without feeding

Two remedies are employed for this trouble. The older is the application of iron chills, which are pieces of cast iron buried in the mold so that they form its inner surface at the points where shrinkage is prevalent. By accelerating freezing they suppress the shrink in their immediate vicinity. However, since the reduction in volume still exists an equal volume of shrinkage will develop elsewhere. This practice is good if the shrink in the new location does no harm, or if in that location it can be suppressed by feeding; otherwise it is merely camouflage. Continuously supplying molten iron until the entire casting is frozen is the only actual preventive of shrinks.

The shrink always is found in the slowest freezing locality. Therefore, if to the pattern there is attached a feeder of still slower cooling rate so located that metal can flow from it to the location in which the shrink was found, then the shrink will be transferred to this feeder and be of no consequence, since the feeder is not a part of the finished product. The actual design of feeders, to meet a given set of conditions may require much skill and experience, but the operating principle is simple.

Feeders are expensive, not only from the molding viewpoint but also because they involve the melting of much additional iron. Nevertheless their use is the safest possible foundry practice to insure sound castings.

The high freezing point of white cast iron necessitates much greater care in gating than is requisite for gray iron. The relatively thin gates commonly used for that metal do not admit of a sufficiently rapid flow to prevent freezing before the mold is filled. Most castings must have metal admitted at a number of points in order to permit the mold to fill sufficiently rapidly. Because of the large gates, it is necessary to use special means to exclude slag or sand floating with the current of metal. The thin knife gates of the gray iron industry will choke the stream enough to permit these impurities to rise to the surface and be trapped in the runners. The same principle is used in malleable foundry but greater care is necessary in making the runners large and providing places for the ascending slag to be trapped on account of the rapid flow of iron required.

Frequently the iron is poured through a strainer core placed at the bottom of the riser, which is intended to cause the latter to remain full of metal and allow the slag to accumulate and float up.

Because of the quick filling of the mold, necessitated by the quick freezing of the iron, great care must be used in selecting molding sands, and in venting the mold. The air and gas must be able to escape rapidly enough to allow the iron to enter at the rate required to keep it from freezing before the mold is filled.

The selection of molding and core sands of core binders, as well as the actual ramming of the sand are further influenced by the high solid contraction of white cast iron. The mold and cores must be made so as to give readily under the heavy contraction of the casting in freezing. If for instance, a core be so hard as not to disintegrate before the metal begins to shrink it may set up such a strain in the casting as to actually cause rupture.

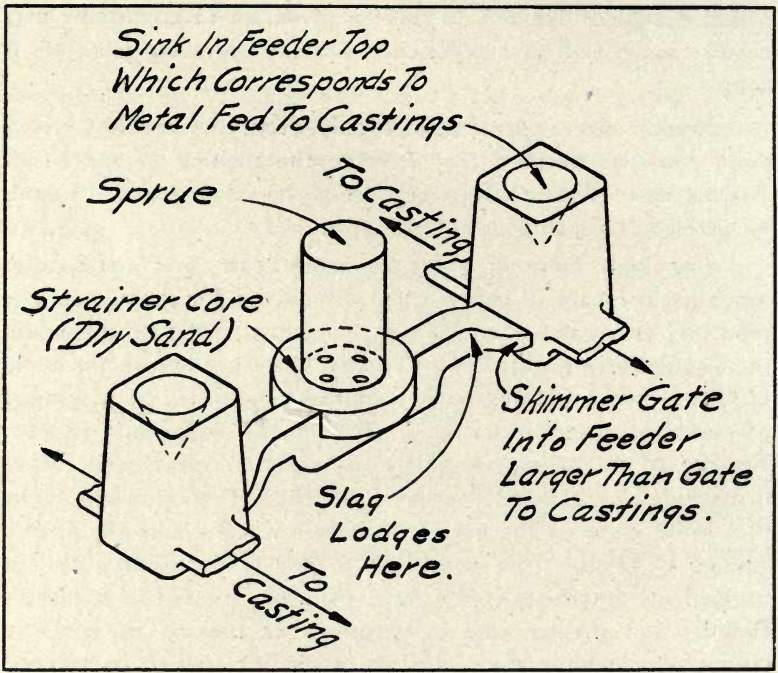


Fig. 112—Typical gate for malleable castings showing strainer, core and skimmer gates for furnishing clean metal for feeders and producing sound castings

The patternmaker can frequently save the customer money by a judicious selection of the number of pieces made in one mold. A reasonable increase in the castings per mold is good economy.

Any attempt to increase the weight per mold by putting in so many pieces as to cause pouring difficulties or to prohibitively increase the dimensions of the mold it not justifiable.

In general the steps in the improvement of molding methods have been as follows:

Starting with a plain pattern as the simplest equipment, the first step was to permanently attach thereto models or patterns of the gates, feeders, etc., in order that these need not be the subject of separate operations. In the case of small parts this leads to the mounting of several patterns on one gate.

To avoid the labor of producing a parting by hand for each mold, match parts were introduced, which are merely a semi-permanent duplicate of one half of the mold (generally the cope).

In the interests of greater stability plate patterns were developed, consisting of fairly thin flat plates, usually of aluminum with the patterns mounted on one or both sides together with the gates, etc. The plate being at least as large as the exterior of the flask separates the cope and drag by its own thickness. Each half of the mold being rammed up off its own side of the plate, the mold when closed corresponds in form to the parts mounted on the plate.

To do away with hand-rapping the pattern to withdraw it from the mold; air or electric vibrators often are attached. In some cases, especially for heavy work, the pattern is withdrawn, usually by a lever motion, without rapping, through a stripper plate. The stripper plate is merely a plate representing the parting of the mold having an opening exactly fitting the contour of the pattern at the parting. When drawing the pattern downward through this plate the latter supports the sand and prevents its following the pattern.

Unless the cope and drag are duplicates, two machines are requisite for each job as the construction is evidently such as to be applicable to one-half the mold only for each unit.

Extremely heavy work is frequently handled on a roll-over machine which is especially available for making the drag. After the drag is rammed up, necessarily parting downward, the machine facilitates turning it over to its proper position by sustaining and counter balancing most of the weight of the mold and pattern by springs. The pattern is sometimes withdrawn through a stripper plate and sometimes by letting the mold sink away from under the pattern by a suitable lever motion. The sand is compacted by hand ramming, by the use of hand or air operated squeezers, and by jolt ramming. The latter operation consists of mechanically raising the mold repeatedly and allowing it to come down on a solid support which uses the inertia of the sand itself for compressing it. On floor work pneumatic rammers sometimes are used.

XIII

CLEANING AND FINISHING

OPERATIONS of cleaning and finishing malleable iron castings are conducted in part by the manufacturer, but frequently also by the consumer. Some of the simpler operations may be dismissed almost with a word but certain others such as machining, welding, galvanizing, etc., which are performed usually after the castings are delivered to the buyer merit more extended discussion.

Castings generally are cleaned of sand as the first step on leaving the foundry. An exception to this is found in some cases of large muffle annealed castings where the finish is relatively unimportant. Such castings are often annealed without cleaning. In most cases, the hard iron castings are cleaned in tumbling barrels, using any of the standard equipment. The operation is in no sense distinctive, the only peculiarity being the brittleness of the castings. To avoid breakage greater care must be used in handling the material and packing the barrels than would be needed in gray iron practice.

Castings of a very fragile character can not be cleaned in this manner without breakage. Therefore, it is usual to pickle or sand blast them, usually the former. Pickling may be in dilute sulphuric acid which loosens the sand largely by the action of the hydrogen gas formed on the surface of the metal or less commonly in hydrofluoric acid which dissolves the silica sand with but little action on the iron. If the latter acid is to be used, economy will dictate the mechanical removal of as much sand as possible before pickling to avoid the needless exhaustion of the acid through the dissolving of loose sand.

Castings Must Be Cleaned

Large castings are sometimes sand blasted one at a time by hand more easily and safely than they could be cleaned by rolling. A second cleaning is practically always necessary after annealing and this may be by rolling, often using scraps of leather, old shoes, etc. to impart a polish. If clean cut edges

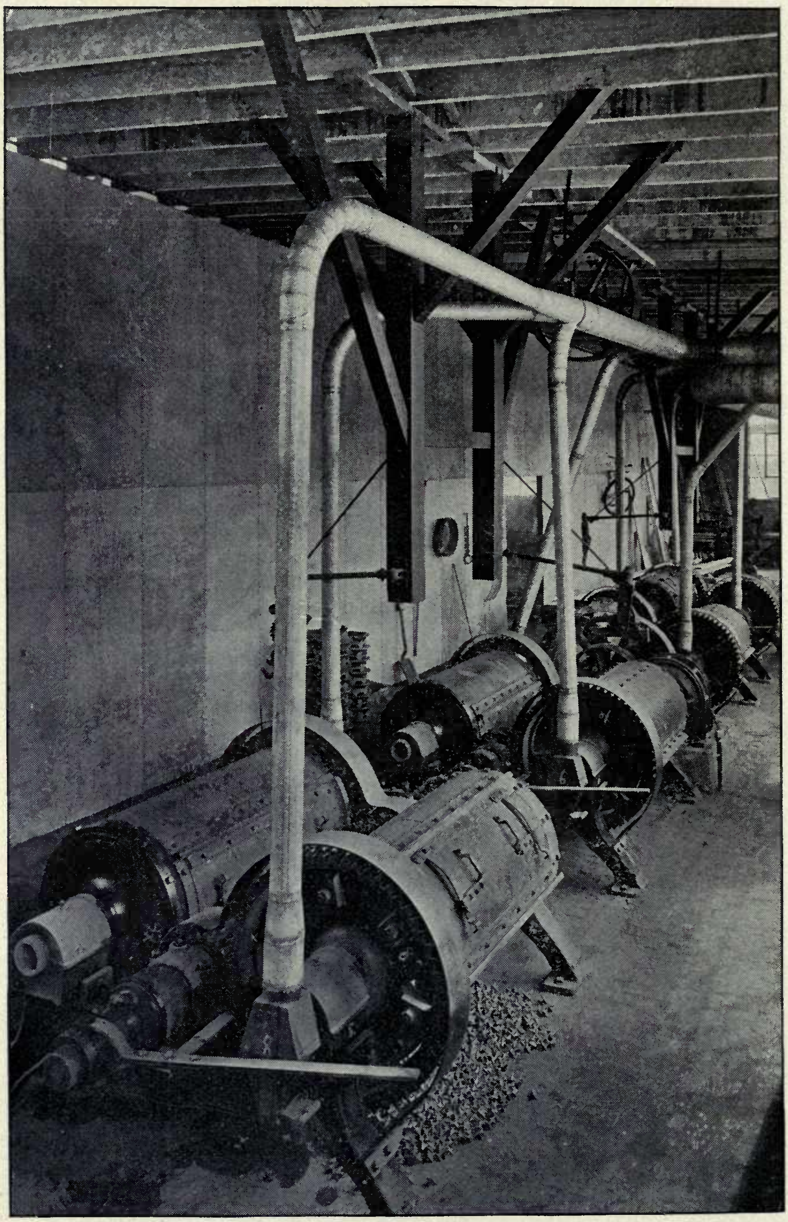


Fig. 113—Tumbling barrels are used for cleaning castings

are required, sand blasting is often resorted to either in barrels or by hand. Pickling is not common except as a preliminary to plating. Sulphuric acid, hydrochloric acid, and a hot solution of acid sodium sulphate may be used to remove the oxide scale left by annealing.

Since the castings are very likely to become warped during the anneal a straightening operation is often necessary if the castings are at all complex in shape.

In many cases, especially on complex and thin work, no better method can be used than the hand method. When possible a drop hammer fitted with suitable dies may be employed. Since the development of arc and acetylene welding, the practice of reclaiming defective material by this process has received attention both by the producer and the consumer. The operation of welding has two entirely different aspects, the repair of mechanically unimportant faults of surface and finish in the producer's plant and the repair of castings broken in service. Reference will be made later to the latter process, that is welding by or for the ultimate consumer. Limiting ourselves for the moment to welding as practiced in the malleable foundry, we may start with the premise that the founder should deliver to the buyer no casting which is not high-grade malleable iron throughout.

In welding, the material of the weld is melted and the casting, in part at least, is brought to this same temperature. Thus in welding with iron, regardless of whether the filler is wrought iron, soft gray iron or any other material, the casting will be heated to a point far above the critical point and hence on cooling will revert to the condition of white iron. No ingenuity in the selection of a filler therefore will overcome the presence of a glass hard spot at the weld. This condition can be obviated only by using for a filler either white cast iron or malleable, more conveniently the former, although both will be white after remelting. If the welded casting is then annealed, or re-annealed precisely as in the regular practice the material in the weld will be the same as that throughout the casting.

The temperature of the arc is so high that a thin layer of metal can be melted and the operation completed before the un-

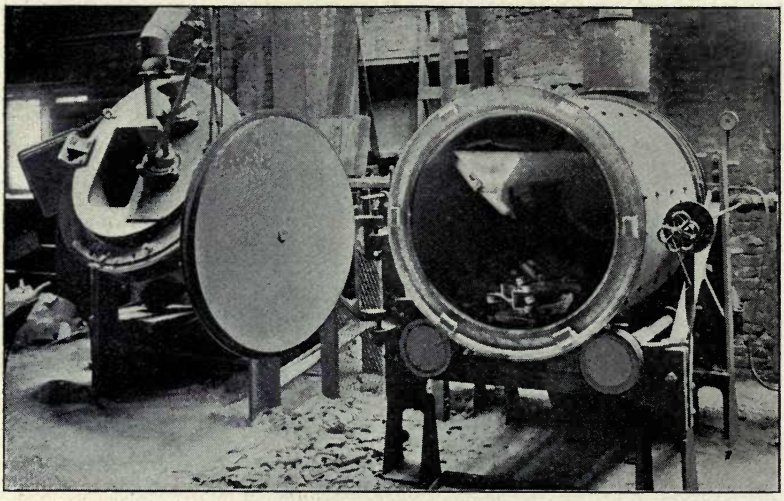


Fig. 114—Sand blast equipment is used for removing sand from castings

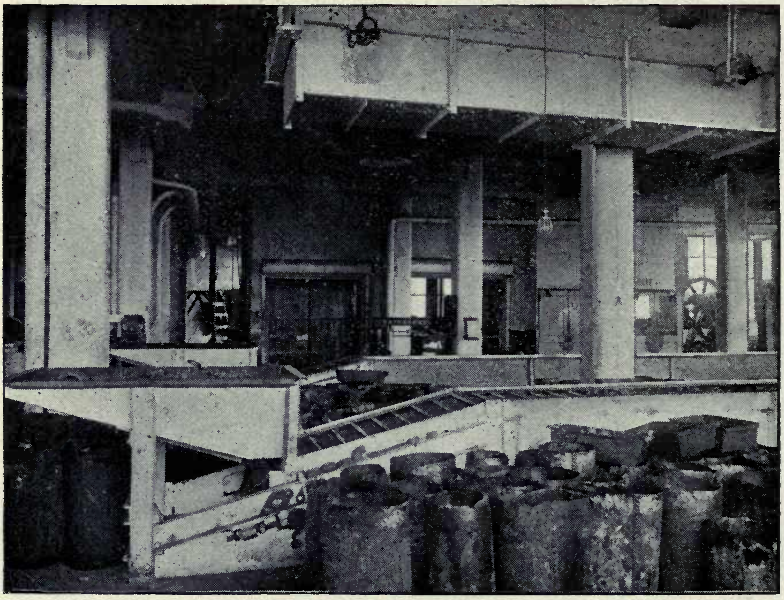


Fig. 115—Sorting and inspecting small castings are important operations in many plants

derlying metal is much heated. The author once had the opportunity to observe the work of an expert arc welder. Working on castings retaining their original ferrite surface, this operator was able to weld so rapidly using Swedish iron wire, that the heat was confined to the ferrite layer and hence a perfectly soft weld resulted. Such a result presupposes two conditions not usually existing; the first, the use of an extremely skillful artisan and the second, a character of repair which does not require welding to a part of the casting below the decarburized skin. The latter condition, depending as it does on the character of defect to be repaired, is entirely beyond control.

All Faults Not Cured by Welding

Whether or not the casting is annealed before welding has no effect on the final product and may be left to the welder's discretion. Welds made in the above manner by a skilled artisan will render the product equal in quality to an initially perfect casting. Since the element of skill enters, however, it may be a measure of safety to exclude from repair by welding, faults which if not perfectly repaired would be the cause of serious failures.

Generally, snagging or the grinding away of gates, fins, etc., is the duty of the producer. The operation is performed either with the casting in the hard state or after annealing. Usually most of these imperfections can be broken off with a light hammer before annealing and the final finish produced by grinding. Grinding before annealing is slower and more expensive than if performed on the finished product. But since the former method produces somewhat better looking castings, especially on sand blasted work, it is sometimes specified when the consumer feels that this feature is worth the extra cost.

Hard iron is ground on a very hard and rather fine grained emery wheel; malleable is ground on a soft and coarse wheel. The size of casting and finish required influence the selection of the exact grade of wheel. For malleable grinding wheels of artificial alumina, 14 and 16 grit, in a hard grade are used extensively.

The preceding discussion covers the usual finishing operations which the malleable foundry performs for its customers, however, the customer may perform a number of additional operations. Disk grinding, machining, straightening, welding, tinning, galvanizing, electro-plating, occasionally local hardening and possibly other operations come into this category. Since the customer's requirements and method are likely to be peculiar to his individual conditions, he is better informed as to his processes than is the manufacturer of the castings. It will be well, therefore, to confine the present discussion to considerations of the producer's attitude toward these several operations.

Of the technique of disk grinding little need be said, the one essential point to be observed being that in this as in all other forms of grinding the operation be not crowded to the point where the temperature of the surface metal reaches Ac_1. Many grinding operations will readily raise the metal in contact with the wheel to a red heat. A portion of a malleable casting which has risen to such a temperature has had some of its carbon recombined and has been locally hardened to a degree which may render it brittle or unmachinable.

Should Allow for Finish

Theoretically, tool life should be long and cutting speeds high for malleable cast iron, since the material being cut is a dead soft steel which is one of the easiest materials to machine. Moreover, the presence of temper carbon should favor machining both by breaking up the chip and by acting as a lubricant for the chip and tool.

That this conclusion is correct is indicated by the conditions under which malleable is machined in practice. In machining malleable cast iron not much over 1/16-inch of stock is removed at one cut. Only in rare cases are cuts of ⅛-inch to 5/32-inch necessary in practice. The commercial speeds in lathe operation seem to run from 70 up to 160 or 170 feet per minute. The heavier cuts usually are run at the lower speeds. Fine feeds are commonly used, ranging from .01 to .02 inches per revolution. Although generally these conditions are successfully met in operation, machining troubles sometimes are encountered. Therefore there is definite reason to believe, either that there exists a fairly wide range of machinability in normal malleable or that in individual cases an abnormal product is unexpectedly encountered in a small amount mixed in with a large mass of normal material.

In the absence of systematic study on the point, no recommendations are possible by the producer. It is well, however, to point out some special features influencing machining. If any pearlite remains in the finished casting, it is generally very near the surface. It is therefore well to design malleable parts with a considerable amount of "finish" for it is usually easier to remove 1/16 to 3/32 inches of metal by turning or planing than to take a very light cut which may be almost entirely in this slightly pearlitic area. At the same time this allowance is a

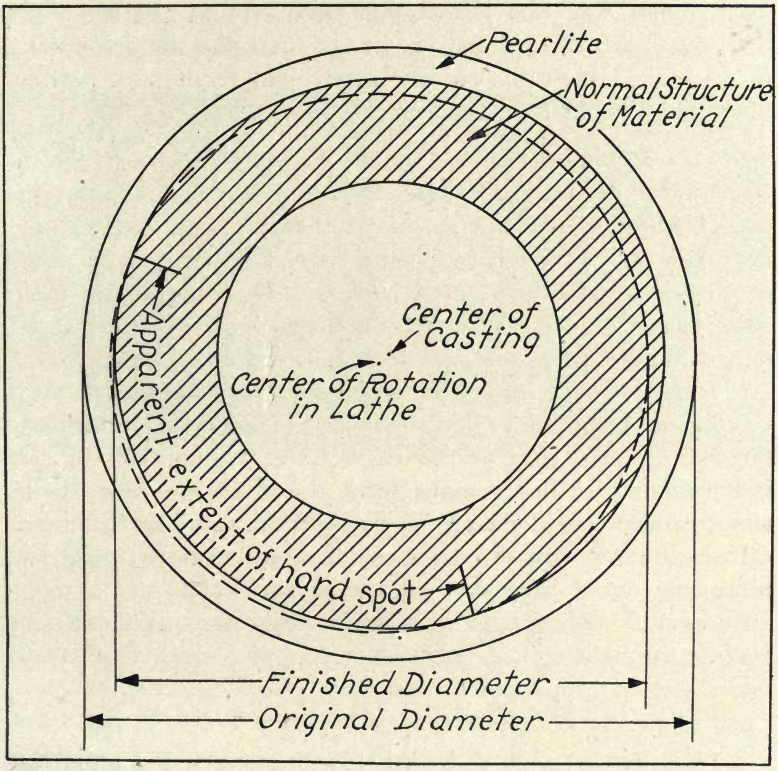


Fig. 116—When machine center and casting center are not concentric, apparent hard spots may be found

necessity to take care of the variations of expansion in annealing which are not yet entirely under control of the metallurgist.

The film of pearlite just referred to sometimes gives the misleading impression of hard spots in an otherwise sound casting. If the finished surface is not concentric with the surface of the rough casting is may be that in only a few places the lathe tool cut traverses the pearlitic areas which then act as hard spots. The fact is that this same area of pearlite exists over the entire surface and had it not been that the eccentricity in machining threw the cut alternately into ferrite and pearlite, no trouble would have been encountered.

Fig. 116 illustrates this condition on an exaggerated scale. Such metal as this, of course, is not of the best quality; the manufacturer should and does usually remove this pearlitic layer. However, attention is called to it here to explain the cause of complaints sometimes made and to suggest means of using such metal which is identical internally with a normally annealed product when the pearlite is removed by a cutting tool.

Hard spots in malleable, in the sense of microscopic areas containing ungraphitized carbon, and scattered irregularly through the mass of a perfect casting are rare indeed. So rare is the occurrence that complaints of this fault are found to be almost always based on erroneous observation. The symmetrical pearlite rim just discussed is the most common cause and represents not a hard spot at one or two points but a tough area of little more than microscopic thickness parallel to the surface throughout.

Shrunken Areas Cause Trouble

Occasionally, also, a defective casting which for some reason has failed of complete graphitization is soft enough to machine, though with difficulty. If after most of the machining is complete, a tool fails on the casting, the machinist is apt to feel that a hard area has just been encountered. In addition it occasionally happens that in castings made without suitable feeder heads, a machining operation may penetrate a shrink. Such areas always show a bright cut and are mistaken for hard spots. Cementite in fine granules frequently is present in the shrunken areas and dulls the cutting tool if much of the cut is in the shrink.

If the turning operation which penetrates the shrink is thread cutting, the threads will crumble away and the metal may be regarded as defective when the fault is with the feeding of the individual casting. Both items are to be controlled by the foundry but frequently the character of the complaint is misleading as to the cause of failure. In the case of threading and reaming operations, it is not uncommon to encounter difficulties with perfectly normal metal. A metal which has been decarbonized considerably may have the entire thread, especially if of fine pitch, cut into the pure ferrite rim. Ferrite cuts freely, but in rather long chips, hence the flutes in dies, taps or reamers may become clogged and prevent a clean cut. In work of this character too deep a decarbonization is objectionable.

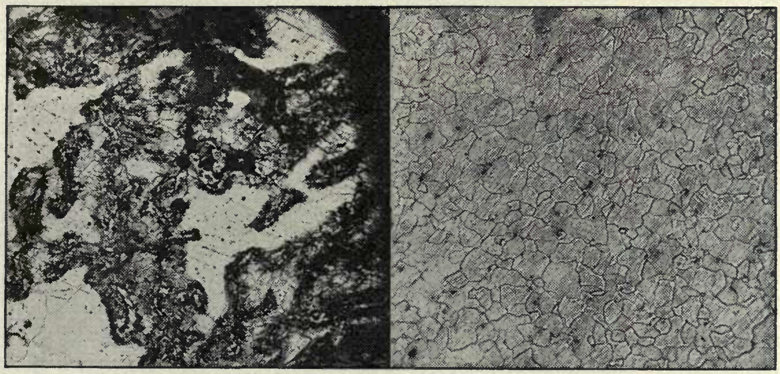


Fig. 117—(left)—Cementite persisting near a shrink. The metal in porous areas is somewhat oxidized. Fig. 118—(right) Hard slag inclusions just below the surface which may dull cutting tools rapidly

An interesting operation other than machine tooling occasionally may be practiced on malleable. This consists of press fitting and is accomplished by applying sufficient pressure to a casting to bring it to the desired dimensions and perfection of surface. To produce reasonable perfect finishes a pressure of 100,000 pounds per square inch is required. The method is

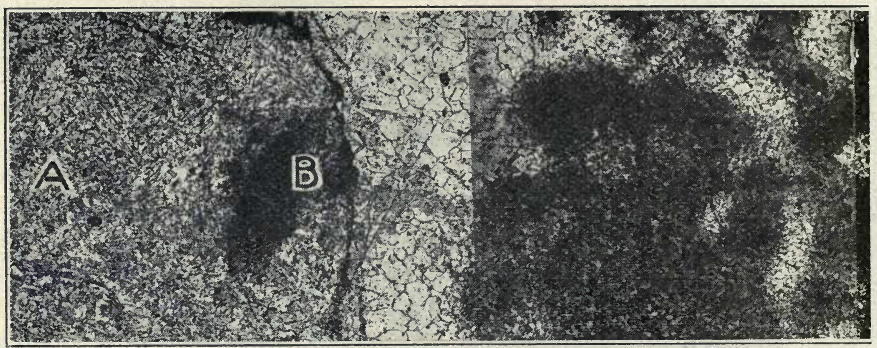


Fig. 119—Malleable casting effectively arc welded with swedish iron. The changes *A* is soft iron but very slightly recarburized from the malleable; *B* is an carbon due to

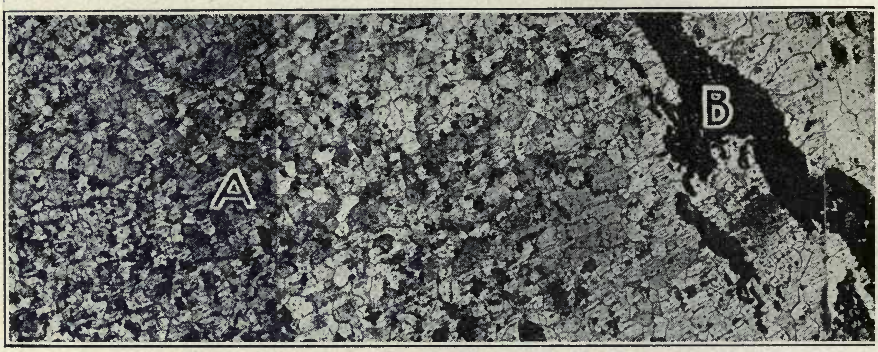


Fig. 120—Hard iron casting successfully acetylene welded with hard iron and slag. *A* is the original casting, *B* the slag, *C* the material of weld as noted of a little pearlite

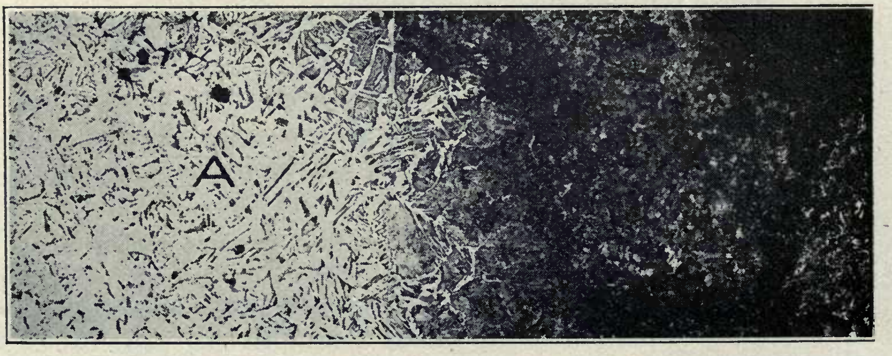
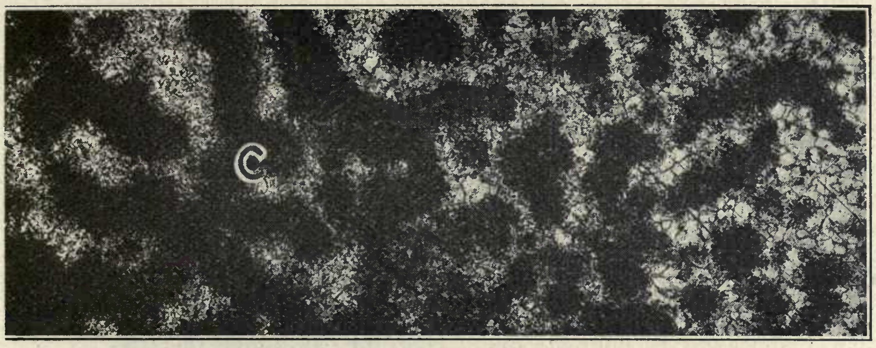
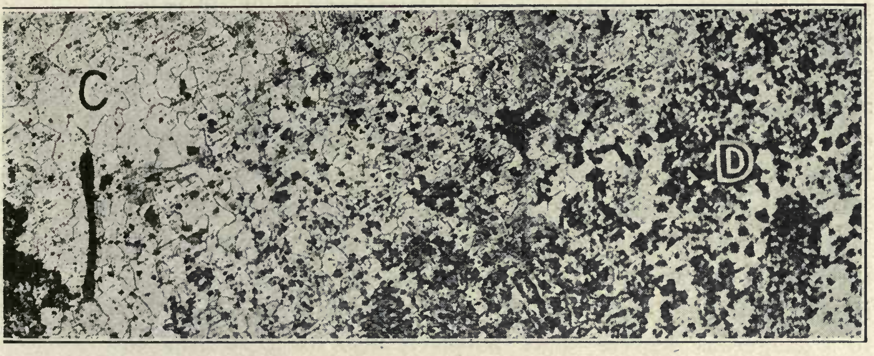


Fig. 121—Ineffective hard weld of malleable casting using ingot iron wire and filler converted into hard iron by migration of carbon from the malleable. bitic due to recombination of carbon at



visible microscopically were insufficient to make notable difference in metal. Area
oxide or slag film, and *C* is the malleable showing but little resolution of
close confinement



then annealed. Note metallurgical homogeneity of casting except for presence of
by larger grain size, and *D* the material of weld as noted by persistence
due to decarburization

acetylene method. Neither material has its original structure. *A* is the soft iron
B is the original malleable iron, the background of which has become sor-
temperature the metal reached in welding

particularly applicable where relatively small objects have to be brought to an exact thickness. It is also possible to form small objects, for example, radiator nipples in press dies. The method is sometimes preferred where it is desired to retain a ferrite surface.

Welding Is Limited

Welding of broken or defective castings by the user is of course subject to the limitations which apply to this operation when carried on by the producer with the additional difficulty that reannealing is impracticable. Had the consumer facilities for the long accurately controlled heat treatments required, he could of course weld in the same manner as does the malleable founder. During annealing finished surfaces would suffer and warping might possibly occur. Under ordinary conditions, therefore, welding with iron is not to be regarded as practicable as a repair operation. Thus no repair can be made, irrespective of the welder's skill, which will restore the original strength of the casting.

The only resource is to braze, that is, to use bronze as the welding material. The melting point of bronze is low enough to permit operating below the critical point for iron hence if care is used a weld can be made without heating the metal to a dangerous degree. This, however, involves great skill and care on the part of the welder. Ordinary brass, Tobin bronze and Parsons' manganese bronze has been suggested as suitable for this work. Of course, welds made with nonferrous metals do not permit of the complete merging into one another of the metal used as filler with the material being repaired.

They apparently fail invariably by tearing apart between the iron and bronze, thus the entire strength of either material is not developed. The strongest welds of this type ever tested by the writer were made by an expert operator using Parsons' bronze. These welds developed an adhesion between iron and bronze of substantially 45,000 pounds per square inch thus producing a tensile strength of the welded part approximately equal to the American Society for Testing Materials, specifications for malleable iron.

The failure occuring entirely along the plane of contact between bronze and iron produced a failure with only a negligible elongation, as might be expected. If the circumstances are such as to permit making a joint similar in form to the wiped lead joint of the plumber, running the bronze up on the side of the iron part some distance each way, welds occasionally can be made with this metal which develop the full strength of the original metal, elongation excepted. Such welds are seldom made. A manufacturer of alternating current arc welding equipment claims that with his apparatus and a nickel filler small machineable welds can be made in malleable cast iron. The writer has not yet personally investigated this procedure.

Work of this character can be intrusted only to very skillful artisans. Unusual care and ability are required to produce mechanically perfect welds without even momentary overheating of the surrounding metal. Theoretically, there should be no reason for preferring electric to acetylene welding or vice versa, but the writer's observation has been that better work is obtained with the gas torch. Possibly this observation may be due to the relative skill of the operators whose work has been observed.

Of straightening operations little can be said here, since these operations are in general entirely mechanical. Occasionally there comes to the malleable manufacturer's attention heavy castings which have been bent in service and straightened in a blacksmith's fire. Such castings originate more particularly in the repair shops of railroads. Hot straightening is an extremely dangerous operation and in general should be avoided by the consumer since even severe punishment under a heavy hammer will do the castings less permanent harm than an instantaneous heating above the lower critical point. The best practice is to straighten in a screw or hydraulic press.

Must Use Accurate Temperatures

Next to this the use of the lightest hammer blows which will accomplish the result is to be recommended. Some castings are of such shape that nothing short of a steam hammer will do any good. In the absence of properly fitting dies such a hammer may so mar the casting as to destroy its utility. Under these circumstances hot straightening is an advantage but can be executed only under conditions permitting of the use of accurately known and controlled temperatures. Such straightening should be done at temperatures between 1000 and 1100 degrees Fahr. At temperatures below 900 degrees Fahr. the metal is not sufficiently more ductile than when cold to justify the heating operation and at temperatures over 1200 degrees, the danger of accidentally overstepping the critical point is so great as to be unwarranted. In the absence of pyrometer control, hot straightening of castings whose failure would cause loss of life or heavy loss of property is almost criminal.

Application of protective coatings to malleable iron to increase its rust resistance yet remains for consideration. Protection is obtained by a coating of metallic zinc, applied molten as in hot dip galvanizing; by a peculiar form of penetration at temperatures below the melting point of zinc, as in sherardizing; and by electroplating as in so-called electrogalvanizing. The relative merits of the three systems is so much in controversy that it is hardly within the province of the article to attempt any decision as between them. It is of course essential to apply such a coating as will furnish the maximum protection under service conditions.

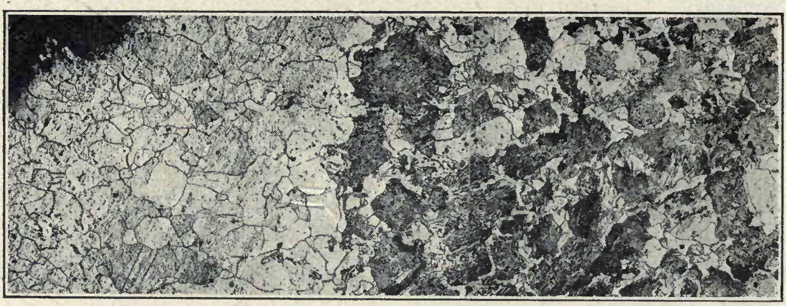


Fig. 122—Photomicrograph showing heavy pearlitic rim which may cause machining difficulties

The prevalent opinion seems to be that the results of hot dipping are in this respect superior to the two competitive processes. On the other hand, the author is informed that a large consumer of malleable in the form of trolley parts after exhaustive tests determined to his own satisfaction the superiority of the sherardized coating. Another extensive user of malleable, who applied his own coating decided upon the electroplating method as being equally satisfactory in service and the least liable to injure the product to be coated.

Hot galvanizing can and should be done without heating the metal to be coated above 900 degrees Fahr. Under such circumstances there is no reason to fear any recombination of the carbon. Unfortunately, however, there are on record a number of well established instances in which originally perfect malleable castings were seriously impaired by galvanizing.

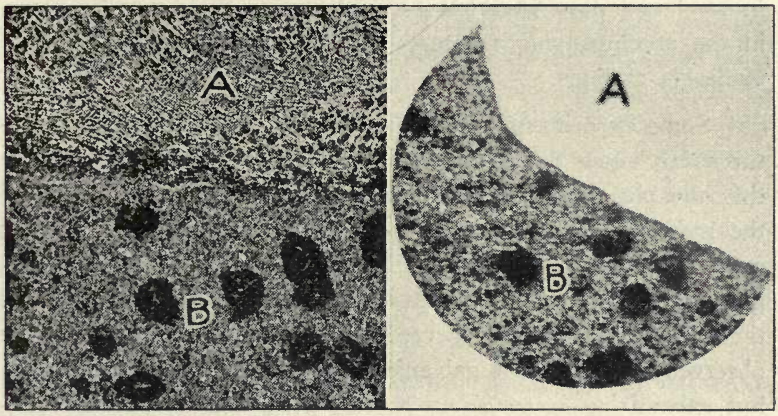


Fig. 123—(Left)—An effective acetylene weld, malleable becoming sorbitic due to resolution of carbon. *A* is gray iron converted into white cast iron by remelting. *B* is malleable. Fig. 124—(Right)—Tobin bronze weld in malleable. Note absence of oxides and slag in weld and absence of recombination of carbon due to relatively low melting point of bronze. *A* is bronze, *B* is malleable

Such castings are white in fracture and quite brittle. The fault is believed to arise from careless galvanizing resulting in overheating of the iron to the point of recombination of the carbon. It seems questionable whether a zinc bath could be heated commercially to above A_1. W. R. Bean, as a result of extensive investigation, believes that such recombination of carbon never occurs in practice. The writer, and apparently some galvanizers, feel that although rare, it can not be said that such a recombination is commercially impossible.

However, a very similar variation in quality has been observed where it was positively determinable that no such overheating has occurred. Indeed, it is sometimes though rarely observed in tinning where the temperature is never too high. The cause of this well established fact is still obscure. Attempts to correlate it with the absorption of hydrogen during pickling, with heat treatment alone and with the action of the zinc in alloying with iron have all been inconclusive. One malleable metallurgist in a preliminary private communication to the author expressed the belief that similar deterioration was caused in steel and pure iron but escaped notice since the difference in the accompanying fractures is less visibly marked than in malleable castings.

Some experiments with various heat treatments at temperatures far below the critical point would indicate the possibility that the phenomenon is associated with the grain structure of the material. How these structural changes are produced or overcome is still entirely too little understood to permit useful conclusions as to operating practice. It appears, however, that these faults are rare in sherardized material and have not been observed in the electric galvanized product. On the other hand, hot galvanizing is so generally successful that it may be concluded this operation is not necessarily harmful to the physical properties of the iron. In the absence of all definite knowledge, the malleable founder as yet is unable to do anything to assure the success of the operation nor can it be said that any one grade of malleable is better adapted to hot galvanizing than another.

The difference in results is more likely to arise from variations in the coating process than from the metallurgical characteristics of the castings. Most manufacturers take the ground that they can assume no responsibility for galvanized material beyond the delivery of acceptable castings to the galvanizer. From time to time also tinners and galvanizers think that they observe differences in the way different lots of castings take the coating. Occasionally the claim has been made that entire shipments could not be galvanized or tinned, that is, that the coating could not be made to adhere. No logical reason for such a phenomenon seemed evident. All malleable castings consist of the same metallographic ingredients, indeed the surface metal is in all cases practically pure iron which can be tinned or galvanized successfully.

Careful following up of material complained of for this reason has disclosed that in no case was the fault with the metal itself. Cases occur where the castings have not been cleaned properly and hence do not present suitable surface conditions for coating. This is at times the fault of improper cleaning after annealing and also occasionally due to the formation of a rust or grease coating while the castings are handled in the consumer's plant. In some cases also the fault has been found due to oxidized and dirty zinc or tin baths and to the use of tinning alloys too impure to give good coatings. A manufacturer for many years producing malleable castings which he tinned himself in large quantities has assured the writer that no cases have ever been found where castings would not take the coating perfectly if proper tinning practice is maintained.

In all that has gone before in this chapter, great stress has been laid on the necessity of avoiding even momentary heating of malleable castings above the critical point. If such heating does occur the carbon instantaneously recombines with iron and can be caused to separate again only by a slow cooling equivalent to that at completion of the annealing process.

In some few cases advantage is taken of this process to reharden malleable purposely. The combined carbon content after reheating is a function of the temperature attained; the hardness depends on the cooling rate adopted. The result of course is a metal of entirely different character from malleable iron, the malleability and ductility being entirely lost and a new product obtained having some of the general characteristics of hardened tool steel. Unless conditions are accurately controlled, the properties of the resulting metal may be quite erratic. To the writer's knowledge, the process has not been applied to any important work. Case hardening is said to have been applied to malleable, particularly when used for wood working tools, but the author is unfamiliar with any such practice. However, he has been assured by a consumer that quite recently at least two producers still furnished castings for edged tools.

XIV

INSPECTING AND TESTING

INSPECTION and testing of the finished product falls somewhat naturally into two subdivisions, the examination of the material as to its metallurgical properties, and the inspection of the individual castings for perfection of form, etc. The first examination is made generally on the basis of a systematic control of the works operations without reference to any particular castings. Insofar as this inspection is conducted by the manufacturer for his own information, but one satisfactory system is used.

This system consists as a minimum in the chemical analysis of every heat, either before or at any rate promptly after casting and the breaking in tension of at least one test specimen from each heat. The chemical analyses are of no interest to the consumer. The permanent recording of a test from each heat is required by specification A47-19, section 11b, of the American Society for Testing Materials.

The maintenance of a systematic record of chemical analyses is an almost unavoidable necessity to insure the foundryman against making heats which will not pass the specifications. Since test specimens will not come through the annealing process for 10 to 14 days after casting, they would not give warning of bad furnace practice in time to prevent the manufacture of a considerable quantity of bad iron. Some difference of opinion may exist as to just what constitutes adequate chemical control of the product, but the greatest weight must be laid of course on the control of those elements most likely to be subject to dangerous fluctuations.

Color Method Unreliable

Carbon and silicon certainly should be determined in every heat. The determination of manganese seems urgent in view of the fact that in air furnace practice this element is oxidized in considerable amounts. The determination of these three elements will furnish a check on the mix, or charge, being fed into the furnaces. The fact that in hard iron all the carbon should be in the combined state has lead some chemists to the poor practice of determining total carbon by color. Since the advent of the cheap and rapid direct-combustion methods there remains no excuse for such a practice. The color method cannot be relied upon to give correct values on high carbon metal and now survives mainly in consulting laboratories doing cheap contract work. While occasional expert operators can consistently check the correct values to perhaps less than 0.05 per cent the author has seen results emanating from supposedly reputable laboratories as much as 0.50 per cent in error. An expert observer can guess more closely by inspection of a broken sprue. Carbon values to be useful must be within 0.05 per cent of correct and should be better. This is only possible by combustion methods. Results by color should be disregarded as inaccurate.

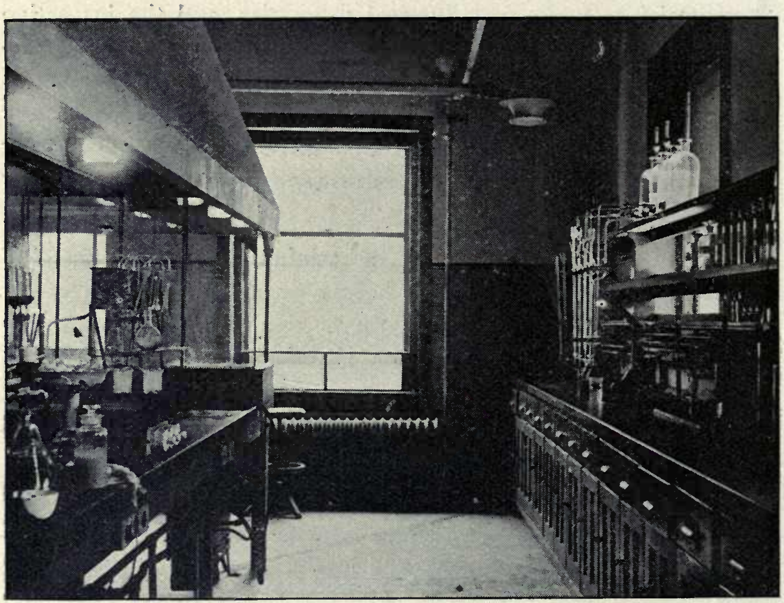


Fig. 125—Analytical laboratory in malleable plant

With good coal and melting stock, sulphur does not vary much from one heat to the next; with poor fuel, however, a close control must be kept. It must be remembered that while considerations of speed usually necessitate sulphur being determined by evolution, the results on white cast iron seldom are exact due to the formation of compounds of carbon, hydrogen and sulphur. Oxidation methods also may fail due to the evolution of gaseous sulphur compounds. Chrome, in the Aug. 10, 1921 issue of *Chemical and Metallurgical Engineering,* presented data on this point. The writer's experience is that evolution methods seldom give accurate results and may be short 25 per cent of the total sulphur. Oxidation methods executed carefully give the total sulphur but only at the expense of much time.

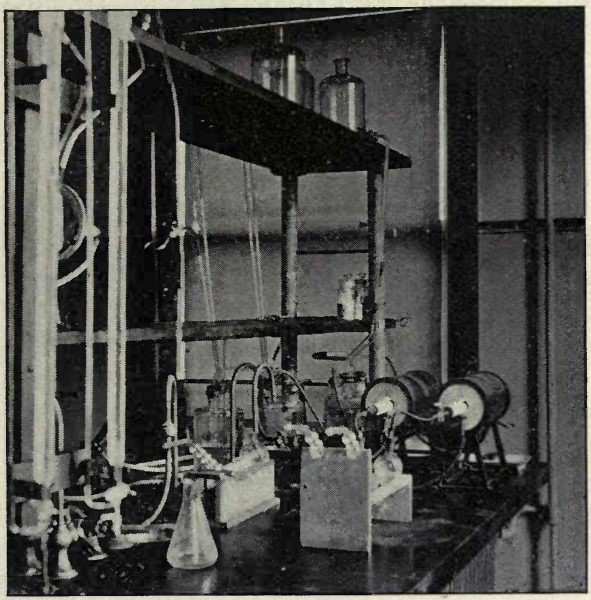


Fig. 126—Apparatus for determining carbon

The phosphorus content of the metal, in a commercial sense, can be predicted exactly from the analyses of the stock, therefore the attention to this element as required by the finished product varies inversely as the supervision given the raw material. Prudence will dictate the determination of silicon and usually also that of manganese at least in every carload of pig iron. The carbon content of pig iron is fairly constant but must not be neglected entirely. Sulphur and phosphorus being subject to specifications should be watched closely. It seems hardly necessary to describe in detail the methods of iron analysis which are applicable to hard and malleable iron. The procedure of iron analysis is becoming so well standardized that mere reference to accepted methods will doubtless give the chemist reader the information he requires without burdening the nonchemical reader with uninteresting data.

Carbon should always be determined by direct combustion in oxygen, determining the CO_2 formed either by direct weighing in soda lime or preferably by absorption in standard $Ba(OH)_2$ solution and titration of the excess alkali with standard HCl.

Solutions in which 1 cubic centimeter = 0.10 per cent on a 1.0000 gram sample are convenient. It is sometimes an advantage to add to the sample about 1 gram of carbon-free iron before burning to secure better combustion. The use of CuO or of platinum black to complete the oxidation is superfluous.

Silicon is invariably determined by a modification of Drown's method substituting a mixture of HNO_3, HCl and H_2SO_4 for Drown's method of solution. The major precaution is to bake well till SO_3 no long comes off to render SiO_2 insoluble.

For manganese the persulphate method of Walters is common, finishing the determination either by color or arsenite titration. It is well to destroy "combined carbon," that is, the colored nitro compounds produced in the reaction of cementite, with HNO_3 by oxidation with persulphate before adding any silver solution.

Phosphorus may best be determined by solution in HNO_3; oxidation, in solution, with $KMnO_4$; precipitation as "phosphomolybdate"; and finishing by alkali titration, all in the usual manner. Where very few determinations are to be made direct weighing of the "yellow precipitate" in Gooch crucibles is convenient.

Evolution sulphurs are made in the usual way. Rapid solution in rather concentrated acid tends toward complete conversion of S into H_2S. It is also a valuable precaution to heat the weighed sample for one hour under graphite and allow to cool slowly before dissolving. The graphite must be sulphur free. The writer prefers KIo_3 to iodine as a titrating solution.

If the oxidation method is used, concentrated acid and slow solution in a capacious and well covered vessel are desirable. This should be followed by evaporation and subsequent baking for one hour at not over 400 degrees Fahr. Precipitation is made in a cold solution not exceeding 100 cubic centimeters in volume containing besides the 5-gram sample 6 cubic centimeters of concentrated HCl using 10 per cent $BaCl_2$ solution. The solution and filtrate should stand one or two days to allow the latter to crystallize. In view of the length of the process care must be used to avoid contamination by the laboratory atmosphere.

Supervise Sulphur Content

Aside from economic considerations sound metallurgical practice would dictate a supervision over the sulphur content of the fuel. Taking into consideration the commercial variations in fuel, stock and furnace operations, a minimum standard for good laboratory control will include the determination of carbon, silicon and manganese in each heat, silicon and manganese in each car of pig iron, sulphur in all fuel taking an average sample from each group of 5 to 15 cars where coal is delivered in large shipments, and occasional determinations of sulphur and phosphorus in the product.

Extending the work to include sulphur in each heat and carload of iron, and phosphorus and carbon in each car of pig iron sometimes may be well repaid. The analysis of scrap material usually is not of value since no means exists for obtaining a true sample. Analytical investigation of steel scrap suspected of containing unusual elements is sometimes justified when buying scrap direct from the producer.

Determination of the tensile properties of one bar from each heat already has been referred to. The best type of works control to insure uniformity of metallurgical quality will include a permanent automatic record of all annealing oven temperatures. The progressive manufacturer will further avail himself of microscopic methods in seeking the cause for defec-

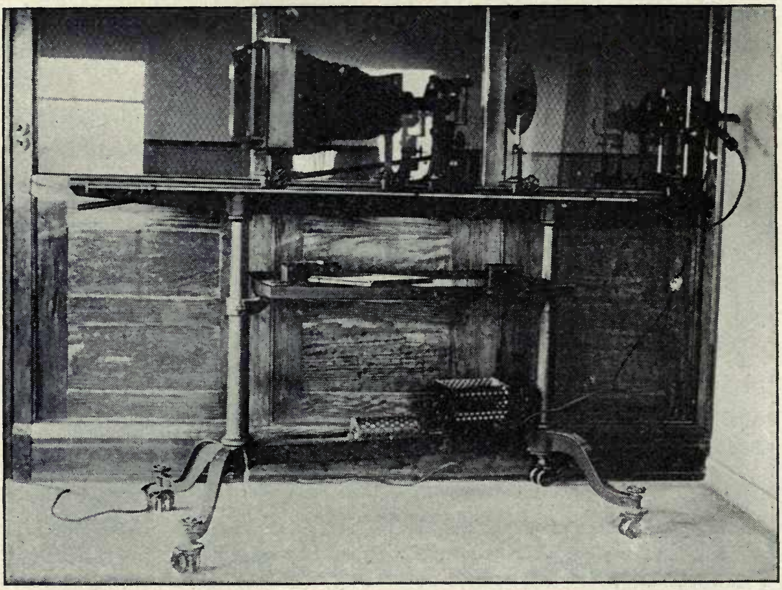


Fig. 127—Inverted types of metallographic microscope

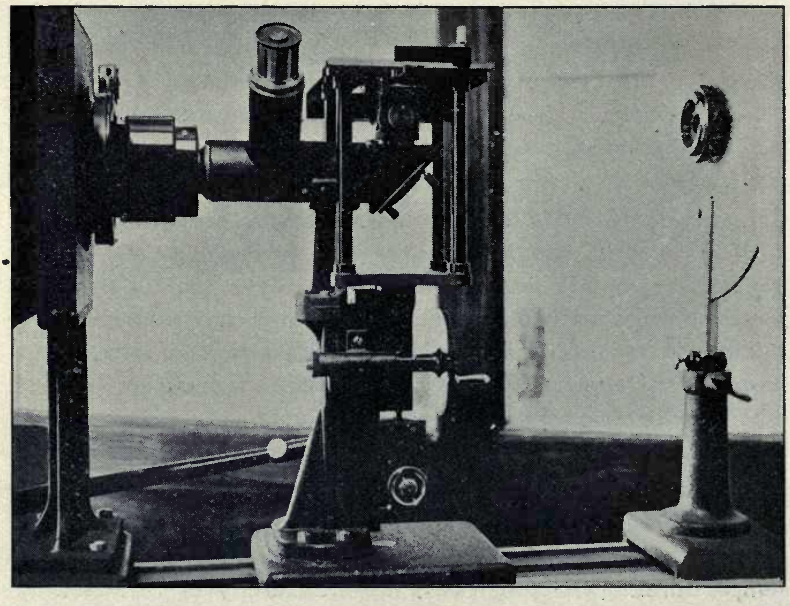


Fig. 128—Detail of inverted type of metallographic microscope (Bausch & Lomb)

tive material. Methods of metallography yield much valuable information relative to the cause of any failures when these are due to mischances in heat treatment.

The metallographic characteristics of hard and malleable iron already have been discussed in connection with the metallurgy of the product. Extended discussion here would amount to little more than needless repetition. Messrs. Bean, Highrighter and Davenport presented in a paper before the American Foundrymen's association in 1920 an extended description of "Fractures of Microstructures of American Malleable Cast Iron," showing some 40 illustrations mainly of typical microstructures. The interested metallographer may well consult the original publication.

The technique of the microscopy of these materials is in no respect unusual. Hard iron is rough ground on an emery wheel polished further upon fine emery cloth and finished upon broadcloth charged with rouge. Some operators conduct the intermediate stages of polishing upon broadcloth charged with F. F. F. emery flour and then upon broadcloth and tripoli. The etching medium is almost invariably alcoholic picric acid.

Method of Polishing

In polishing malleable care is necessary to prevent undue deformation of the soft material and the "smudging" of the temper carbon. Polishing speeds above 600 feet per minute seem undesirable. The specimen is best flattened by milling or planing followed by filing and finished as previously indicated. Suspended alumina has occasionally been used as the polishing medium.

The etching may be with picric acid if pearlite is to be examined or usually better, especially if grain boundaries are important, with 10 per cent alcoholic nitric acid. A solution of nitric acid in amyl alcohol sometimes overcomes a tendency to stain. Special reagents such as alkaline picrate or Stead's are occasionally required for particular investigations.

It is well to begin the examination of malleable at 50 or 100 diameters, to obtain an idea of the form and distribution of temper carbon pearlite, etc. At 200 diameters grain size can conveniently be studied. The identification of solid solutions may require 500 to 1000 diameters and the finer details such as the boundary structures, minute residues of cementite, crystals of titanium cyanonitride or nitride can be seen only at 1000 to 2000 diameters.

From the manufacturer's viewpoint, inspection and control of his product in a metallurgical sense involves chemical analyses of raw materials and finished castings to insure uniformity of product, autographic pyrometer records to insure uniformity of heat treatment, systematic testing of tensile specimens to determine the quality attained and metallographic work to seek the cause of otherwise unexplainable faulty material. Inspection for physical properties of the product when conducted by or for the consumer best can be made in accordance with the American Society for Testing Materials, specification A47-19, adopted Sept. 1, 1919. For completeness these specifications are quoted in full as follows:

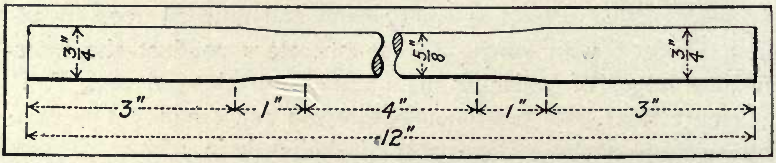


Fig. 129—A. S. T. M. Tension test specimen

1—These specifications cover malleable castings for railroad, motor vehicle, agricultural implement, and general machinery purposes.

I—Manufacture

2—The castings shall be produced by either the air-furnace, open-hearth or electric-furnace process.

II—Physical Properties and Tests

3—The tension test specimens in Section 5 shall conform to the following minimum requirements as to tensile properties:

Tensile strength, pound per square inch	45,000
Elongation in 2-inch, per cent	7.5

4—(a) All castings, if of sufficient size, shall have cast thereon test lugs of a size proportional to the thickness of the casting, but not exceeding ⅝ x ¾-inch in cross-section. On castings which are 24 inches or over in length, a test lug shall be cast near each end. These test lugs shall be attached to the casting at such a point that they will not interfere with the assembling of the castings, and may be broken off by the inspector.

(b) If the purchaser or his reperesentative so desires, a casting may be tested to destruction. Such a casting shall show good, tough malleable iron.

5—(a) Tension test specimens shall be of the form and dimensions shown in Fig. 129. Specimens whose mean diameter at the smallest section is less than 19/32-inch, will not be accepted for test.

(b) A set of three tension test specimens shall be cast from each melt, without chills, using heavy risers of sufficient height to secure sound bars. The specimens shall be suitably marked for identification with the melt. Each set of specimens so cast shall be placed in some one oven containing castings to be annealed.

6—(a) After annealing, three tension test specimens shall be selected by the inspector as representing the castings in the oven from which these specimens are taken.

(b) If the first specimen conforms to the specified requirements, or if, in the event of failure of the first specimen, the second and third specimens conform to the requirements, the castings in that oven shall be accepted, except that any casting may be rejected if its test lug shows that it has not been properly annealed. If either the second or third specimen fails to conform to the requirements the contents of that oven shall be rejected.

7—Any castings rejected for insufficient annealing may be reannealed at once. The reannealed castings shall be inspected and if the remaining test lugs or castings broken as specimens, show the castings to be thoroughly annealed, they shall be accepted; if not, they shall be finally rejected.

III—WORKMANSHIP AND FINISH

8—The castings shall conform substantially to the patterns or drawings furnished by the purchaser, and also to gages which may be specified in individual cases. The castings shall be made in a workmanlike manner. A variation of ⅛-inch per foot will be permitted.

9—The castings shall be free from injurious defects.

IV—MARKING

10—The manufacturer's identification mark and the pattern numbers assigned by the purchaser shall be cast on all of sufficient size, in such positions that they will not interfere with the service of the castings.

V—INSPECTION AND REJECTION

11—(a) The inspector representing the purchaser shall have free entry, at all times while work on the contract of the purchaser is being performed, to all parts of the manufacture's works which concern the manufacture of the castings ordered. The manufacturer shall afford the inspector, free of cost, all reasonable facilities to satisfy him that the castings are being furnished in accordance with these specifications. All tests and inspection shall be made at the place of manufacture prior to shipment, unless otherwise specified, and shall be so conducted as not to interfere unnecessarily with the operation of the works.

(b) The manufacturer shall be required to keep a record of each melt from which castings are produced, showing tensile strength and elongation of test specimens cast from such melts. These records shall be available and shown to the inspector whenever required.

12—Castings which show injurious defects subsequent to their acceptance at the manufacturer's works may be rejected, and, if rejected, shall be replaced by the manufacturer free of cost to the purchaser.

These specifications contain a number of points which perhaps may be subject to criticism, nevertheless representing as they do the consensus of opinion of a committee acting for all interested parties and having the approval of a large body of able engineering specialists, the specifications* may be considered the best practicable solution of the problem of inspection of malleable.

The specifications further have the approval of the American Foundrymen's association and of the American Malleable Castings association. Therefore, it would seem to the best interests of all that this specification, together with its further authorized versions, should be adopted by all producers and consumers as a universal guide to quality. Any attempt to modify or adapt it to supposed special conditions as a rule will be productive of intolerable confusion and secure no compensating advantage. The benefits of standardization will be lost and the resulting specification, not having the foundation of mature consideration by many minds is likely to be less satisfactory than the standard. If in any special case it is agreed by buyer and seller that it is to their mutual interest to waive the specifications, of course no objections can be made to that course provided the understanding is clear to both parties.

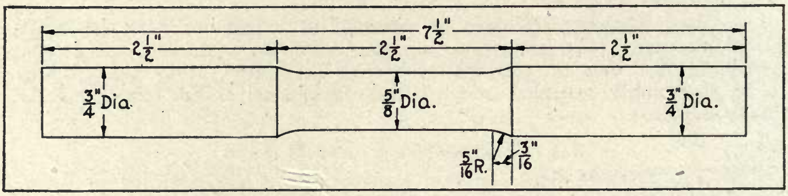


Fig. 130—Dimensions of proposed tension test bar

It will be seen that inspection by means of test lugs is provided for in the specification. This is a valuable check on the

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*Revisions in the specifications quoted on pages 274 and 275 were adopted as tentative at the 1922 meeting of the A. S. T. M. *Section 3,* is tentatively changed to read:

"The tension test specimens specified in section 5 shall conform to the following minimum requirements as to tensile properties:

Tensile strength, pounds per square inch	50,000
Elongation in 2-inch, per cent	10.0

In *Section 6 (b),* the following sentence is added:

"In case one of the retest specimens contains a flaw which results in the failure of the bar to meet the specifications, at the discretion of the inspector additional test specimens from the same oven may be tested, or test specimens may be cut from castings."

It is further recommended that the standard test specimen be modified to conform to the dimensions shown in Fig. 130.

quality of individual castings. Test lugs are projections in the form of a frustum, of a rectangular pyramid, or of a cone which are broken off by the works inspector or by the consumer to determine the quality of the metal in the casting. The size of these test lugs depends upon the size and thickness of the castings to which they are attached. Thus it is impracticable to lay down definite rules for their size, form and location. In general, lugs should be applied to all castings where quality is important. Pieces weighing less than 3 pounds or heavier of thin cross section are usually too small to permit of putting on a lug and breaking it off without damage to the casting.

The round test lug is much affected in appearance by shrinks and is quite deceptive at times. The author's preference is for rectangular test lugs in which the smaller dimension at the point of fracture is ¼-inch less than the layer. Generally the height of a test lug should be about equal to the larger dimension at the point of fracture, and the taper about 1/32 to 1/16-inch per 1 inch on each side.

Useful sizes of lugs are specified as follows:

	Dimensions at breaking point in inches		Dimensions at top in inches		Height in inches
Class of work	Length	Width	Length	Width	
Very heavy sections 1¼-inch thick and over	¾	½	11/16	7/16	¾
Intermediate	⅝	⅜	9/16	5/16	⅝
Light castings up to ⅜-inch thick	9/16	5/16	½	⅜	9/16

Test lugs, to represent the metal properly, must be free from shrinks; hence in general should be located in the drag of the mold. In inspecting castings by test lugs, care should be used that the lug is not bent in opposite directions to break it off. The practice of nicking lugs with a chisel before breaking also interferes with a correct interpretation of the result. Under such circumstances the lug breaks off "shorter," that is, shows less toughness than it should.

Three factors must be given consideration in determining the quality of a casting from test lug inspection. These items are the effort required to break off the lug, the distortion it sustains before breaking, and the appearance of the resulting fracture. While the effort cannot be measured and recorded in figures, after a time it becomes simple to compare different results fairly accurately. In general the hammer should not be so heavy as to break off a good lug with one or two blows. A fair idea of the energy consumed can be formed from the number of blows required to produce fracture.

The amount of distortion in breaking usually increases with the blows required to do the breaking. Test lugs should bend out of line materially before fracture. All conditions being equal, small test lugs will bend further than large ones. On small work where small lugs may be unavoidable, they will often hammer over flat before breaking. On heavy lugs a displacement of 30 degrees will indicate very good material. The intermediate and smaller sizes listed in the table may bend somewhat more, even up to 60 degrees. Distortion is greater when the break is made by frequent light blows than by a few heavy

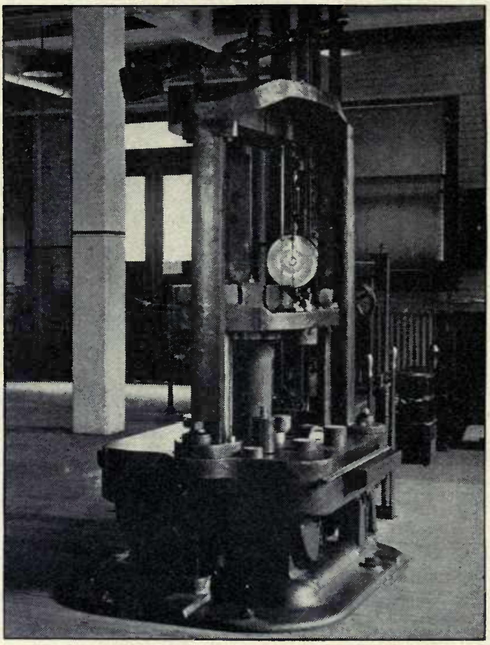

Fig. 131—A 200,000-pound Olsen universal testing machine

blows. Striking the lug alternately on opposite sides of course will produce no distortion and hence is valueless.

The fracture of normal malleable iron, in the absence of much compression, is of a velvety black appearance, having a mouse gray rim of fair depth. Occasionally two bands are observed, the outer one being somewhat lighter than the inner. The outer rim in such cases, however, is never steely in appearance. In bending the lug over, the concave side is of course considerably compressed and this compression so distorts the crystal structure of the ferrite as to materially alter its appearance. Toward the concave side of such a lug the fracture will be silver white in color and rather fine in grain, that is, not coarsely crystalline. This structure may occupy half or even more of the entire fracture. However, a band free from any steely rim and of normal appearance will always be found toward the convex side.

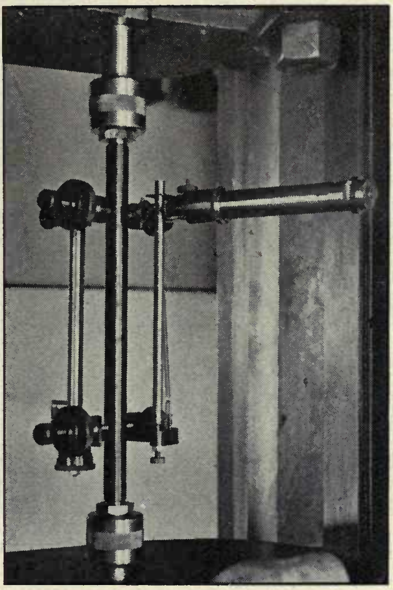

Fig. 132—Ewing-type extensometer for determining elongation under load

When the so-called "compression fracture" is but slightly developed, danger exists for mistaking it for a rim unless it is observed that the white edge is along one boundary of the fracture only instead of uniformly around it. Lugs broken by being struck on opposite sides may show this compression edge on the two opposite boundaries and may be difficult of interpretation. They may even be clear white.

Occasionally fractures are encountered which have a so-called "picture frame" rim or "shuck." This is a rim, usually of crystalline appearance, completely surrounding the fracture as a band of uniform width. If the rim is narrow, the material may be strong and will bend fairly well. Such rims usually contain pearlite and the resulting metal is not readily machinable. Where machining is no object, a reasonably narrow edge of this character need not condemn the product if the lug withstood punishment well. Where machining is involved, the inspector should use discretion in taking any material with edges in order to exclude this condition.

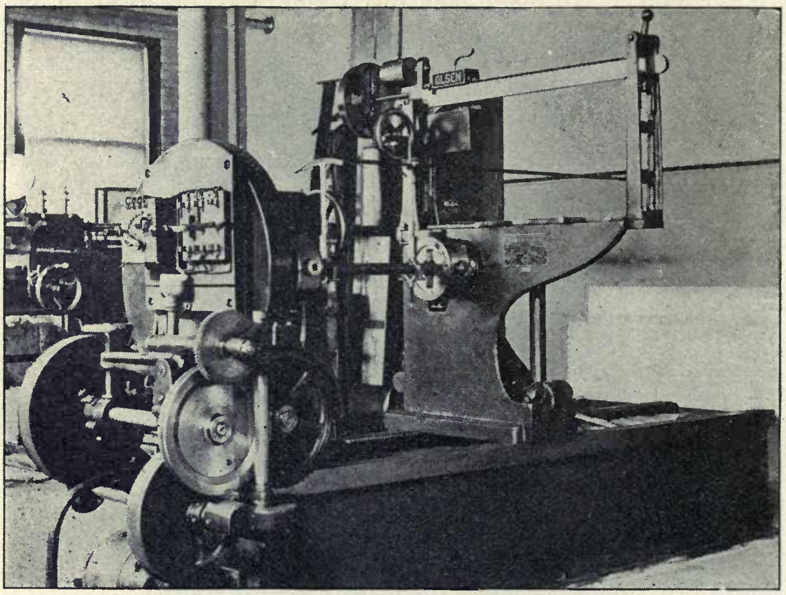

Fig. 133—Olsen-type torsion testing machine

Entirely white fractures somewhat rarely occur. These may be due to an anneal so incomplete that the original hard iron

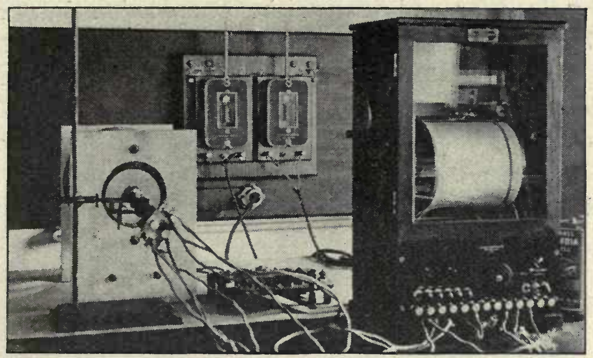

Fig. 134—Leeds & Northrup Co. apparatus for determining critical points by Roberts Austens method

structure is but slightly altered, in which case the castings should be returned for reannealing. Occasionally the fracture is composed entirely of steely brilliant facets surrounded by a narrow rim of a more gray color. Such iron is useless from the American viewpoint, being that normal to white heart malleable. It is due to radical faults of chemical composition and cannot be saved by any ordinary reannealing.

A further type of white fracture sometimes met with

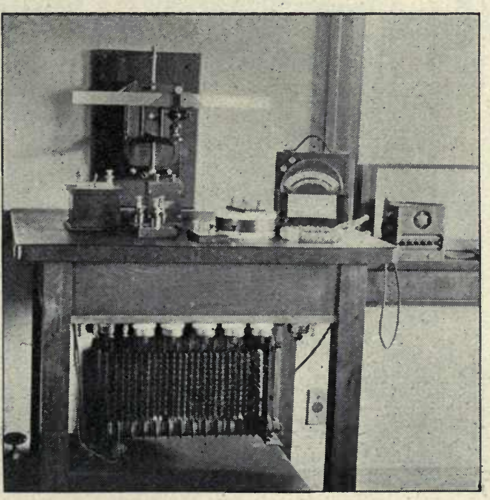

Fig. 135—Apparatus for measuring magnetic properties of metal

resembles in color and texture the compression fracture mentioned before but extends over the entire fracture. Such lugs usually bend but litlte though they are decidedly tougher than those defective on account of an incomplete anneal. This material is normal under the microscope and contains no combined carbon. The fault lies with the crystalline structure of the ferrite and can be remedied by suitable further heat treatment.

A coarse black center surrounded by a slate-colored rim accompanies weak lugs and is characteristic of poor, high carbon material. Considerable experience is necessary to interpret abnormal fractures properly. Indeed, those who pretend off hand and from inspection alone to solve all problems as to quality of material and causes of failure, usually overestimate their own abilities.

In many cases all the resources of a chemical and metallographic laboratory are required to diagnose troubles. Since the consumer's inspector is not interested in the cause of trou-

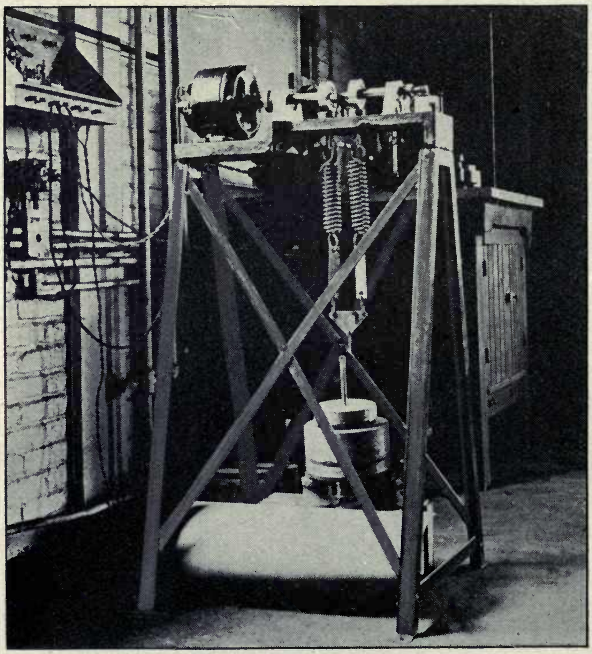

Fig. 136—Farmer fatigue testing machine

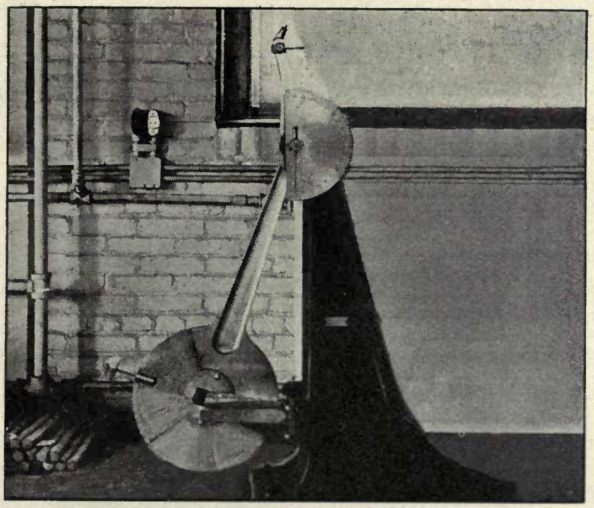

Fig. 137—Charpy hammer for impact tests

bles he may be guided in the acceptance of material by the following considerations;

1.—Deformation of the lugs must be up to standard.

2.—Bending should require a fair degree of effort.

3.—Irrespective of the fracture, reject all material in which the lugs snap off sharply.

4.—Irrespective of a fracture, accept any material in which the lug has sustained much more than average punishment as a result of which indications are rendered worthless due to the heavy distortion.

5.—Where machining is to be done, reject any castings which have more than a paper thin rim.

6.—Where machining is no object, accept castings with a wide steely edge only if the performance of the lug under punishment is unquestionable.

7.—Reject all castings having a coarse structure and the slate colored rim. Such lugs generally are defective with respect to the first three tests also.

8.—Return for annealing all condemned castings in which the fracture is partially or entirely silver or steely in color.

It may be well also for the inspector to assure himself of the absence of injurious shrinkage by breaking hard or annealed castings from time to time and by watching the fracture of heavy unannealed castings for the presence of primary graphite "mottles." Both shrinks and mottles are found preferentially in the last cooling sections.

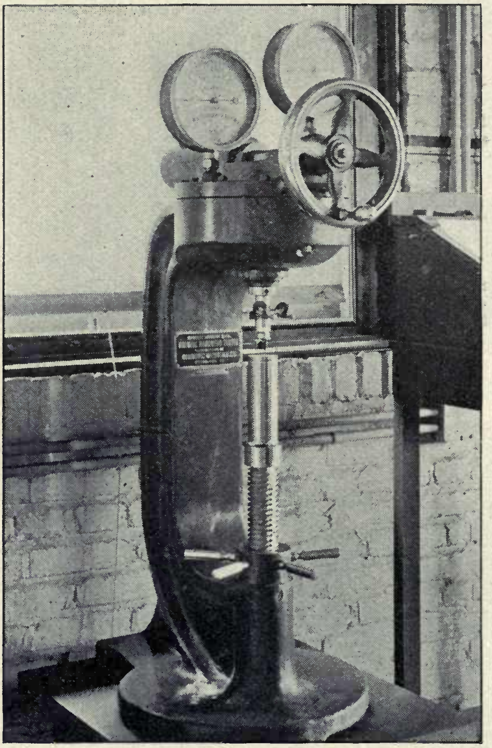

Fig. 138—Brinell hardness tester

Occasionally questions are raised as to inspection for various purposes after arrival of the product at the consumer's plant. Except in very exceptional cases, inspection and condemnation of entire lots on the basis of faults observed on individual pieces cannot be resorted to fairly. As the average malleable foundry is operated, it is quite possible that no two castings in a given sack, or barrel, are representative of the same heat in the melting department and oven in annealing.

The fact that in an impartially drawn sample a certain small number of defective pieces are, or are not found proves nothing as to the remaining pieces. Therefore, only an inspection piece by piece is equitable after the castings can no longer be identified with certain specific lots made in the foundry. The test lug inspection was devised for this very purpose. Upon occasion the problem has arisen of selecting from a large and indiscriminate mass of castings those too hard to machine.

Brinell and Shore tests are useless for the purpose unless the material is practically unannealed. Some inspectors feel that the behavior under a preliminary drilling operation is suitable as a means of weeding out hard castings. Others have used the ring of the casting, that is, the pitch of its musical note when struck. However, none of these methods are as cheap, as simple, or as conclusive as the breaking of a test lug.

Occasionally it is desired to inspect the finished or semifinished article to make sure of its fitness for the intended loads. Where the maximum loads do not require a proof load beyond the yield point of the article, the application of such a load is an ideal test. Thus a link belt can be loaded in tension to about the yield point and defects which would result in failure under-service conditions can be discovered.

Castings which are straightened after a material deformation receive of course a test similar in principle to such a proof test. It is therefore hardly necessary to deal with them here in any detail. Inspection of castings as to their being true to size and form, etc., has not been discussed but this is done by the usual methods of gaging and is not different from similar inspection on any other product.

XV

TENSILE PROPERTIES

TENSION is the simplest stress which can be applied to a material. The ease of execution of this form of loading has made tensile tests a favorite means of judging the quality of a metal even though relatively few structural details are subjected to pure tension in service. When an elastic material is stretched it first lengthens in exact proportion to the applied load, in other words, it follows Hook's law of the proportionality of stress to strain. Beyond a certain definite loading the stretch increases more rapidly than the applied load. The point where this occurs, beyond which the material no longer obeys Hook's law, is always referred to as the *proportional limit.*

In many materials the increasing rate of stretch is at first so slight as to escape detection by any but the most sensitive of measuring instruments. As more and more load is applied a point is usually reached, however, where the material begins to elongate very rapidly with practically no increase in the load applied. This load is called the *yield point* and is more easily recognized than defined. The term *elastic limit,* frequently used and also frequently misused, signifies that stress up to which the material is not permanently deformed. In other words, a material may be loaded to any amount up to its elastic limit and when the load is removed will return to exactly its original length. This test is seldom employed. Like the proportional limit, the elastic limit depends largely on the sensitiveness of the available means of measurement.

Explanation of Terms

Frequently the three points are confused and used as if they were identical. The proportional limit is necessarily below the yield point; how much below depends on the material being tested and the accuracy of the measurements. The elastic and proportional limits may be considered identical in principle, but up to the yield point the permanent set, or elongation, might be so small as to escape recognition.

The reader should remember that by the very definition of the proportional and elastic limits the apparent location of these points will vary with the available methods of measurement, the proportional limit being the largest load the material will sustain without visible departure from Hook's Law, and the elastic limit the largest load it will sustain without taking a permanent set. The greater the precision of the measurement, the lower will be the stress corresponding to these definitions. Doubt is frequently expressed whether cast metals actually have any proportional limit larger than zero, the thought being that with sufficiently delicate extensometer measurements, the graph would be a curve from the origin. In view of these facts an attempt to find the elastic limit by watching the drop of the testing machine beam will give apparently higher values than determining this point by the divider method and the divider method will give materially higher results than the extensometer. The engineer will therefore require to know how these points have been determined in making intelligent use of the information.

Action of Metals in Tension

Most ductile materials when loaded in tension beyond the yield point do not stretch uniformly at all points of their length. The larger part of the deformation usually occurs quite close to the point of failure. The specimens accordingly neck in and finally break at the smallest portion of the necks. The per cent of elongation is therefore less the longer the gage length in which it is measured. The difference between the area at the point of fracture and the original cross-sectional area, expressed in per cent, is called the reduction in area. A high reduction in area is even more indicative of a very ductile material than a high elongation. The ratio of stress to strain, below the proportional limit, is known as the modulus of elasticity. These various constants, proportional limit, yield point, elongation, reduction in area, modulus of elasticity, and ultimate strength and the relationships between them give a very good picture of the behavior of any material under static loads. These constants also yield some information regarding its behavior under dynamic stresses. The application of each constant is fairly evident. The proportional limit is useful when the deflection must be temporary and predictable. The yield point limits the stresses which may be applied without producing visible permanent changes of shape in the material. Elongation and reduction of area are indicative of the amount of distortion a material can stand without fracture. The ultimate strength measures the load that can be sustained without failure, although with permanent deformation. The modulus of elasticity serves to determine the elastic deflection under relatively small loads. The behavior of a material under tension is most conveniently expressed by means of a stress-strain diagram, in which the elongation in per cent in some definite gage length is plotted against the increasing load in pounds per square inch. Fig. 139 shows a graph of this kind somewhat typical of malle-

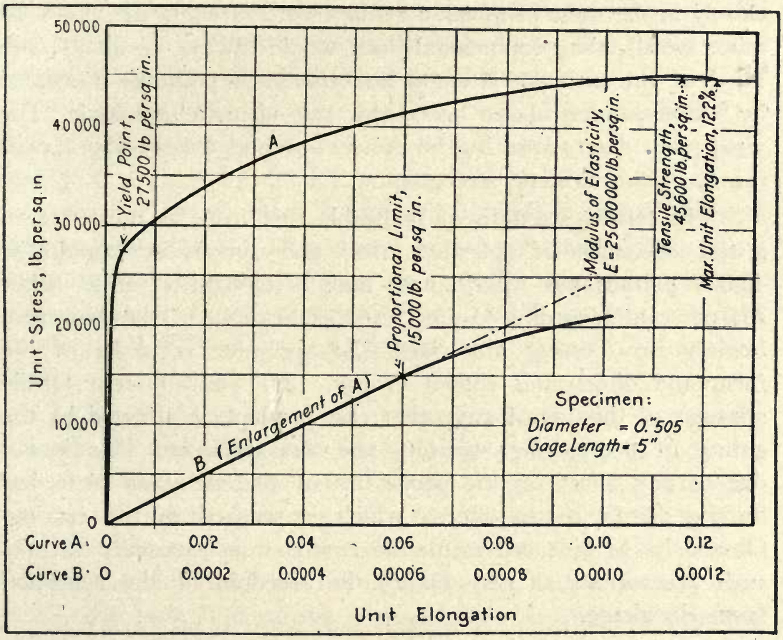

Fig. 139—Stress-strain diagram of malleable cast iron in tension

able cast iron. The various constants are marked in the graph in the appropriate places. The curve is made from a malleable casting about the tensile strength prescribed by the A. S. T. M. specifications.

Malleable iron of higher tensile strength would have the proportional limit, elastic limit, and yield point raised very closely in the same proportion as the tensile strength increased. In other words, the proportional limit would always be about one-third of the ultimate strength and the yield point as measured by extensometer about six-tenths the ultimate strength. The yield point determined by the divider method will be about two-thirds of the ultimate strength.

The tensile strength of malleable cast iron, as measured in a test specimen of specified form and dimensions should be 45,000 pounds per square inch and its elongation in 2 inches 7½ per cent according to the 1919 specifications of the American Society for Testing Materials. The specimen is to be of the form and dimensions shown in Fig. 129. The apparent tensile strength of this, as of any other cast product, is affected by the gating of the castings forming the test specimen. This is not due to any effect on the properties of the metal as such, but on the degree of soundness which is secured in the casting. Obviously, to give representative results it is necessary to take such precautions as may insure the freedom of the specimen from shrinkage.

Specimens Must Be Representative

The point seems worthy of discussion in this chapter because criticism and confusion often arise when specimens cut from castings or parts of castings do not conform in properties to the American Society for Testing Materials specimens from the same heat. The discrepancy frequently is due mainly to internal defects of the castings from which specimens are taken.

Failure of such specimens to pass the test indicates improperly fed castings rather than weak metal. The tensile strength and elongation of malleable as made today by the leading manufacturers exceed the American Society for Testing Materials specification by a safe margin, the metal now sold by reputable makers rarely being under 48,000 pounds per square inch in tensile strength and 10 per cent in elongation. The product probably averages about 51,000 pounds ultimate strength and 12 per cent elongation.

The tensile strength and elongation of daily specimens submitted by all of the more than 60 members of the American Malleable Castings association have been averaged by months and the results plotted as shown in Fig. 140. The recent data average better than the author's personal estimate.

Occasional record performances have been noted. The highest grade malleable known to the writer was a single piece having a strength of 58,000 pounds per square inch, and an elongation of 34 per cent. A strength of 64,000 pounds coupled with an elongation of 18 per cent was once noted. These were single isolated cases and in no sense typical of a routine product. One plant produced castings over 57,000 pounds ultimate strength and 20 per cent elongation continuously for about a month.

As might be expected from its microstructure, the tensile strength of malleable cast iron is largely dependent upon its carbon content, since the more carbon the greater the interruption to the mechanical continuity of the casting. This applies rather to the original carbon content than to that after anneal. Carbon once liberated has accomplished its destruction of continuity and even if it can be removed after formation, it leaves behind the hole it occupied.

Furthermore, the other elements present besides carbon may affect the physical properties of the ferrite just as they affect

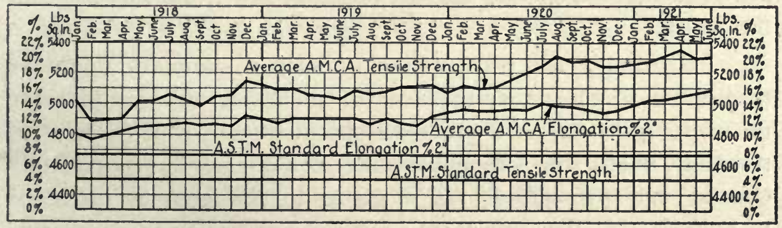

Fig. 140—Tensile strength and elongation plotted from specimens submitted by members of American Malleable Castings Association

the properties of a dead soft steel. This, however, is of less practical importance than the variations due to carbon, since within the limits capable of commercial annealing none of the other elements are likely to have an effect of the order of magnitude of those due to the latter element. The writer in the past has had occasion to make comparisons of the tensile properties of many thousands of heats with their chemical compositions. As a rule investigations of this character are influenced by so many variables that a summary which is strictly accurate as well as fairly simple is hardly possible, save at the expense of space for detailed technical explanation which could be spared only in a monograph upon that one subject.

Increased Carbon Lowers Strength

In general it may be said that an increase in carbon always carries with it a decrease in strength and elongation. The decrease in strength per unit increase in carbon is greater the greater the total amount of carbon and the higher the silicon.

Manganese and sulphur when present in correct relative proportion and within anything resembling commercial limits have relatively little effect. Phosphorus up to about 0.20 or 0.25 per cent strengthens the metal without decreasing its ductility.

The considerations just outlined would seem to furnish a basis for a graphical or tabular summary of the relation between tensile strength and chemical composition. The great difficulty is that even though the effect of each element may be well established, there remain variables due to the form of test specimen, the soundness of the specimen and the effect of the previous thermal history on the physical and grain structure of the ferrite.

Accordingly the presentation of such a summary might be misleading to the interested user of malleable and would serve no useful purpose as a guide to specifications or to successful practice, unless the other variables could also be successfully defined and prescribed. As a guide to the general order of magnitude of the effect of carbon and silicon on normal malleable iron, Fig. 141 shows the average tensile strength of malleable of varying carbon content but of constant silicon as averaged from a large number of heats. An increase of 0.01 per cent silicon decreases the tensile strength about 20 pounds per square inch for low-carbon iron (about 2.25 per cent), and about 75 pounds per square inch high-carbon iron (about 3.25 per cent). From these data it would seem that a simple arithmetical calculation should show what the strength of malleable cast iron in pounds per square inch measured in the American Society for Testing Materials test specimen should be for any given composition.

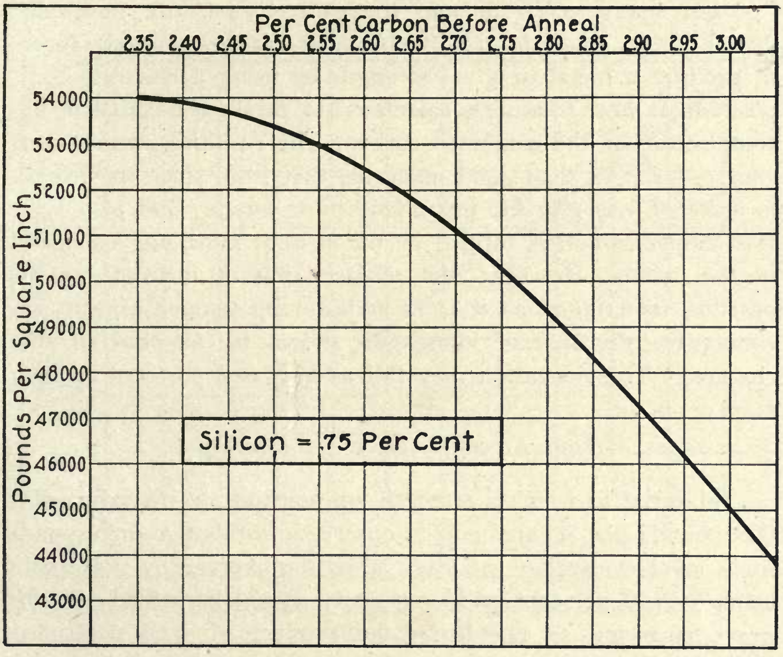

Fig. 141—Effect of carbon on tensile properties of malleable iron

Any attempt, however, to apply these figures literally is not likely to be productive of results, since the formula is purely an empirical one and since no account is taken of some of the other variables, notably of the effect of heat treatment in the properties of ferrite.

Malleable iron, when completely annealed, stands alone among the ferrous materials in that variations of composition affect the elongation in the same direction as the strength. That is, malleable cast iron has a higher elongation the greater its strength.

The reader should not lose sight of the fact that what has just been said concerning the proportionality of tensile strength and elongation is only true of completely graphitized products.

For many years and up to relatively recently misguided efforts were made by ill-informed or careless manufacturers to produce a metal of great strength by using a chemical composition or heat treatment calculated to produce incomplete decomposition of the combined carbon. The resulting metal is, of course, stronger than good malleable cast iron, since the matrix is more or less pearlitic instead of pure ferrite; and also since less temper carbon is formed by the amount remaining combined in the matrix. However, the relative lack of ductility of the pearlite, interrupted as it is in addition by temper carbon, accounts for the lack of elongation shown by material of this character. The elongation may fall as low as 2 per cent in such cases.

High Strength May Be Deceptive

Material in which a strength approaching or exceeding 60,000 pounds per square inch is observed, without a correspondingly good elongation (at least up to the average or preferably as high as 12 per cent or 15 per cent) should be looked on with grave suspicion as not being the product of well controlled malleable practice.

Each circle in Fig. 142 shows a group of heats of a given analysis, the different circles representing different analysis. They are located according to the strength and elongation of the resulting product. It is plainly evident that increasing strength is accompanied by higher elongation. This graph furnishes some basis for conclusions as to the effect of chemical compositions on elongations by demonstrating the approximate proportionality of the two properties. An exception has been noted in that while silicon slightly decreases tensile strength and hence should decrease elongation, the reverse is true for very low silicons, especially in the presence of low carbons. The departure may perhaps be explained in the light of minor interferences with complete graphitization.

The tensile strength of malleable iron further varies with the cross-sectional area of the piece under consideration. This phenomenon is not due to the long-exploded thought that the strength of malleable iron is only in the skin. This thought persisted from the days when malleable iron was made "malleable" by decarburization only, as is the case with the so-called "white heart" product of Europe.

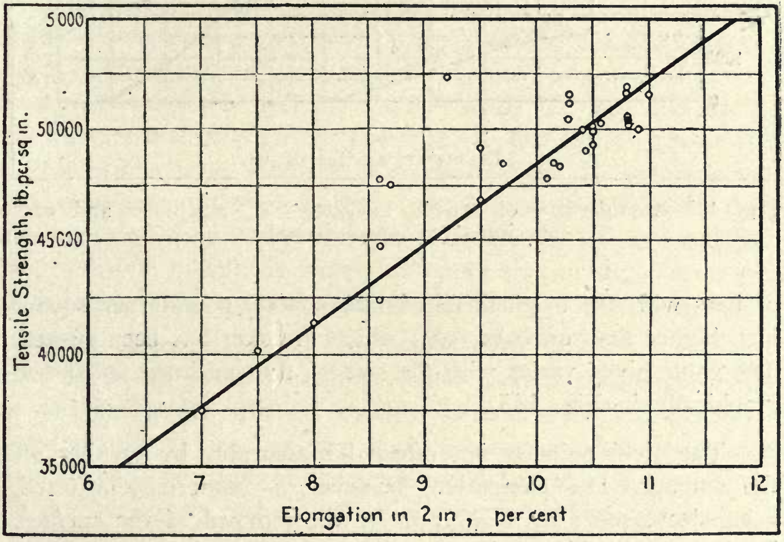

Fig. 142—Relation between tensile strength and elongation of malleable cast iron

The skin of normal American or black heart malleable differs only in degree from the center. W. R. Bean* gave figures indicating that specimens from the same heats tested in their condition as cast and after machining off at least 1-16 inch, and sometimes ⅛ inch of the surface, had practically the same strength. Tests made by the writer indicate that on sections up to one inch in diameter, after machining, the ultimate strength

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*Paper presented at the annual meeting of American Society for Testing Materials, 1919.

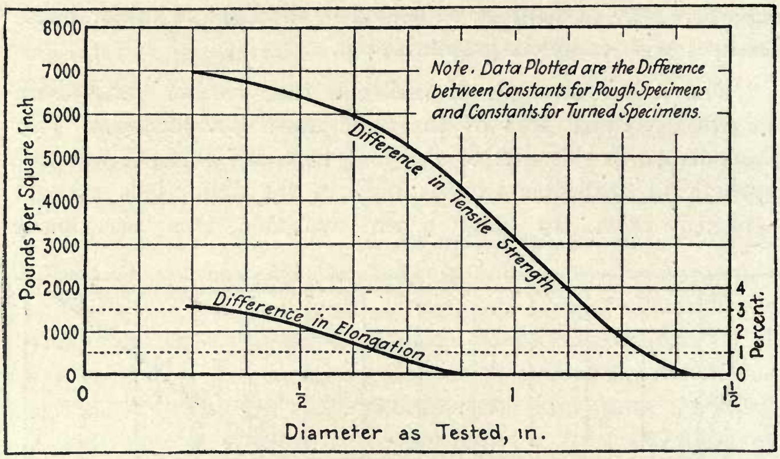

Fig. 143—Comparison of tensile properties of machined and cast specimens of equal diameters

of bars with the original skin is about 4000 pounds per square inch higher than on bars from which the skin has been turned. The value given varies with the size of the specimen, as shown graphically in Fig. 143.

The yield point is not affected measurably by turning off the surface. The elongation, however, is materially affected, being decreased 3 or 4 per cent by the removal of the surface. In the case of thin sections, turning off the surface reduces the reduction of area 5 or 6 per cent and in extremely thin specimens considerably more. It will be seen that these differences, although not by any means negligble, are not of an order of magnitude to warrant the conclusion that the properties of the surface metal are all that gives malleable cast iron its value.

The difference in unit strength between large and small cross sections may be due to either of three general reasons. The large specimen may not be so molded and poured as to be free from shrink. This difficulty usually can be avoided in castings by proper feeders, unless the casting be of especially intricate design. In test specimens this remedy can always be applied because in this case commercial molding restrictions affecting production never apply. Even when this difficulty is entirely overcome there remain two other variables which always prevent a large section from having the same strength in pounds per square inch possessed by a small one of the same metal.

Both of these variations arise from the cooling rate of the casting. The rate of cooling of the casting in the molds affects the final product by its effect on the formation of primary graphite and by its effect on the grain structure in the hard iron.

The former difficulty is easily suppressed by making the chemical composition such that no graphite will form on freezing, even when the cooling is as slow as any to be expected. Even when it is completely overcome, as is usually the case, the effect on grain structure persists. The size of the ferrite grains in malleable in a large measure is determined by the graphitizing heat treatment, although perhaps not to the exclusion of the freezing conditions. However the size and distribution of the temper carbon nodules is largely an expression of the concensus of fineness of the original dendritic structure of the hard iron.

Iron alloys in crystallizing while freezing obey the same laws as do all other crystalline solids in that slowly growing crystals are larger whereas quickly formed crystals are small. Consequently a large casting always has a coarser structure than a small one made of the same metal and to a slight extent the surface of any casting will be of finer grain than the center.

These differences are carried over into the annealed product since the form and distribution of the cementite will more or less affect the distribution of the ferrite and temper carbon into which it breaks up, hence the quickly cooled casting will have finer and more uniformly distributed grains of free carbon than one cooled more slowly. Fig. 144 shows the strength and elongation of specimens varying in diameter from ¼ to 1.5 inches.

A further word of caution may be necessary. It has just been explained that of the same metal a small specimen is stronger than a large one. It is quite possible, at least within limits, to produce a metal of any desired strength in any given section even if that section be large. Thus castings having a cross section 4½ x 9 inches have been produced experimentally with the material at the center having properties conforming to

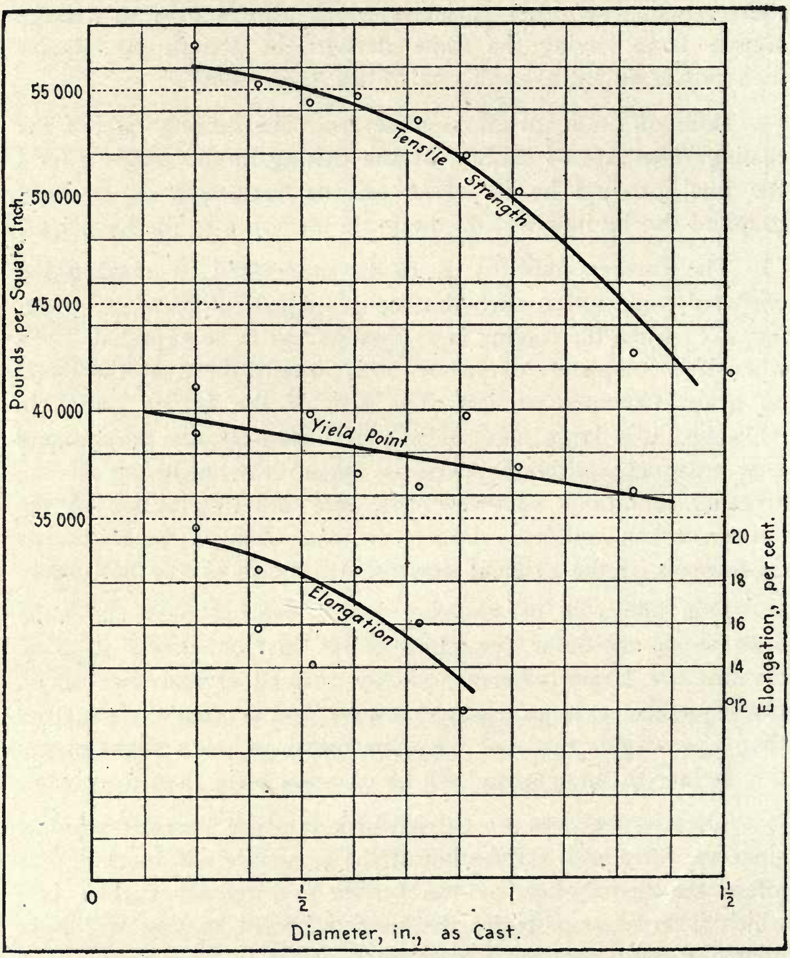

Fig. 144—Results of tests on specimens not machined

the American Society for Testing Materials requirements. Reduction of area is not frequently determined on malleable cast iron since the material is tested without machining. The impossibility of determining the area of a comparatively rough specimen before testing precludes the determination of this constant under standard conditions. Occasionally the author has determined this constant for specimens ground truly cylindrical before annealing. The following table gives an idea of what may be expected when the specimens are about ⅝ inch in diameter.

Ultimate strength in pounds per square inch	Per cent of elongation in 2 inches	Reduction in area in per cent
51,600	21	18
51,500	20	17
55,200	19	18
55,100	13	20
55,200	17	23

In malleable cast iron, as in other materials, the reduction in area decreases as the diameter of the specimen increases. It is a general principle that the reduction is greater the fewer grains of iron are contained in the cross section.

In a certain series of tests on a given metal the following results were observed:

Diameter inches	Reduction in area per cent
¼	28
⅜	20
½	18
¾	14
1⅜	6½

Castings Not in Tension

In engineering design malleable castings are seldom subjected to pure tension. Loads in cross bending, compression and in shear are much more common. Indeed, where tension is applied to malleable castings the load usually is transmitted to the casting by screwing the latter into a nut or similar detail. Typical cases are malleable eyebolts in turnbuckles. Although the shank of the bolt may be in tension, consideration must also be given to the shearing strength of the threads where strength calculations are requisite. Unless the design of such bolt-like details is such that the threaded end has an outside diameter sufficiently larger than the shank's diameter so that the area at the root of the thread exceeds that of the cross section of the cylindrical body of the bolt a further complication enters.

This complication is not limited to malleable castings, but is common to all structural materials. Nevertheless, it is not infrequently overlooked. Tensile properties are measured on test specimens usually cylindrical, but at any rate of as nearly uniform cross section as can be produced. So measured, they do accurately define the material. However, if the form of the actual structural detail is such that the area of minimum cross section is decidedly less than the maximum and is localized in a relatively short portion of the axial length of the detail, the loading conditions are not comparable to those obtaining in the testing machine.

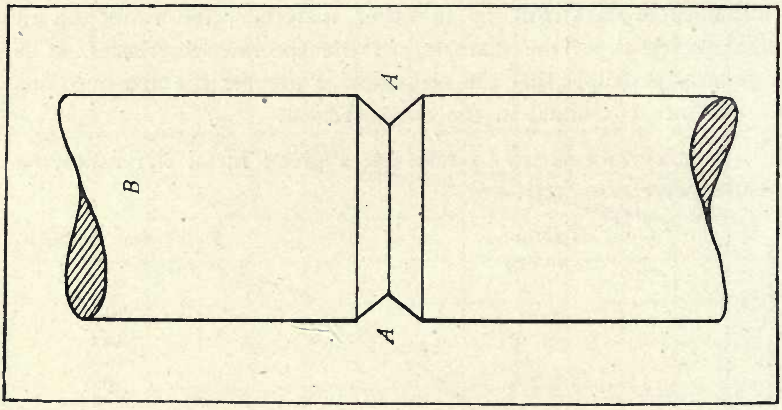

Fig. 145—V groove in bar

Thus if a cylindrical bar has a sharp *V* groove turned into it as illustrated in Fig. 145, fracture will take place in the area at the root of the groove. However, there will be no significant elongation of the piece as a whole, for if the total carrying capacity of the section at *A-A* at the smallest part of the bar is not such that when distributed over the area of the body of the bar at *B,* an intensity of loading above the yield point is obtained, the piece will tear apart at *A-A* without any deformation to each side of the groove. Even if the area *A-A* is sufficiently near that at *B* so that the body is stressed beyond the yield point the intensity of stress at *B* must be less than in *A-A* and an inspection of the stress strain diagram will show the localization of stretch to be expected due to the rapid increase in rate of deformation at the higher stress intensities.

Furthermore the minimum area of cross section apparently receives some support from the much larger areas immediately adjacent. The net result of both phenomena is that a grooved specimen shows an abnormally low elongation and high strength, as calculated on the basis of the area of fracture.

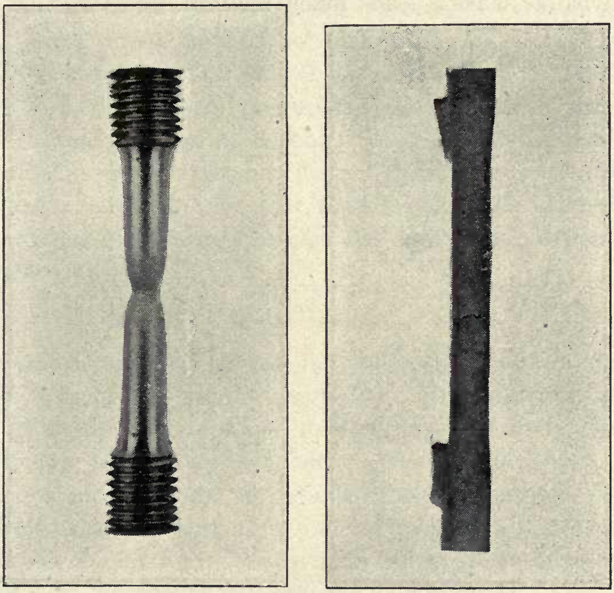

Fig. 146—Necked specimens of pure iron (left) and malleable (right)

This condition exists in all bolts in which the thread is not cut on an upset end. The magnitude of the departure from the results which would be expected from tension tests is shown in the following comparison. Pairs of malleable test specimens of the American Society for Testing Materials taken from each of six heats were annealed together. One specimen of each pair was broken, the other had a sharp V thread turned into it, 20 threads per one inch, to produce a diameter at the root of the thread of 0.505 inch. These specimens were then broken, the elongation being measured in the threaded portion of the bar.

The standard specimens showed a tensile strength of 52,080 pounds per square inch and an elongation of 15 per cent, and the threaded specimens a strength of 60,130 pounds per square inch and an elongation of 6½ per cent. Therefore, in the design of threaded members a calculation based on the normal ultimate strength distributed over the area at the root of a thread will give very safe results. Such threaded details, however, will not elongate and inferentially will have their resistance to longitudinal dynamic tension loads much reduced.

XVI

COMPRESSION, CROSS BENDING AND SHEAR

COMPRESSION is exactly the reverse of tension and is a stress often applied to malleable cast iron. In the absence of free carbon, in products such as steel and wrought iron, the elastic properties in compression are very nearly the same as those in tension. In cast iron the resistance to compression is considerably higher than that to tension, as may be expected from the fact that the graphite flakes completely enclosed in iron are less harmful under compression loads than under tension.

Difficulty With Ductile Metals

Ordinary cast iron specimens fail in compression by shattering into fragments, usually with but little bulging at the center. It therefore is possible to determine definitely the ultimate strength of a given specimen. The ductile metals, soft steel for instance, are not so definite in their behavior. Instead of reaching a load where they fail completely by shearing on planes at 45 degrees to the direction of applied stress or by rupturing into fragments and ceasing to sustain any load, these ductile metals merely flow as the load is applied and never reach a point of complete rupture. Thus a cylindrical specimen of steel takes a barrel-shaped form, increasing in diameter and decreasing in length. The increased diameter reduces the intensity of the applied stress and more load therefore can be applied. No actual point of failure can be established, but there is a limit beyond which distortion of a commercial detail would be equivalent to failure.

Malleable cast iron, being capable of great plastic deformation, behaves in this manner under compression, as indicated in the two stress strain diagrams in Fig. 147. Curve *B* in this diagram indicates the behavior of the same material but not the same specimen from which the diagram, Fig. 142, was charted.

It will be seen that no definite point of failure can be found up to a load of 90,000 pounds per square inch. The permissible intensity of compressive stress depends therefore on the permanent set which can be tolerated. The graph readily permits of the selection of the load corresponding to any assumed condition of this kind. Note the general similarity of the elastic constants in tension and compression. The proportional limit is 15,000 pounds per square inch in tension and somewhere above 13,000 pounds per square inch in compression. The modulus of elasticity in tension is 25,000,000 pounds per square inch as

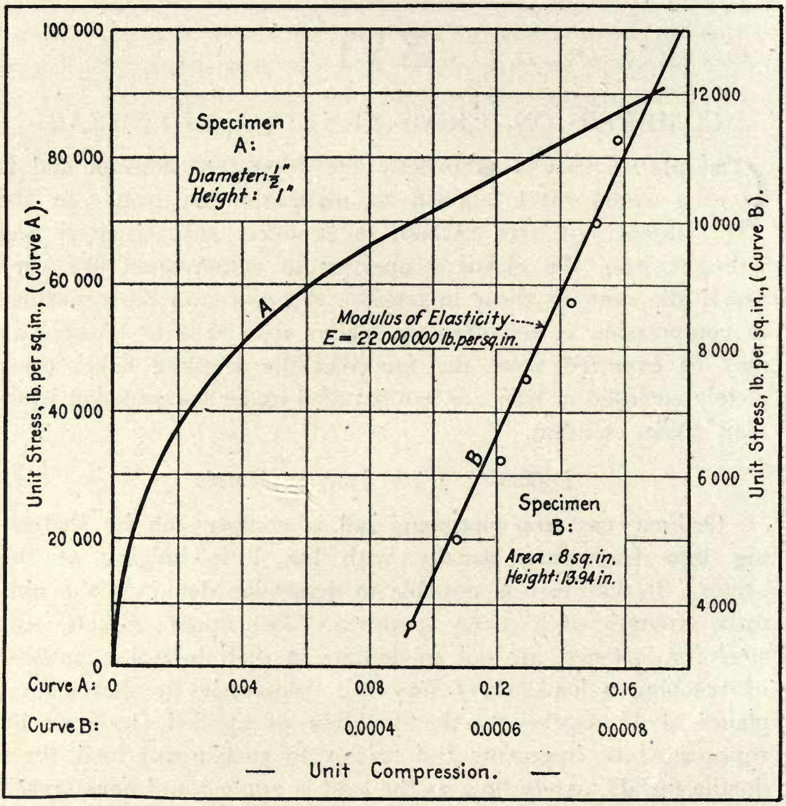

Fig. 147—Stress strain diagram of malleable cast iron in compression. The apparent deflection of 0.00043 at 0 load, Curve *B*, represents lost motion in the machine.

compared with 22,000,000 pounds per square inch in compression. Therefore the material behaves in a manner very similar to soft steel under the two systems of loading.

Stresses More Complex

The foregoing applies only to pure compression loads, which exists only in specimens in which the height is not much greater than the diameter. In longer columns it is practically impossible to keep the axis of the specimen exactly in line with the direction of load; the column springs out of line and the stresses become more complex. Tests on columns with fixed ends 5/8-inch in diameter and 10.6 inches high indicated that up to the proportional limit the modulus of elasticity is about 16,000,000 pounds per square inch. The fact that this figure is materially less than that obtained in pure compression would seem to indicate that even below the proportional limit the stress is not a purely concentric compressive one. In this column a very definite failure at 30,000 pounds per square inch was observed.

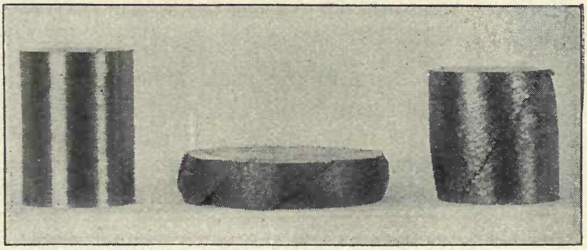

Fig. 148—Malleable (center) and cast iron (right) in compression. Each specimen before testing was of the size and shape shown at the left

Stresses in Columns

The yield point is quite definitely marked at 25,000 pounds per square inch. Insufficient data are at hand to warrant the definite acceptance of any special column formula for malleable cast iron. The columns tested have a ratio of length to diameter of about 17 and therefore are more slender than the average column in actual use Hence calculations based on an ultimate strength of 25,000 pounds per square inch for strut details should be amply safe.

A well known formula for cast iron columns with safety factor of 6 is:

$$\text{Safe load} = \frac{13{,}333 \text{ x area of column}}{1 + \dfrac{(\text{column length})^2}{266 \text{ x } (\text{diameter of column})^2}}$$

This formula is equivalent to the statement that the ultimate strength for cast iron columns is equal to

$$\frac{80{,}000 \text{ pounds per square inch}}{1 + \dfrac{1}{266}\left[\dfrac{L}{D}\right]^2}$$

The ultimate strength of the malleable columns tested was 30,000 pounds per square inch, the ratio L/D being 17. If a malleable column is subject to the same general laws as a gray iron column then to conform to the observed conditions the ultimate strength of a malleable column will be

$$\frac{62{,}000 \text{ pounds per square inch}}{1 + \dfrac{1}{266}\left[\dfrac{L}{D}\right]^2}$$

This formula applied to the specimens tested in pure compression would give a breaking load of nearly 62,000 pounds per square inch at which figure the material was still carrying load but had badly deformed.

On the basis of a safety factor of 6 on which the formulas were developed the safe crushing strength of malleable comes out 10,300 pounds per square inch, which is well below the proportional limit.

It is the writer's opinion that the foregoing formula can be safely used as a basis of design. The safety factor could probably be reduced readily to 5 and possibly to 4 without serious risk. For hollow cylinders Kidder uses the value 1-400 instead of 1-266 in the above formula; 1-500 for a rectangle and 1-135 for an equal armed cross. In any case *D* is the least diameter of the column section.

When the material is used in the form of a beam, it is subject to cross bending stresses. This type of loading is very common in practice and is readily reproduced in a testing machine. The specifications of the American Society for Testing Materials before 1918 and of the United States railway administration provided for cross bending test results about equivalent to a modulus of rupture or apparent maximum fiber stress of 64,000 pounds per square inch. This value is decidedly too low to correspond to the required tensile strength. The modulus of rupture seems to be about twice the ultimate tensile strength of the product, the proportional limit corresponding to a fiber stress about equal to the ultimate strength in tension. While not absolutely exact quantitatively, the foregoing statements do express the general relationship. Thus a specimen cast from metal having a tensile strength of about 51,000 pounds per square inch, showed a proportional limit of 50,500 pounds per square inch, a yield point of 72,000 pounds per square inch and a modulus of rupture of 113,000 pounds per square inch. The specimen was rectangular in cross section, ½-inch deep, 1 inch wide and 12 inches long between supports. The constants on specimens of different form might be somewhat different.

Stresses in Cross Bending

It is interesting to discuss why the modulus of rupture can be higher than either the tensile or compression strength of the material. When a specimen is bent there is a tendency to compress the material on one side and to stretch it on the other. Somewhere between there is a so-called neutral axis where there is no change of length. In material in which the elastic behavior in tension and compression is the same the neutral axis is midway across the section. The surface fibers of the specimen are strained most under such a condition, the compression or stretch decreasing uniformly as the neutral axis is approached. As long as the material is perfectly elastic the intensity of stress, being proportional to intensity of strain, also varies uniformly each way from the neutral axis. Accordingly the material behaves as a perfectly elastic body as long as the outer fiber is not loaded beyond the proportional limit. However, after that loading is passed part of the specimen is subject to plastic de-

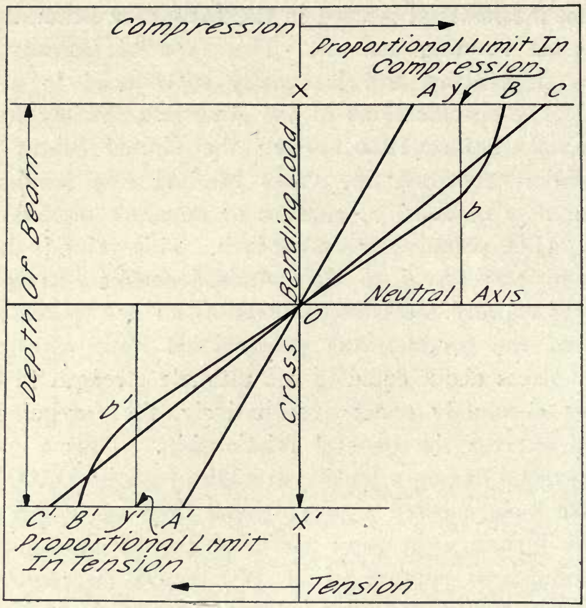

Fig. 149—Diagram of stresses in cross bending of malleable iron

formation. The intensity of stress then no longer varies uniformly from O at the neutral axis to a maximum at the top and bottom of the cross-section, but there is a band of considerable width next to the upper and lower boundaries of the cross-section in which the stress is fairly uniform. It is only below this area, where the stress is below the proportional limit, that the uniform decrease is observed.

The stress in the outer fibers is then not so great as would be calculated, since the permanent deformation of the specimen has transmitted some of the stress from the outer fiber to those further in. Therefore the modulus of rupture is a purely theoretical value not corresponding to any stress actually occurring in the specimen. It is merely the extreme fiber stress which would be produced at the breaking load if the material behaved as an elastic solid up to the breaking point.

In Fig. 149 the stresses in a beam are indicated in diagramatic form. In a beam of depth xx; having its neutral axis O, compression stress is measured to the right from xx and tension to the left. The proportional limit assumed to be the same under either stress is shown by y and y. Loads which do not stress the beam above the proportional limit produce a distribution of stresses within the beam as shown by AOA. If the load is sufficient to produce plastic deformation the stresses may be as indicated by $Bbob'B'$, which is straight only between b and b'. If OC is drawn so that the area XOC equals the area ObB, the C marks the modulus of rupture if $Bbob'B'$ corresponds to the load when failure occurs.

Value Unexpectedly High

In the cross-bending tests a load of 700 pounds at the center of a 12-inch span produced in a ½ x 1-inch beam a deflection of 0.076 inch at the proportional limit. Up to this point the deflection of the beam has been elastic, hence the value of the modulus of elasticity can be readily calculated.

Letting W be the load = 700 pounds
X = deflection at center = .076 inches
L = span of beam = 12 inches
b = width of beam = 1 inch
d = depth of beam = ½ inch

$$E = \frac{W L^3}{x\,4\,bd^3} = 31{,}800{,}000+ \text{pounds per square inch}$$

The value is unexpectedly high both as compared with figures for the tension and compression experiments, and as compared with the value for steel, which is about 29,000,000 pounds per square inch. It is barely possible that the error is due to slight errors in the uniformity of d in the above formula. Furthermore the proportional limit and cognate elastic constants are necessarily somewhat obscured in a beam specimen owing to the fact that a relatively small portion only of the beam is subjected to maximum stress. Only metal near the surface and in the plane of maximum bending moment actually is subjected to maximum strain, hence the observations are largely influenced by the behavior of the much larger mass of metal subjected to a much lower intensity of stress. It is probable therefore that the elastic constants will be apparently too high in specimens of such form that a considerable amount of material is located close to the neutral axis. The departure of the apparent elastic properties in cross bending from those determined in tension will be greater the greater the ratio of the area of cross section of the beam to its moment of inertia of that area about the neutral axis. For purposes of calculation a conservative value probably would be below 29,000,000 and possibly as low as 25,000,000 pounds per square inch to conform to the tensile results for the modulus of elasticity.

Shear and Torsion

Shear and torsion are the two remaining static stresses to be considered. They are closely related with one another and involve the sliding of the metal on itself, the slip taking place along a series of planes within the material. Shear involves a linear diplacement, while in torsion the displacement is angular. Rivets, bolts or pins are subject to shear when an attempt is made to slide the parts they hold together in a direction at right angles to the axis of the pin. It also is the shearing strength of a material which resists the punching or cutting in a die in a punch press. A knowledge of the shearing strength of malleable therefore is important both in the design of the shackle pins and similar details and in the selection of punch presses to be used in fabricating the product. Determinations made by driving a punch of known diameter through a plate of known thickness and measuring the force exerted in a testing

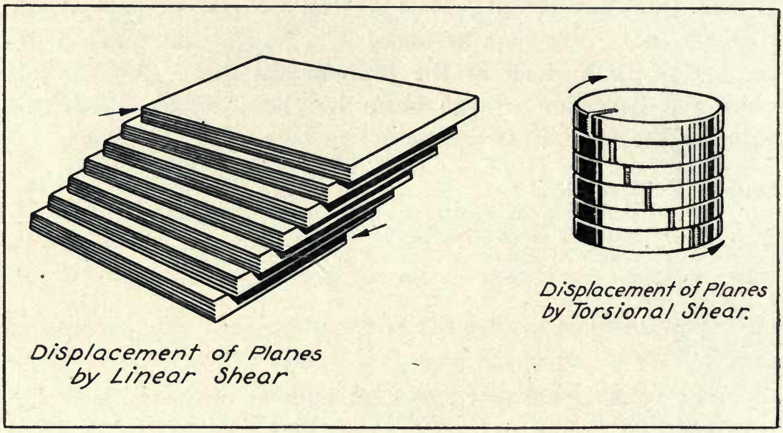

Fig. 150—Displacement of planes by linear shear and (at right) by torsional shear

machine have shown the shearing strength of malleable to be about 45,000 pounds per square inch. Similar experiments made by shearing off a cylindrical pin (double shear) gave values on the same metal of a little more than 41,000 pounds per square inch. The first mentioned experiments probably are the more trustworthy. The experiments were made on metal having a probable tensile strength of 50,000 to 52,000 pounds per square inch. Therefore the shearing strength apparently is about 15 or 20 per cent less than the tensile strength of the product.

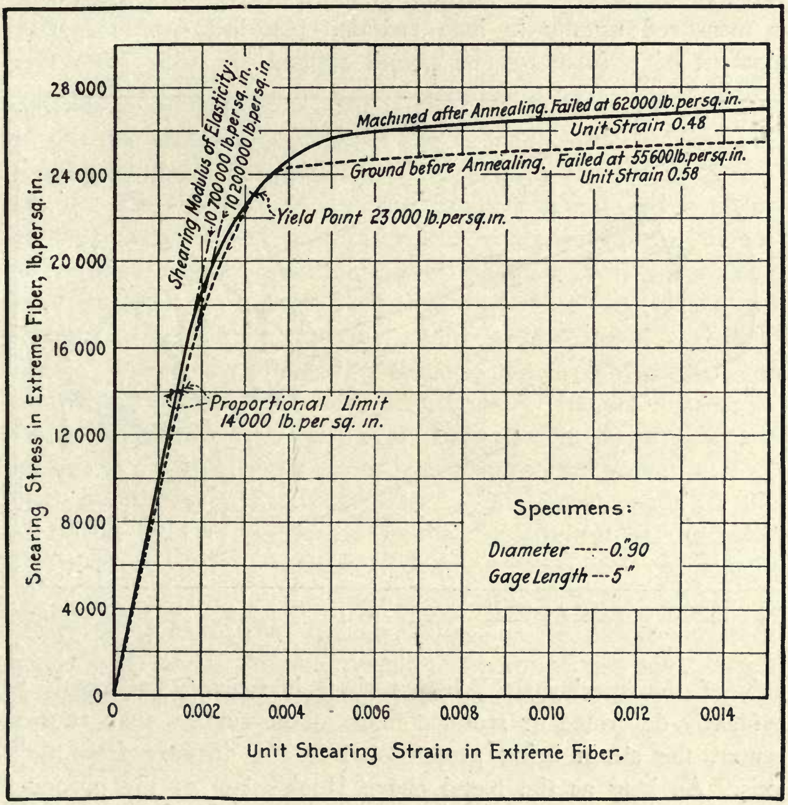

Fig. 151—Stress strain diagram of malleable cast iron in torsion

In the case of elements in a design subject to twisting loads there is a tendency to shear—not by a sliding motion of the planes within a solid—but by a rotating action, one plane over another as shown in Fig. 150. Evidently the action is of exactly the same character in both cases. A twisting load is measured by the product of the force applied and its distance from the axis of rotation. This product is called the moment of the force about the axis of rotation, or more briefly the torque, and is measured usually in inch pounds. An inch pound is the moment of a force of one pound applied one inch from the axis of the specimen. When a shaft is twisted the metal is evidently deformed or strained more at the surface than at the center, the strain being proportional to the distance from the axis. As long as the metal obeys Hook's law of the proportionality of stress to strain—that is, as long as it is not stressed beyond the proportional limit—the stress also is proportional to the distance from the center and mathematical analysis will define the moment of torsional resistance of a section of given geometric form in terms of the dimensions of the cross section and of the shearing stress in the outside fiber.

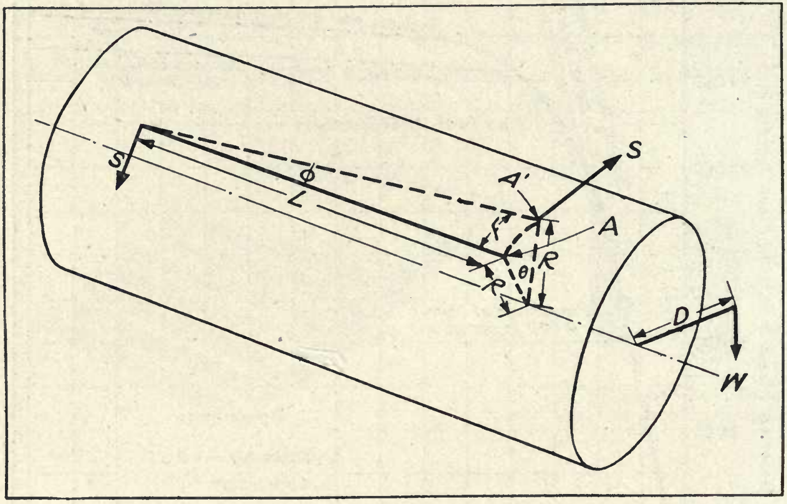

Fig. 152—Diagram showing factors to be considered in determining torsion stresses

The condition is similar in character to that existing under cross-bending stresses. When the intensity of stress in the outside fiber passes the proportional limit a mathematical analysis of the load condition is no longer possible, since the distribution of stress is no longer proportional to the distribution of strain. The modulus of rupture in shear or the apparent stress in the extreme fiber when breaking occurs is higher than the true value, since these layers stressed above the proportional limit carry a stress more nearly equal than their distance from the axis of rotation would indicate.

Fig. 151 shows a stress strain diagram of the behavior of the material in torsion. The load is recorded in terms of intensity of shearing stress in pounds per square inch. This is calculated from the known dimensions of the specimen and the measured torque. The intensity of shearing strain is determined in terms of the ratio of the linear displacement of a point on the surface to the gage length. If within a gage length of 5 inches a given load has produced a twist such that a point on the surface has advanced .07 inch the shearing strain is $.07/5 = .014$. In other words, the intensity of shearing strain is measured by the tangent of the angle Φ through which an originally straight element of the cylindrical surface is displaced. Thus in Fig. 151, if W is the load and D its distance from the center, the torque is WD. S is the stress in the outer fiber, L the gage length of the specimen, F in linear measure is the displacement of the point by twisting under the torque WD from its original position, A to A'. The intensity of the shearing strain is F/L, the value of F being determined from the known radius of the specimen R and the angle θ, through which one end of the gage length has been twisted with respect to the other.

θ (in radians) being $\dfrac{R}{F}$

$F = .01745\theta R$

if θ is in degrees. The value of S is computed from the couple WD and the moment of inertia of the circle of radius R about its center on the supposition that the stress increases uniformly from the center to circumference,

this giving $S = \dfrac{2WD}{\pi R^3}$.

It will be seen from Fig. 151 that the proportional limits and yield points are not very different from those in tension and compression. The shearing modulus of elasticity, however, is not the same as Young's modulus. The course of the curve during plastic deformation is not very instructive, since it is considerably influenced by the testing speed. The preceding discussion summarizes the available information with regard to the resistance of malleable cast iron to the various well known forms of static loading.

XVII

FATIGUE, IMPACT, HARDNESS AND WEAR

THUS far only static loads have been considered in the discussion of the mechanical properties of malleable cast iron. There are many industrial applications of castings in which the structural detail, instead of merely sustaining a steady load of some specific character, is subjected to blows, shock, or repeated reversals of the applied stress. Unfortunately, our knowledge of the principles underlying the behavior of a material under dynamic stress still is imperfect. A great deal of experimental work of this character has been done and the results published but no method is as yet available for systematically correlating the data and deriving general principles.

In general the energy of rupture of a given specimen and material can be calculated from its stress strain diagram, the area below the graph representing the product of stress and strain measuring the energy, in foot pounds, for example. The specimen may absorb this amount of kinetic energy from an impact or other dynamic stress. This however, does not tell the entire story for the possibility of a time factor enters. Assume that the impact is due to a weight moving with a given velocity. The specimen absorbs energy from the weight by retarding, and ultimately stopping its motion. Energy is measured as a product of mass and therefore acceleration in the energy absorbed by the specimen is measured by the product of the mass of the weight and its (negative) acceleration when being stopped by the weight. If we have means of knowing the maximum rate of retardation while the weight is being stopped, we can calculate the maximum stress as being $\frac{M}{G}$ and where M is the mass of the hammer; A, its maximum retardation and G, the acceleration due to gravity. Obviously this value cannot be greater than the ultimate strength of the specimen without producing failure.

Dynamic Stresses in Two Groups

Two groups of dynamic stresses may be recognized. One of these results from impact or blows. In general such stresses are in one direction only and usually are of considerable intensity. They may be applied axially, either in tension or compression to the detail involved, or may be applied to a cantilever beam or to one supported at both ends. Occasionally the loading is even more complex.

The other group of stresses results from repeated, usually rapid, reversals of stress, sometimes of small magnitude, and usually through an extended period of time. The stresses in a rotating shaft acting also as a beam are of this character, as are also the stresses in the leaves of an automobile spring, those in the couplers of a train while in motion, and those resulting from vibration.

In the former group a mathematical analysis of the service conditions is almost impossible. The material usually is stressed beyond its elastic limit by each blow so that it is impossible to determine the stress distribution within the metal. The energy absorbed by a given specimen before breaking is frequently less if the energy be delivered by a single impact than if delivered by a series of equal smaller impacts whose sum is equal to the energy of the single impact required for fracture. If fracture takes place under a series of blows the energy absorbed depends on whether the successive blows are of the same intensity or increase in intensity with each succeeding blow. The subject will be discussed more fully in the next chapter.

Thus it is seen that practically no two cases are alike in practice and that the problem is so complex as to prevent generalization from the results of different groups of tests by mathematical analysis.

Therefore it is impossible to furnish quantitative data to be used as a basis of computation for mechanical details subject to impact.

The comparison of the behavior of several materials under impact is easier since the tests of all can be made under the same circumstances and on geometrically similar specimens.

To avoid the complication resulting from the cumulative effect of repeated stresses each insufficient to produce failure, the experiment usually is designed to break the specimen at the first blow and to measure the energy absorbed in breaking by taking the difference in the kinetic energy of the system before and after failure. The tests so made on various types of machines do not give comparable data; the results differ with the design of the hammer, the shape of the specimen and its manner of support.

It is said that on the Charpy machine, which takes a specimen 10 millimeters square by 53.3 millimeters long, with a 45-degree V notch 3 millimeters deep at the center, about 7½ foot pounds are absorbed in breaking a specimen of normal malleable cast iron. On similar specimens except that the notch is made by a thin saw cut running into a hole 1 millimeter in diameter, 7½ to 8½ foot pounds of energy usually produce rupture in tests in the author's laboratory. On the Olsen machine breaking a round cantilever specimen with a 45-degree V notch 0.122 inch deep 1.10 inches from one end and with the notch clamped even with the vice jaws holding the specimen and the hammer striking 0.625 inch above the notch, the indicated energy absorption in breaking is 13 foot pounds.

Testing Tensile Impact Stresses

Impact tests may also be made in tension. In such cases the test is made on a screw-end tensile piece, one end of which screws into the hammer of the Charpy machine. The other end of the specimen carries a yoke which strikes a fixed portion of the frame of the machine just as the hammer is at the lowest point of its travel. The dimensions are so chosen that the energy of the hammer is sufficient to rupture the piece.

Evidently, for a given material the energy to produce rupture varies as the cross sectional area and as the length of the specimen. Upon the area depends the resistance of the material to tensile loads, and the length is a factor, since obviously twice as much work is done in stretching a piece two inches long a given percentage of its length as in stretching a piece one inch long an equal percentage.

Speaking more technically, the expression for work is fs where f is the force exerted and s is the distance through which the hammer moves while the specimen is breaking. If a is the area of the specimen, E its elongation and l its length, and if t is its ultimate tensile strength:

$$f = Kta$$
$$s = El$$
$$fs = Kta \ El = KtEv$$

where K is a constant depending upon the form of the stress strain diagram and v the volume of the specimen equal to $a\ l$.

The resistance to tensile impact is thus to be expressed not in pounds per square inch of section but in foot pounds per cubic inch of metal deformed.

It is noteworthy that while in static tension a defect operates to reduce the strength rather less than in proportion to its area and the elongation considerably, in dynamic testing practically absolute soundness of specimen is required. If a notch or shrink exists sufficiently large to so far reduce the area as to localize the stretch within its own length the gage length upon which the work is expended becomes only the axial length of the shrink. This may be only 10 per cent or even only 1 per cent of the apparent gage length and the foot pounds absorbed if calculated on the intended gage length would be only 10 or 1 per cent, respectively, of the correct values. Care must further be used to see that the specimen increases in size immediately beyond the gage length. Any stretch outside the gage length erroneously credits additional energy to the specimen.

Sound specimens of good malleable iron 0.1 square inch in area and 2 inches long showed results as follows when tested:

Energy of rupture (foot pounds per cubic inch)	Elongation (per cent in 2 inches)
755	15
640	13½
999	20
930	19½

The relation between resistance to dynamic tension and elongation is plainly shown and is still more plainly visible by examining the following tests on good malleable containing small shrinks.

Energy of rupture (foot pounds per cubic inch)	Elongation (per cent in 2 inches)
102	3½
115	3
345	7½

The graph in Fig. 153 which summarizes these data indicates the almost direct proportionality of elongation and resistance to tensile impact even when the former is artificially affected by mechanical defects.

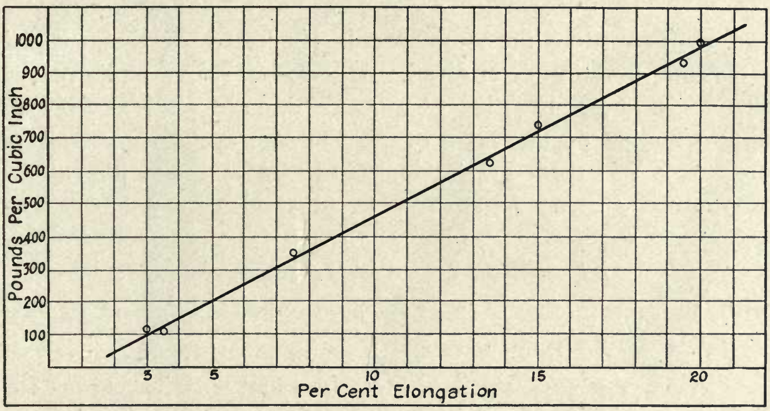

Fig. 153.—Effect of elongation of specimen on the resistance to dynamic tensile loads

The presence of temper carbon nodules operates just like any other mechanical discontinuity. Accordingly it is almost impossible to obtain consistent results in tensile impact from malleable. All the results doubtless are lower than the correct value and since they are far from concordant their practical interpretation is doubtful. At best the test is poorly suited to so heterogeneous a material.

From the energy of rupture, the measured elongation and the known dimensions of the specimen we can calculate a modulus of rupture as the average intensity of tensile stress in pounds per square inch developed during rupture of the material. Disregarding the very small elastic deformation which has disappeared when the permanent elongation is measured we can proceed in the light of the previous formulas to solve the equation:

$$fs = KtEv$$

for $K\ t$, the modulus of rupture. The values of fs, corresponding to given value of l, are shown in the preceding tables on the basis of v being unity.

The average value of Kt on the four sound specimens previously quoted was 58,600 pounds per square inch, the three imperfect ones showing in order 3500, 4700, and 5500 pounds per square inch.

Unfortunately the static tensile properties of the material were not actually determined. From the stress strain curve shown in Fig. 139 in Chapter XV, we may derive an approximation of the value of K. The average abscissa (stress ordinate) of that graph is about 0.88 times the stress at rupture. Using K as 0.14 we can calculate t in the expression

$$Kt = 58{,}600 \textit{ pounds per square inch}$$

with the result that t has an approximate value of 66,600 pounds per square inch.

While the data are both too few and too inaccurate for definite conclusion there is a presumption at least that in tension the material fails under impact at materially higher stresses than under static loads but that the elongation is not greatly different in the two conditions.

The effect of velocity of impact on maximum stress is among the most interesting but least understood phenomena in the utilization of materials. It is hoped that work in preparation under the author's direction will be productive of more accurate and useful conclusions.

A number of tests have been devised in which repeated impact is applied. Such tests must be closely standardized as to the form of specimen and the energy of the blow. The amount by which the stresses set up by a single blow exceed the yield point greatly affects the results of the tests. Any variable in design or material which affects the yield point of the specimen as a whole therefore profoundly alters the result of such a test.

A dynamic test developed especially for application to malleable iron was devised at the general suggestion of the late B. J. Walker and is sometimes known by his name. In this test a wedge specimen 6 inches long by 1 inch wide, tapering from ½ to 1-16 inch thick is used. The specimen is set on its thicker end on the anvil of a drop hammer and subjected to blows of 70 foot pounds. The first blow is struck straight down on the point of the wedge, curling it over, and for each succeeding blow the specimen must be held so that the point which will be struck by the hammer is directly over the point of support. This is a difficult requirement to fulfill and the test, while measuring a very useful property, is almost incapable of quantitative reproduction and is accordingly of only slight interest to the consumer.

Fig. 154.—Walker test wedges

A normal malleable is supposed to survive 20 blows (aggregating 1400 foot pounds) in this test and to break not more than 1⅞ inches from the thick end of the wedge. A better mechanical execution of this test possibly would yield

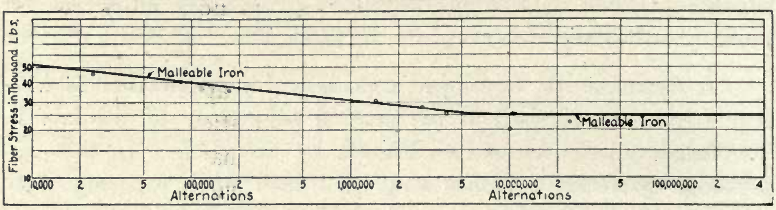

Fig. 155.—Behavior of malleable iron under fatigue as a rotating beam

results of value and has been studied by the writer for some time.

The writer has been informed that tests by the Humphrey static notched bar method yield valuable data as to brittleness but has not personally investigated the matter.

Tests can readily be made under dynamic stresses of the second type, involving repeated reversals of direction under rather small loads. Machines of the Upton Lewis type, especially when equipped for alternate torsion, are valuable for this purpose, particularly when considerable intensity of stress is desired. Machines of the Wöhler, Whiter Souther, or Farmer-type apply well to the repetition of smaller stresses existing in rotating specimens subjected to bending.

W. W. Flagle in the author's laboratory has determined the relation between maximum fiber stress and life of a typical malleable, using the Farmer-type machine. The results of his investigation are shown in Fig. 155 in which life is plotted against stress to a logarithmic scale as suggested by Moore. It will be seen that the fatigue or endurance limit of malleable is at 25,000 pounds per square inch. Malleable will resist alterations of stress of this magnitude indefinitely—certainly hundreds of millions of times. Reference should be made to Moore's data for similar information on a variety of rolled products.

Prof. H. F. Moore is quoted to the effect that ingot iron (ferrite) will withstand 100,000,000 repetitions of a stress 1.6 times its proportional limit, as determined in tension. This would indicate the probable great endurance of the matrix of malleable.

It will be seen that much remains to be done in the quantitative investigation of the resistance of malleable to fatigue and to impact. Fortunately, qualitative information of this character is readily accessible in view of the long continued application of malleable iron in the industrial arts. The practical experience which attracted consumers to this product when searching for a shock resisting material and in a period when methods of tests and metallography were practically unknown seems to have been well founded.

A logical reason now is available for this quality. Being largely ferrite, malleable is soft and ductile, as are all other materials in which ferrite predominates. Wrought iron is a conspicuous example of such materials; malleable is not as ductile as wrought iron because of the temper carbon present. Its resistance to deformation and shock, however, depend upon this principle.

Malleable has a further great advantage over many other materials in that the temper carbon granules, while of a form to affect the physical properties only to a relatively slight ex-

Fig. 156.—Separation of grains by repeated cross bendings

tent, operate as a hindrance to failure under alternating stresses by fatigue. Such failures frequently occur by the penetration of a crack between adjacent grains of the metal. When such a crack begins to form in malleable it does not penetrate far before it strikes one or more carbon granules. These stop its further progress just as a hole drilled at the end of a crack in a bell prevents the growth of the crack.

The best evidence available as to the shock resisting qualities of the material are derived from the years of service which properly made malleable, has given in draft gears, rail anchors, automobile hubs and spring brackets, car couplers (until high train loads forced the adoption of a material capable of higher unit stresses), and an indefinite number of similar applications.

For some kinds of service the fitness of a material for the use intended may depend not so much upon its strength under load as upon its machineability, resistance to abrasion, coefficient of friction and similar properties.

The property which enables a material to resist cutting or wear is somewhat loosely called hardness. Unfortunately this term is not clearly defined and often it is misinterpreted. Moreover, the commercial methods for measuring hardness in metals actually measure resistance to penetration under defined conditions—a property bearing no practical or theoretical relation to hardness as understood in the definition given above.

Two methods of measuring so called hardness are in common use. In Brinell's method, hardness is determined by the depth to which a 10-millimeter ball will penetrate under a load of 3000 kilograms. In Shore's method, the rebound of a hammer falling from a fixed height measures, in effect, the work absorbed by the plastic deformation of the material under a standard load. The results of the Brinell test bear a fairly close relationship to the ultimate strength of the material, while the data obtained by the Shore method should conform to the elastic limit.

The Brinell number of normal malleable cast iron is from about 101 to 145 and increases as does the tensile strength with decreasing carbon. Common values are around 110-120. Fig. 157 shows the relation between the Brinell number and the strength of a wide range of malleable iron. The heavy line indicates the probable relationship and the shaded area the limits of variation from the probable value. The scleroscope number is somewhat erratic, running from about 15 to about 20.

The Shore number actually is surprisingly constant in malleable of quite variable tensile properties. Some experimental data as to the relation between this hardness number and the Brinell number are presented in Fig. 158. The explanation of the approximate constancy of the Shore number is as follows:

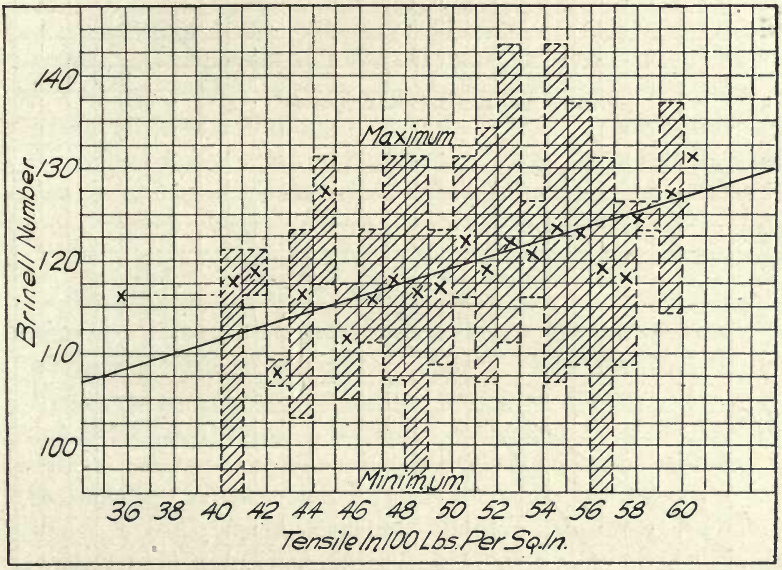

Fig. 157.—Relation between Brinell number and strength of malleable iron specimens

The variation in physical properties of malleable are due primarily to the ratio of ferrite to temper carbon and not to variations in the properties of the ferrite. The Shore test being made on an almost microscopic area determines only the properties of the ferrite. If by accident a temper carbon grain is struck no rebound at all is observed. The composition of the ferrite is not sufficiently variable to alter its physical properties.

Neither of the hardness numbers bears any particular relation to completeness of anneal. White iron is harder than malleable so that the effect of annealing is to soften the metal under both tests. Under commercial conditions, however, annealing is almost never so far from complete that this fact is of any value in inspecting material. Malleable castings which are sufficiently annealed to pass any ordinary inspection usually contain only very small amounts of ungraphitized carbides. The remaining combined carbon is either found as cementite in very minute grains scattered throughout the castings or as a thin layer of pearlite just under the surface.

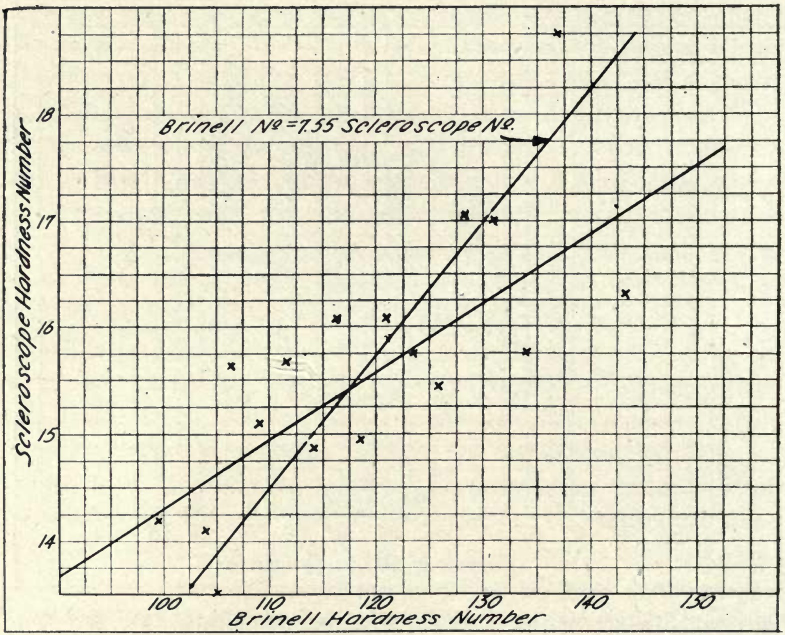

Fig. 158.—Graph showing comparison of Brinell and Shore numbers indicating relation between them is not definite

The former condition would have no effect on the Brinell hardness and would affect the scleroscope hardness only if the hammer struck such a grain by accident. The thin sheet of pearlite does not increase the Brinell hardness appreciably, since the pearlite layer is merely crushed down upon the deeper material which is soft. The Shore number may be affected by pearlite if this be present at the finished surface of this sample and if the layers are heavy enough to absorb the impact. Neither of these conditions usually exists for the pearlite is originally covered with ferrite and if in producing a finished flat surface for test any considerable amount of material is removed the pearlite layer may be completely destroyed. The point has been emphasized by Prof. Touceda and also by W. R. Bean.

Therefore these tests are not directly applicable to the commercial valuation of malleable with reference to its cutting properties. The important considerations in industrial uses of malleable involve cutting hardness which is undesirable in fabricating the product in the machine shop, and wearing hardness or resistance to abrasion, which resists the destruction of a bearing or similar detail where subjected to friction.

These two conditions are different manifestations of nearly the same property. Ease of machining and resistance to wear are incompatible with one another. No direct means of measuring cutting hardness are known. The hardness of minerals is measured by comparison with an arbitrary scale ranging from talc, having a hardness designated as 1, to diamond, with a hardness of 10. Any given mineral can be rated by determining between which two numerals its hardness lies. Thus, pyrite, which scratches feldspar, hardness 6, but is scratched by quartz, hardness 7, is given an intermediate number, in this case 6.3. On this scale iron has a hardness of about 4 or 5 and steel a hardness of from 5 to 8.5. This test besides being very unsensitive can be applied only to the extreme surface of a metal. In the case of malleable this always is ferrite, which shows a hardness of 4.

Turner has devised a method based on cutting a line into the surface of the material. This is done by pressing the V-shaped nose of a diamond against the metal under a definite pressure. The cross section of the furrow cut, as measured by the width of the groove, is intended to be the measure of cutting hardness. This method is applicable only to the surface of an article. Since the surface must be smooth, it is difficult to apply this test to malleable containing a pearlite layer, as pointed out in the discussion of the Shore hardness. The test is not used extensively, and the writer knows of no data obtained from its application to malleable iron.

Similar tests, made by scratching polished samples and examining the scratch under the microscope indicate that the hardness of the micro-constituent present in normal hard iron and malleable iron is in the following order: Ferrite, pearlite, cementite. Ferrite is soft and cementite nearly as hard as carborundum, as measured by resistance to scratching.

Study of Cutting of Metals

The principles underlying the machining of metals have been investigated by a number of experimenters, notably, Nicholson, Frederick Taylor and Herbert. The special case of machining by twist drills has been still more fully investigated—for example, in the engineering experiment station of the University of Illinios.

While these studies have thrown much light upon the principles underlying the cutting of metals and have served in some cases, notably in Herbert's experiments, to test the quality of cutting tools, they were not generally conducted so as to develop any technique for the testing of a material for machineability. Accordingly, no method is yet available for determining how readily an existing structural detail can be machined. Therefore it is not surprising that there are no means for quantitatively comparing the machining properties of malleable cast iron with those of similar materials.

However the fundamental relationships involved are easily summarized. To the consumer, machineability means the removal of the required amount of metal in the minimum of time and with the minimum of tool destruction. Many investigations have approached the subject by measuring the load on the nose of the lathe tool. Nicholson measured this load parallel to three rectangular co-ordinates—radial, tangential, and axial—with reference to the revolving specimen and used only two materials, soft and medium steel. His work resulted in a mass of data concerning the relation between the cutting angles of the tool and the direction and magnitude of the resultant forces. He also made a limited number of tests on the effect of cutting angles on tool life.

For the present purpose his work may be summarized as having demonstrated that the tangential thrust on the tool is independent of the cutting speed and that the life of the tool increases as the cutting angle increases. Taylor in his monumental monograph "The Art of Cutting Metals," covered exhaustive investigations on feeds, depth of cut, form of tool, cutting speed load on the tool point and tool life. He deduced the fact that the load on the tool point is dependent only on the area of the chip being removed and the material being cut and independent of the cutting speed, form of tool, relation between depth of cut and feed, or any other variable.

This seems to indicate that the load on the tool point per unit area of cut is a constant, readily determined for a given material. This is true, but unfortunately the determination of this constant has no practical use since Taylor also proved conclusively that no determinable relationship exists between this constant and tool wear or economical cutting speed.

Herbert has shown from Taylor's data that tool failure results from the heat evolved in cutting and has deduced a formula for determining the relation between the tool temperature and feed, cut, and speed. He also has proved that the most economical tool service corresponds to a definite temperature which is a function of the tool steel used.

From this it will be seen that all of the work previously done has not resulted in conclusions applicable to the defining of the machineability of a given material in terms of permissible cutting speeds.

Consumer Wants Cutting Speed

In general the consumer is not interested in the load at the tool point, since he is quite willing to adopt machine and tool designs capable of sustaining any loads which may be developed, providing only he is informed as to the probable stress to be encountered. The power consumed in removing the material also is of little interest, since this is not a major item of expense and can be met by the installation of a sufficiently heavy drive. His chief requirement is a fast cutting speed with long tool life. Tool life when determined by normal conditions is fixed by the working temperature of the tool, determined by cutting conditions and the material being machined. Suitable investigation by Herbert's methods should yield useful results in the relative rating of different metals, but the data are not available.

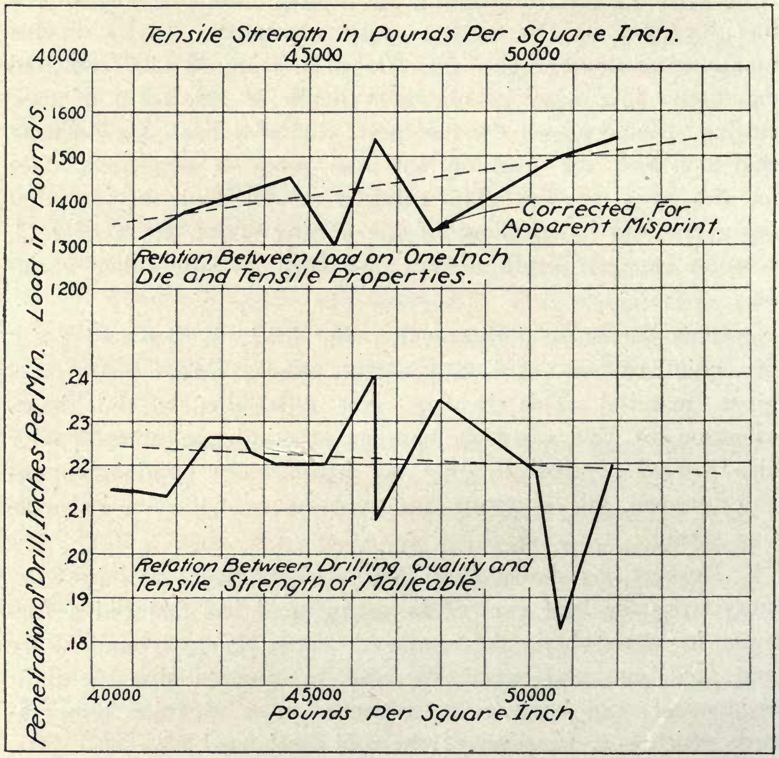

Fig. 159.—Tests of machining properties of malleable cast iron

The curves are plotted from data presented by Edwin K. Smith and William Barr, Milwaukee, in a paper prepared for the American Foundrymen's association, 1919.

Smith and Barr have attempted to determine the relative machineability of different samples of malleable and to compare the data with that for other materials. Their experiments were based on the torque required to cut threads into the different samples with two dies taken as standards and also by measuring the penetration per revolution of a standard drill under a standard load.

Unfortunately the data are incapable of conversion into absolute figures. Smith and Barr apparently felt that they had secured evidence pointing toward the fact that iron high in tensile strength is relatively difficult to machine. The author does not feel that this conclusion is necessarily justified by the observed facts. Fig. 159 shows graphically the results of their investigations and in the writer's opinion they indicate that the machineability of normal malleable is within the limit of error of the data.

However these investigators have accumulated useful data comparing the resistance to drilling of malleable cast iron, gray cast iron and steel. Their results indicate that the penetration of a drill under standard conditions is at the rate of 0.249 inch per minute and 0.196 inch per minute in two specimens of gray iron; 0.209 to 0.240 inch per minute in 17 samples of malleable and 0.052 to 0.085 inch per minute in three samples of steel. This proves the general thesis that malleable is comparatively easy to machine.

An exhaustive study of all types of machining operations, using the best equipment known, is in progress under the writer's direction. In connection with this work, W. W. Flagle has gathered data as to the load on twist drills of standard form when drilling fully annealed malleable.

The investigation included a study of the effect of drill diameter, feed, speed and character of metal being cut. The effect of drill form, of lubricants and the life of drills is being further investigated.

The work is far too voluminous for presentation in detail in the present connection and is reserved for publication, in a more appropriate place. A few of the more interesting conclusions may be abstracted as follows.

The torque on a drill, cutting malleable iron varies as the square of the diameter and approximately directly as the feed. The thrust varies directly as the feed and approximately as the drill diameter. The effect of speed on torque and thrust is but small for rates from 40 to 640 revolutions per minute. Both loads decrease slightly with increasing speed and are more nearly constant with variations in speed at high speeds than at low.

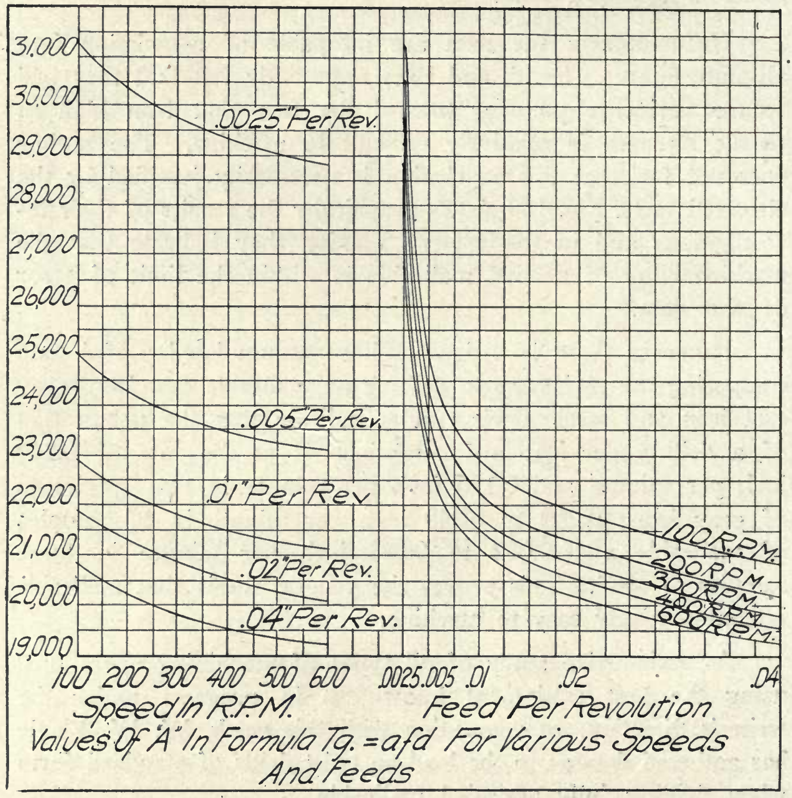

Fig. 160.—Graph showing values of *a* in drilling formula

Representing by T_v the torque and by T_t the thrust of a drill of diameter *d*, running at *s* revolutions per minute with a feed, *f*, in a certain uniform iron

$$T_v = afd^2$$

and

$$T_t = bfd$$

in which a and b are constants depending on s, t, and d. The values of a and b can be interpolated from the graphs in Fig. 160 and 161 respectively.

The drilling properties are further affected by variations in the character of the metal. The investigation disclosed that machining stresses were not related to either Brinell number or strength as effect to cause. However, there is a general coincidence between the three properties in completely annealed malleable.

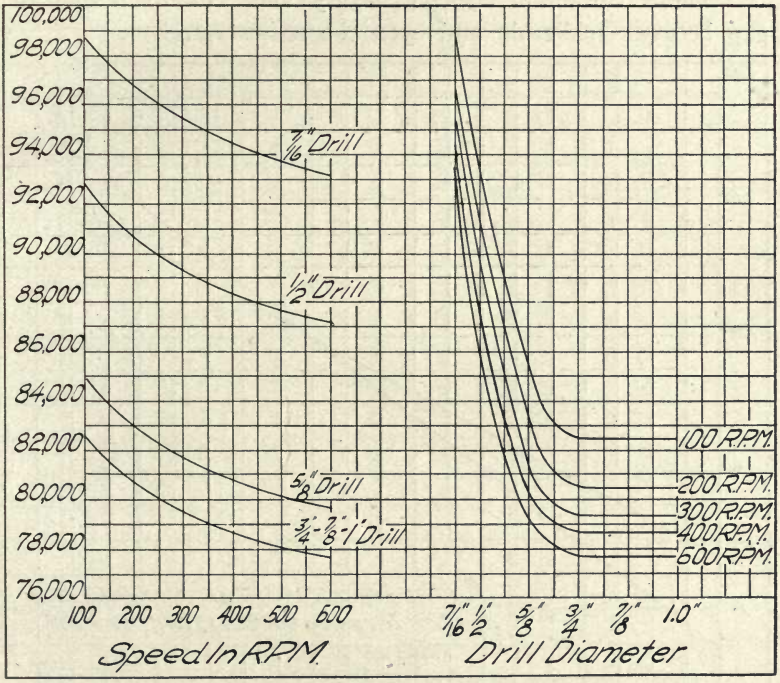

Fig. 161.—Graph showing values of b in drilling formula

The data of Figs. 160 and 161 were obtained from malleable equivalent to a tensile strength of 52,000 pounds per square inch and a Brinell number of 120. In Figs. 162 and 163 the effect of Brinell number and strength on T_v and T_t are plotted in the form of coefficients for reducing the previously calculated values to suit other tensile or hardness properties.

The observations in a measure substantiate Smith and Barr's ideas as to the increased machining difficulty of stronger metal. Apparently there is a variation of from 25 to 30 per cent in the stresses developed as between the weakest and strongest malleable.

These variations are not nearly sufficient to bridge the gap between malleable and even the softest steel.

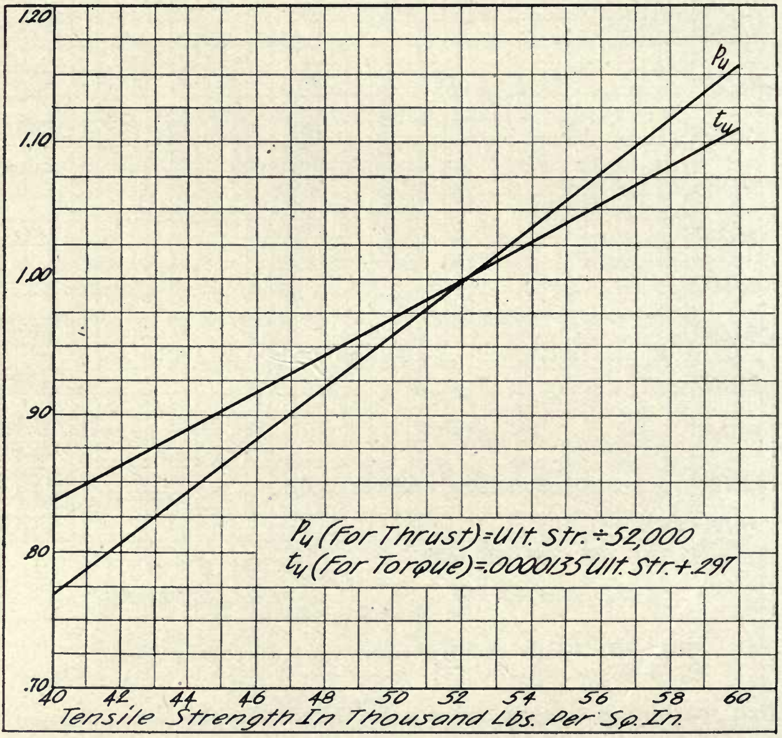

Fig. 162.—Correction factor for drill torque and thrust in terms of ultimate strength

It is again to be emphasized that neither the author's data nor that of Smith and Barr can be interpreted in terms of tool life. Furthermore, it must be clearly remembered that the data were all obtained on completely graphitized material and that nothing heretofore said has any relation whatever to white edged or white material resulting from mischances in annealing. The subject has already been referred to in connection with the discussion of Brinell numbers where it was shown that such mischances do not necessarily influence the hardness test. They do, however, greatly affect machineability both with respect to tool life and stresses.

The machining difficulties occasionally encountered might be explained on either of three grounds. First, the material may be so tough that the heat developed per unit of time causes the tool temperature to increase rapidly. The tool fails for perfectly normal causes but under much accelerated conditions. Second, the material may contain particles sufficiently hard to work as an abrasive and so destroy the cutting edge. Third,

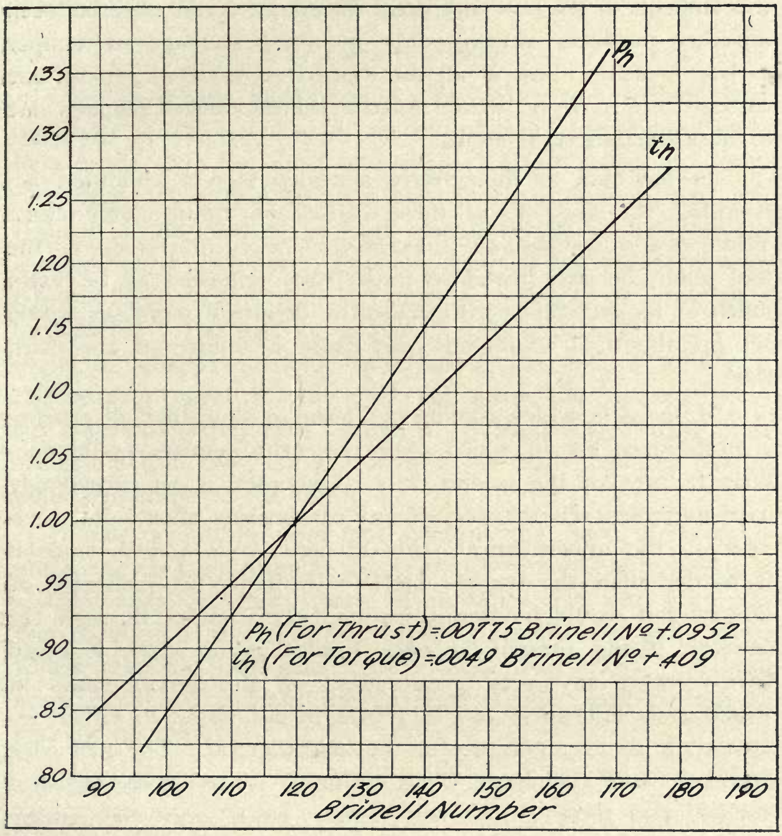

Fig. 163.—Correction factor for drill torque and thrust in terms of Brinell number

the material may set up so heavy a tangential load in the tool point as to cause it to break off irrespective of the failure of the cutting edge.

A study of abnormally early tool failures seems to indicate the occurrence of failures of all three types. Since all malleable cast iron consists only of ferrite and temper carbon it is difficult to see how any great difference could exist between different products varying only in the percentage of temper carbon present. This is all the more true since in general the cutting is in a region where relatively little carbon remains due to decarburization in anneal.

In the case of imperfectly annealed iron a condition accounting for any or all these causes of failure may exist. White cast iron is known to exert very heavy unit stress on the tool point, hence a metal so imperfectly annealed as to retain much of its original pearlite-cementite dendritic structure would set up abnormal tool loads and cause a failure of the third class.

Material in which cooling has been so slow that all pearlite is graphitized but in which some cementite persists would produce failures of the second class. Cementite is an exceedingly hard ingredient, the hardest of any carbon-iron alloy. Its hardness on the mineralogical scale is between 8 and 9, since it is harder than the hardest steels. In imperfect malleable of this kind it would be found scattered as granules through the ferrite. Being present in very small amount only, it could hardly exert any very great effect on the ferrite mass in which it is imbedded and therefore is not likely to either increase the tool temperature or the load thereon. The tool edge however, will encounter those granules lying in the finished surface and these grains will rapidly wear away the cutting edge which rubs against them.

Failures of the first class are very largely due to so called "picture frame" iron in which there remains a considerable pearlite layer just under the surface. This layer is identical in composition and properties with annealed tool steel. As such the cutting speed will not be great before sufficient heat is generated to rapidly destroy the tool. Unusually bad cases of this character may also produce failures of the third class.

It should be remembered that all normally made malleable is easily machined, there being minor differences only between the machineability of malleable of varying composition. When machining difficulties are encountered the explanation generally is due to failures of execution in individual cases rather than to the character of the product as a whole.

Resistance to Friction

To all intents and purposes, resistance to frictional wear obviously is the converse of machineability. Experience seems to indicate that the most successful bearing metals are those consisting of fairly soft matrix in which a relative hard constituent is imbedded. The hard constituent takes the wear and is supported by the soft. Further, the soft constituent wearing down a little, furnishes the certainty of a supply of lubricant to the bearing. The soft ingredient is further desirable since if a grain of abrasive enters the bearing and lodges tightly in the bearing metal it will soon cut away the rotating member where the latter rubs against it. With a soft bearing metal the grit will at most cut a groove in the easily replaced bearing without damage to the shaft.

Since malleable does not contain the hard skeleton or grain required to promote long life it cannot be regarded as suitable metal to resist wear. By analogy also with gray iron this conclusion seems warranted. Extremely soft gray irons, which resemble malleable more closely than those containing more combined carbon, are inferior to the harder irons as bearing materials.

Malleable is not a suitable material of construction, where the major requirement is resistance to wear, as for instance in journal bearings.

It will of course resist minor friction incident to other service. . Under such circumstances, the conditions as to hardness and smoothness of the material rubbing against it is of prime importance in determining the service to be expected. Determinations of the coefficient of friction for the metal are not available. While they would be highly interesting, they are not of great practical application because of the general unsuitability of malleable for friction service and because under normal lubricating conditions in machine parts there is not metallic contact between shaft and bearing. Therefore the friction losses depend mainly upon the lubricant and not upon the material of the shaft and its support.

XVIII

PLASTIC DEFORMATION

IN CONSIDERING the behavior of malleable cast iron under mechanical stress we have noted that like most other materials its deformation, or strain, under load is of two entirely distinct characters, depending upon the intensity of the stress. Under light loads the deformation is elastic; that is, it is proportional to the applied stress and is not permanent, the metal returning to its original dimensions upon the removal of the load. At higher stresses the strain increases very rapidly and the specimen becomes permanently deformed.

This change of form is termed "plastic" deformation as distinguished from "elastic," and especially characterizes ductile metals. Much interesting work has been done in the investigation of the phenomenon of plastic flow, the property by virtue of which a material is malleable and ductile. The property is usually measured in terms of yield point, reduction in area and elongation.

Nutting has developed the thesis that plastic strain may be expressed as the product of constant and exponential functions of the stress and time. In other words, the strain is measured by the expression AS^xt^y where S is stress, t time and A, x and y characteristics of the material. Hook's law is a special case of this formula when $x=1$ and $y=0$.

The author has no desire, in the present connection, to attempt any exposition of the theoretical aspects of plastic flow. However, since malleable cast iron is in quite a marked degree capable of plastic deformation, and in fact, owes many of its most valuable properties to this property, it seems well to summarize the effect of plastic deformation on the metal.

Summary of Theory

As has been shown, malleable is in effect a mass of ferrite made up of individual grains. Each grain is made up of many crystals all oriented in space in the same direction. The several grains are held together, according to the now generally accepted view, by a thin layer of amorphous (non-crystalline) iron acting as a cement. This amorphous iron is supposed to be stronger than the crystalline variety and is supposed to behave like a very viscous liquid. It is also supposed that crystalline iron will go over into amorphous iron under heavy stresses.

The behavior of a metal under even the simplest stresses is as a rule complex. Even when a stress is applied in only one direction the behavior of the material indicates that complex systems of forces result. While we speak of the elongation or compression of a metal these terms are in a sense misnomers, since solids are but slightly compressible in the sense of a decrease in volume or *mutatis mutandis* capable of elongation. Metals compressed or lengthened by plastic deformation do not materially gain or lose bulk. For example a specimen compressed until it was only one-fourth its original height had its density reduced from 7.206 to 7.196 in the process, a change in the opposite direction to what might be expected.

Behavior of Specimens

The increase or decrease of dimensions parallel to the direction of applied stress is made up by decreases or increases of cross section in a plane normal to the axis of stress; the tensile specimen necks in, the compression specimen becomes barrel shaped.

We note also that plastic materials do not fail in tension or compression in a plane normal to the stress. The tension specimen shows a cup shaped fracture, at least on one side of the break. The compression specimen tears apart either in a plane approximately at 45 degrees to the direction of stress, or more rarely on a conical surface whose axis of symetry coincides with the direction of load.

From these observations it is evident that there is a considerable motion of translation within the stressed material in directions at right angles to the direction of the applied stress. This rearrangement may conceivably be of two kinds in a material composed of crystalline grains either a deformation of the individual grain (intragranular) or a separation and rearrangement of the grains at their boundaries (intergranular).

Both phenomena are easily recognized. A deformation of the grain itself is accomplished by a shearing of the grain along intragranular crystal boundaries. Such a slip, if occurring in a grain in a polished surface, shows a series of parallel lines on the polished surface which are fine grooves and ridges in the originally plane surface.

Fig. 164.—Slip bands in ferrite of malleable iron

Nitric acid etch 1000 diameters

Note that there is but little evidence of any separation at grain boundaries

Fig. 164 shows a micrograph at 1000 diameters of such slip bands in a ferrite grain in malleable cast iron. Such a deformation, increased in magnitude, may result in the rupture of the grain itself at right angles to the slip bands, as shown in Fig. 165, or by producing such a distortion of the grains that it can no longer articulate with the surrounding grains closely enough to be held to them by the cement of amorphous iron at the boundaries.

Change of Structure When Deformed

On the other hand examination of the originally polished plane surface of a specimen parallel to the direction of stress which had failed by primary intergranular fracture would show no slip bands but a considerable displacement of the polished surfaces of the individual grains from their initial location in the polished plane provided the failure was due to shear at the grain boundaries. On the other hand, if failure was due to forces having a tensile component normal to the grain boundary, the separation of originally adjacent grains would be shown.

Fig. 165.—Intragranular fracture of a ferrite grain in malleable
Nitric acid etch 1000 diameters
Note that the path of rupture has advanced about two-thirds through the grain at right angles to the slip bands

Where the conditions have been such as to produce fairly great plastic deformation it may even be possible to note the effect of intragranular flow in the changed orientation of the polygons marking the individual grains.

In unworked ductile metal there is no preference as to the direction of the longer diameters of the grains in any given surface nor are the diameters in various directions widely different. After plastic deformation however the originally equi-axed grains may be flattened into sheets, drawn out into threads, etc., etc., depending upon the character of the stress and the direction of the stress with reference to the polished surface under examination. Of course it is obviously necessary that such changes of form can be detected best in a plane parallel to the direction of load and are visible only as changes of grain size in a plane normal to the deforming stress.

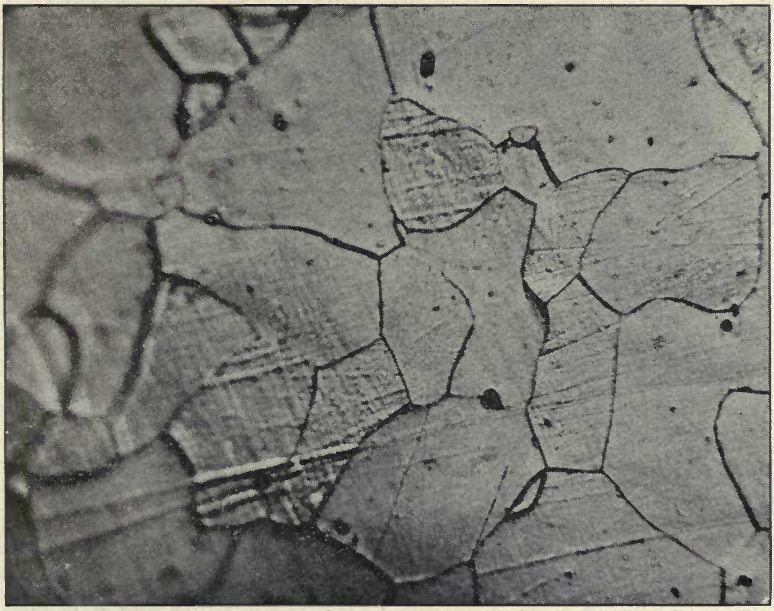

Fig. 166.—Intergranular failure of malleable

Nitric acid etch 400 diameters

Note that the surfaces of the different grains no longer seem to be in the same plane

Microscopic examination of the path of rupture through a metal, of the deformation of grains under load or, when applied to surfaces prepared before the application of the stresses, of intragranular slip and intergranular displacements is capable of interesting disclosures as to the mechanism of plastic deformation or ultimate failure under various types of stress.

Shows Two Systems of Slip Bands

A very cursory summary of the changes in malleable is attempted in the accompanying photomicrographs. Fig. 166 shows an unusual failure of intergranular type. It will be seen that at several points the grains have the appearance of being above or below the general surface. These grains have slipped not on the crystal faces within the grains but at the surface of contact of adjacent grains. The field of view is near the compression side of a piece distorted by cross bending and it is possible that this slip at grain boundaries produces the white so called compression fracture. The comparative absence of slip bands is interesting.

Fig. 167.—Ferrite grains in malleable, showing slip in two planes at right angles

Nitric acid etch 400 diameters

Note the cohesion at grain boundaries even after severe plastic deformation

Fig. 167 is reproduced from the tension side of the same piece and shows well developed bands. In some grains two systems of bands are seen due to slip along two directions. The fact that the adjacent grains are not separated even under heavy strain shows the strength and ductility of the amorphous boundary.

Fig. 168, taken from a piece loaded in pure compression, shows that the structure of Fig. 166 is not always characteristic of this type of loading and also shows plainly two systems of slip bands in practically every grain. In all of these photomicrographs, note that the direction of slip is constant in any given grain, but is not usually the same in adjacent grains. The direction of slip has no direct relation to the direction of the stress but is determined by the direction of the crystallographic axis of the ultra microscopic crystals making up the individual grains.

Figs. 169 and 170 show the distortion of grains in compression as seen on a polished section parallel to the direction of stress prepared after the distortion has occurred. The grains are much flattened as are the nodules of temper carbon. The grain boundaries are nearly obliterated but there is no separation of the adjacent grains. The effect is more strongly marked at the axis of the specimen than near the surface due to the fact that the barreling out of the specimen has permitted part of the reduction in height to be made by bending the outer fibers instead of upsetting them. The specimen from which these illustrations were made was compressed to a little less than one-half of its original height.

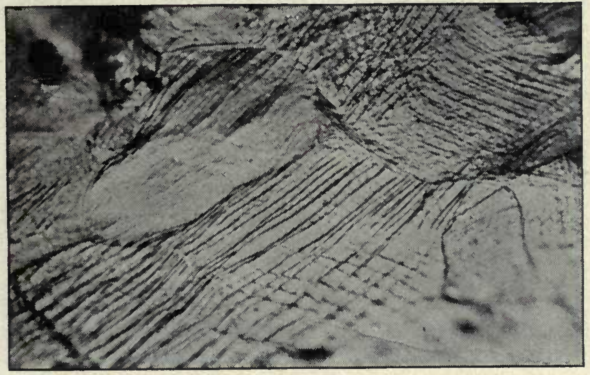

Fig. 168.—Slip bands due to plastic compression in malleable iron
Nitric acid etch 500 diameters

The effects of plastic deformation upon the grain structure can be destroyed by somewhat prolonged heat treatment below the critical point. By such treatment a new series of equi-axed

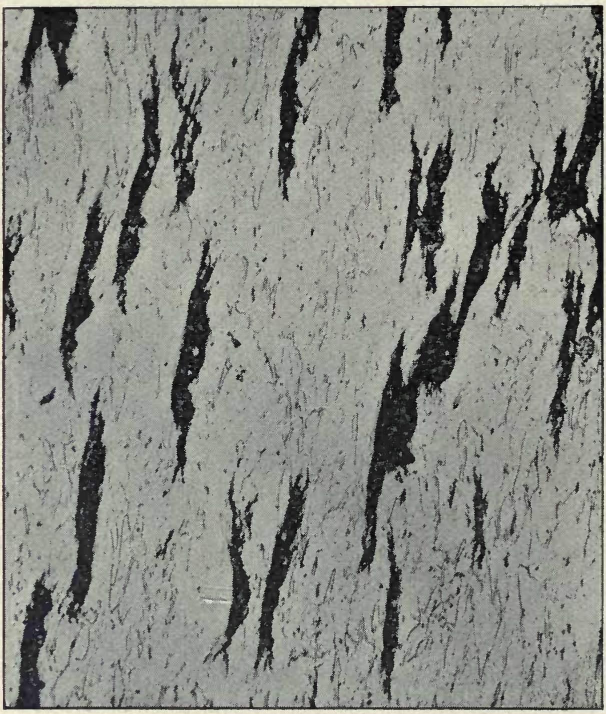

Fig. 169.—Plastic deformation of malleable in compression

Nitric acid etch 100 diameters

Field near axis of the specimen in a plane parallel to the stress. Note the flattening of ferrite grains, faint grain boundaries and distortion of temper carbon

grains is formed, whose size depends upon the degree of the previous plastic deformation and the heat treatment adopted. Fig. 172 shows an axial section of a specimen similar to that shown in Fig. 169, after about five hours at 650 degrees Cent. While the ferrite becomes equi-axed and fine grained the deformation of the temper carbon still persists.

Path of Rupture Shown

Fig. 171 shows the path of rupture of malleable broken in cross bending. It was prepared by breaking a wedge-shaped piece by bending it over until fracture occurred. The fracture was then plated with copper, the specimen sawed in two at right angles to the ruptured surface and parallel to the cross bending stress and the exposed surface polished.

Fig. 170.—Same specimen as shown in Fig. 169

Nitric acid etch 100 diameters

Field near surface of specimen in plane parallel to stress. Note the difference from Fig. 169 in lessened intensity of all changes

It is particularly interesting to note how the path of rupture goes far out of its way to include temper carbon nodules. This makes many deep depressions in the broken surface and due to the shadows in the bottom of these depressions produces the characteristic black fracture of the product. It is not often recognized that the presence of temper carbon is not a sufficient explanation of the black fracture for this material, representing about 6 per cent of an average cross section, would not be nearly sufficient to darken the surrounding silver white metal.

It is only due to the fact that the plane of rupture takes in many more nodules of carbon than would be found in an average section and in so doing produces a sort of "nap" that

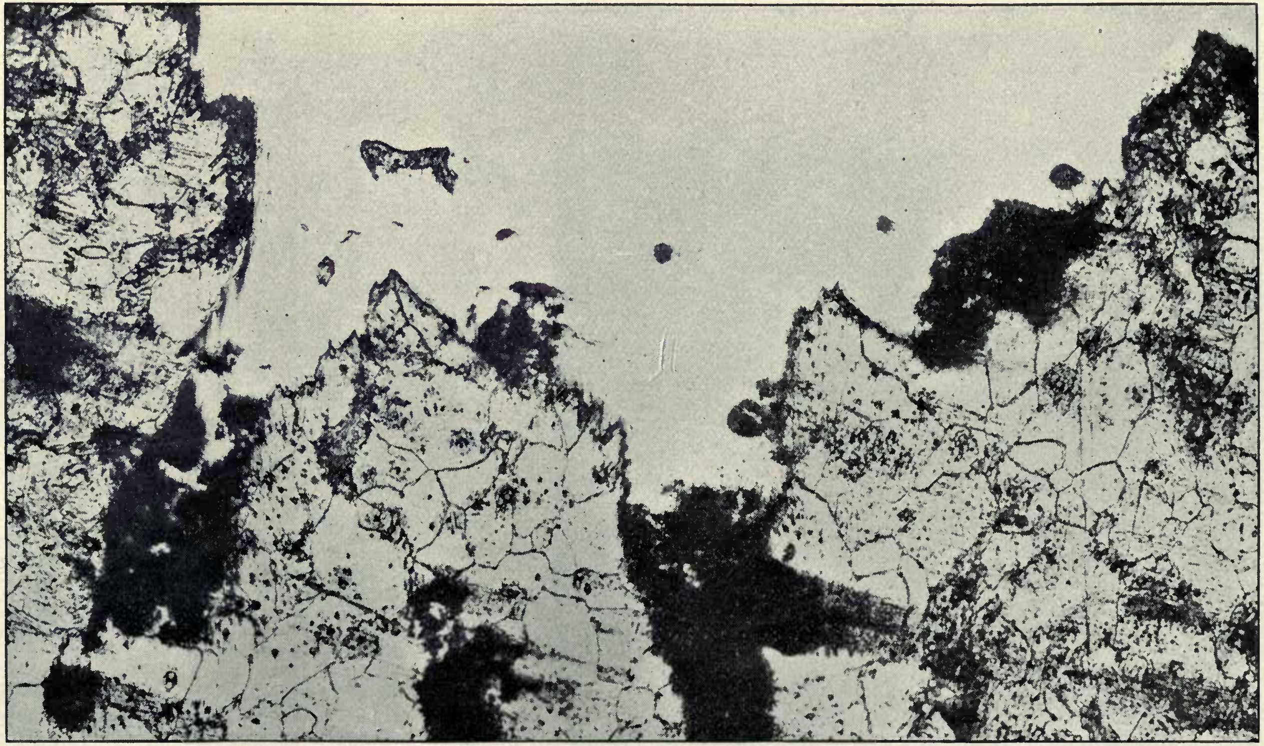

Fig. 171.—Path of cross-bending rupture through malleable

Nitric acid etch 200 diameters, slightly reduced in reproduction

The white structureless background is copper deposited to protect the broken surface. In the malleable, white is ferrite and black is temper carbon. Note that the path of rupture has gone far out of its course to include temper carbon and that at places, especially just to the left of the temper carbon near the middle of the fracture, there apparently has been transgranular failure, the grain being pulled into shreds the fracture appears as dark as it does. A fracture running at random along grain boundaries would be steely and crystalline in character.

The mechanical effects of plastic deformation offer a most interesting field of investigation. Most engineers are acquainted with the effects produced by cold rolling on steel and brass rods and sheets, and by cold drawing on copper and iron wires; the hardening is a consequence of the distortion of the metallic grains.

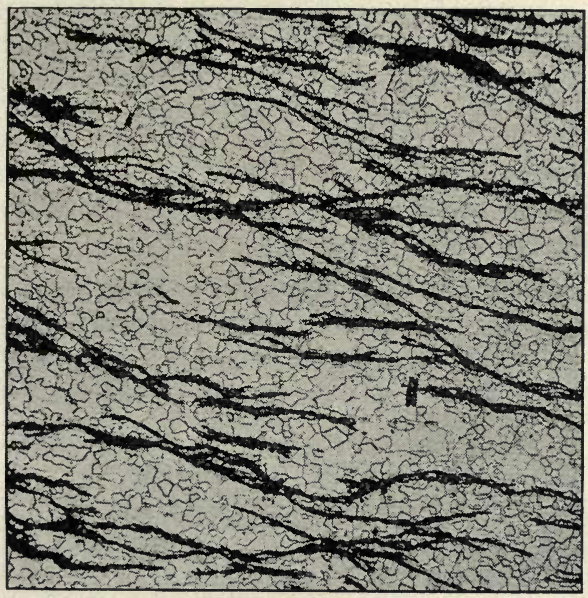

Fig. 172.—Malleable iron compressed about one-half. Annealed 5 hours at 650 degrees Cent.

Beilby's theory suggests that the change in properties is caused by formation of amorphous iron due to the partial destruction of the normal crystal structure when this becomes distorted. In this view the greater the coldwork the more nearly does the material as a whole assume the properties of this noncrystalline iron. Jeffries and Archer have dealt ably with the relation between slip and hardness in an article appearing on page 1057 of the June 15, 1921 issue of *Chemical and Metallurgical Engineering.*

For the purpose of the present study we may dismiss from consideration the more abstruse theoretical considerations and assume it to be an experimentally determined fact that metal which has suffered plastic deformation has become permanently altered as to its physical properties.

As a matter of fact this premise is of far reaching effect. Although it is becoming more and more usual to base engineering design upon the elastic limit rather than upon ultimate strength, still there always remains the possibility that a structural detail will be subjected, during manufacture or in use, to stresses which although insufficient to produce rupture will produce plastic deformation and the accompanying changes in physical properties.

In utilizing a given specimen of a ductile metal we must consider not only the normal physical properties of that metal but its entire previous history with respect to applied stress and also its subsequent service in so far as that is predictable.

In the case of pure iron chemical means are available for detecting the presence of plastic deformation. The products of the reaction between nitric acid and unstrained iron differ from those if the iron has suffered strain. An analysis of the reaction products thus will permit of conclusions as to the conditions of the metal. The method has not yet been applied to malleable owing to the disturbing effect of the residue of graphitic carbon.

We might assure ourselves of the absence of cold work by a heat treatment just before use but this is impracticable. For the purpose of the designer and manufacturer we must assume that the behavior of any ductile material in service involves each stress applied in its previous history and not single stresses.

It is possible that the entire problem is so complex that a clear understanding of the effects of sequences of stress is beyond our grasp. Four cases can be distinguished:

1. The stresses in the sequence differ neither in character,

magnitude or sign. This may be illustrated by a load which is alternately applied and removed.

2. The stresses do not differ in character or sign, but differ in magnitude. A load that is constantly applied but varies in intensity is an example.

3. The stresses do not vary in character but vary in magnitude and algebraic sign. Such a condition could be caused by alternate compression and tension, crossbending in opposite directions as in rotating beam test, torque in opposite directions etc.

4. The stresses vary with respect to all three characteristics. This would be the case if torque were followed or preceded by tension or compression or if compression in one direction were followed by tension or compression at right angles thereto, etc.

The ever increasing complexity possible will be readily observed. To this complexity must be added the fact that according to Nutting's conclusions the stress under plastic deformation is a function of the time of application.

A formal study of the entire phenomenon therefore is scarcely possible by any individual or laboratory; indeed the vast amount of work which has been done in impact and fatigue testing has but incompletely studied a small portion of this immense field.

New Data Is Available

It is therefore with humility that the author ventures to record certain observations, not much better than qualitative in character, on some of the mechanical effects of plastic deformation of malleable. According to the Nutting formula the strain under plastic flow is proportional to a higher power than unity of the applied stress and to a fractional power of the time of application.

Up to the proportional limit, the deformation is elastic and proportional to the stress. The exponent of the stress is unity and not greater than unity and the strain does not depend upon time. The exponent of time is zero. The course of the usual stress strain diagram, in tension, for malleable seems to indicate that, for rather quickly increasing stresses the plastic deformation of malleable is approximately proportional to the sixth power of the applied stress. There is a surprisingly

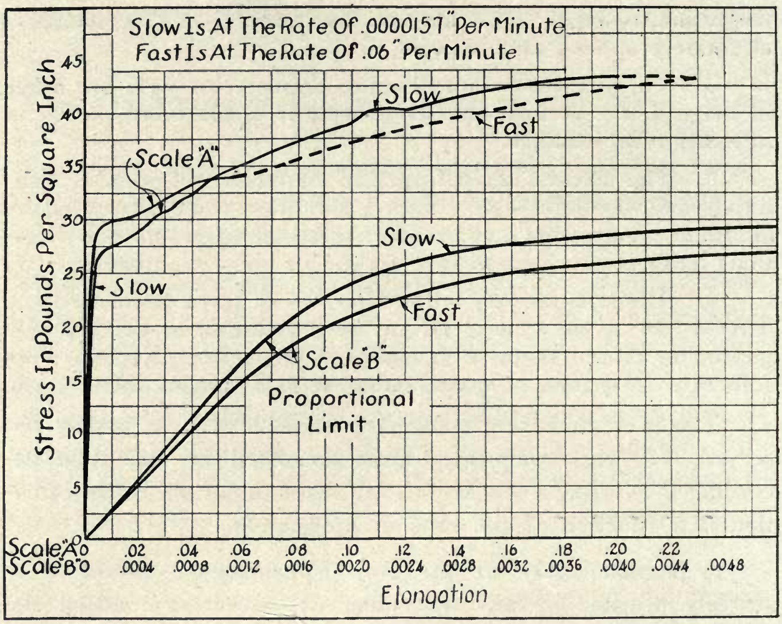

Fig. 173.—Stress strain diagram of malleable iron in tension for two rates of loading

short transition range between the point where the strain is directly proportional to the stress and the point where it begins to be proportional to the sixth power.

Stress Exponent Changes

During the transition range the exponent of stress obviously changes progressively from 1 to 6. To illustrate the effect of time on plastic deformation two stress strain diagrams are shown in Fig. 173. In one of these the diagram was made rapidly as extensometer readings could be taken while in the other each increment of load was maintained till no further increment of length was observed. In the former case the time was perhaps four or five minutes; in the latter case it was 250 hours.

It is obvious that if quickly loaded, to moderate stress, the metal will be stiffer than if the stress must be endured indefinitely. The ultimate strength and elongation are unaffected however. In Fig. 174 is shown the progress of deformation with time at two intensities of stress, in each case the last 500 pounds increment of load having been applied only after equilibrium had been attained under the previous load. In Fig. 175 a similar graph is plotted for behavior under a quickly applied load well above the yield point. Below the proportional limit no increment of strain with time is observed stress being constant.

Having thus given concrete examples of the application of the Nutting hypothesis to this particular metal we may turn

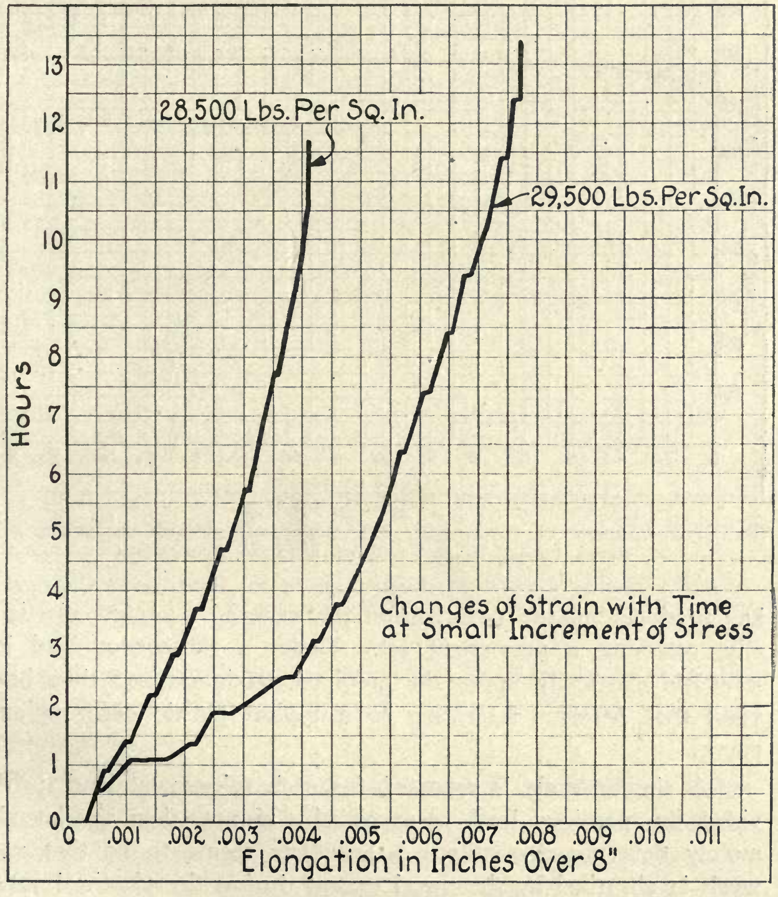

Fig. 174.—Changes of strain with time at small increment of stress

to the effect of previous tensile stresses to the stress-strain relationships during subsequent stresses of the same character.

It is well known that a material to which a tensile strength in excess of the elastic limit has been applied, thereafter has an elastic limit equal to the previous load. The stress-strain diagram under successive increasing tensile stress is shown in Fig. 176. It will be seen that up to the proportional limit the stress leaves no permanent effect. On releasing a stress which has produced plastic deformation the material contracts elastically, retaining a permanent set. Under a subsequent load it stretches elastically up to the previous maximum and then beyond that deforms according to a typical plastic deformation curve.

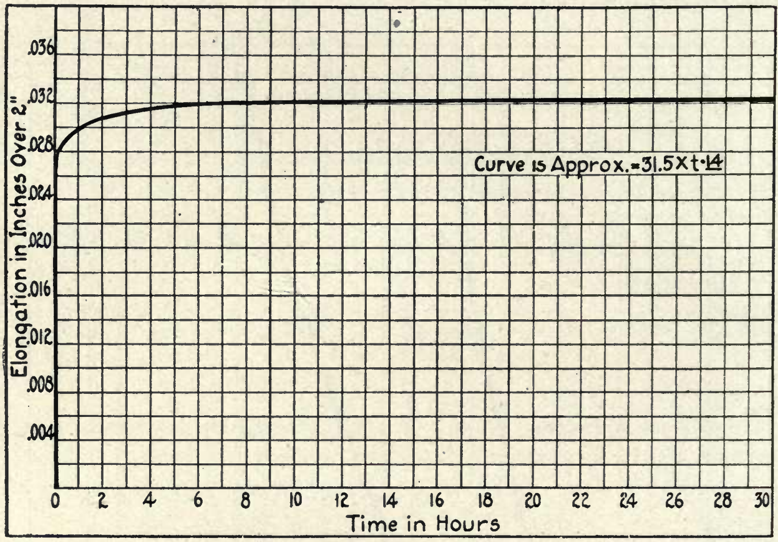

Fig. 175.—Changes of strain with time under considerable increment of stress (about 70 per cent of ultimate strength)

A similar cycle is repeated for each subsequent load, provided the previous load is exceeded. If not, then the metal merely deforms elastically. A corollary seems to be that no work is absorbed by the metal except during the plastic deformation, hence it is difficult to see how the material could fail in fatigue by repetitions of any tensile stress which is of sufficient intensity to cause rupture on its first application. Dalby finds that although the speciman appears perfectly elastic on successive loadings actually no part of the curve on unloading or reloading is a straight line but the two form a series of loops one for each repetition which of course amount to an absorption of energy. Similar loops can be observed in malleable if the magnification be sufficient. They are barely visible in the diagram.

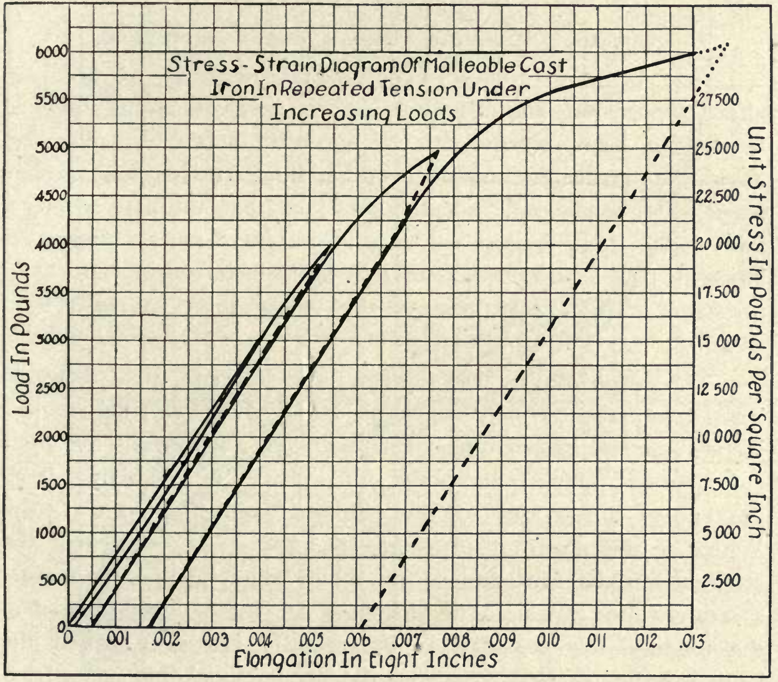

Fig. 176.—Stress strain diagram of malleable iron in repeated tension under increasing loads

The simplest case of stress reversing in algebraic sign is that alternating between tension and compression of equal intensity although alternate torsional shear is also of considerable importance. We have seen in the earlier chapters of this series that the behavior, at least within the elastic limit, of malleable in tension and compression, is similar; the proportional limit, being about 15,000 pounds per square inch and the modulus of elasticity about 25 x 10^6 pounds per square inch. Thus there is an elastic range of about 30,000 pounds per square inch, one half on each side of the neutral or unloaded condition through which the intensity of stress can be varied without plastic deformation.

Applying Alternate Tension and Compression

One of the simplest experimental methods of applying alternate tension and compression to a specimen is that of bending a beam to and fro in opposite directions. The behavior of malleable under cross bending stresses has already been fully considered, notably the fact that ultimate strength and elastic limit determined in this manner bear no direct relation to these constants as determined in pure tension and compression. The explanation of this observation has also been detailed.

The graph in Fig. 176 indicates the response of a malleable beam nominally ½-inch wide and 1-inch deep on supports 10-inches apart to alternations of stress. The deflections are plotted against apparent maximum fibre stress, as calculated from the known dimensions of the specimen and the applied load. When as the apparent proportional limit is not exceeded, the stress-strain diagram under this cyclic cross bending is merely a straight line through the origin at an angle depending upon the modulus of elasticity of the metal. However, when the load in either direction exceeds the proportional limit the stress strain diagram becomes a curve, plastic deformation taking place. As the specimen is unloaded the elastic deformation alone is removed and at zero a certain permanent set equal to the plastic deformation remains.

Elastic Limit Increases

The effect of this plastic deformation is represented not only by the measurable permanent set but also by the increased elastic limit in the direction of the previously applied load. On reversing the direction of stress the elastic limit is encountered sooner than it should be and the plastic deformation begins at a lower stress than was the case in the unstrained metal.

When an intensity of stress equal to the previous maximum but of opposite sign is attained in a perfectly homogeneous specimen, an equal and opposite strain would ensue although in the present case the negative deflections all seem somewhat less than the corresponding positive ones.

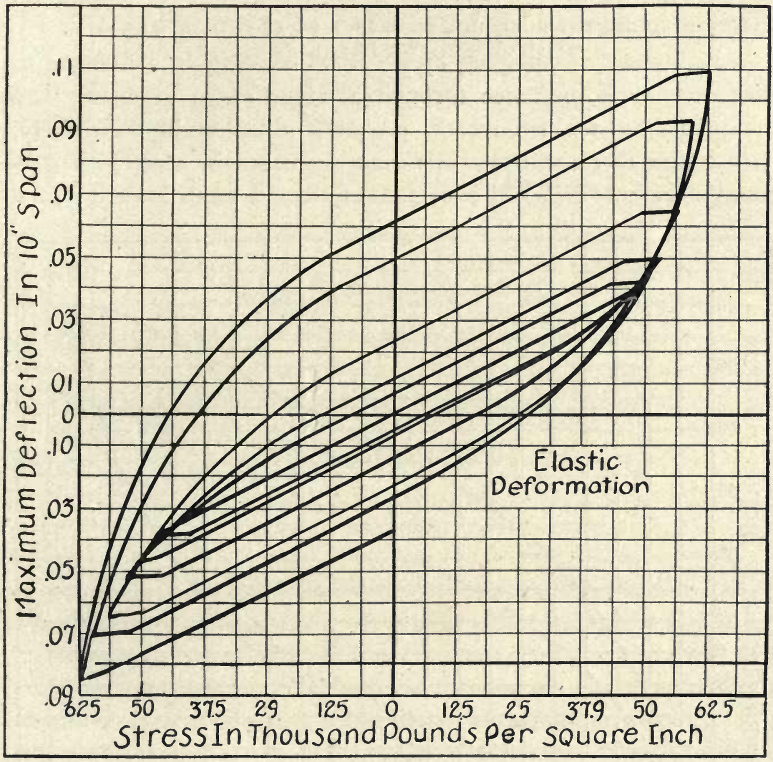

Fig. 177.—Behavior of malleable under cyclic bending under increasing loads

Action of Specimen

On unloading the specimen it straightens out first elastically, retaining a negative set at zero load. Under reversed loads it finally deforms plastically until at the stress corresponding to the first (positive maximum) it has the original deflection.

Thus the cyclic cross bending stress-strain diagram is a spindle shaped loop whose area represents the work done in plastic deformation. Plastic deformation in a given direction raises the elastic limit in that direction and decreases the absolute value of this constant in the opposite direction, the elastic range remaining approximately constant. With successively increasing intensities of stress the area of this mechanical hystersis loop grows larger and larger as shown in Fig. 177.

If instead of applying cyclic cross bending in a manner so that each cycle oscillates through a wider range of stress than the preceding one we merely repeat a given cycle indefinitely, it is found that the hysteresis loop decreases in area with successive cycles. Fig. 178 shows the first and tenth loops of such

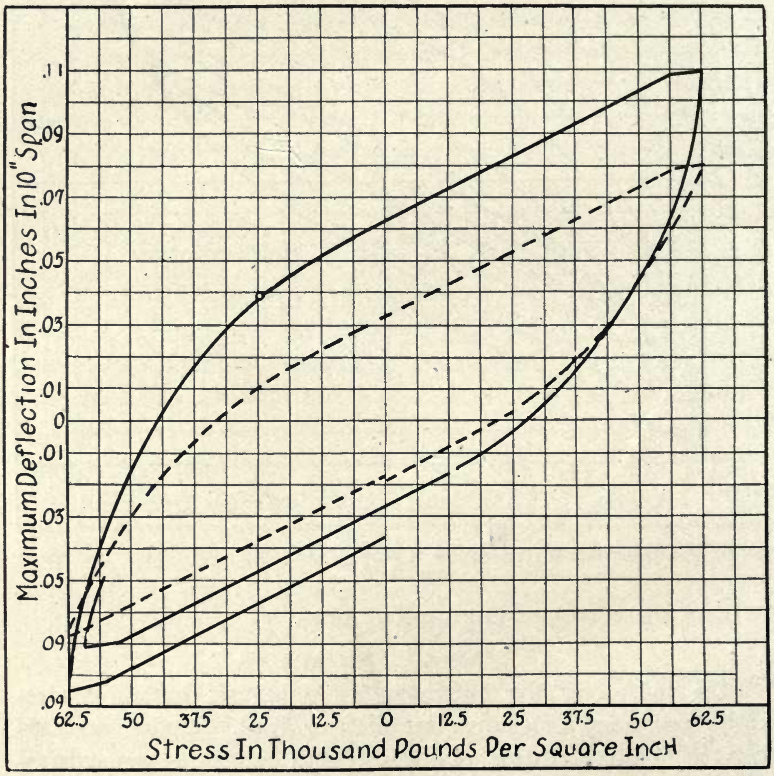

Fig. 178.—Behavior of malleable under cyclic cross bending at constant maximum stress

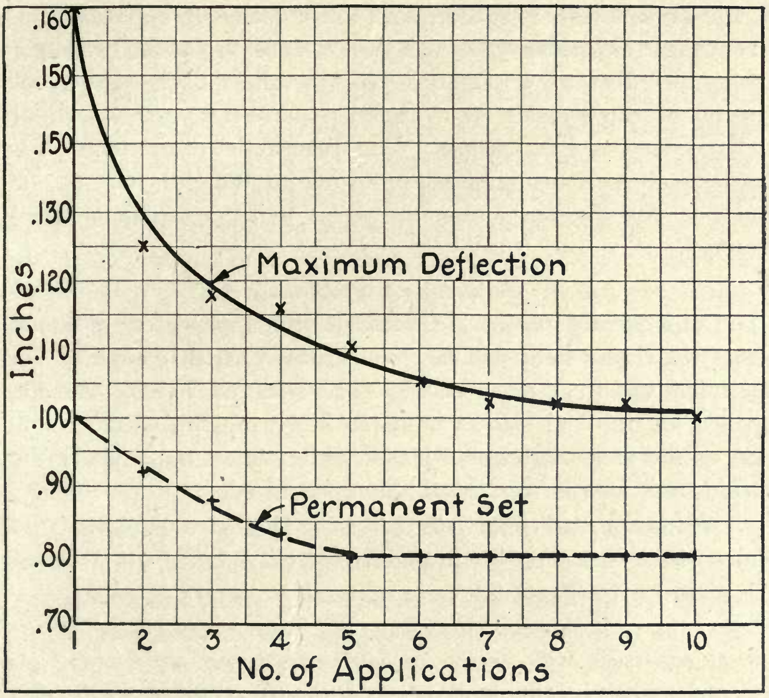

Fig. 179.—Maximum deflection and permanent set under cyclic cross bending at constant maximum stress

a series. The decrease in work per cycle is due to the smaller plastic deformation in each successive cycle due to the hardening of the metal from the cumulative effect of all the slip produced. The decrease in deflection and permanent set is not at constant rate but decreases with each successive loading as shown in Fig. 179 and approaches a fixed minimum of finite size. The deflections and sets are shown to be different according to which half the specimen is in tension. This is presumably due to lack of complete symmetry about the neutral axis. The work done by a great number of such alternations will finally rupture the specimen. This constitutes the phenomenon of fatigue. The phenomenon of fatigue of metals so far as it is known has been discussed in another chapter. The experiments just recorded having shown the approximate extent to which tensile or compressive loads strengthen the material for subsequent loads in the same direction and weaken it for loads of opposite sign. From these experiments we can gain at least a qualitative insight upon the effect of a previous cross bending upon subsequent tension or compression in a direction parallel to the length of the specimen and *vice versa*. The quantitative interpretation is impractical—perhaps impossible—owing to the difficulty of accounting for the distribution of stress in a plastically strained material.

Behavior of Specimen

Consequently under the subsequently applied longitudinal stress the elastic limit will be first exceeded on that edge of the specimen which is experiencing a reversal of stress. As the applied longitudinal load is increased a greater and greater portion of the area experiences plastic deformation until finally the elastic limit also is reached at the opposite edge.

At intermediate intensities of stress in a portion of the specimen elastic strain exists, in another portion plastic strain. From the nature of the case the ratio of strain to stress is greater for plastic than elastic deformation. The side experiencing a reversal of stress will stretch or compress more rapidly and an eccentricity of loading will result from the unequal strain distribution. Such an eccentricity in the case of compression will result in the superposition of a bending moment on the longitudinal stress, as in the case of columns which are eccentrically loaded and a given load will produce far greater unit stresses than might be expected.

In the case of tension the eccentricity of loading will result in the transfer of a disproportionate amount of load to a few of the stiffer fibers with an accompanying high unit stress.

Conversely the effect of a previous longitudinal stress upon subsequent cross bending loads is to shift the neutral axis toward that surface of the specimen which is being stressed in the same sense as the first load. This shift goes on until the moment of resistance of the portion of the specimens in opposite sides of the axis about the axis are equal.

The sum of the two moments, constituting the moment of resistance is thereby decreased. In either event, although we may not be able to solve numerically the complex mechanics we may draw the conclusion that cross bending weakens the material for subsequent tension or compression and *vice versa.*

The practical application of this conclusion is that a detail which in fabrication has been subjected to severe cold work cannot be expected to be as strong under loadings involving a reversal of the stress previously encountered as unworked metal would be. This conclusion applies equally to all ductile materials and should serve as a warning against needlessly energetic straightening or bending operations. Many malleable castings are cast to a simpler form than intended and then bent to the more complex shapes demanded. Air brake hose clamps are examples of this practice. Such parts will never develop the full strength of the original metal.

In all the preceding cases the loadings have been such as to set up strains parallel to the subsequent stresses. A variety of circumstances are possible in which the final load has no component parallel to that producing the plastic deformation.

Two typical cases are torsional shear followed by tension and compression followed by tension or compression in a direction normal to the first compression. Compression followed by a cross bending load parallel to the direction of compression is, of course, a special case of the preceding involving both tension and compression.

The combination of compression followed by tension, compression, or both, normal to the original strain is the condition which may arise where a piece is reduced to the desired dimensions by compression in a press rather than by machining. In Fig. 180 are shown two stress-strain diagrams on specimens nominally ½-inch square subjected to cross bending load on supports 10 inches apart. One specimen, *A*, is of normal metal in its original condition, while the other, *C*, was produced from a thicker bar by compressing it to a final depth of ½ inch. The compressed dimension is vertical, that is, parallel to the direction of the load in the final test. The effect of relatively heavy compression under these circumstances can be learned by a comparison of the two graphs.

A few scattering tests of the effect of shear upon subsequent tensile stress have been made.

In Fig. 180 certain tests of this character are tabulated. Standard A. S. T. M. tension specimens were twisted through various angles and then broken in tension. In the illustration the angle of twist under load is plotted against the tensile properties of the resulting metal.

It will be noted that a rapid and continuous decrease in elongation is encountered with increasing torsional deformation. The tensile strength first rises rapidly to a maximum and then decreases still more rapidly. The location of the maximum tensile strength corresponds approximately to the torsional yield point, as may be seen from the torsional stress strain diagram. The curve suggests a hardening of the metal due to the formation of amorphous metal followed at higher strains by disruption at the grain boundaries.

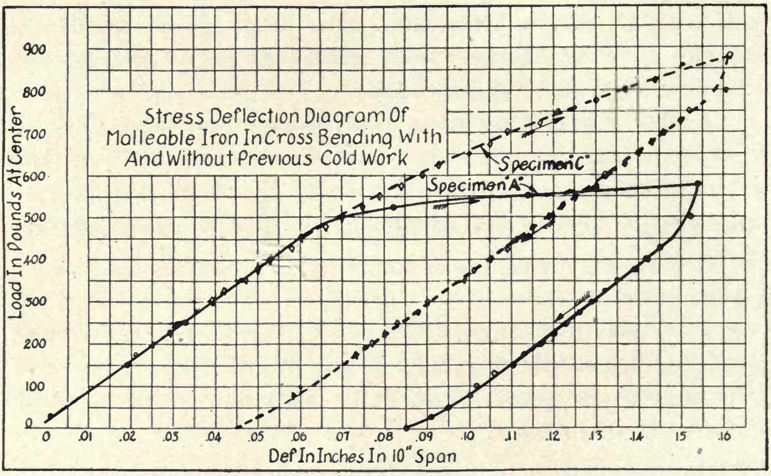

Fig. 180.—Stress deflection diagram of malleable in cross bending with and without previous cold work

Failure in tension after great torsional strain did not result approximately normal to the axis but in a spiral surface approximately normal to the helix angle into which the originally straight elements of the specimen have been strained. There is a suggestion here that distortion is not due to pure shear.

We have considered the effect of a series of stresses of known intensity and direction upon a ductile material. Another important condition is that in which, instead of a series of known stresses the specimen is required to undergo a series of known increments of energy.

Impact testing by a series of equal or increasing blows, is the principal application of this type of plastic deformation.

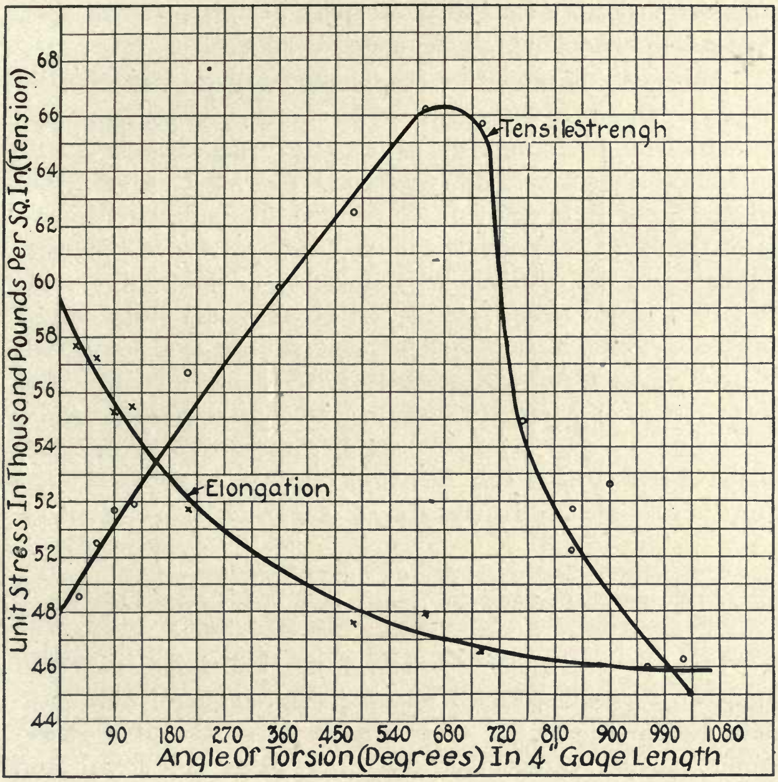

Fig. 181.—Effect of torsional deformation upon subsequent tensile strength of malleable

In this case the intensity of maximum stress is a function both of the energy input of the blow and the elastic and plastic deformation of the specimen. The latter factor depends upon the previous plastic deformation of the specimen and hence is a function of the magnitude and number of the preceding series of inputs of energy.

Since malleable is often subjected to repeated impact in service and occasionally in testing, this condition is of special importance in connection with a study of that metal.

If the load deformation curve of a given specimen under plastice deformation were capable of mathematical definition in terms of its dimensions and properties and the rate of application of the load, a mathematical study of this problem would be feasible although probably quite complex.

However, the problem may be simplified by assuming that we have experimentally determined the load-deformation diagram of a given specimen under given conditions. The load-deformation diagram in every respect is similar to a stress-strain diagram except that the co-ordinates are actual load and actual deflection instead of unit stress and unit strain. We can conceive that for a given specimen such a graph might be autographically produced under rates of application of load as rapid as are encountered in impact testing.

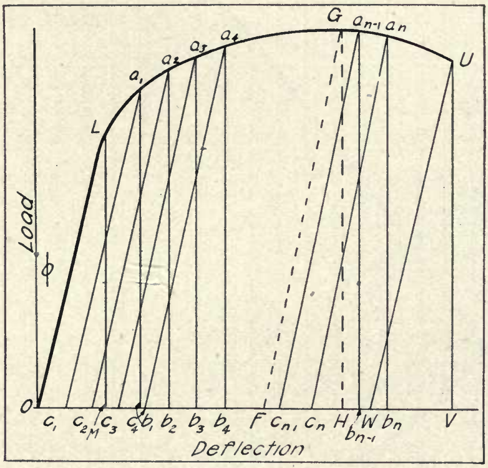

Fig. 182.—Absorption of energy from successive impacts

Referring to Fig. 182 let *OLU* represent the load-deformation curve described above, *L* being the elastic limit and *U*, the ultimate strength and tan Ø the modulus of elasticity. Then the energy imparted to the specimen at any given load and deformation for instance is the area below the curve beginning at *O* and ending at a_n. For example, OLa_1a_2 etc., a_nb_n. If this energy input be large enough the point a_n will then reach U, the energy being the represented by OLa_1a_2 etc., UV and this energy will produce rupture under impact.

Therefore, if impact is produced by a single blow, the energy of rupture is measured by the entire area below the curve as shown above. A blow having an energy of impact of OLM or less will not produce a plastic deformation, the specimen will return to its original form after the load is removed and will have absorbed no energy. If the energy of impact be equal to OLa_1b_1 for example, when the load is removed the deformation will decrease along a_1c_1 (parallel to OL) and a permanent set Oc_1 will remain. The energy OLa_1c_1 will have been used up in plastic deformation and the elastic limit will be raised to a_1 and the deflection at the elastic limit to c_1b_1. The new load deflection curve becomes $c\,a\,a$ etc., UV. Thereafter any impact of energy not greater than $c_1a_1b_1$ will produce elastic deformation only. Suppose the second impact is equal to $c_1a_1a_2b_2$ then by similar measuring the new load deflection curve becomes $c_2a_2a_3a_n$ etc., UV the third impact moves it to $c_3a_4a_n$ etc., UV and so on, and after n blows it becomes c_na_n UV and finally perhaps WUV in which case a blow equal to or greater than WUV will break the specimen.

Suppose now that we assume an equal energy input with each blow. Then $OLa_1b_1 = c_1a_1a_2b_2 = c_2a_2a_3b_3$ etc., $= cn_{-1}an_{-1}an\ bn$. It is obvious by inspection that up to the point of maximum load G each succeeding one of the similar triangles ca_1b, $c_2a_2b_2$ etc., is of larger area than its predecessor. These triangles represent the portion of the energy of impact expended on elastic deformation. Consequently a smaller percentage of the constant increment of energy is available for plastic deformation with each succeeding blow up to that producing maximum deflection. Beyond this point an increasingly larger amount of each energy increment is available for plastic deformation.

Finally if $\Sigma c_1a_1a_2c_2 + c_2a_2a_3c_3 - c_{n\text{-}1}a_{n\ 1}a_n\ \ c_n$ etc., is commensurate with $OLGUW$ the specimen absorbs on the last blow energy equivalent to UVW.

The specimen has then absorbed plastically the energy $OLGUV$ which it would have absorbed if broken by a single impact. Since, however, the area $c_{n-1}a_{n-1}a_n\ c_n$ is always less than the area $c_{n-1}a_{n-1}a_n\ b_n$ the energy absorbed by the metal at each blow is measurably less than the total energy of impact, a large part of the energy of impact being returned by the specimen during its elastic recovery.

Obviously since there is a definite amount of energy not absorbed by the specimen at each blow a smaller percentage of the energy of impact is absorbed the lighter the blow. If the energy of rupture be measured by the aggregate of the energy of the entire number of blows to produce rupture this sum will be higher the smaller the individual blows. Consequently testing a metal by successive impacts can yield quantitatively comparable results when all the specimens are identical in form and quality in addition to the constancy of the hammer blow. Of course this condition is impracticable of attainment, the quality being unknown before the test.

In practice this means that only carefully prepared specimens of similar material are capable of fairly accurate comparison by repeated impact test.

One or two further conclusions may be gained from the study of the diagram. Energy equivalent to the area OLM is absorbed by the specimen elastically. The material will withstand an indefinite number of impacts of this magnitude without permanent deformation.

Were a similar triangle FGH drawn with its apex at G, this area will represent the maximum elastic absorption of energy the specimen can sustain when by repeated impact the elastic limit has been raised to the ultimate strength. Any increment of energy less than this will never fracture the piece but will produce a maximum deflection after a given number of blows which will not be further increased by further repetitions of the impact.

The area $OLM = LM$. $LM \tan \phi =$ modulus of elasticity × square of elastic limit.

The area $FGH = GH$. $CH \tan \phi =$ modulus of elasticity

× square of ultimate strength.

From the above we may calculate the blows required to make an impact test workable on a given specimen.

The deflection at each successive blow can be determined graphically under given conditions from the diagram. An impact test in which the energy increment increases with each blow can be studied in a similar manner. In that case there is no possibility of coming to a maximum deflection without fracture for the increased energy of the succeeding blow would carry the deformation beyond *G*. In such a test there is great danger that the last blow will be equivalent to far more than the energy *WUV* and the unabsorbed energy of the blow will be credited also to the specimen.

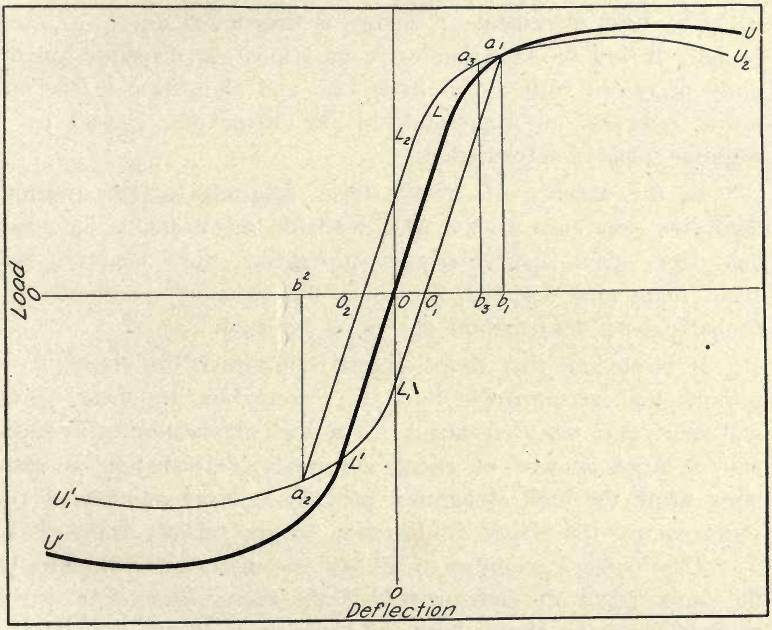

Fig. 183.—Load deformation diagram of specimen subjected to alternate impact

We may generalize to the effect that no method of repeated impact can correctly measure the energy of rupture of a ductile metal. In a similar manner we may study graphically the effect of alternate impact in opposite directions, although we may be confronted with the difficulty of securing the necessary load deformation curves. In Fig. 183 U^1L^1OLU is the original curve for the specimen. An increment of energy Oa_1b_1 deforms it to a_1 and raises the elastic limit to that point. The load-deformation diagram then becomes $a_1O_1L^1{}_1U^1{}_1$ and an increment of energy in the opposite direction to the first $O^1L^1{}_1a_2b_2$ produces a load of a_2b_2 and a deformation O_1b_2. The new elastic limit becomes a_2 and the new diagram $a_2O_2U_2$.

The next increment of energy is diagramed as $O_2a_3B_3$ and so on. It will be seen that each impact in one direction apparently decreases both the ultimate load and elongation in the opposite direction an expression of the weakening caused by a negative plastic deformation.

In the absence of stress strain diagrams under dynamic loads we may turn as the best available substitute to the various stress strain diagrams given throughout these chapters and from them and the dimensions of the specimens estimate the probable load deformation curves to be used.

It is obvious that those materials in which the elastic limit is quite high accompanied by a high elongation are these which will well resist repeated impact. The high elastic limit will dissipate a large amount of energy in elastic deformation at each blow while the high elongation provides a large amount of reserve energy for plastic deformation before rupture takes place.

The Young's modulus of all ferrous materials is practically the same, hence the deformation at the elastic limit is in direct proportion to the elastic limit. In steel high elastic ratio is obtained only at the expense of elongation and *vice versa*. The various graphs for malleable, indicating a constant and high elastic ratio and an elongation increasing with strength account for its excellent behavior under repeated impact even when of sufficient magnitude to produce plastic flow.

In this connection, incidentally the yield point of metal is the governing factor in ferrous materials for the small reduction in the area representing energy due to the curvature of the stress-strain diagram between the proportional limit and yield point is negligible.

Plastic deformation has been discussed mainly because of its great importance in the utilization of malleable. No one realizes more than the author the unsatisfactory state of knowledge and the lack of precise numerical data. If this chapter has enabled the reader to form even a qualitative image of the resistance of the metal above the elastic limit that is all that can be expected. An infinite amount of further study will be required before concrete mathematical analyses will be possible.

XIX

THERMAL AND ELECTRICAL PROPERTIES

WHILE it is true that materials of construction in general are used to resist mechanical stress, yet there are service conditions when other properties, such as thermal, chemical or electrical, for instance, are of greater consequence.

The most important condition of this kind arises in the use of malleable as a material for field frames of electrical apparatus, where the magnetic characteristics of the metal are much more important than the mechanical strength. It is a well known fact that if a coil of wire is wound around a piece of iron and a current is passed through the coil, the iron becomes magnetic. This property of iron, which it shares in a very limited degree with a few other metals, is of importance in electrical machinery. If the power to become magnetic is the quality desired, evidently the metal which forms the strongest magnet with the same coil and current is the most valuable. Therefore it is desirable to determine the degree to which a given material possesses this valuable property. Avoiding a discussion of the electrical principles and of the mathematical reasoning involved in the study of magnetism, it is sufficient to say that the intensity of magnetization, represented by the symbol H, and expressed in gausses (lines per square centimeter) can be calculated from the dimensions of a magnetizing coil and measurement of the current. When an iron core is inserted in the coil it will be found that the intensity of magnetic field is much greater than the calculated value H. This higher value, known as magnetic induction, is symbolized as B and is measured in the same units as H. The ratio of B to H, that is, the number of times stronger the magnet is with the iron core than without any core, using the coil only, is called the permeability of the material and is the variable represented by the Greek letter μ.

It is further found that the value of μ depends not only upon the material being used but also on the value of H at which the experiment is made. In general, the permeability of a material first increases as H increases, soon reaches a maximum and then falls off, first rapidly and then more and more slowly.

The value of μ for an indefinitely strong field is probably 1 for all materials. Owing to experimental difficulties determinations close to the zero value of B are not very reliable. The behavior of a magnetic material is usually represented by a so-called magnetization or "B-H" curve in which the value of H, the strength of the magnetic field, is plotted horizontally and the magnetic induction in the iron, B,, which is equal to μH, is plotted vertically. The fact that μ is variable, depending on B and hence on H, gives this curve a general form which rises from the origin ($H = 0$, $B = 0$) first at a rapidly increasing rate as H increases and then more slowly until it becomes horizontal when H is infinite. As a matter of fact the curve becomes nearly horizontal fairly soon, and the "knee" in the curve, somewhat resembling the yield point in a tensile stress strain diagram, represents practically the maximum flux density which can be attained in a given metal. This value varies widely in different metals and is quite definite in each metal having almost the significance of a physical constant. This characteristic for malleable iron is shown in curve *A*, Fig. 184. The specimen was in the form of a closed ring about 6 inches in diameter and having a rectangular section 0.33-inch thick radially and 0.9-inch wide. The permeability, $\mu = \dfrac{B}{H}$

for various values of H based on the data for the ring described above, is shown in curve *B*. The values of μ as related to B are plotted in curve *C*.

When a material has been magnetized and the magnetic field H is then reduced, the magnetic induction B in the iron decreases but not at the same rate as it increased with increasing values of H. When H is reduced to 0 there usually remains a considerable magnetic induction and it is only after H has reached a definite value in the opposite direction to that first developed that B falls to 0.

This lag of induction behind magnetizing force is due to hysteresis. The value of B when H is reduced from a high value to 0 is called residual magnetism, and the negative value of H required to bring B to 0 is called the coercive force. It is quite possible to plot a curve, similar to a B-H curve beginning with a fairly high value of H, lowering H gradually to 0, then increasing it in the opposite direction until a negative value is reached equal in magnitude to the original positive value, then back through 0 to the starting point. Such a

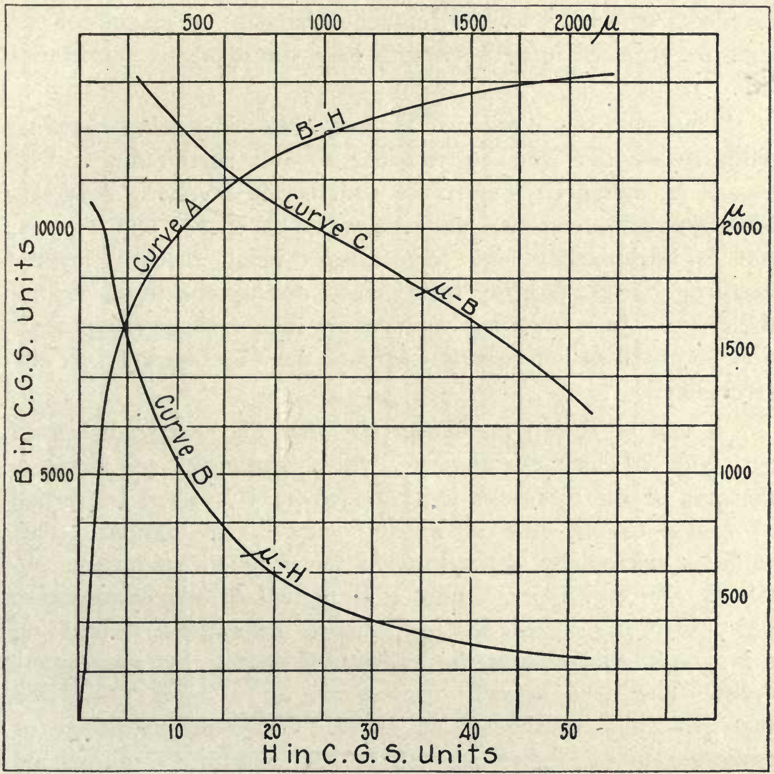

Fig. 184.—Magnetization and permeability curves of malleable cast iron

curve forms a closed loop of distinctive form called a hysteresis loop. The area of this loop represents energy consumed in magnetizing and demagnetizing the specimen. Materials strongly retaining their magnetism, and therefore suitable for permanent magnets have a larger hysteresis loop due to great residual magnetism and coercive force. Material for electromagnets, especially where frequent changes in magnitude or sign are required in field strength have the opposite characteristics.

This energy is dissipated as heat, either in raising the temperature of the iron or radiated to the surroundings. The loss is of industrial importance for service involving reversals of magnetism in that it involves a waste of energy and may result in inadmissably high temperatures being reached in the magnetic circuit, possibly sufficient to destroy the insulation on the coils. The energy is lost once for each cycle of magnetization so that for alternating currents the loss depends on the frequency.

It can be shown mathematically that the energy dissipated per cycle of magnetization per cubic centimeter of metal is the area of the hysteresis loop divided by 4π, regard being had of course to the scale to which *B* and *H* are plotted. This value is necessarily dependent on the magnetic induction obtained. In Fig. 185 a condition is plotted in which saturation has practically been attained, hence calculations based on this graph would give the energy dissipated by a complete cycle. The area actually corresponds to a value of 11,388 ergs per cubic centimeter of metal. Cyclic magnetization of malleable to an inductance of 13,200 centimeter-gram-second units by the usual 60-cycle alternating current would raise the temperature of the iron a little over 2 degrees Fahr. per minute, assuming no radiation of heat.

Steinmetz has determined empirically that the work done in a cycle of magnetization on any given material is approximately proportional to the highest magnetic induction, *B* reached in the cycle raised to a power between 1.66 and 1.70. This formula serves to derive the work done on the same material by cycles ending at different inductions. Therefore, the hys-

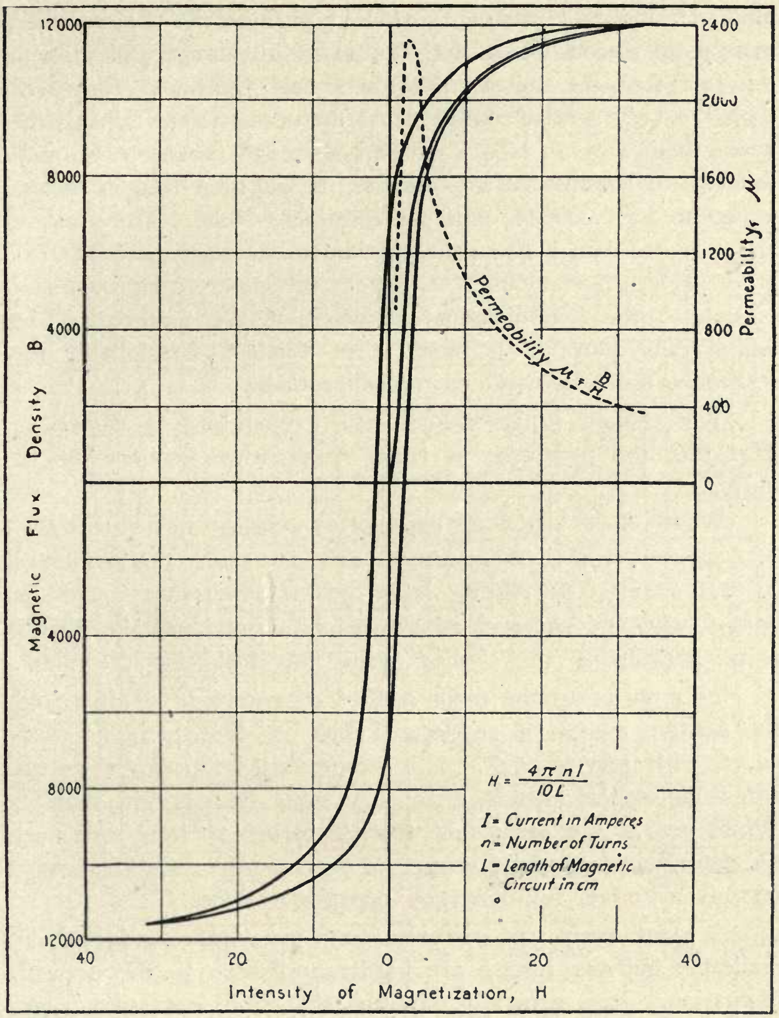

Fig. 185.—Magnetic properties of malleable cast iron

teresis loss on any given material is a constant times $B^{1.68}$ when B is the maximum induction reached in the cycle. This constant varies with different materials and is designated by the Greek letter η. Calculation from the preceding data gives a value of 0.00136 for Steinmetz's constant.

This very low value is logically due to the fact that the bulk of a malleable casting is a fairly pure ferrite contaminated mainly by silicon whose presence is an advantage and also to the fact that the anneal involves a heat treatment consistent with the very softest condition of ferrite possible. So far, the writer knows of no case where the electrical resistance of malleable is of commercial importance. It has been roughly determined to be 0.000044 ohm per centimeter cube. More recent and accurate data indicate the specific resistance to be 0.0000295 ohms per centimeter cube. A part of this descrepancy no doubt is due to the heterogenous character of the material. The newer value however is much more reliable. Presumably the resistance decreases with the carbon content.

The change in resistance with temperature is shown in Fig. 186, the resistance at room temperature being taken as unity.

Where metal parts are exposed to weather or to the action of water or steam, circumstances arise in which the resistance of the material to rusting is of prime importance. This is particularly true under circumstances which preclude the use of paint, galvanizing and similar means for protecting the metal.

This opens up the moot subject of corrosion of iron and the relative merits of accelerated tests in dilute acid as compared with service tests. All commercial iron alloys, except a few high-silicon metals, dissolve in acids more or less rapidly. While not at the same rate for all forms of iron and steel the deterioration is rapid enough to preclude the use of ordinary ferrous materials for corrosion resisting services.

A great many acid corrosion tests have been conducted on malleable but the results are hardly applicable to the present discussion. It is generally admitted that since corrosion is an electrolytic phenomenon, the more nearly homogeneous a metal is the better it will resist corrosive action either of the elements or of acids, salt water, etc.

Manganese sometimes is alleged to be an offender in starting corrosion. The surface of a malleable casting is always nearly carbon free; it contains rather small amounts of manganese, less than any material except wrought and ingot iron. Silicon is supposed to dissolve in ferrite, when present in moderate amount. It would appear therefore that malleable should resist rusting moderately well. This general conclusion is borne out by the fact that malleable has been used for many years in the manufacture of pipe fittings, radiator nipples, etc., and complaints that the material has failed by rusting are very rare.

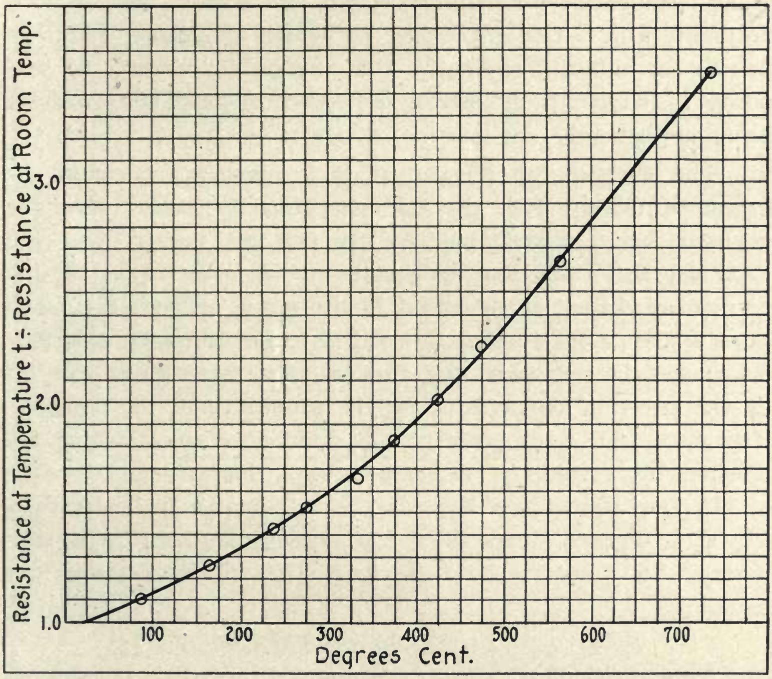

Fig. 186.—Variation of electrical resistance of malleable cast iron with temperature

There is also of record the case of a malleable iron harness part which was found in excavating for a foundation. The circumstances were such as to make it certain that the article had been in the soil over 40 years, yet it had suffered but little injury to the surface. The only service test with which the writer is familiar was conducted to determine the relative life of malleable and steel railway tie plates. Plates of both materials were laid in the same track at the same time. When the steel plates had completely rusted away the malleable plates were still practically in their original condition. It seems rather doubtfull whether in the present state of our knowledge any quantitative method exists of measuring resistance to corrosion other than a direct comparison under the conditions expected in practice.

In a great many cases mechanism is required to function under temperature conditions either abnormally high or abnormally low. The principles to which malleable owes its properties indicate obviously that malleable cannot be exposed to temperatures above Ac_1 even momentarily, without being permanently destroyed.

The question of its use at high temperature cannot be dismissed merely with the statement that it should never be exposed, even momentarily to temperatures higher than say 1300 degrees Fahr. lest by chance Ac_1 be overstepped and a permanent change be produced in the metal. There are many cases where castings are to be used at temperatures considerably below the danger point and the designer must guide himself by the effect of temperature on the properties of the material. Even so simple a property as the dimensions of a casting are affected by variations of temperature. Experiments by the author have shown that if L_0 be the length of a malleable casting at 0 degrees Cent. when the casting is raised to a temperature of t degrees Cent. its length L_t will be given by the equation

$$L_t = L_0 \ (1+.000006 \ t+.0000000125 \ t^2)$$

Translating into terms of Fahrenheit temperature the revised formula becomes

$$L_t=L_{32} \ [1+.0000033 \ (t-32)+.00000000385 \ (t-32)^2]$$

These figures are somewhat cumbersome. For engineering purposes it may be more convenient to take the expansion at various Fahrenheit temperatures in per cent of the length at 75 degrees Fahr. from the graph, Fig. 187. It is to be noted that the change in size of large castings where raised to moderately high temperatures is quite significant. Thus a casting 3 feet long when raised to 600 degrees Fahr. expands over 0.1 inch which may be very important where clearances are to be allowed.

The author is not aware of any actual or experimental determinations of the specific heat of malleable cast iron. Since the material is a mechanical mixture of graphitic carbon and nearly pure iron we may use provisionally data calculated from the known constants of the two elements.

The conductivity of a metal for heat represented by the symbol *k* is defined as "the quantity of heat, in small calories transmitted through a plate 1 centimeter thick per square centimeter of surface when the difference in temperature between the faces is 1 degree Cent.

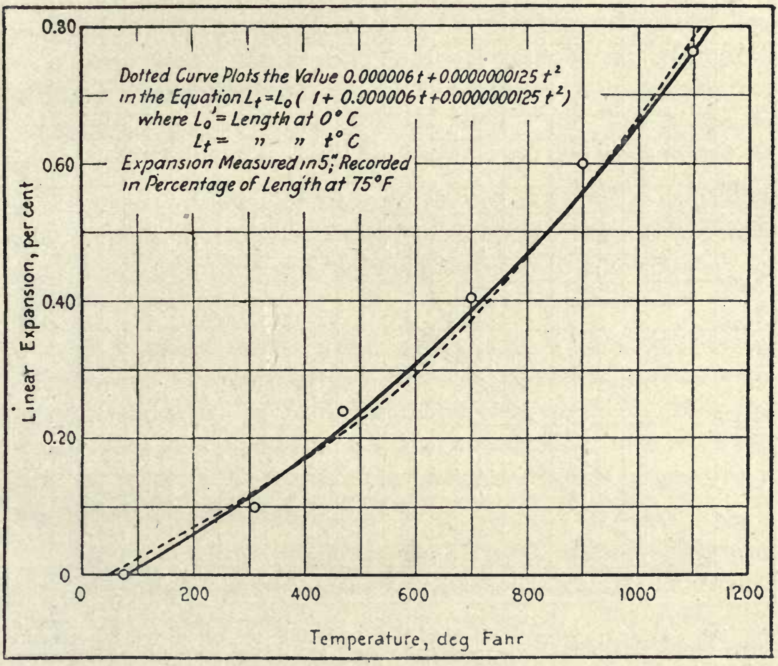

Fig. 187.—Expansion of malleable cast iron

The heat transmitted through a plate of metal varies directly as its area and as the difference in temperature between the faces and inversely as the thickness.

The value of *k* varies slightly with the temperature, decreasing for iron and increasing for carbon as the temperature rises. At room temperature (17 or 18 degrees Cent.) the values for *k* for iron and graphite are .161 and .037, respectively. (*Smithsonian Physical Tables,* 1921.)

At that temperature malleable cast iron of 2 per cent to total carbon should have a value of *k* between .1578 and .1585, depending on how readily heat can be transmitted from carbon to iron and vice versa.

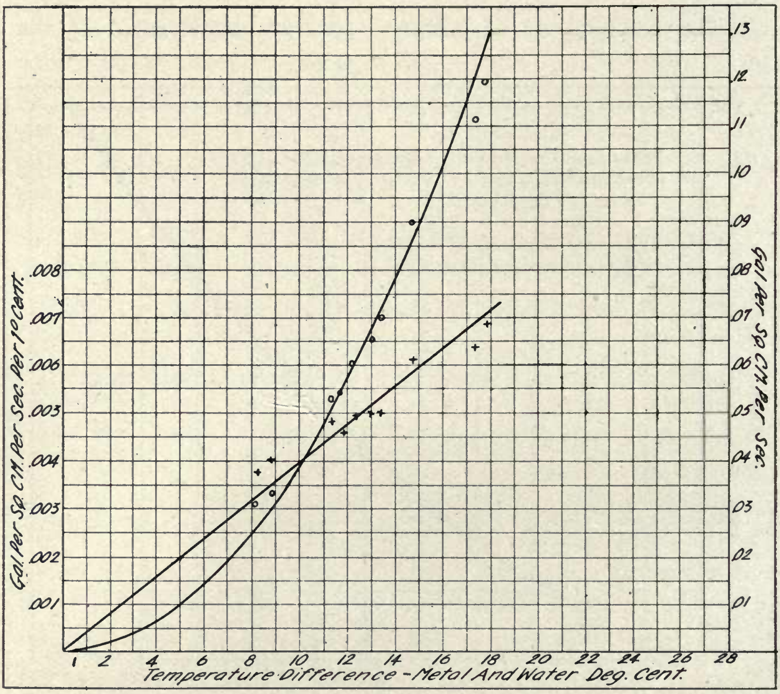

Fig. 188.—Heat transfer from machined malleable to still water for various temperature differences

On the same authority for the interval between 100 and 720 degrees Cent. the value of *k* becomes .202 for iron, .306 for graphite, and between .198 and .204 for malleable iron.

The values are higher than certain approximate experimental values determined in the author's laboratory. Malleable heated above A_1 will have its thermal conductivity permanently decreased since this constant decreases with the combined carbon content.

The specific heat of a substance is the quantity of heat in small calories to raise the temperature of one gram 1 degree Cent.

Iron at 37 degrees Cent. has a specific heat of .1092 (loc. cit.) and graphite at 11 degrees Cent. a specific heat of .160. As a mechanical mixture of 98 per cent iron and 2 per cent graphite and neglecting corrections for a change of specific heat with temperature, the specific heat of malleable at room temperature should be .1102. The value probably is quite accurate, since cast iron of about 3¼ per cent Cent. has a specific heat of .1189. The specific heat rises with the temperature.

In view of the approximate character of these deductions and of their intended application a detailed study of the relation between temperature, thermal conductivity and specific heat seems unwarranted.

All ferrous metals grow softer and weaker at elevated temperatures. Accordingly it becomes important to know the quantitative effect of temperature upon strength in order that where very high temperatures are unavoidable, due allowance may be made in design for the changed physical properties at the higher temperatures.

Since the tensile properties can be more definitely measured than any other, studies on the effect of temperature on strength have usually been made on tensile specimens. The author has conducted experiments of this character by breaking very carefully made specimens at temperatures from —80 to 1450 degrees Fahr.

The data up to 1200 degrees Fahr.—the highest commercially safe temperature to provide against the possibility of heating up to a temperature which will permanently affect the product—are shown in Fig. 189. It will be seen that malleable cast iron has tensile properties equal to those it possesses at room temperature at all temperatures from—100 to 800 degrees Fahr. Above 900 degrees the strength decreases rapidly and at 1200 degrees the maximum allowable temperature, the metal is only one-fifth as strong as at room temperatures. Presumably very similar relationships will be observed under other loads, compression cross bending, etc.

Temperature affects the magnetic properties of iron. For large values of *H, B* decreases as the temperature increases; the reverse is true for very small values of *H*. The effect of the temperatures is not strongly marked at room temperatures but increases rapidly as the temperature goes beyond 1200 degrees Fahr. Presumably the behavior of malleable is in accord with these principles. Actual measurements are lacking. The specific heat of malleable, that is the number of heat units required to raise a given weight of that material 1 degree in temperature as compared with the heat units to raise an equal weight of water 1 degree varies from 0.11 at 75 degrees to 0.165 at 800 degrees Fahr. The intervening curve is nearly straight, being but slightly concave upward. The values are calculated from the specific heats of iron and carbon. Malleable, being a mechanical mixture of these two elements, can have this constant calculated in that way.

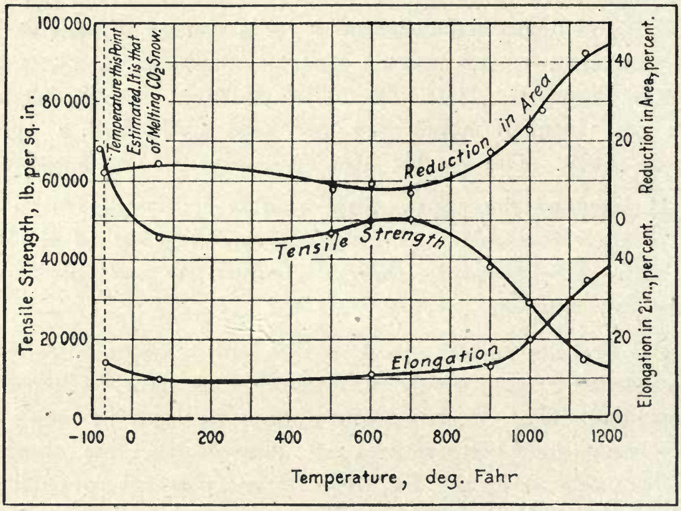

Fig. 189.—Effect of temperature upon tensile properties of malleable

As the name implies, the thermal conductivity of a metal is the rate at which it will conduct heat. The constant is defined in terms of the quantity of heat conducted per unit of time through a cross section of unit area of a slab of unit thickness whose opposite sides differ by unity in temperature. The quantity of heat conducted varies directly as the area of the conductor and as the temperature difference between its ends and inversely as its length. However the thermal conductivity is not constant but varies with the temperature.

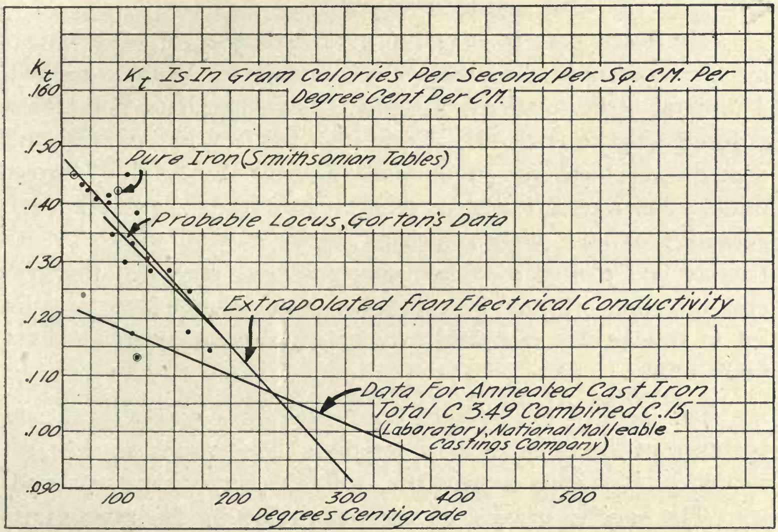

Fig. 190.—Thermal conductivity of malleable cast iron

It will be seen that the flow of heat obeys the same law as the flow of electric current; indeed in a given metal the ratio of thermal to electrical conductivity is nearly constant at all temperatures.

The determination of thermal conductivity is not altogether easy especially at high temperatures and consequently data on this constant are somewhat infrequent and not concordant.

The British Aeronautical Research committee gives data on an annealed gray iron (1.84 per cent silicon) containing very little combined carbon but much free carbon as determined in the National physical laboratory. The committee determined the conductivity between 40 degrees Cent. and various temperatures up to 700 degrees Cent. The data, translated into mean temperatures, have been plotted in Fig. 190. The conductivity of pure iron is shown for comparison.

Both on account of the lower carbon content and the geometric form of the free carbon, malleable should have a higher conductivity than a cast iron specimen, but a lower than pure iron.

The black dots in Fig. 190 give a number of observations by Dr. Gorton in the author's laboratory, by Wilkes' method. The data, while made as carefully as possible, have not always appeared above criticism. From the mean value of Gorton's data the conductivity can be taken as near .135 at 100 degrees Cent. The conductivities at other temperatures have been calculated from the known thermal coefficients of electrical resistance and plotted as a line which follows very well the general direction of our observations. From these facts we are led to believe that our data may be concordant enough to have some utility.

The density of malleable cast iron is occasionally of importance in the calculation of weights. This varies as does the shrinkage allowance on patterns, with the composition of product. The specific gravity of malleable, that is, the ratio of its density to that of water is between 7.25 and 7.45 and depends on the temperature at which the experiment is made. The metal made to pass the specifications of the American Society of Testing Materials will have a specific gravity of about 7.40. The "shrinkage allowance" referred to under such circumstances should be about 0.9 to 1 per cent, agreeing rather well with the usual ⅛-inch per foot used by patternmakers. It should be noted in passing that the differences in "shrinkage" between metal differing in carbon content is actually annealing.

All white cast iron shrinks very nearly the same amount in cooling from the molten state (¼-inch per foot) but iron high in carbon increases in size more when the carbon is liberated than those low in that element.

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The twelve chapters cover every phase of accurate cost methods and their various application to different branches of the foundry industry. The principles and forms used, the classification of accounts,

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Coal—Its Origin and Use in the Air Furnace, by F. Van O'Linda.
The properties of coal for air furnace melting are described and suggestions for firing given. Cost per B.t.u. is stated. 1600 words. *Transactions,* A. F. A., Vol. XXIV, p. 251.

Pulverized Coal for Melting Malleable Iron, by W. R. Bean.
An explanation of the factors controlling the use of powdered coal in malleable melting. *Foundry,* Vol. 45, p. 487.

Powdered Coal as a Fuel in the Foundry, by A. J. Grindle.
Uses in the foundry, problems of feeding and burning, carburization, economy, kind of coal to use, preparing fuel, and cost, are the principal topics discussed. 4000 words. *Transactions,* A. F. A., Vol. XXVIII, p. 303.

Efficient Use of Pulverized Coal in Malleable Foundry Practice, by Milton W. Arrowood.
The author discusses methods of preparing pulverized fuel, mixing it with the air, introducing it into the furnace, and controlling furnace conditions. The theory of combustion receives considerable attention. 8400 words, 9 illustrations. *Transactions,* A. F. A., Vol. XXVIII, p. 277.

Plant and Equipment

Foundry Molding Machines and Pattern Equipment, by Edwin S. Carman; published by the Penton Publishing Co., Cleveland. (1920.)
A treatise showing the use of molding machines in all types of foundries. Parts of the book are of particular interest to malleable foundrymen. 225 pages, 220 illustrations.

Electric Furnaces in the Iron and Steel Industry, by Rodenhauser-Schoenawa-Von Baur; published by John Wiley & Sons. (1920.)
This book answers clearly and untechnically every question that may arise in the electric steel industry. Malleable iron is included. 460 pages, 133 illustrations.

A Study of the Malleable Furnace, by Harbison-Walker Refractories Co. 98 pages, illustrated.

A Continuous Malleable Foundry.
An illustrated description of the new (1911) foundry of the Crane Co., Chicago. *Foundry,* Vol. 38, p. 1.

Making Large Castings from Air Furnace Iron, by H. E. Diller.
A description of a foundry of the Westinghouse company equipped with two 40 and one 15-ton air furnaces. *Foundry,* Vol. 48 (1920), p. 973-77.

A New Annealing Furnace.
Description of malleable annealing furnace operated by the Arcade

Malleable Iron Co. *Foundry,* Vol. 48 (1920), p. 769-71.

Foundry Plant and Machinery, by J. Horner.
A chapter of a series. This chapter is devoted to the equipment and practice in malleable foundries. *Engineering,* Vol. 90, pp. 787-91.

Annealing Furnaces, by George Rietkolter.
A description, with drawings, of malleable annealing furnaces. *Stahl und Eisen,* Vol. 27 (1908), p. 1652.

Malleable Cast Iron and the Open-Hearth Furnace, by G. A. Blume.
A description of two open-hearths built in a malleable plant in Finland in 1910-11. The operation is discussed in detail. 8000 words, 3 illustrations. *Transactions,* A. F. A., Vol. 21, p. 431.

How an Oil Fired Malleable Furnace Operates.
A description of an oil fired air furnace with data on consumption, costs, etc. *Foundry,* Vol. 45, p. 503.

The 25-Ton Air Furnace, by F. C. Rutz.
A brief description of a 25-ton furnace, with dimensions, operating expense, melting ratio, flexibility of operation, etc. 800 words. *Transactions,* A. F. A., Vol. XXV, p. 522.

The Waste Heat Boiler for Malleable Furnaces.
The author believes waste heat installations in the foundry will be justified by results. *Foundry,* Vol. 46, p. 220.

The Theory of the Modern Waste-Heat Boiler and the Possible Application of Such Boilers to Malleable Melting Furnaces, by Arthur D. Pratt.
An explanation of the theory of the waste heat boiler and a description of the installation of one attached to an air furnace at the McCormick works of the International Harvester Co. The performance of this boiler is given and results tabulated. 600 words, 6 drawings and charts. *Transactions,* A. F. A., Vol. XXVI, p. 349.

Pointers from the Practice of a Malleable Iron Foundry.
A description of the installation of waste heat boilers on air furnaces at the plant of the Buhl Malleable Co., Detroit (1909), 1500 words, 11 illustrations. *Castings,* Vol. III, p. 196.

A Modern Coreroom, by Donald S. Barrows.
A description of the coreroom built in 1918 at the malleable plant of the T. H. Symington Co., Rochester, N. Y. 2000 words, 10 illustrations. *Transactions,* A. F. A., Vol. XXVII, p. 429.

A New Research Department for a Large Malleable Plant, by H. A. Schwartz.
A description of the laboratory built in 1919-20 by the National Malleable Castings Co., Cleveland. The laboratory is for the research requirements of a group of scattered foundries and the article lists and describes the apparatus and outlines the arrangement of depart-

ments. 3700 words, 4 illustrations. *Transactions,* A. F. A., Vol. XXIX, p. 380.

Early Laboratories in Malleable Industry.
Discussion by Richard Moldenke and H. A. Schwartz of the pioneer laboratories of 1891 to 1903, with reference to the work of Dr. Moldenke, H. E. Diller, A. A. Pope and others. 1200 words. *Transactions,* A. F. A., Vol. XXVII, p. 400.

Melting Practice

Calculating Mixtures for Malleable Cast Iron, by Harrold Hemenway.
A system of calculating mixtures is fully explained and the importance of the various constituents emphasized. 8000 words, 27 tables. *Transactions,* A. F. A., Vol. XXIII, p. 413.

Influence of Changing the Composition of Malleable Castings, by P. Rodigin.
Results of tests showing effects of additions of manganese, silicon, aluminum, titanium, antimony and tin, copper, bismuth and lead, sulphur and phosphorus to malleable. 1000 words. *Transactions,* A. F. A., Vol. XXII, p. 201.

Malleable Troubles, by Richard Moldenke.
A discussion of melting problems, particularly those related to the selection of iron, use of scrap, etc. Annealing also is discussed. 3500 words. *Transactions,* A. F. A., Vol. XXII, p. 251.

Effect of Varying Silicon and Carbon in Malleable Iron Mixtures, by A. L. Pollard.
A discussion based on records of analyses and tests covering a period of 8 months, during which time the silicon and carbon contents were varied. 1200 words. *Transactions,* A. F. A., Vol. XXIII, p. 437.

Titanium for Malleable Iron, by C. H. Gale.
Ferro-titanium was added to malleable in the ladle and tests of the resulting product made. The paper is a discussion of the results. 2400 words, 5 tables. *Transactions,* A. F. A., Vol. 20, p. 271.

Malleable Castings by a New Process (1908), by E. C. Origley.
Wrought iron and soft steel are melted in a crucible, the metal is quieted by additions, and poured. *Iron Age,* Vol. 81, p. 1312-13.

Standardization of Air Furnace Practice, by A. L. Pollard.
A discussion of design, touching on length of hearth, depth of bath, length of firebox, height of roof, opening at neck and wall thicknesses. Advantages and disadvantages are compared and notes on operation presented. 1800 words. *Transactions,* A. F. A., Vol. XXIV, p. 245.

Melting in an Air Furnace with Fuel Oil, by J. P. Pero.
Disadvantages are compared with advantages, and data on oil-operated

air furnaces in three plants are given in parallel. 2000 words, 1 table. *Transactions,* A. F. A., Vol. XXVIII, p. 316.

The Equipment of Air Furnaces Using Oil as Fuel, by W. N. Best.
Method of changing air furnace from coal firing to oil firing, with suggestions regarding design of burners and method of operation. 1500 words. *Transactions,* A. F. A., Vol. XX, p. 421.

The Application of Pulverized Coal to Malleable Melting Furnaces, by Joseph Harrington.
The author discusses factors affecting successful use of pulverized coal in air furnaces, covering rapidity of heating, temperature, effect on furnace lining, amount of carbon burned out, etc. 2600 words. *Transactions,* A. F. A., Vol. XXVI, p. 394.

Application of Pulverized Coal to the Air Furnace, by W. R. Bean.
A discussion of the disadvantages of hand firing and of the possibilities of overcoming some of them by using pulverized coal. Methods of altering air furnaces for this fuel and results of tests are given. 2800 words. *Transactions,* A. F. A., Vol. XXVI, p. 337.

The Triplex Process of Making Electric Furnace Malleable, by H. A. Schwartz.
A complete description of the triplex process invented by W. G. Kranz and employed by the National Malleable Castings Co. This process involves the use of the cupola, converter and electric furnace. 3200 words, 5 illustrations. *Transactions,* A. F. A., Vol. XXIX, p. 342.

The Refining of Cupola Malleable Iron in the Electric Furnace, by A. W. Merrick.
The advantages of cupola melting of malleable are recounted, and the results of experiments in refining the cupola metal electrically are presented and discussed. 2400 words, 3 illustrations. *Transactions,* A. F. A., Vol. XXVIII, p. 322.

Molding

Foundry Work, by Burton L. Gray; published by the American Technical Society. (1920.)
A practical handbook on standard foundry practice, including hand and machine molding, cast iron, malleable iron, steel and brass casting, foundry managements, etc. 224 pages, 191 illustrations.

The Control of Chill in Cast Iron, by G. M. Thrasher.
Bulletin, A. I. M. E. (1915), p. 2129.

Malleable Cast Iron, by F. Erbreich.
Methods of molding and annealing are described and illustrated. *Stahl und Eisen,* Vol. 35, pp. 549-53, 652-58, 773-81.

Producing Machinable Malleable Iron Castings, by A. T. Jeffery.
The author explains how to avoid common machining difficulties by

adopting good foundry practice. *Foundry,* Vol. 45, p. 449.

Gating Malleable Iron Castings, by A. M. Fulton.
Methods of properly gating malleable castings with various typical sections, avoiding chills wherever possible. Shrinkage defects are discussed. 2100 words, 9 illustrations. *Transactions,* A. F. A., Vol. XXV, p. 239.

Annealing

A Study of the Annealing Process for Malleable Castings, by E. L. Leasman.
A review of the metallography of white cast iron is followed by a description of tests to study the effects of different packing materials, of different annealing temperatures, of different times of annealing and different rates of cooling. 3200 words, data on 23 experiments, 15 micrographs. *Transactions,* A. F. A., Vol. XXII, p. 169.

Experiments in Annealing Malleable Iron, by H. E. Diller.
The author discusses the two actions occurring in the anneal, and describes tests made to ascertain proper temperatures, time, rate of cooling, etc. 3000 words, 4 illustrations. *Transactions,* A. F. A., Vol. XXVII, p. 404.

Continuous Tunnel Annealing, by Philip d'H. Dressler.
A description of the Dressler type tunnel annealing furnace for malleable castings, on the basis of its development in 1918. 2400 words, 5 illustrations. *Transactions,* A. F. A., Vol. XXVII, p. 414.

The Application of Powdered Coal to Malleable Annealing Furnaces, by Charles Longnecker.
Following a brief historical sketch of the subject, the author describes the installation at the plant of the Pressed Steel Car Co., comparing results with those obtained by the use of natural gas and fuel oil. 2100 words, 3 illustrations. *Transactions,* A. F. A., Vol. XXVIII, p. 270.

Effects of Annealing Gray and Malleable Iron Bars in Copper Oxide Packing, by H. E. Diller.
Malleable iron bars were packed in black oxide of copper and annealed in an experimental furnace. In one case the copper soaked through, the bar analyzing 21.4 per cent copper. Similar tests at various annealing temperatures are described. 1600 words, 8 illustrations. *Transactions,* A. F. A., Vol. XXVIII, p. 261.

Malleable Annealing Experiments, by S. B. Chadsey.
Results of tests of malleable subjected to repeated annealing. *Foundry,* Vol. 37, p. 215.

Reducing the Malleable Iron Annealing Period, by A. E. White and R. S. Archer.
Time can be saved by raising the annealing temperature slightly above

the critical point and maintaining it at 700 degrees long enough to change 0.70 per cent combined carbon to graphitic carbon. *Foundry*, Vol. 47, p. 61.

Graphitization of White Cast Iron upon Annealing, by Paul D. Merica and Louis J. Gurevich.
A description and discussion of experiments in which the graphitization ranges of temperatures for three compositions for car wheels were determined. Light is thrown on certain moot questions of the metallurgy of annealing. 2400 words, 7 illustrations. *Transactions*, A. I. M. M. E., Vol. LXII, p. 509.

The Annealing of Malleable Castings, by A. E. White and R. S. Archer.
Following a discussion of the constituents of malleable castings, the authors describe experiments with white iron, covering the time of annealing, the temperature and method of treatment. In conclusion, the authors state an ideal heating cycle is impossible, each case depending on local requirements. *Transactions*, A. F. A., Vol. 27, p. 351.

Researches in the Annealing Process for Malleable Castings, by Oliver W. Storey.
A discussion of research work on packing materials, temperature of annealing, time of annealing, and rate of cooling, with important conclusions. 4400 words, 10 micrographs. *Transactions*, A. F. A., Vol. XXIII, p. 460.

Copper Diffuses Through Cast Iron, by H. E. Diller.
An investigating effect of oxidizing packings in annealing malleable, it was found that copper penetrated bar packed in copper oxide. *Foundry*, Vol. 47 (1919), p. 779-80.

Production of Malleable Castings, by Richard Moldenke.
An extensive discussion of the principles of annealing, with data on operation and description of apparatus. *The Iron Trade Review*, Vol. 44 (1910), pp. 540, 776.

Notes on Malleable Cast Iron, by R. Namias.
A discussion of composition of metal, rate of cooling during anneal, etc. *Engineering*, Vol. 88, p. 669.

Finishing

Oxy-Acetylene Welding Manual, by Lorn Campbell, Jr., John Wiley & Sons, Inc.
Apparatus and methods of oxy-acetylene welding of various materials, including malleable. Glossary of welding terms.

Oxy-Acetylene Welding Practice, by Robert J. Kehl, published by American Technical Society.
A practical presentation of the modern processes of welding, cutting and lead burning with special attention to welding technique of different metals. Simple and complex cases of expansion and con-

struction—preheating steel, cast iron, malleable iron, aluminum, copper, brass and bronze welding. 110 pages, 117 illustrations, diagrams and tables.

Oxy-Acetylene Welding, by S. W. Miller; Industrial Press.
Twelve chapters on oxy-acetylene welding of various materials, including malleable cast iron. 287 pages, 192 illustrations.

Troubles Encountered in Machining Malleable Iron: Causes and Remedies, by A. T. Jeffery.
A discussion of machining difficulties due to pure hard white iron, under-annealed iron, iron cooled too quickly, burned iron, and "tough and stringy" iron. The use of test lugs, effect of low silicon, etc., are considered and in summary, the author urges co-operation between founder and user of castings. 2400 words, 7 illustrations. *Transactions,* A. F. A., Vol. XXVI, p. 383.

III—METALLURGY AND METALLOGRAPHY

The Chemical and Metallographic Examination of Iron, Steel and Brass, by Hall and Williams; published by McGraw-Hill Book Co. (1921.)
Malleable iron is included in the volume. 500 pages, illustrated.

Cementation of Iron and Steel, by Frederico Giolitti; published by McGraw-Hill Book Co. (1915.)
Information on the theory of malleablized castings. 407 pages, illustrated.

Cast Iron in the Light of Recent Research, by William H. Hatfield; Charles Griffin & Co., Ltd.
The iron-carbon alloys and cast iron from the standpoint of the equilibrium diagram, with chapters on the influences of silicon, phosphorus, sulphur, manganese, etc. Malleable iron is given considerable attention, the heat treatment of white iron, influence of sulphur on the stability of iron carbide in the presence of silicon, and the phosphorus content permissible in malleable being discussed. Mechanical properties of malleable are outlined. 292 pages, 199 illustrations.

An Outline of the Metallurgy of Iron and Steel, by A. H. Sexton and J. S. G. Primrose; Scientific Publishing Co.
An outline of processes of iron and steelmaking, with a discussion of metallurgy involved. Malleable iron is included. 587 pages, 271 illustrations.

An Elementary Textbook of Metallurgy, by A. Humbolt Sexton; published by Charles Griffin & Co., Ltd.
This work is intended for the use of students, both for those commencing the study of metallurgy and those who are already engaged in metallurgical industries and who desire some knowledge of the principles on which the processes they are using are based. Mal-

leable iron is taken up in Part I under metallurgical processes. 263 pages, 71 illustrations.

Principles of Metallography, by Robert S. Williams; published by McGraw-Hill Book Co. (1920.)
Malleablizing is included in this text. 158 pages.

Practical Metallography of Iron and Steel, by John S. G. Primrose; published by Scientific Publishing Co.
Contains information on malleable cast iron. 129 pages, illustrated.

Methods of Chemical Analysis and Foundry Chemistry, by Frank L. Crobaugh; Penton Publishing Co. (1910.)
Sampling and preparation of samples; determination of iron, phosphorus, sulphur, etc.; analysis, etc., as applied to white and chilled castings, malleable castings, gray iron castings, etc. 110 pages.

The Metallurgy of Iron and Steel, by Bradley Stoughton; McGraw-Hill Book Co. (1913.)
Iron and carbon, manufacture of pig iron, bessemer process, open-hearth process, defects in ingots and castings, treatment of steel, iron and steel founding, constitution of cast iron, malleable cast iron, introduction to metallurgy, etc. 539 pages, illustrated.

Metallurgy of Iron and Steel, by A. Humbold Sexton; published by Scientific Publishing Co.
This book covers in one volume the whole field of metallurgy of iron and steel. Method of making malleable iron is described. 600 pages, 270 illustrations.

Metallurgy of Iron, by Thomas Turner; published by Charles Griffin & Co., Ltd. (1920.)
Contains information on the production of malleable cast iron. 486 pages, illustrated.

The Metallography of Steel and Cast Iron, by Henry Marion Howe; McGraw-Hill Book Co., New York. (1916.)
A finished treatise on general metallography, with numerous references to malleable iron. 641 pages, hundreds of illustrations, numerous tables and diagrams, and complete indices.

The Metallography and Heat Treatment of Iron and Steel, by Albert Sauveur; Sauveur and Boylston, Cambridge, Mass. (1916.)
A thorough study of metallography covering all types of iron and steel. One chapter is devoted exclusively to malleable cast iron, and several others are pertinent to malleable producers and users. 486 pages, 437 illustrations.

Metallography Applied to Siderurgic Products, by Humbert Savoia; published by E. & F. N. Spon, Ltd.
A complete chapter of 23 pages is devoted to malleable cast iron. 180 pages, illustrated.

Metallography, by Arthur H. Hiorus; published by Macmillan & Co. (1902.)
An introduction to the study of the structure of metals chiefly by the aid of the microscope. Several pages are given over to malleable cast iron. 158 pages, illustrated.

Iron and Steel, by O. F. Hudson; Constable & Co., Ltd.
An introductory textbook for engineers and metallurgists. Methods of production are not covered in this book. Metallurgy of malleable cast iron is discussed briefly. 184 pages, 47 illustrations.

Fractures and Microstructures of American Malleable Cast Iron, by W. R. Bean, H. W. Highriter and E. S. Davenport.
A discussion of typical specimens of malleable cast iron based on chemical, miscroscopic and mechanical examination. 6500 words, 40 illustrations. *Transactions,* A. F. A., Vol. XXIX, p. 306.

Some Remarks Regarding the Permissible Phosphorus Limit in Malleable Iron Castings, by Enrique Touceda.
Dynamic tests of malleable containing .181, .252, .325 and .388 per cent phosphorus were made, and the author interprets the results for the guidance of malleable foundrymen. 3500 words, 5 illustrations, 2 tables. *Transactions,* A. F. A., Vol. XXIV, p. 209.

Report on Methods of Etching Malleable Iron for Visual Investigation of Structure, by E. Heyn.
The author recommends a solution of 1 gram of copper-ammonium chloride in 12 grams of water. Etching requires a minute. 1500 words, 8 illustrations. International Association of Testing Materials, Brussels, 1906.

Change of Structure in Iron and Steel, by William Campbell.
Review of iron-carbon equilibrium diagram, illustrated by photomicrographs of irons and steels. *Journal,* Franklin institute, Vol. 163, pp. 407-34.

Constitution of the Iron-Carbon Alloys.
A discussion of Sauveur's article in *Journal* of Iron and Steel institute by Benedicts, who upholds Roozeboom's application of phase rule. Also discussed by Howe, Stansfeld, Stead and others. *Metallurgie,* Vol. 4, pp. 216-41.

Influence of Silicon upon the Iron-Carbon System.
Author determines amount of carbon remaining in solution after adding definite amounts of silicon to molten pig iron. Influence of silicon upon solidification point also determined. *Stahl und Eisen,* Vol. 27, 482-87.

Note on the Liquids in the Iron-Carbon Diagram, by G. Cesaro.
Discussion of an attempt to determine the course of the curve joining the points at which molten iron-carbon alloys begin to solidify. *Journal,* Iron and Steel Institute. (1919.)

The Alloys of Iron and of Carbon, by Georges Charpy.
A lecture on the iron-carbon system, in which the author reviews the knowledge of the subject as of 1909. *Bulletin de la Societe Chimique de France,* Vol. 3, p. i-xlvi.

Some Iron-Silicon-Carbon Alloys, by W. Gontermann.
A review of binary systems contributing to the above equilibrium, with the author's theory on the Fe-C system. *Zeitschrift fur anorgische Chemie.* Vol. 59 (1909), p. 373-414.

Development of the Fusion Diagram of Iron-Carbon Alloys, by F. Wust.
An explanation of the theory underlying the construction of the fusion diagram. The author proposes the term "Ledeburite." *Zeitschrift fur Elektrochimie,* Vol. 15 (1910), p. 565-584.

Chemical Equilibrium in the Reduction and Cementation of Iron, by Rudolph Schenck.
Zeitschrift fur Elektrochimie, Vol. 21 (1915), p. 37; Vol. 22 (1916), p. 121; Vol. 24 (1918), p. 248.

Separation of Graphite in White Cast Iron Heated under Pressure, by Georges Charpy.
Change of carbide to graphite when the metal is subjected to high pressure and a temperature of from 700 to 1000 degrees. *Comptes Rendus,* Vol. 148 (1909), p. 1767.

The Stable System: Iron-Carbon, by Rudolf Ruer and Nikolaus Iljin.
A thorough discussion covering the solubility of carbon in solid iron and the separation of temper carbon. *Metallurgie,* Vol. 8, p. 97.

The System Iron-Carbon, by A. Baikov.
A study of the solidification of iron showing that separation of graphite and cementite follows the same line on the diagram. *Revue de Metallurgie,* Vol. 8, p. 315.

The Solubility of Carbon in Iron, by O. Ruff and O. Goecke.
A discussion attending the determination of the solubility of carbon in iron at temperatures between 1200 and 2600 degrees Cent. *Metallurgie,* Vol. 8, p. 417.

The Equilibrium Diagram of Iron-Carbon Alloys, by Otto Ruff.
Metallurgie, Vol. 8, pp. 456-64, 497-508.

A Study of the Annealing Process for Malleable Castings, by Oliver W. Storey.
The effects of packing material, temperature of annealing, time of annealing and rate of cooling are studied. A thorough and original discussion on annealing. *Metallurgical and Chemical Engineering,* Vol. 12, p. 383.

The Nature of the A_2 Transformation in Iron, by K. Honda.
A study of recent investigations. *Scientific Reports,* Tohoku Imperial University, Vol. 4 (1915), p. 169.

Phosphorus Limit in Malleable Castings, by Enrique Touceda.
The author describes tests which showed that when combined carbon was low, evil effects of phosphorus were slow to make themselves felt. *Iron Age,* Vol. 96, p. 92.

Sulphur in Malleable Cast Iron, by R. H. Smith.
The author concludes that sulphur is not removed in the annealing process and does not appear to have evil effects below 0.15 per cent. *Journal,* Iron and Steel Institute. Vol. 92, p. 141.

Recrystallization after Plastic Deformation, by H. M. Howe.
Bulletin, A. I. M. E. (1916), p. 1851-60.

Decarburization of Iron-Carbon Alloys, by W. H. Hatfield.
The author opposes theory that carbon must be in the form of temper carbon before it can be removed by oxidation. *Engineering,* Vol. 87 (1910), p. 801.

Graphitization of Iron-Carbon Alloys, by Kotaro Honda and Takejiro Murakanu.
In pure iron carbon alloys, graphitization is caused by the decomposition of the cementite solidified during cooling from the melt. *Journal,* Iron and Steel Institute (Sept.). (1920.)

Graphitizing of White Cast Iron, by R. S. Archer.
The author draws conclusions regarding the initiation of graphitization below the *A* point and completion near or at that point. *Foundry,* Vol. 48 (1920), p. 192-4.

Concerning the Solubility of Graphite in Iron, by Carl Benedicts.
Tests show that graphite is appreciably soluble in ferrite at 940 degrees Cent., therefore, iron-carbon diagram should be drawn as proposed by LeChatelier, Stansfield and Charpy. *Metallurgie,* Vol. 5 (1908), p. 41-45.

Influence of Phosphorus on the Iron-Carbon System, by F. Wust.
The subject is brought up to date (1908) and results of tests and experiments are given. *Metallurgie,* Vol. 5, p. 73-87.

The Nature of the Cast Irons, by G. B. Upton.
Discussion of Fe-C diagram, relating particularly to liquidus and solidus lines. *Journal of Physical Chemistry,* Vol. 13 (1909), p. 388-416.

The Effect of Foreign Substances Upon the Fusion Diagram of Iron-Carbon Alloys, by P. Goerens.
An investigation of the iron-manganese-carbon and iron-phosphorus-carbon systems. *Metallurgie,* Vol. 6 (1910), p. 537-50.

Theory of Malleablizing, by W. H. Hatfield.
The European and American methods of making malleable castings are described. From a lecture before Institution of Engineers and Shipbuilders of Scotland. *Foundry,* Vol. 36, p. 30.

Graphitization in Iron-Carbon Alloys, by Kuniichi Tawara and G. Ashara.
Twenty-seven iron-carbon alloys were melted and after slight cooling cast into molds and cooled at varying rates. Deductions from these tests are discussed. *Journal,* Iron and Steel Institute (1919).

The Theory of Annealing, by F. Wust.
A discussion of the metallurgy of annealing with special reference to the migration of carbon. *Metallurgie,* Vol. 5 (1908), p. 7-12.

The Evolution of the Malleable Iron Process, by J. P. Pero and J. C. Nulsen.
An account of the advance in metallurgy of malleable practice, touching upon the importance of sulphur and phosphorus, "steely" iron, uses of the microscope, value of strength tests, fatigue failure, and properties of malleable. 4000 words. *Transactions,* A. F. A., Vol. XXV, p. 222.

What Is the Normal Fracture of Good Malleable Iron? by Enrique Touceda.
The author explains how the test lug should be secured and describes the appearance of various fractures, interpreting the significance of each. 2000 words, 6 illustrations. *Transactions,* A. F. A., Vol. XXV, p. 506.

Judging Malleable by Fracture, by Richard Moldenke.
Photographs of typical fractures, with suitable explanation of each. *Foundry,* Vol. 37, p. 237.

IV—PROPERTIES AND USES

Materials of Construction, by Adelbert P. Mills; published by John Wiley & Sons, Inc., New York. (1922.)
Manufacture and uses of cements, clay products, ferrous and nonferrous metals, timber, rope and mechanical fabrics. One chapter (2500 words), devoted to malleable cast iron, describes methods of production and lists properties and uses.

Materials of Construction, by M. O. Withey and James Aston; John Wiley & Sons, Inc. (1918.)
Principles of mechanics of materials including timber, stone, cement, metals, etc. Constitution of iron and steel and the properties of metal products, including malleable cast iron. 840 pages, illustrated.

Machinability of Malleable Cast Iron.
A discussion of the paper by Messrs. Smith and Barr (A. F. A. Vol. XXVIII, p. 330), covering threading tests and data on cutting speeds. 1700 words. *Transactions,* A. F. A., Vol. XXVIII, p. 338.

Relation Between Machining Qualities of Malleable Castings and Physical Tests, by Edwin K. Smith and William Barr.
A discussion of the effect of higher physical properties of malleable upon its machinability, based on the results of tests and replies to a

questionnaire. 2100 words, 2 drawings and 5 tables. *Transactions,* A. F. A., Vol. XXVIII, p. 330.

Some Physical Constants of American Malleable Cast Iron, by H. A. Schwartz.
A review of the properties of malleable with detailed data and charts showing the behavior of the metal under various stresses and physical conditions. 5000 words, 12 diagrams. *Proceedings,* A. S. T. M., Vol. XIX, Part II, p. 248.

Physical Properties of American Malleable Cast Iron, by W. R. Bean.
A discussion of the strength, elongation, resistance to bending, hardness, machinability, density, etc., of malleable. 2400 words, 3 illustrations, 3 tables. *Proceedings,* A. S. T. M., Vol. XIX Part II, p. 266.

Testing Hardness of Malleable, by Enrique Touceda.
The author explains why hardness tests are inadequate as a measure of machinability. 1000 words, 2 illustrations. *Proceedings,* A. S. T. M., Vol. XIX; Part II, p. 273.

Effect of Machining and of Cross Section on the Tensile Properties of Malleable Cast Iron, by H. A. Schwartz.
A description of tests made to determine the effect of decarbonization, grain structure, area of cross section, rate of cooling, shrinkage, etc., on the relative strength of a specimen. The results are discussed and conclusions drawn. 2400 words, 6 diagrams. *Proceedings,* A. S. T. M., Vol. XX; Part II, p. 70.

Standard Specifications for Malleable Castings (A 47-19).
The standard specifications adopted in 1919 by the American Society for Testing Materials. 800 words, 1 illustration. *A. S. T. M. Standards,* 1921, p. 354.

Some Needs of the Malleable Iron Industry, by W. P. Putnam.
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