The Making, Shaping and Treating of Steel

EDITED BY

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UNITED STATES STEEL

Eighth Edition

CHAPTER 1

Evolution Of Iron- And Steelmaking

SECTION 1

FERROUS METALS IN ANTIQUITY

Prehistoric and Ancient Use of Iron—The antiquity of man's use of iron is attested by references to that metal both in fragmentary writings and in inscriptions on monuments, palaces and tombs that survived the collapse of such ancient civilizations as those of Assyria, Babylonia, Egypt, China, India, Greece and Rome. In addition to these written records, archeologists have unearthed actual iron tools, weapons and ornaments used by many of these historic ancient peoples, as well as some implements and jewelry of iron in sites in many parts of the world that were occupied by prehistoric peoples who left no written records. The chemical composition and the properties of the metals in these specimens vary widely. Some closely resemble modern wrought iron; some are more nearly like steel as it is known today. For the sake of simplicity, all of the ancient ferrous metals discussed in this section will be referred to as "iron." In later sections the modern meanings of "iron," "steel," "wrought iron," etc., will be clearly defined and the words used in their proper, more exact sense.

Meteoric Iron—Mere mention of the use of iron in the oral traditions or writings of primitive or prehistoric peoples does not necessarily mean that they knew how to produce iron by extracting it from ore. Actually, there is evidence that most of the iron used in earliest times was not man-made, but was obtained from fragments of meteorites. This belief in the origin of the iron used by very ancient peoples is based on three facts. In the first place, practically all of their names for iron, when translated, mean "stone (or hard substance or metal) from heaven," "star metal" or have similar meanings that suggest that the metal they used came from outside the earth. Secondly, chemical analysis of numerous archeological specimens has established that they contain considerable quantities of nickel which likewise is found in similar quantities (usually 7 to 15 per cent, but sometimes as high as 30 per cent) in the iron of meteorites. The third instance supporting this belief is that many primitive peoples of relatively recent times used iron from meteorites to make useful implements. In several historical cases, the main masses of huge meteorites from which the natives had laboriously severed bits of the metal were still in existence in the places where they had fallen and still served as sources of supply.

Telluric (Native) Iron—Gold, silver, copper and some other metals known to the ancients often are found on or near the surface of the ground in a fairly pure metallic condition, in the form of nuggets or rough masses. Being bright in appearance, such native metals are noticed readily and, as they are capable of being shaped by hammering without heating, they were put to eventual use by primitive peoples. The softness of gold and silver made them useless for ordinary tools and weapons, and their ultimate chief use was for vessels and ornament. The metal copper, however, can be hardened appreciably by hammering it without previous heating, and the very hammering required to shape a tool from native copper makes it sufficiently hard to be useful for many purposes.

Iron, however, is very rarely found in the native state. One of the few known occurrences of native iron is in Northwestern Greenland; the iron occurs as grains or nodules in basalt (an iron-bearing igneous rock) that erupted through beds of coal. Mention might be made of two very rare natural nickel-iron alloys, given the mineralogical names of awaruite ($FeNi_2$) and josephinite (Fe_3Ni_5), that have been found in the form of granules and small bean-shaped pebbles. It is improbable, therefore, that primitive man could have found any useful quantity of naturally occurring metallic iron, certainly not enough to account for the widespread distribution of iron artifacts that have been discovered by archeologists.

Man-Made Iron—From the foregoing it may be deduced that iron must have been a rare metal for many centuries and that any specimens of it would be highly prized by the possessor. It was not until man learned how to extract iron from its ores that it could have become a common metal.

Archeological evidence seems to indicate that a knowledge of how to obtain copper from its ores existed long before iron was intentionally made by man. Mixtures (alloys) of copper and tin that formed bronze, and of copper and zinc that formed brass, provided the ancients with metals that found widespread usage. In a book such as this, devoted to a discussion of iron and steel, space limitations permit only brief mention of these non-ferrous metals. It should be remembered, however, that for many years after man learned how to extract iron from its ores, the

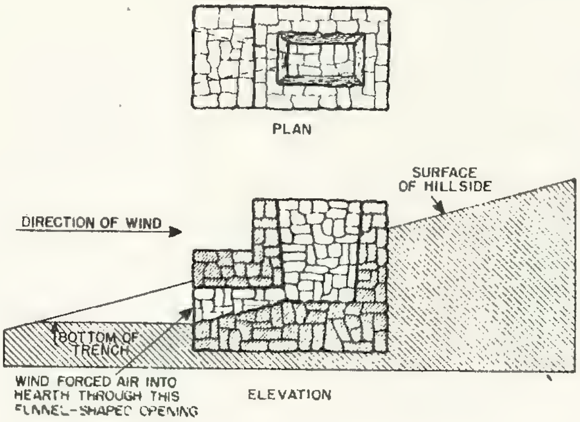


Fig. 1—1. Schematic representation of an early smelting furnace, built on a hillside to take advantage of the direction of prevailing winds to supply a gentle blast. Actual discovered remains of similar furnaces indicate that the hearth of such furnaces may have been relatively shallower and greater in area in proportion to their height.

the direction of a prevailing wind (Figure 1—1). A wind of suitable direction and velocity could be led into the burning fuel bed through an opening in the hearth or furnace wall to provide the air blast required to produce strong combustion of the charcoal fuel. Still later, devices for blowing air into the fuel bed were developed to make the process independent of wind and weather. These devices ranged all the way from mouth-blown hollow reeds, through foot-operated bladders of animal skins, foot-operated bellows, hand-operated bellows, and air-blowing devices operated by treadmills and water wheels. Another device somewhat widely used was the **trompe,** which made use of the aspirating effect of a falling column of water inside a tube, to draw air in through holes in the sides of the tube near its top, and expel the air into a closed chamber at the bottom; the air was piped from this chamber to the furnace (see Figure 1—2).

In view of the many centuries in which the direct process was used, it is to be expected that many different methods and types of apparatus would have been developed. Little is known of the furnaces in use prior to the eighteenth century, but the majority were of the hearth type, while the remainder were of the shaft type and may be compared to small blast furnaces, as will be discussed later. While these furnaces might, and did, differ widely as to form, size, and materials of construction, the fundamental metallurgical principles were the same in all. Charcoal was the only fuel used: it served the triple purpose of (1) a fuel to supply heat, (2) a reducing agent, and (3) a protector to shield the hot reduced metal from the oxidizing influences of the air.

The Catalan Process—The **Catalan hearth,** as the furnace used in this process was called, was anywhere from 20 inches square and 16 inches deep to around 30 inches by 40 inches and something over two feet deep. The **nozzle** or **tuyere,** through which the blast

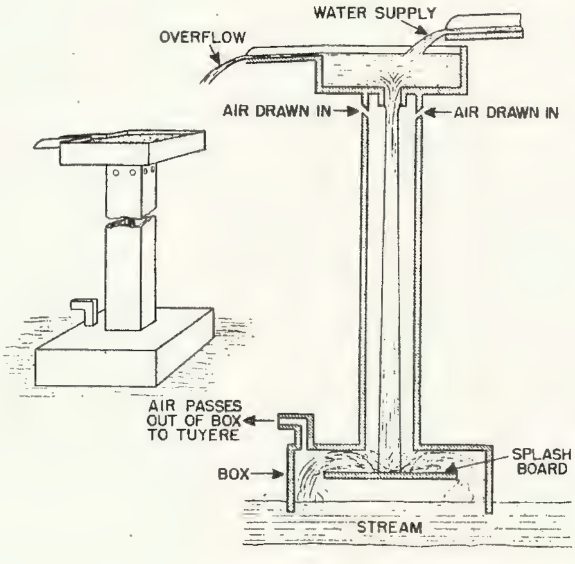


Fig. 1—2. (Right) Schematic representation of the operation of the trompe for utilizing the principle of aspiration to provide air blast for smelting furnaces. (Left) Sketch of external appearance of a trompe. The cross-section of the vertical column was more commonly round than square.

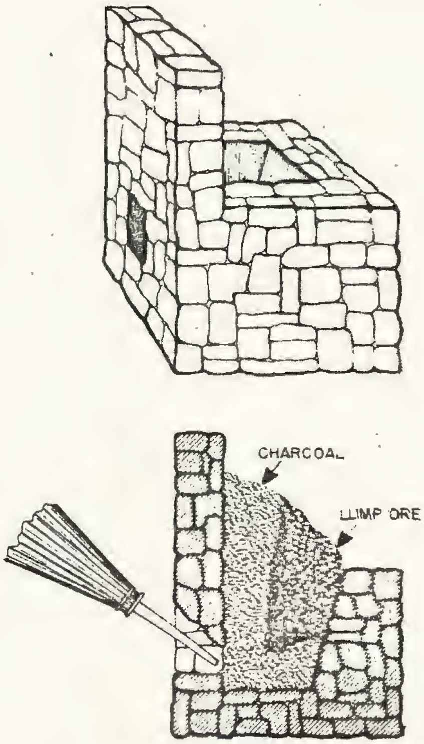


Fig. 1—3. (Above) Representation of a Catalan hearth or forge used for smelting iron ore up until relatively recent times. (Below) Cross section showing method of charging fuel and ore in the Catalan hearth, and approximate position of the nozzle supplied with air by a bellows.

was blown into the furnace, was placed about 9 inches from the bottom in the smaller hearths and about 15 inches from the bottom in the larger hearths. The hearth was filled to the level of the tuyere with charcoal, on which was piled lump ore together with charcoal. These materials were placed so as to form two separate columns, the charcoal against the tuyere side of the hearth, and the ore against the other side (Figure 1—3). A gentle blast of air was applied at first and carbon monoxide, formed by combustion of the charcoal, passed preferentially through the open pile of lump ore. The ore was reduced to metallic iron when the oxygen in the iron oxide of the ore combined with some of the carbon monoxide to form carbon dioxide. The waste gases escaped at the top of the charge. Charcoal (along with fine ore) was added at regular intervals to replace that consumed in combustion. After about two hours, the lump-ore column was gradually pushed downwards and the temperature of the hearth was raised by increasing the blast. As successive portions of the ore became reduced, they were pushed nearer the tuyere where the hearth was hottest. By the time the ore had reached the hotter regions, it was largely reduced to the metallic state.

The unreduced portion of the lump ore, along with part of the fine ore added periodically with charcoal, formed a siliceous slag of high iron content with the **gangue** (waste material). The metallic iron resulting from reduction of the ore became pasty at the temperatures existing near the tuyere, to form a coherent **loup or bloom**. After as much as possible of the ore had been reduced, the bloom was pried out of the hearth and hammered into bar form.

The American Bloomery—Among the variations of the process just described was the **American Bloomery Process** which was very similar to the Catalan process, differing from it chiefly in the fact that ore in a fine state, instead of in lumps, was mixed with charcoal to form the charge. The American bloomery represented the highest development in the simple hearth type of furnace for producing wrought iron. The bellows supplying the blast was operated by a water wheel or steam engine. The hearth was provided with a water-cooled metal bottom-plate, and cast-iron plates lined the sides. These hearths, rectangular in shape, were about 2 feet deep and 3 feet wide, and were surmounted by a tall chimney in the form of a truncated pyramid for carrying off the hot waste gases. The blast was heated (to save fuel) by passing the air through cast iron pipes around which the hot waste gases passed on their way from the furnace to the opening of the stack. Usually, bloomeries were open in front like an open fireplace, with the tuyere placed either at one side or at the back, about 20 inches above the bottom. Charcoal was first put into the hearth, the blast turned on, and when the fire was burning well, some ore was spread on the charcoal. Thereafter, charcoal and ore were added alternately until a sufficient amount of metal had collected upon the bottom. Then the iron, in a pasty mass and mixed with much slag, was removed from beneath the fuel bed with bars and tongs and hammered into a bloom. The last wrought iron to be produced by the bloomeries in this country was made in 1901.

SECTION 3

DEVELOPMENT OF THE BLAST FURNACE

It may be said in general that the blast furnace for producing molten high-carbon iron developed gradually from the early hearths in which only wrought iron was produced. The development consisted in gradually increasing the height of the furnace and introducing the charge at intervals through the top. These higher furnaces, distinguished as a class from the Catalan type of hearth or bloomery, were termed **shaft furnaces.** Originally developed by ironmakers of Central Europe, the new type of furnace was built of masonry that enclosed a vertical chamber in the form of two truncated cones placed base to base—in a crude way resembling the lines of a modern blast furnace (see Figure 1—4). The iron ore, flux and charcoal were charged into the top of the shaft, while air under relatively low pressure was blown into the furnace through a **tuyere** or tuyeres near the bottom of the structure.

Early Shaft-Type Furnaces—The **stuckofen** or **old high bloomery**, variations of which appear to have been called **salamander furnace**, **wolf furnace**, **wolf oven**, **wulf's oven** and **luppenofen** or **loup furnace**, evolved as described above from the Catalan type of hearth furnace. The earliest recorded sites of such shaft-type furnaces were in territories included in pre-World War II Germany (in Nassau, Siegen, and Saxony) and in parts of Austria, Belgium, and the Netherlands.

The stuckofen, in the state of development described around 1350 A.D., was a furnace 10 to 16 feet high; having a round, elliptical or rectangular shaft cross-section (greatest cross-sectional dimension about 3 to 4 feet).

One or two tuyeres supplied the blast, which entered the stuckofen somewhat over a foot above the hearth. Fuel and ore were charged into the top of the furnace, being replenished from time to time as smelting proceeded. A drawing hole was provided in the wall at the bottom of the shaft for extracting the blooms. This hole was closed by brick or stone work that was torn out each time a bloom was removed, after which the hole was again closed. Charcoal was the only fuel used.

The furnace called the wolf oven has been described as lower than the stuckofen, perhaps 6 to 7 feet in average height. Intermediate in size, between the wolf oven and the stuckofen, are the **blasofen** and **bauernofen**. The bauernofen corresponds to the **osmund furnace** (about 8 feet high) used in Sweden (a similar type was used in India). A type of furnace which originally resembled and was operated like the stuckofen, and was later adapted to produce either blooms of low-carbon wrought iron or molten, high-carbon iron, resembled a crude blast furnace and was termed **blauofen, blau furnace** or **blue furnace.**

The stuckofen may be considered as the forerunner of the modern blast furnace which produces only liquid, high-carbon iron. Liquid high-carbon iron often was produced in the stuckofen, intentionally or otherwise. This occurred when the reduced iron was in contact with hot fuel away from the blast long enough to absorb sufficient carbon to reduce its melting point to where it would become liquid. The height of the furnace made this possible, especially if the operating temperature was high enough. A **flussofen** was strictly a primitive blast furnace intended only to produce molten, high-carbon iron. The modern blast furnace, then, is a shaft furnace, gradually evolved from the stuckofen and flussofen. In its early days it was called a **high furnace**, from its German name, **hochofen** (French: **haut fourneaux**). It is designed solely to produce molten iron and operates continuously, in that the solid raw materials (ore, coke and limestone) are charged at the top at regular short intervals, and the molten iron and slag which collect in the hearth are tapped out at longer intervals.

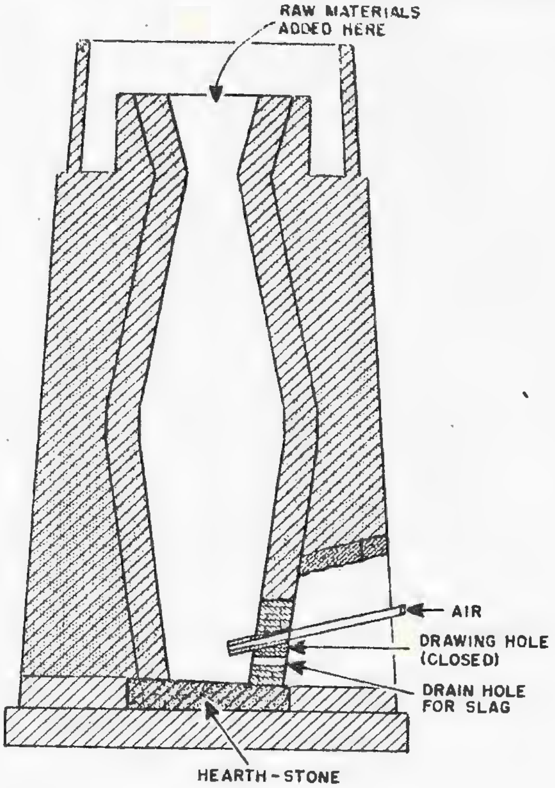


Fig. 1—4. Schematic cross-section of a stuckofen, equipped with a drawing hole for the extraction of the blooms. (After Percy.)

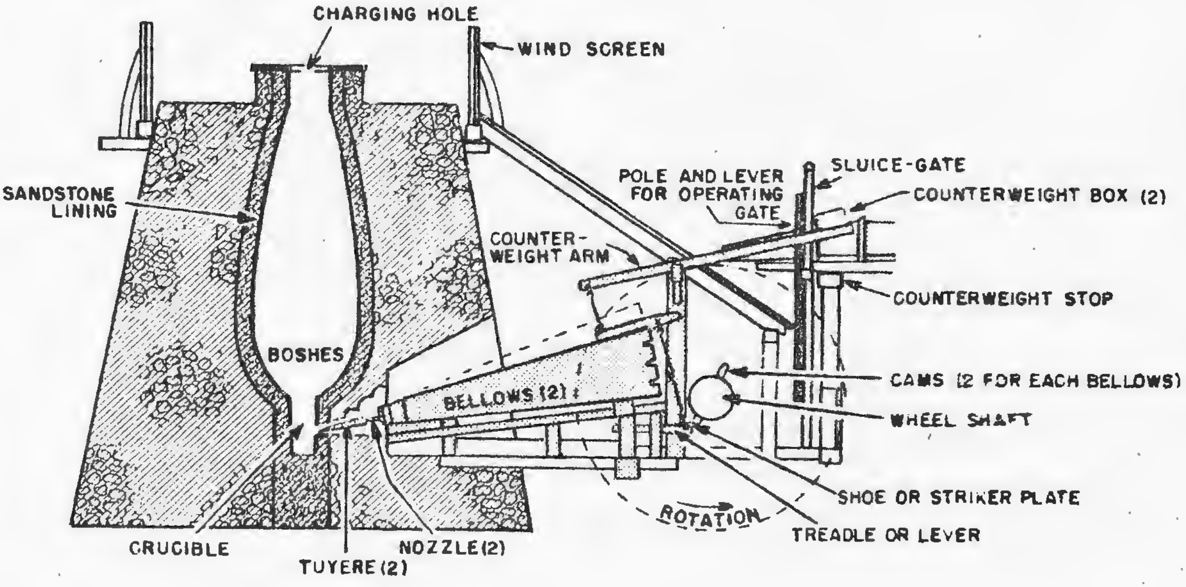


Fig. 1—5. Schematic cross-section of the Hammersmith furnace near Saugus, Massachusetts, restored by the American Iron and Steel Institute. Water from the sluice turned the overshot water wheel. Cams on the axle of the wheel engaged the treadle or lever and exerted a squeezing force on the bellows that compressed the air for the blast. The raw materials were dumped into the charge hole at the top of the stack, and molten iron was run from the furnace through an opening in the wall of the crucible. This opening was near the bottom of the crucible on the side facing the reader, and was kept plugged except when molten iron was run. (See also Figure 1—8.)

The blast furnace was introduced into England about 1500 A.D. Coke was first used as a blast-furnace fuel in England in 1619. About 200 years later—again in England—the principle of heating the air before it was blown into the furnace was introduced: air so heated is referred to as **hot blast.**

In America, an iron works was established in Virginia on the James River about 1619; this was destroyed in an Indian raid in 1622 and never rebuilt. The Hammersmith (now Saugus), Massachusetts iron works was begun in 1645 and was the first successful iron works in what is now the United States, not being abandoned until 1675.

It is an interesting fact that the principal development connected with the blast furnace for over 400 years after its inception was the spread of its use to new localities. There was a strong family resemblance among all of the furnaces built during this period, although there were variations in size and in the design of machinery for supplying the blast, etc. For this reason, the Hammersmith furnace shown schematically in Figure 1—5 can serve as typical of American blast furnaces of as recently as 100 years ago.

The American furnaces of the middle Nineteenth Century now would be called very crude affairs. They were usually in the form of a truncated cone or pyramid, twenty to thirty feet high, and constructed of stonework which enclosed a shaft about four feet across at the top and eight feet at the bosh. The hearth was either round or square in cross section. The capacity ranged from one to six tons a day. In 1850, for example, the production of iron in the United States was reported to be 563,755 tons, produced by 377 establishments.

Rods and bands of wrought iron were employed in the construction of some of the larger furnaces to increase the stability of the stack, but the expansive forces present burst even the strongest practicable ties. The obvious answer was to completely enclose the stack in a "shell" constructed of wrought-iron plates: a furnace built at Port Henry, New York in 1854 was said to be the first to be enclosed completely in an iron shell. The shell type of construction gave to such furnaces the name of "cupola blast furnaces" (Figure 1—6).

The top of the early furnaces was open and the escaping gases burnt in the air above the furnace. Eventually, attempts were made to use the heat of the burning gases to preheat the blast air. The first devices for heating air were mounted on top of the stacks. A later development was the adoption of the closed top, that involved the invention of a bell-and-hopper arrangement that kept the top closed except when the bell was lowered to charge materials into the furnace. One of the first American furnaces to adopt the closed top was the Fletcherville charcoal blast furnace near Mineville, New York about 1870. This principle was later extended to the use of a double bell and hopper (1883) that made it possible to charge materials without ever completely opening the furnace top (Figure 1—7): this is the present usual closure.

As early as 1859 in this country (earlier abroad) attempts were made to collect the gases at the top of the furnace before they burned, and lead them through suitable piping to ground level, where they could be burned in special structures called "stoves" in which the blast air could be heated before it was blown into the furnace through the tuyeres. Stoves of both recuperative and regenerative types were developed: only the regenerative type is employed at present.

The development of better machinery for com-

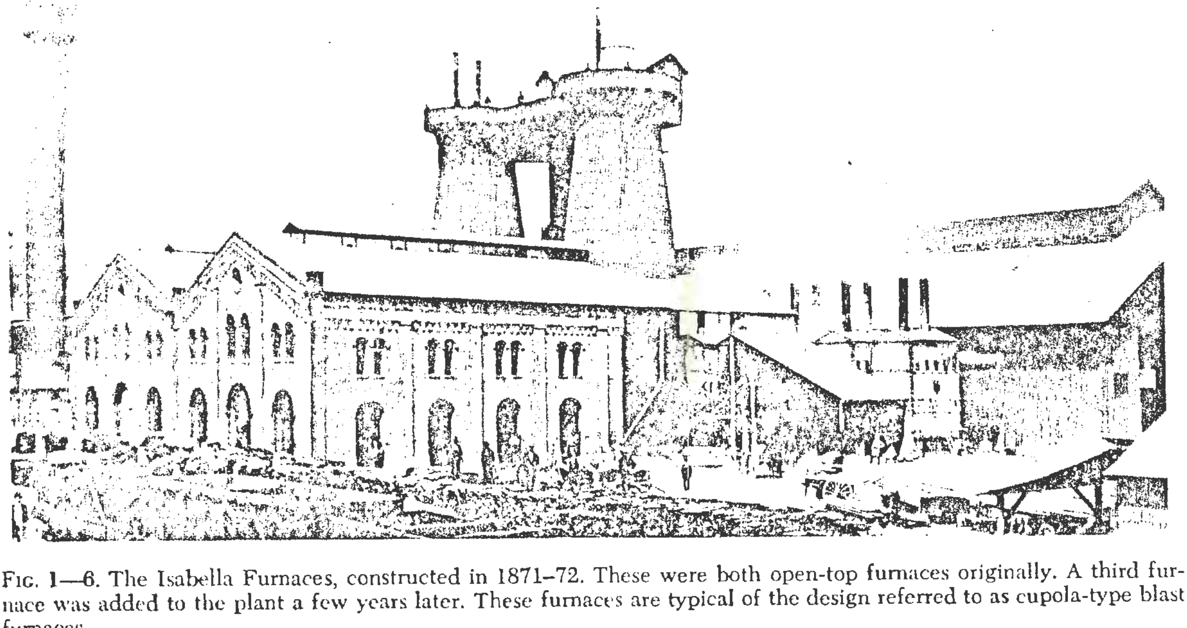
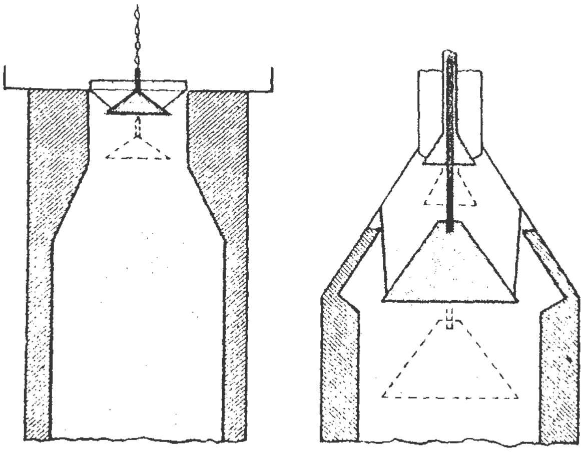


Fig. 1—6. The Isabella Furnaces, constructed in 1871–72. These were both open-top furnaces originally. A third furnace was added to the plant a few years later. These furnaces are typical of the design referred to as cupola-type blast furnaces.



EARLY SINGLE BELL MODERN DOUBLE BELL

FIG. 1—7. Schematic representation of the principle of operation of the single and double bell methods for effecting closure of a blast-furnace top. The distance the bells are lowered (as indicated by the dotted outlines) has been exaggerated for clarity.

pressing the blast air kept pace with—or even preceded—the construction of taller and larger furnaces. The water wheel that operated bellows or wooden cylinder-type blowing tubs was first replaced by the steam engine. Soon, steam-driven blowing engines of high capacity were developed and became standard for the larger furnaces about 1880. In the United States, the first gas-driven blowing engines were installed in 1903: these were internal-combustion engines that used cleaned blast-furnace gas as fuel. The most recent development for generation of the air blast is the turboblower, first used in 1910 and now the accepted means for the purpose. Some recently installed turboblowers have a capacity of 140,000 cubic feet per minute at a pressure of 40 lb. per sq. in.

The ore, fuel and flux for many of the early furnaces were brought to the charging hole atop the stack in barrows or wheeled carts that passed over a bridge leading from an adjacent elevation to the furnace (Figure 1—8). As furnaces grew taller, vertical hoists similar to elevators were employed to raise the barrows loaded at ground level to the top of the furnace (Figure 1—9). The men called "top fillers" then wheeled the materials to the charging position and dumped them onto the bell. As furnace capacity increased, it was impractical to handle the huge quantities of raw materials by manual methods. In 1883, the first inclined skip hoist (in conjunction with the first double bell and hopper) was installed on an American furnace to raise the raw materials in a skip car to the top of the furnace and automatically dump the contents of the car into a hopper above the small bell. The fact that a skip car always dumped its load in the same location interfered with the proper distribution of materials that was essential to smooth furnace operation, so that various means had to be developed to mechanically distribute the charge over the top bell: one of these consisted of a rotating hopper over the small bell that, with modifications, is generally employed on modern furnaces. Another method em-

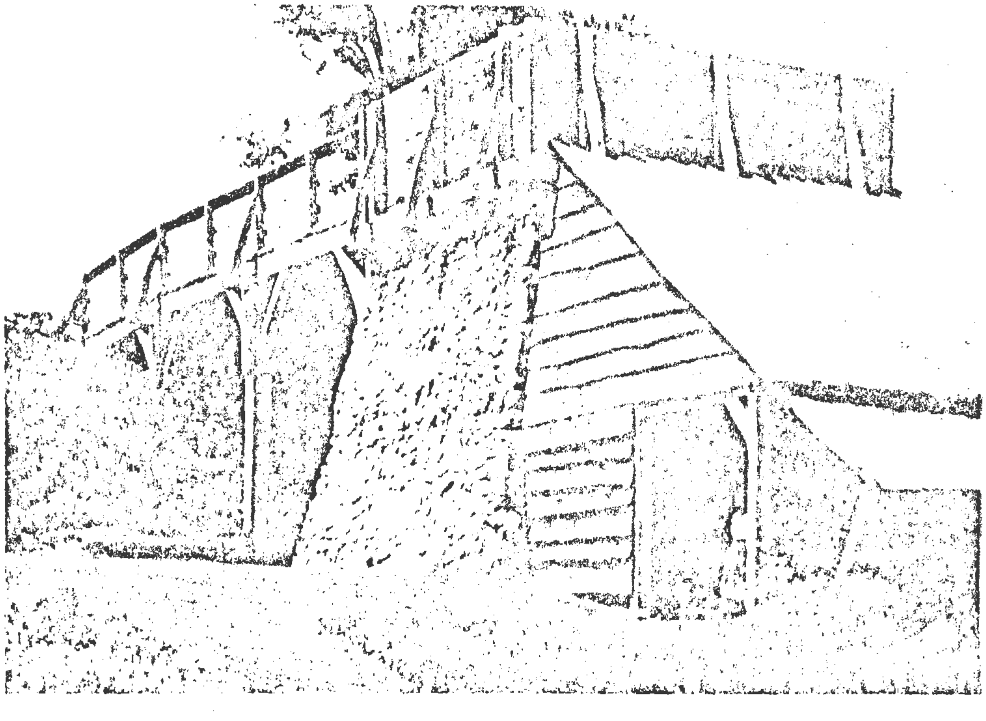


FIG. 1—8. Exterior view of the restored Hammersmith furnace. Raw materials were brought to the charge hole at the top of the stone stack over the bridge in the upper left. The wooden wall surrounding the top of the stack served as a windbreak. The shed in the right foreground protected the area in front of the tap hole from which molten iron was run from the furnace. See also Figure 1—5. (Courtesy, M. H. Snyder.)

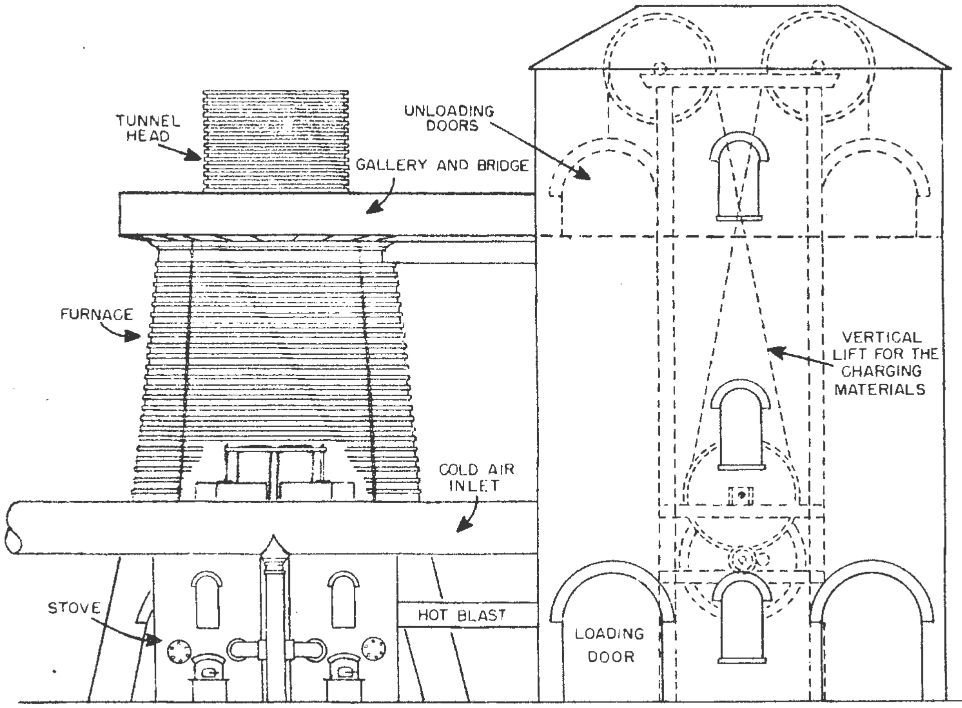


FIG. 1—9. An early blast-furnace plant, showing the vertical hoist (structure at the right) for lifting raw materials to the filling platform atop the stack. (After Percy.)

ployed a charging bucket that was rotated after filling in the stockhouse before delivering to the furnace top.

Increased production rates also forced the adoption of mechanical handling methods for handling and stocking raw materials before they were charged into the furnace skip car or bucket. Prior to 1890, raw materials were dumped from railroad cars run onto an elevated trestle, and manually moved to the stockhouse where the skip car or bucket was filled. In 1895, construction of the blast-furnace plant at Duquesne, Pa., included an ore yard with a stocking-bridge system similar to that employed in present-day blast-furnace plants: this was such a radically new principle that it was referred to as the "Duquesne revolution." The success of the new method led to its general adoption by the industry. This brief resume describes only some of the principal ideas and inventions that led, step-by-step, to the designs employed in contemporary blast-furnace plants. A detailed description of a modern plant is given in Chapter **14.**

SECTION 4

INDIRECT PROCESSES FOR MAKING WROUGHT IRON

After furnaces which produced molten high-carbon iron became commonly employed in Europe, part of their product was used to produce iron castings by pouring the liquid metal into molds of the desired shape. Such cast iron had limited usefulness, since it was inherently hard and brittle due to its high-carbon content and the presence of other elements that entered the iron during reduction of the iron ore. It was not malleable, that is, it could not be shaped at any temperature below its melting point by either hammering or rolling.

In order to utilize the high-carbon product of these furnaces for making forged or wrought articles, it was necessary to develop purifying processes that would remove the excess carbon, manganese, silicon, etc., from the impure iron to produce relatively soft, malleable wrought iron that would have the same general composition and characteristics as the iron formerly produced directly from the ore in the Catalan and similar processes. As might be expected, a very great number of methods were developed in different localities. Two types of processes eventually became prominent: the **charcoal-hearth processes** and the **puddling process**. Since the production of wrought iron from ore by any of these processes involved two separate steps: (1) reducing the ore to make pig iron and (2) remelting and purifying the pig iron to make wrought iron, they were referred to as **indirect processes.**

Some of the most widely used charcoal-hearth processes for purifying pig iron are described below (the Walloon, South Wales and Lancashire processes).

WALLOON PROCESS

Just how, when, where, and by whom wrought iron was first produced from pig iron is unknown, though it is probable the process originated in Belgium. The first attempts were, no doubt, made in the forge or on a hearth such as those already described for the production of iron directly from the ore. Here the action of the air from the blast (by that time in general use) would, if the iron were handled properly during melting, result in the oxidation of the silicon and the greater portion of the manganese and carbon, giving a ductile and workable product. The first reference to the process in written records appeared about 1620, but by that time the process had reached a stage of considerable development. Previous to that date, the Walloons of Flanders had gone to Sweden, where they had introduced the process, since known as the Walloon process. In this process a rather deep hearth with one or two tuyeres was used (Figure 1—10). With the hearth filled with charcoal and heated to a high temperature, the pig iron, in the form of long pigs, was fed into the fire so that the lower end of the pig would be gradually melted, and the molten metal would trickle to the bottom directly in front of the blast. The metal, desiliconized and decarburized by the oxygen in the air blast, would collect as a pasty mass upon the bottom, being worked vigorously as it collected. The ball of pasty metal was then separated into lumps that were raised above tuyere level and remelted. The new ball formed on the bottom was then removed from the hearth and hammered into a bloom. The second melting freed the metal from much of its entrapped slag. The pig used in Sweden, since it was reduced from the famous Dannemora ore in charcoal furnaces, was exceptionally low in silicon, sulphur and phosphorus, hence was especially adapted to this process.

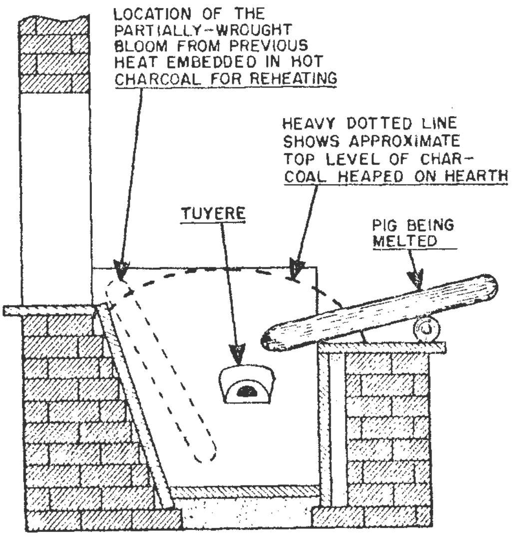


FIG. 1—10. General arrangement of a Walloon hearth used for purifying pig iron to make wrought iron.

SOUTH WALES PROCESS

Few districts outside of Dannemora are favored with ore so free from phosphorus, or were able to continue using charcoal for fuel for such a period of many years. The use of coke in the blast furnace leaves no alternative but the production of high-silicon iron, if the sulphur content is to be kept suitably within limits. At the lower temperatures necessary to produce low-silicon iron, more of the sulphur content of the coke will be picked up by the iron. Such iron, high in sulphur and silicon, could not be purified in a single operation, as in the Walloon process, where the purification was carried on in the combustion chamber with the metal and slag in contact with the fuel. It was found, however, that this iron could be purified and converted into wrought iron very readily in two stages. The South Wales process (sometimes confused with the Lancashire process) was a typical two-stage process. For the first stage, a small, rectangular, water-cooled hearth, surmounted by a stack and provided with a number of tuyeres, was used. In some cases, this hearth was a separate structure; in other cases this hearth for melting the pig iron formed part of a two-hearth furnace in which the melting hearth was slightly above the second hearth where final refining took place. When a separate melting hearth was employed, coke was used as fuel to melt the pig iron; for refining the melted iron, the second hearth was fired with charcoal. When the two hearths were incorporated into one furnace structure, charcoal was used as fuel in both. Sometimes two charcoal hearths were served by one melting hearth that tapped directly into them. The hearths were known by various names. The melting hearth, when separate, was called the **refinery,** or **refinery fire,** if the metal tapped was allowed to partially or completely solidify before being transferred to the second hearth. If the metal was allowed to flow directly from the refinery into the second hearth or hearths, as in the two-hearth furnace, the melting hearth was known as the **melting finery** or **running-out fire.** In both cases, the second hearth was known as the **finery, charcoal finery** or, more often, **knobbling fire.**

With a good fire burning upon the melting hearth, alternate charges of coke and pig iron were made upon it. As the metal melted, it would collect upon the bottom of the melting hearth where the blast from the tuyeres impinged upon it, oxidizing the silicon and some of the phosphorus along with a part of the iron. Assuming that the melting hearth in this case was a separate unit, when a sufficient quantity of partially purified and partially solidified metal had collected, it was transferred to the second hearth from the melting hearth, being piled in front of the tuyere and completely remelted while exposed to the blast. During the remelting, the metal was worked constantly and repeatedly raised slightly off the bottom, which treatment promoted the oxidation of the carbon. As the carbon was being removed, the metal gradually assumed a pasty condition, when it was worked into a ball, taken from the furnace, and hammered.

LANCASHIRE PROCESS

The Lancashire process differed essentially from the South Wales process, to which its name was sometimes loosely given, in that the pig iron was both melted and refined in a single hearth using charcoal as fuel. With some of the slag left from the previous operation to cover the bottom, the hearth was piled with charcoal up to above the tuyeres. The pig iron in lumps was placed on top of the charcoal pile, covered with more charcoal, and the blast turned on. The pig iron melted in drops which became partially decarburized in passing through the tuyere area and collected on the bottom. When all of the pig was melted, it was worked with bars to mix it with the slag and become thoroughly purified. As purification proceeded the metal became stiff and pasty, and when purification was completed the pasty mass was raised above the tuyeres and melted down again to free it from the intermingled slag. The pasty lump resulting from the remelting process was then taken from the furnace and hammered into a bloom.

These three are only a few of the many types of charcoal-hearth indirect processes developed for purification of pig iron to produce wrought iron.

HAND PUDDLING PROCESSES

About 1613, Rovenson invented the reverberatory furnace, which he described as a bloomery, finery or chaffery "in which the material to be melted or wrought may be kept divided from the touch of the fuel," but it was not employed for purifying pig iron until 1766, when the Cranege brothers received a British patent on a process which later came to be known as **puddling**. With careful manipulation of a reverberatory furnace, they were able to convert "white iron," or pig iron from which most of the silicon and phosphorus had been removed in a refinery, as described under the "South Wales Process," into a good malleable form of iron by the use of raw coal alone for fuel. In 1784, Henry Cort hollowed out the bottom of the furnace so as to contain the metal in the molten state, then by agitating this "puddle" or bath of metal with an iron bar or paddle he was able to convert white or partially-refined pig iron into a malleable form (wrought iron), the carbon being burned out by the oxidizing gases of the furnace atmosphere.

As the furnace bottom was made up of sand, it was rapidly fluxed away by the iron oxide formed. Besides, the process consumed much time and was wasteful of iron, the yield being less than 70 per cent of the metal charged. These objectionable features were largely overcome by Joseph Hall, who, in 1830, substituted old bottom material for the sand, thus introducing the iron oxide bottom, which adapted the process to any grade of iron, shortened the time of the heats, and increased the yield to about 90 per cent. On account of the boiling action of the bath caused by the rapid oxidation of the carbon by the oxides on the bottom, Hall's process came to be known as the **pig boiling** process. Later, this process became the leading method for the production of wrought iron.

The original method was designated as **dry puddling** because of the small quantity of slag formed, the slag-forming impurities having been removed in the refinery (see "South Wales Process," above). Hall, or his associates, also introduced the use of air-cooled iron plates for supporting the bottom and sides, which materially increased the life of the furnace. During the next 30 years, few changes were made in the process, for the new process was so far superior to previous ones that there was left little incentive for improvement. This attitude was changed, however, with the introduction of the pneumatic, or Bessemer, process in 1856. Then, in order to overcome competition of the Bessemer steel, and incidentally lessen the labor of puddling, which, like all its predecessors, was very arduous, hundreds of attempts were made to improve and cheapen the process (as shown under "Mechanical Puddling"). Few of these attempts were successful, and even the most promising of the successful ones, for various reasons, failed of universal adoption.

Between the years 1920 and 1930, however, hand puddling was almost entirely abandoned to be supplanted by the Ely mechanical puddler and the Aston process, the former duplicating conditions of hand puddling as closely as possible and the latter employing radically different principles and methods to obtain a similar but more uniform product. These three methods are briefly described in the following sections not only because they will help to define wrought iron and illustrate different methods of producing it, but also because they supply some fundamental knowledge as an introduction to the study of steelmaking processes.

Construction of the Hand Puddling Furnace—Although various modifications were introduced in the construction of puddling furnaces, affecting both size and design, the tendency was to adhere to the smaller and simpler types, such as the one shown in Figure 1—11. This type was known as a single furnace, had

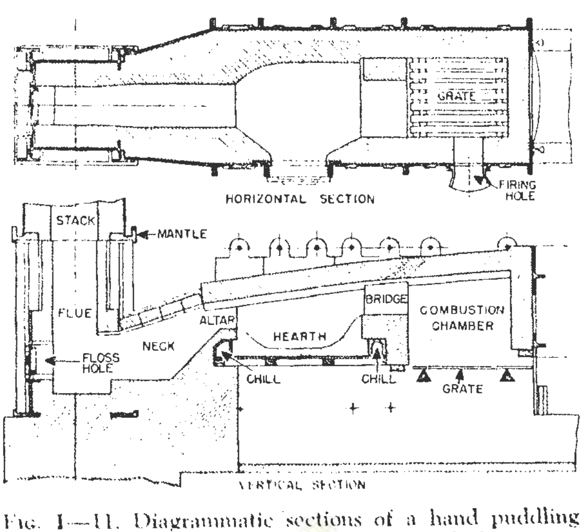


FIG. 1—11. Diagrammatic sections of a hand puddling furnace of the simple design known as a single furnace.

a capacity rating of 500 pounds per heat, and was coal-fired. The furnace was made up of the following parts: the **grate,** or fireplace, located at one end of the furnace; the **neck,** at the opposite end, leading to the **flue** that connected to the **stack;** and the **hearth,** or **puddling basin,** centrally located between the grate and the neck. The furnace was constructed entirely of brick, but was encased on the sides by a shell of iron plates held in place by tie rods. As the furnace was of the reverberatory type, all these parts were covered by an arched roof which sloped down from the fireplace to the uptake flue at an angle of 8 to 10 degrees. The roof over the fireplace was built of firebrick, but usually silica brick were used over the hearth and neck. The fireplace, which measured about 3½ feet in length, 2¾ feet in width, and 3¼ feet in height at the rear, was enclosed on each side by 12-inch firebrick walls and at the rear by a 9-inch wall of the same material. To support the fire bed the space over the ash pit was bridged with iron bars. About 16 inches above the bars a 10-inch square hole in the firebox on the front side of the furnace was provided for firing. The neck, at the other end of the furnace, was an inclined firebrick flue, frequently lined with a course of best-quality silica brick. The neck terminated in a short uptake, or vertical flue, that led to the stack, which was independently supported upon a **mantle.** At the base of the uptake, directly opposite the neck, was an opening or door, called the **floss hole,** which was provided primarily for the removal of the cinder that was carried, or overflowed, from the puddling basin.

The hearth, or puddling basin, was the most vital part of the furnace. Externally, the bottom of this basin consisted of three iron plates, 1 inch thick, which were supported upon four heavy bearer bars laid transversely across the space between the side walls of the furnace. This construction provided all the benefits of air cooling. A low brick wall, laid across the furnace and known as the **bridge,** separated the hearth from the fireplace and also served as a backing for one end of the basin. At the opposite end of the hearth, a somewhat lighter and lower wall, known as the **breast wall** or **altar,** separated the basin from the neck. Imbedded in each of these walls next to the lining, was a hollow iron casting, called a **chill,** through which air or water was circulated to keep these parts cool. The other two sides of the basin were supported by the walls of the furnace itself, and were similarly air-cooled. The back wall was built up solid to the roof, but the front wall contained the arched opening to the hearth. The sides of this opening were made of specially formed silica brick, known as the **jambs,** while its bottom was made of a heavy iron plate called the **fore plate.** This opening was closed by a brick-lined sliding door, in the bottom of which was a small U-shaped opening, the **rabbling hole,** through which tools for working the heat could be inserted without raising the door.

Before the newly-built furnace was put into productive operation, a smooth one-piece working bottom or basin was built up in the hearth. The details of this operation were varied considerably with equally good results. In general, the bottom was composed of a refractory fettling consisting mainly of the ferrosoferric oxide of iron (Fe_3O_4). Certain grades of ore or of heating-furnace cinder were frequently used, but more often the bottom was made by applying, oxidizing, and fritting in successive layers of fine iron cuttings (such as thread cuttings from a pipe mill) known as swarf.

Operation of the Hand Puddling Furnace—With the hearth properly built up or repaired and the furnace in good working order and at a proper temperature, about 500 pounds of pig iron were charged by hand through the door. Following this operation, occupying 2 to 3 minutes, the purification of the pig iron and the process of puddling advanced by stages, known as **melting, clearing, boiling, balling** and **drawing.** To achieve quick melting, the door and other openings were closed, the furnace was fired vigorously, and the pigs turned once or twice by the puddler or his helper. In this way the charge was usually melted within 20 to 25 minutes after charging. The molten metal, covered with a thin layer of slag, was then stirred or rabbled by the puddler to hasten the oxidation of the silicon, the manganese, and a part of the phosphorus, an operation known as clearing and requiring 8 to 10 minutes. As soon as the metal had cleared, as revealed by a change in its appearance, the puddler endeavored to bring on the boil by raising the temperature of the furnace, charging some dry roll scale (iron-oxide scale detached from bars in rolling), and stirring the bath vigorously. After some 8 to 10 minutes of strenuous effort, the oxidation of the silicon and manganese was brought to a point where the carbon could also be oxidized.

As the product of this reaction was the gas, CO, and since the slag was somewhat viscous, the action caused the latter to foam or boil and rise in the furnace. At this point the slag was permitted to flow from the furnace freely unless it was desired to hold the phosphorus high in the iron, when a little coal was added from time to time and as much of the slag as possible was held in the furnace. As the elimination of carbon became more rapid, the gas would escape in larger bubbles and burst into flame at the surface of the slag to form small flames called **puddler's candles.** With the disappearance of the candles, the puddler increased the stirring of the bath during the **lowering of the heat** until the metal in terms of the puddler, would **come to nature.** In this phenomenon, most characteristic of puddling, the metal appeared in small globules, like butter in churned milk, each globule representing a portion of the iron that had become decarburized. As this reaction neared completion, the bath became pasty and very hard to work. This change occurred because the high-carbon pig iron, which was molten at that temperature, was converted to low-carbon iron, which is solid (though pasty) at the same temperature. The change progressed rapidly, lasting only 6 to 8 minutes, so that in some 30 to 35 minutes after clearing the metal was ready for balling.

The globules agglomerated by the rabbling tended to collect in sponge-like clusters on the bottom; these clusters had to be raised constantly and exposed to the heat to prevent them from freezing to the bottom.

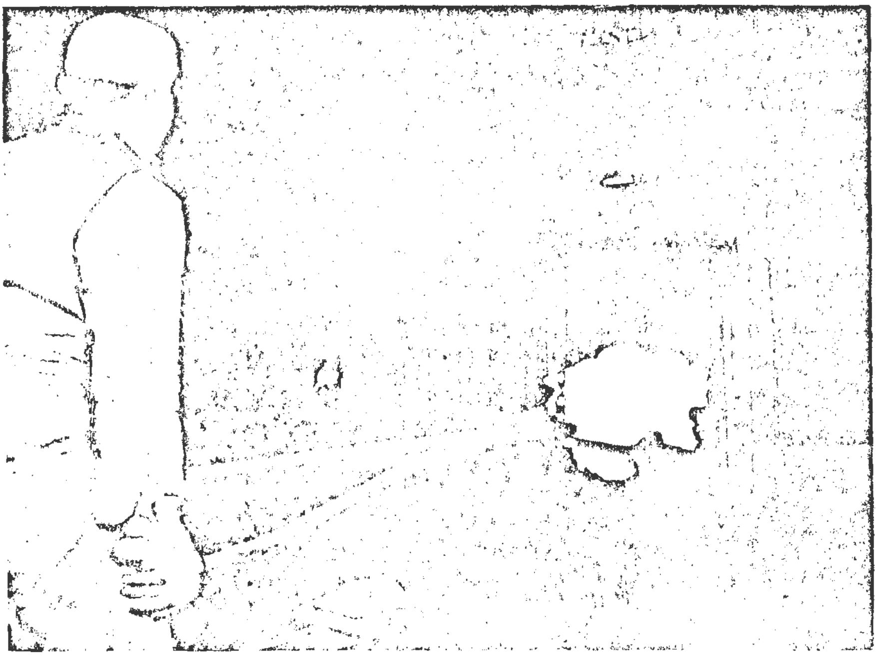


FIG. 1—12. Puddler removing a ball from a puddling furnace for transfer to the squeezer. This photograph, taken in 1949, shows one of the last puddling furnaces still in operation in the United States. (Courtesy, Lockhart Iron & Steel Company.)

So the temperature of the furnace was raised as high as possible, and the metal was worked into a mass which was next separated into three parts or balls of about 150 pounds each, a size convenient for handling with tongs. This operation required about 15 minutes. Each ball in turn was then grasped by the tongs supported from the trolley (Figure 1—12) and drawn through the door. After the last ball was removed, the furnace was permitted to cool to some extent, and the bridge and breast were covered with a special ore mix. Any necessary patching of the bottom was done, and another charge of metal was placed on the hearth for the next heat. These operations required about 2½ hours from heat to heat.

Rolling of Hand-Puddled Wrought Iron—At one time the balls were worked into the form of a rough bloom with a hammer, an operation called **shingling.** Later, hammering was superseded by the use of a device known as a **squeezer,** of which there were different types. One, known as the Burden squeezer, was most used (Figure 1—13). It was of the rotary type and consisted essentially of a toothed cylinder mounted upon a vertical shaft so as to revolve within a section of a somewhat larger stationary cylinder set eccentrically to the revolving cylinder. Since the larger cylinder bore teeth or cogs on its inner surface and described only about three-fourths of a circumference, a ball placed in the larger opening between the cylinders was carried around the circumference by the smaller revolving cylinder to be compressed and discharged through the smaller opening in the form of a short round bloom. This action squeezed most of the excess slag out of the ball and compressed it into a form more suitable for rolling. As soon as the ball was delivered by the squeezer, it was grasped with tongs and at once delivered to the first pass of the rolling mill.

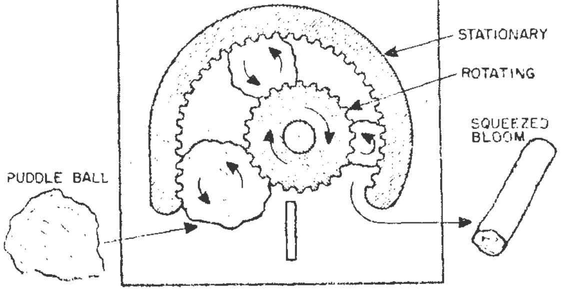


FIG. 1—13. Schematic representation of the path of a puddle ball passing through a Burden squeezer.

Rolling the Squeezed Ball—The **muck bar mill** for rolling the squeezed ball into muck bar was usually a 16- or 20-inch mill and consisted of a single stand or set of rolls, or of two stands in train; that is, end to end and coupled together. The first pass was of the open-box type* with large fillets at the corners in order to take the cylinder from the squeezer, while the second pass, generally an edging pass, was of similar design, thus working the metal into the form of a round-cornered square and squeezing out more of the slag at each pass. The remaining passes were all of the closed-box or tongue-and-groove type for rolling the bloom into flats called **muck bars,** with some open-box edging passes for use in producing the narrow widths. The size of the muck bars, of course, was regulated by the product to be made from them and the manner or system used in forming the product. For ordinary bar iron, which was the chief product, the

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* See Part 1 of Chapter 20 on "Rolling Mill Rolls and Their Parts" for descriptions of the roll passes mentioned here.

muck bar was usually about ¾ inch thick and 2½ to 8 inches wide. Bars of these sizes required from 5 to 9 passes. On account of the rapid cooling of the bar in the rolls, it was not practicable to attempt to roll sizes smaller than these, as the slag was no longer fluid enough at this stage to be worked out of the bar. As slag was squeezed out of the bar at all passes in the mill, the muck bar had a very rough surface with some torn edges and was otherwise unfit to do service as a finished bar. Having been rolled to the size required, the muck bar was allowed to cool before being subjected to further treatment.

Variables in the Muck Bar—Owing to irregularities in the pig iron used, differences in manipulation by different puddlers, and in different plants, the small quantity of metal refined with each heat, and the fact that the metal solidified before purification was complete, muck bar was an exceedingly variable product. Since the retention of the characteristics of wrought iron did not permit melting, this variation had to be overcome through heat and mechanical treatments. To effect the necessary refinement, two methods were used, known as busheling and piling, followed by rolling.

Busheling—Obviously, the surest way to obtain a thorough mixing of the iron, was to shear the muck bars into small pieces—the smaller the better. These small pieces from the different muck bars were allowed to collect in a pile, or piles, from which portions weighing 180 to 600 pounds were removed with a scoop or fork and charged into a reheating furnace, called a **balling furnace**, where they were heated "white hot," or to a self-welding temperature. With a paddle, these pieces were then collected into a ball, similar to a puddle ball, which was squeezed or shingled, then rolled or hammered into a bloom, which was then reheated and worked into the form desired. This process, known as **busheling**, was used for working up muck bar only when iron of the highest quality was desired. The process was also used in working up small scrap. In this case there was no necessity for shearing, and the cost of the scrap was usually considerably less than the cost of muck bar, but unless the scrap was very carefully selected it was liable to contain much steel, in which case the iron produced was considered to be of inferior grade.

Piling—The more common practice, therefore, was to shear the muck bar into lengths of from 2 to 3 feet, then arrange these pieces in piles of from 5 to 7 or more each and bind the pieces together with wire or bands. The piles were carefully charged into a furnace and heated white hot. The high temperature caused the different bars to weld together, so that they could then be removed and rolled into bars. The first 2 or 3 passes squeezed out more and more of the liquid slag, but in the last passes the bar had cooled to a point where the slag was merely plastic and would not flow. Thus, a fairly smooth and uniform bar was produced, which would be sold as **merchant bar, single-rolled iron, single-refined iron,** or **No. 2 iron.** To attain the highest degree of uniformity, particularly with respect to distribution of slag fiber, the once-piled or so-called single-refined bars were in turn cut into short lengths, repiled and rerolled.

Double Refining—To further improve uniformity, then, merchant bar was cut up into short lengths, fagoted, reheated, and rerolled to produce the products known as **double-rolled iron, double-refined iron, best bar,** or **No. 3 bar.** The manner or **fagoting** (binding together into a bundle) or piling these bars varied in numerous ways, and depended only in part upon the use to which the iron was to be applied. Therefore, each manufacturer generally had his own methods of fagoting, which imparted to his iron an individuality detected by etching. Some of the more common methods of fagoting are illustrated by the accompanying sketches (Figure 1—14). When these fagots were heated and rolled into bars, more slag was expelled, the bar was made more uniform in composition, and the fibers were much elongated and reduced in size. As a result, the bars showed an improvement in mechanical properties, including both strength and ductility. There was a limit, in addition to the factor of cost, however, to the number of times the iron could be worked to advantage. After five or six workings its physical properties began to be lowered, and the bars decreased in strength and were less ductile. The cause, or causes, of this change was questionable; probably, it was due to the elimination of much of the silicate slag or possibly too much reheating and rerolling caused the ferrous silicate fibers to become oxidized to the ferric condition, thus destroying some of the characteristics of wrought iron. Wrought iron in this condition was often referred to as **dry iron.**

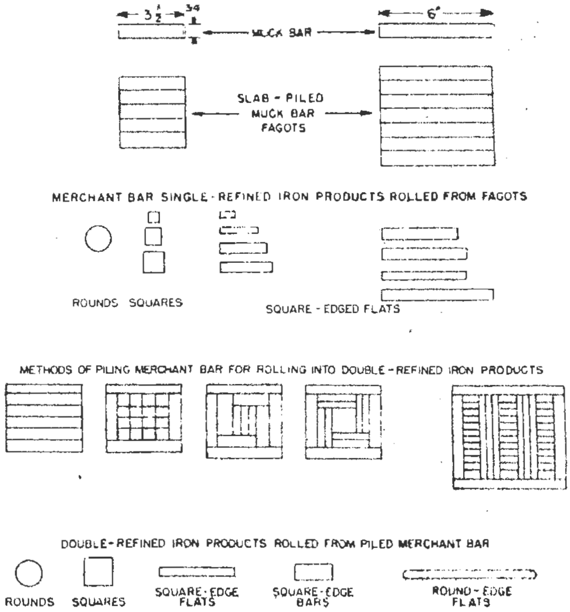

Fig. 1—14. Some of the more common methods of fagoting or binding together piles of single-refined wrought iron bars prior to heating for re-rolling to produce double-refined wrought iron bars.

Reactions and Process Losses in Hand Puddling—The changes in composition of the pig iron during puddling involved the elimination, or oxidation, of silicon, manganese, phosphorus, and carbon about in the order mentioned. In these reactions, the oxidizing agents were FeO and Fe_3O_4. That Fe_2O_3 played little, if any, part in the reactions was evident from the fact that Fe_2O_3 decomposed at temperatures above 2010° F (1100° C) to form Fe_3O_4. Also, it had been found that if hematite ore (Fe_2O_3) was used as the oxidizing medium, the boil came on very slowly; but if roll scale (Fe_3O_4 or $FeO \cdot Fe_3O_4$) were used, the reactions proceeded with much greater speed. Nearly all of the silicon and manganese and a part of the phosphorus were oxidized before the boil began, and at some period after melting and after the elimination of some of the silicon, the oxidation of all four elements, including carbon, might have proceeded simultaneously.

A study of the probable reactions that occurred in puddling indicates that a gain in weight of the puddled iron over the pig iron used could be expected, because iron was formed by reduction from the slag in the elimination of practically all impurities. By careful manipulation, furnaces could be operated to show a slight gain or a very slight loss. Nevertheless, in ordinary working, there was a loss of from 3 to 6 per cent, which was sometimes a little more, at other times a little less, than the total of the impurities present. If the heat were properly handled, the loss was largely due to oxidation of iron after solidification had begun in the after-part of the boil and during the balling stage. If the heat were not skillfully handled, a variable part of the loss may have been due to the escape of the metallic granules with the "boilings" before the "heat was lowered." In reheating and rolling the muck bar, there was a variable loss of from 10 to 20 per cent for each time the iron was worked depending upon the number of times it was worked, the manner of the working, and other factors incidental to the operations of heating and rolling. In general, these losses were due to surface oxidation of the metal in heating and rolling, expulsion of the slag, and cropping. Slag expulsion was the smallest item of loss, except in the case of muck bar, and depended mainly upon the number of times the iron was worked, but was also affected by the temperature at which the iron was worked, and the nature of the incorporated slag itself. The loss was a little greater on iron with a high phosphorus content than on iron low in phosphorus.

MECHANICAL PUDDLING

The never-ending competition in the iron and steel industry has been a constant spur to improve methods or lower costs of production. Just as the puddling process virtually eliminated the more primitive direct-reduction methods for the production of iron, so the Bessemer and open-hearth processes for the production of steel threatened the life of the wrought-iron industry. Even before the invention of these steelmaking processes, much attention was given to improving the puddling process, because the process was costly and the labor arduous, and the furnace was wasteful of heat. With a reverberatory puddling furnace of the type described earlier, from 2000 to 2400 pounds of coal were required to produce one ton of muck bar. This consumption of fuel was reduced somewhat by the use of double furnaces with enlarged hearths, but, since the application of regenerative and recuperative furnaces appears to have been impracticable, efforts along this line failed to achieve much in the way of lowering costs. The installation of waste-heat boilers in the stacks effected marked economies, and their use became general. To overcome the high labor cost, many attempts were made to carry out the puddling operations mechanically. Such was the situation up to about 1880 when the Danks puddling furnace appeared. From this time up to 1925, wrought iron lost ground to steel in spite of several efforts to revive it. In the meantime, however, it came to be recognized as a product with characteristic properties unlike those of steel, and in 1925 attempts to revive the industry were noted. These endeavors advanced along two lines, the one mechanical and the other metallurgical, the former aiming to duplicate the process of hand-puddling as closely as possible and the latter aiming to produce a material having all the characteristics of wrought iron through the use of the same metallurgical principles but applied in a manner entirely different from that of hand puddling. These two lines of effort are described under the headings of mechanical puddling and the Aston process, the latter representing a successful and most revolutionary method of producing wrought iron by A. M. Byers Company.

Principles of Mechanical Puddling—At first these mechanical puddlers took the form of stirring or rabbling appliances that could be attached to the top of the ordinary furnace. Because of the great variety of motions necessary in the different operations of charging, raising and stirring the heat, balling the iron, and drawing the balls, none of these were successful. The more successful attempts at mechanical puddling have involved a complete change in the design of the furnace, and some changes also in the process. These attempts have been too numerous to warrant description here. The furnaces themselves may be classified as follows:

1. The rectangular furnace that oscillated about a horizontal axis of rotation.
2. The circular flat-bottom furnace that revolved about an axis slightly inclined to the vertical.
3. The circular furnace with flat or troughlike bottom that oscillated about a horizontal axis of rotation.
4. The cylindrical furnace that rotated about a horizontal axis coincident with the center.
5. The cylindrical furnace that oscillated about a horizontal axis coincident with the center, or both oscillated and rotated about such an axis.

Furnaces built on any of these plans were made to puddle iron successfully, but those of the fourth and fifth types were most successful, partly on account of the facilities they afford for controlling the agitation of the metal, and partly because of the simplicity of their construction. The **Danks furnace,** somewhat widely used in this country from 1868 to 1885, was of the fourth type, while the **Roe furnace,** built and successfully operated in 1905, is of the third type. **H. D. Hibbard's furnace,** first operated on a commercial scale in 1921, was somewhat similar to the Danks furnace. The **Ely furnace,** patented by W. C. Ely, was first designed for busheling scrap but was later (about 1920) applied to the puddling of iron. It represents the fifth type, and, along with the Roe furnace, survived until recent years as one of the two successful mechanical methods for making wrought iron.

THE ASTON PROCESS*

From the descriptions given in the preceding sections, it is apparent that the basis of wrought-iron manufacture consists in refining the base metal to a close approach to pure iron, and incorporating therein an iron-silicate slag of desirable chemical composition in proper amount and distribution. Obviously, as has been brought out previously, several correlated steps are involved, quite distinct in nature and capable of separation, but carried out in the usual methods for hand or mechanical puddling as one interconnected operation. Departing radically from these former methods is the Aston process developed and put into large scale operation by the A. M. Byers Company of Pittsburgh. In this process, metal refining, slag melting, and processing to form the slag-impregnated sponge ball are carried out as separate stages, each stage in a separate furnace or kind of equipment. The last stage is the crux of the process, and is based upon a positive and effective physico-chemical influence; namely, the change in gas solubility from a very high amount in molten iron to an amount practically negligible on solidification. This stage of the Aston process is carried out by pouring the refined metal in a continuous stream into a large volume of molten slag. The slag acts as a heat absorbing agent which effects solidification of the metal with accompanying liberation of its dissolved gases, at a steady rate and with a force sufficient to disintegrate the plastic metal into a spongy mass, conforming in all particulars to the characteristics of high-quality wrought iron.

A large plant, with a daily capacity in excess of 1000 tons, is in operation in the Pittsburgh district. The essential features of the operation are illustrated in the accompanying Figures 1—15 to 1—20.

Three cupolas are operated to produce molten iron (hot metal) of Bessemer grade which is ladle desulphurized with caustic soda and subsequently further refined in acid-Bessemer converters (Figure 1—15).

The iron-silicate processing slag is melted to exacting chemical requirements in special furnaces, which are described later (see also Figure 1—16), and then transferred to the processing cups.

The molten desulphurized hot metal from the cupolas is "full-blown" in an acid-lined converter (Figure 1—17) and the highly refined, deoxidized metal is poured at a controlled uniform rate into a thimble holding molten iron-silicate slag (Figure 1—18). After the metal from the converter has been poured, the surplus slag is poured from the thimble, leaving the white hot sponge ball of wrought iron (Figure 1—19). This sponge iron is first pressed into a bloom of rectangular section (Figure 1—20) and is then rolled into slabs or billets.

Equipment for melting iron-silicate slag for the

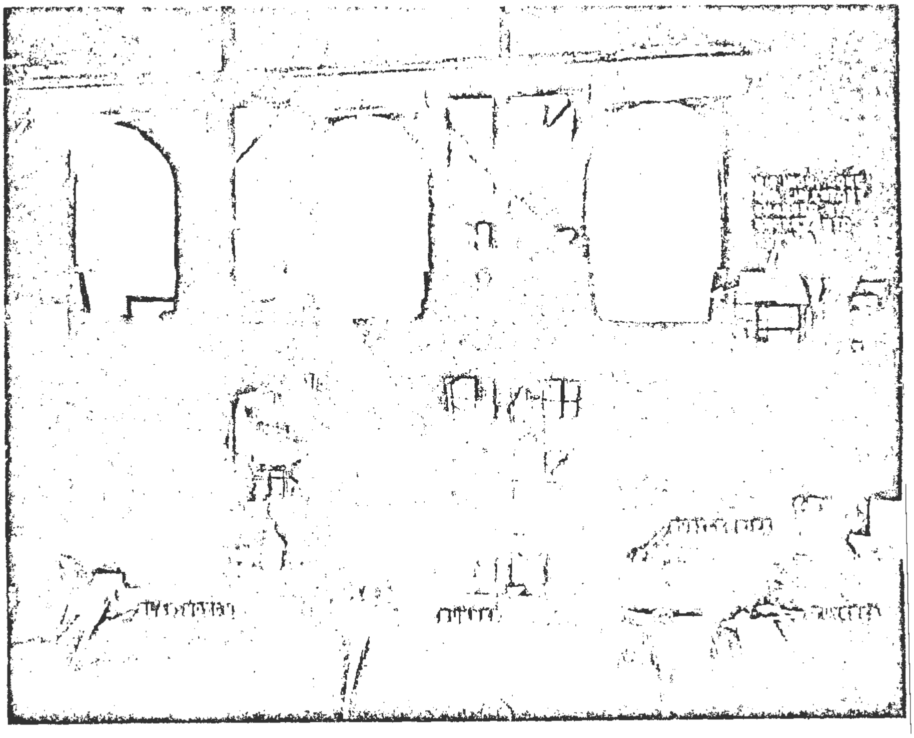

FIG. 1—15. Hot metal tapped from these cupolas runs into a ladle where it is desulphurized and transferred to acid-Bessemer converters, one of which is shown in Figure 1—17. (Courtesy, A. M. Byers Company.)

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* Special acknowledgement is made of the assistance rendered by A. M. Byers Company, in the preparation of this section.

FIG. 1—16. Molten iron silicate slag is tapped from rotary furnaces and transferred by ladle to replenish the slag in the processing ladles (processing cups) shown at lower level in Figure 1—18. (Courtesy, A. M. Byers Company.)

FIG. 1—17. Desulphurized hot metal is "full blown" in acid-Bessemer converters to refined iron, then deoxidized and transferred by ladle to the processing machine ladles shown at upper level in Figure 1—18. (Courtesy, A. M. Byers Company.)

FIG. 1—18. At the processing floor, molten refined iron (2900° F.) is poured by processing machines into molten iron silicate (2500° F.) to form an iron sponge ball characteristic of the Aston process for making wrought iron. Processing machines, scale mounted, have traverse, oscillating, and tilting motions insuring distribution of the metal into the slag. (Courtesy, A. M. Byers Company.)

FIG. 1—19. Empty processing ladle receives surplus decanted processing slag, is replenished if necessary, and returned by rail to processing floor for reuse. The welding-hot iron sponge ball, "wet" with molten iron silicate, is moved to the press by overhead traveling crane. (Courtesy, A. M. Byers Company.)

FIG. 1—20. The welding-hot sponge ball, "wet" with molten iron silicate retained in the processing ladle in which it was produced, is immediately transferred to and dumped on the press table, lowered between side and end rams, and pressed into a rectangular bloom prior to rolling. (Courtesy, A. M. Byers Company.)

processing operation (sponge-making), and for incorporating in the matrix of iron, consists of four rotary furnaces. These furnaces, which are fired with oil or powdered coal, have no refractory lining and are operated in such manner that the lining material is composed of the same silicate slag that is being melted. This eliminates all contamination which would occur with customary refractory linings and makes it possible to produce the iron-silicate slag for processing to a very exacting chemical composition.

The key operation is effected by pouring the molten refined and deoxidized metal in a steady stream into a "processing cup" or vessel containing molten slag as illustrated by Figure 1—18. The metal ladle is automatically oscillated and moved forward and backward, insuring uniform distribution of metal into the slag. As the stream of molten metal poured at the rate of a ton a minute disintegrates in the molten slag, solidifying droplets are formed which are burst apart by the liberated gas and the resulting shattered fragments settle to form a welding-hot spongy mass in the molten silicate. Individual iron sponge masses—"sponge balls"—varying in weight from three to four tons are produced.

These processing cups are on cars, so that the decanting of surplus slag and the dumping of the sponge ball (Figures 1—19 and 1—20) can be effected at a station remote from the pouring platform.

Pressing and rolling follow, using the original heat of the ball, to form intermediate products such as billets or slabs conforming to standard mill practice. Furnaces, mills, and auxiliary equipment, as well as man power, follow closely the standards of the modern rolling mill. In view of the large mass of the pressed bloom, most of the product—skelp, plate, etc.—is rolled from reheated solid sections, in marked contrast to older wrought-iron practice of building muck bar piles.

COMPOSITION, STRUCTURE AND PROPERTIES OF WROUGHT IRON

Chemical Composition of Wrought Iron—Chemical composition has a place in the determination of wrought-iron quality comparable with its importance in the steel industry. One must bear in mind, however, that the customary metalloids may be, in greater or lesser degree, alloyed with the base metal or associated as oxidized constituents with the intermingled slag. The commonly reported composition of wrought iron lists the carbon, manganese, phosphorus, sulphur and silicon of the composite mass. On the basis of analyses as commonly made, the following statements apply to wrought iron of high quality: Carbon seldom, if ever, exceeds 0.035 per cent in quality wrought iron. Silicon content is 0.075 to 0.150 per cent, normally almost negligible in alloyed association with the metal, and existing almost entirely as silicates in the slag. Sulphur is always undesirable, and in well-made wrought iron, it should be under 0.02 per cent. A sulphur content of 0.015 per cent or under is quite common in quality wrought iron. Phosphorus is almost invariably higher in wrought iron than in steel. It must be borne in mind that phosphorus is in part dissolved in the base metal, and in part associated with the slag. Good wrought iron may have a phosphorus content of from 0.10 per cent or less to 0.25 per cent or more, according to manufacturer's preference, nature of raw materials, or adaptability to service conditions. The lower order is advisable for materials subjected to shock, high temperature, or requiring higher ductility. Traditionally, the manganese content of hand-puddled or processed wrought iron (Aston process) is less than 0.10 per cent; British specifications generally have a 0.10 per cent maximum and in the United States most specifications carry a limit of 0.06 per cent. Low manganese in wrought iron has usually been an earmark of quality, although there is no logical ground for condemning an otherwise well-made product because of a relatively high manganese content.

Macroscopic Structure of Wrought Iron—In view of the composite nature of wrought iron, its quality is obviously affected by the nature of the association of base metal and slag. Methods of disclosing this internal structure have an importance greater even than the prominent place which the metallurgist assigns to them in the study of steel. Wrought iron exhibits a well-recognized fibrous fracture. The fracture test is a good over-all means for determining the general characteristics of wrought iron, but it should not be relied upon solely.

Macroscopic etching will reveal gross structure, reflecting such features of manufacture as methods of piling, and general slag distribution. Deep etching has a useful place but, like the fracture test, gives only a limited amount of information pertaining to the finer points of quality.

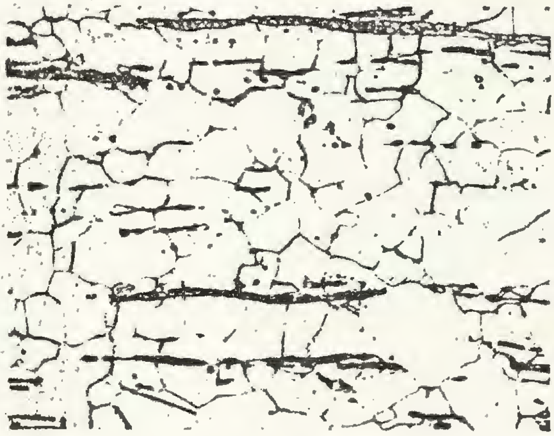

FIG. 1—21. Photomicrograph at 100X showing typical structure of wrought iron parallel to the direction of rolling. White areas are the highly refined iron matrix. Dark gray elongated lines are iron-silicate slag filaments. (Courtesy, A. M. Byers Company.)

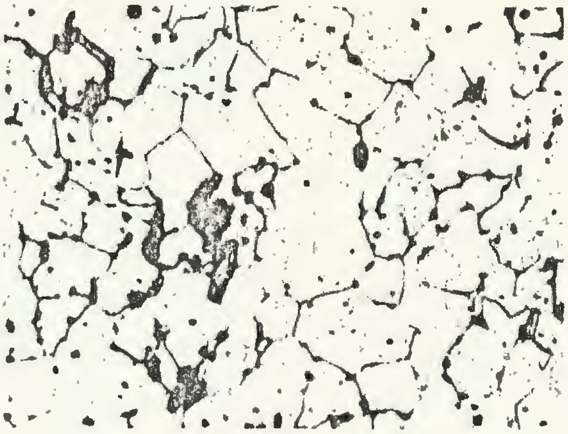

FIG. 1—22. Photomicrograph at 100X showing typical structure of wrought iron perpendicular to the direction of rolling. White areas are the highly-refined iron matrix. Dark areas are cross-sections of iron-silicate slag filaments. (Courtesy, A. M. Byers Company.)

Microscopic Structure of Wrought Iron—Wrought iron consists essentially of a ferrite matrix, through which the slag is uniformly disseminated in the form of several hundred thousand filaments per square inch. Important disclosures of the microscope are:

a. **Grain Size**—Coarse grain, distortion, or lack of uniformity have a bearing upon quality in relation to mill history and use of product.

b. **Pearlitic areas** indicate the quantity and nature of distribution of the carbon, generally practically negligible or quite small in amount in real wrought iron.

c. **Slag—Type and Distribution**—Coarse, pocketed slag is undesirable. Finer textures result from progressive rolling reductions, and promote better mechanical properties, especially ductility.

d. **Chemical Composition**—The microscope is of no value in detection of alloying elements in solid solution in the base metal; for example, manganese, nickel, silicon, copper, etc.

Two photographs (Figures 1—21 and 1—22) illustrate typical structures and features related to the quality characteristics of wrought iron. These micrographs are of wrought iron produced by the A. M. Byers Company (Aston process), and show a typical longitudinal structure and a typical transverse structure.

Mechanical Properties of Wrought Iron—The mechanical properties of wrought iron are essentially those of pure iron, modified only slightly in general practice by metalloid content of the base metal and profoundly by the quantity and distribution of the incorporated slag. Up to certain limits, the ductility is increased by greater work in forge or mill, which causes a finer and more threadlike distribution of the slag. This is reflected in the common practice of the puddle mill of once or twice piling in products designated as "single" or "double-refined" iron. Obviously, a similar result will be achieved by rolling relatively large initial blooms into small final sections.

In comparison with steel or ingot iron, the longitudinal ductility of wrought iron is somewhat lowered, due to slag incorporation, while the transverse strength and ductility are markedly reduced. However, rolling history is an important factor with respect to quantity and direction of reduction.

The values below are representative of tensile properties for various wrought-iron products, compiled from standards of the American Society for Testing Materials. Because of the physical size of the products listed, only the longitudinal properties are reported, except for plate for which both longitudinal and transverse properties are given.

BAR IRON—SINGLE-REFINED

Under 1¼ Sq. In. Section

Tensile strength, lb. per sq. in.	48,000 (minimum)
Yield point, tensile strength factor	0.6
Elongation in 8 in., per cent	25 (minimum)
Reduction of area, per cent	45 (minimum)

BAR IRON—DOUBLE-REFINED

Under 1¼ Sq. In. Section

Tensile strength, lb. per sq. in.	48,000—52,000
Yield point, tensile strength factor	0.6
Elongation in 8 in., per cent	28 (minimum)
Reduction of area, per cent	48 (minimum)

The higher ductility accompanying greater work is reflected in the figures for double-refined material. For heavy sections, such as large diameter bars and forgings, strength and ductility requirements are somewhat lowered.

WELDED PIPE

Tensile strength, lb. per sq. in.	40,000 (minimum)
Yield point, lb. per sq. in.	24,000 (minimum)
Elongation in 8 in., per cent	12 (minimum)

Herein are reflected the effects of high temperatures in welding, and the lessened stretch in testing tubular sections. However, where special precautions are taken in the making of pipe for bending purposes, the ductility figures are bettered in practice by several per cent in the elongation obtained.

PLATE

Under normal rolling practice, plate exhibits the maximum of difference in longitudinal and transverse properties. The A.S.T.M. specifications for usual rolling require plate meeting the following tensile properties:

Tensile strength, lb. per sq. in.	
Longitudinal	48,000 (minimum)
Yield point, lb. per sq. in.	
Longitudinal	27,000 (minimum)
Elongation in 8 in., per cent:	
Longitudinal	14 (minimum)
Transverse	2 (minimum)

By proper attention to rolling practice, it is feasible to equalize the properties, so that a specification requirement of a tensile strength of 39,000 lb. per sq. in. (minimum) and an elongation in 8 in. of 8 per cent (minimum) in either direction may be obtained. This feature is of great value in producing plate for flanging or other forming purposes.

SECTION 5

EARLY PROCESSES FOR CONVERSION OF IRON INTO STEEL

PROBABLE ANCIENT METHODS

It is probable that most of the steel produced in ancient times consisted of partially case-hardened wrought iron. Wrought iron, when heated and suddenly cooled by quenching in some liquid, will not harden because it does not contain enough carbon. By increasing the carbon content in the manner to be described, the outer portions and edges of a piece of wrought iron could be made to harden by heating and quenching.

The hardenable outer portion or "case" was produced by allowing a wrought-iron object to remain in a forge fire in contact with hot carbon, which completely surrounded it and protected it from oxidation. The carbon absorbed by the surface "layers" of the wrought iron would make it possible to obtain very hard surfaces and edges on a weapon, for example, by quenching the heated metal in a suitable liquid. The interior of the tool or weapon, of course, would remain relatively soft. Undoubtedly some steel was produced, intentionally or otherwise, when an imperfectly decarburized product was obtained from the South Wales, Lancashire, Walloon or similar processes. Another method, used in some of the Eastern countries to produce what very commonly is known as "Damascus steel," consisted of piling alternately pieces of soft iron on pieces of high-carbon iron and then heating, forging, fagoting and reforging the billets. The layering that resulted from incomplete diffusion of carbon from the high-carbon bars into the low-carbon iron resulted in the surface appearance called "watering," which was characteristic of the so-called Damascus steels.

It is difficult to say how or when the first processes for intentional making of steel were developed. Archeological specimens from as far back as 1000 B.C. exhibit evidences of having been deliberately treated (case-hardened) to produce points and edges that were hardened by rapidly quenching the heated steel. One example is a chisel with a hardened point, found in one of the ancient cities of Ceylon and believed to date back to about 500 B.C. Early writers mention steel razors, surgical instruments, files, chisels and stone-cutting implements as early as several hundred years before the Christian Era.

The steel called **wootz** was produced in India for many centuries. Its method of manufacture has been variously described. It is generally agreed that the first step consisted of heating pure ore with carbonaceous material such as charcoal or finely-chopped wood in closed crucibles. After heating at a high temperature for several hours, the ore was reduced to metallic iron and absorbed sufficient carbon from the excess of charcoal to have a low enough melting point to become fluid. The crucibles were allowed to cool and, when broken open, a small "button" of high-carbon steel was found at the bottom. Two methods have been recorded for lowering the carbon content of the buttons to give steel having the desired carbon content or "temper." One method consisted of repeatedly heating the buttons while they were covered with a layer of iron-oxide paste. The other recorded method comprised heating the buttons for several hours in a charcoal fire to a temperature not much below their melting point and turning them over in the path of the blast, so that the metal would be partially decarburized. In both cases, the partially decarburized buttons would then be heated to be welded together by hammering to form bars. Ambiguous records of various other processes for making steel by carburizing wrought iron appear in fragmentary literature from very early times.

In summary then, it may be said that prior to the invention of the Bessemer process for steelmaking in 1856 there were only two methods of making steel. One was the process of increasing the carbon content of wrought iron by heating it in contact with hot carbon away from air; this came to be called the **cementation process**. The other method, the **crucible process**, consisted of melting wrought iron in clay crucibles in which carbon had been added for the express pur-