ORIGINALLY, a more extended use of cast iron was only brought about because of the low price and ease with which it conformed to pattern when cast. Recently, the metallurgist turned to cast iron as a material which was worthy of his research, and the result was a greatly improved metal which conformed to the rigid specifications of design engineers. This manuscript includes a study and examination of heat treatments which result in particularly high strength cast irons of unusual ductility, shock resistance and fatigue strength. Future applications are indicated. Mr. Morken presented this paper at the Detroit meeting of the A.S.S.T.

Because of its humble origin and homely methods of production, cast iron has for generations been considered an inferior material and was held to be quite unsuitable where strength, ductility, and shock resistance were necessary. It occupied an obscure position during a period of tremendous metallurgical development in other fields. During only the last few years, cast iron has begun to receive attention as an alloy capable of refinement and worthy of intensive study. Improved metal from the electric melting furnace awakened in the metallurgist a new interest in cast iron as an engineering material, and as the metallurgist became able to produce better irons, the engineer began adopting them as materials worthy of his use.

Use of the electric furnace resulted in cast iron which possessed more than four times the strength of the conventional "old" cast iron, and in addition iron of greatly improved shock-resistant properties. During the last two years a number of startling and revolutionary applications of heat treated cast iron have been made and others, still more startling, are in the process of development.

Heat Treatment of Gray Iron

In considering the heat treatments applicable to cast iron the first type to be examined will be ordinary gray iron. The gray appearance of the fracture is caused, of course, by free graphite, and the matrix may be composed of pearlite, pearlite and ferrite, or pearlite, ferrite and cementite, with other minor constituents present. The gray iron foundryman has learned that the ideal is an iron, similar to that illustrated by Fig. 1, in which the matrix is pearlite, and the graphite is of individually fine particles, uniformly distributed through the matrix. This iron contained 2.70 per cent total carbon, 1.70 per cent silicon and had an unalloyed tensile strength of 52,210 pounds per square inch. His attempts to produce such iron are frequently frustrated by unforeseen or uncontrollable foundry conditions, and free ferrite results, to the detriment of hardness and wear resistance, or free cementite is obtained, much to the detriment of machinability. In many instances, due to the design of castings, stresses are set up in the casting as the metal freezes. Since the ultimate value of any casting is equal to the theoretical strength less the internal stresses, it

FIG. 1 (upper left)—Pearlitic gray cast iron produced in rocking indirect arc electric furnace. Etched, 500 diameters. Fig. 2 (upper right)—Air furnace malleable iron made by standard long cycle anneal, 140 hr. Note large graphite particles and equally large average grain size. Etched, 100 diameters. Fig. 3 (lower left)—White iron melted in indirect arc rocking electric furnace. Note relatively large proportion of pearlite to cementite and the manner in which the free cementite has been broken up and distributed. No primary graphite is present. Etched, 100 diameters. Fig. 4 (lower right)—Same iron as Fig. 3 but annealed with 20-hr. cycle, having fine graphite nodules, uniformly distributed and fine grain size. Note absence of pearlite. Etched, 100 diameters.
is desirable to remove those internal stresses created during the freezing.

The stress removal is accomplished by a simple heat treatment frequently referred to as "normalizing" or "aging." The castings are heated to a point ranging from 800 to 1100 deg. F. (430 to 595 deg. C.), and maintained at maximum temperature until equilibrium is reached. An ordinary treatment for relief of internal stresses consists of holding for four hours at 900 deg. F., and, when properly conducted, such treatment has no apparent effect upon the physical properties of the castings. Because of the graphitizing tendency of silicon, it is advisable to use low temperatures for relieving stresses in high silicon irons, and, per contra, higher temperatures are permissible for a low silicon content.

A second heat treatment for gray cast iron is the anneal, used to break down the free cementite so that rough castings may be more readily machined. The treatment consists mainly of heating above the critical temperature and cooling slowly to a temperature well below the critical, followed by dumping the charge into the air for convenience in handling. The general treatment consists of holding at a point from 1400 to 1650 deg. F. for two to six hours and cooling in the furnace to black heat. The brief soak above the critical temperature serves to decompose the free cementite without seriously affecting the eutectoid cementite. Slow cooling through the critical range facilitates this decomposition. The annealing, as outlined, decreases the hardness and causes a reduction in the physical strength of the iron. The reductions in hardness and strength are variable, depending upon temperature, time, and the composition of the iron. The ideal treatment is that in which the hardness is decreased only enough to produce the desired machinability.

A third treatment is a hardening, which is frequently called "martenitic quench," and it may or may not be followed by a draw. The object of the quenching is to produce extreme hardness, to increase hardness while retaining machinability, or to increase the strength of the iron.

The casting is quenched from above the critical temperature. One limitation that immediately suggests itself is the formation of quenching cracks, but these are obviated by: (1) selection of quenching medium, (2) correct design of heating and quenching cycle, (3) redesign of the casting, and (4) use of alloys to increase the hot strength of the iron or to lower its critical temperature, whereupon lower quenching temperatures are used.

Since the critical temperature of cast iron varies with the carbon and silicon content and with alloys, it is common practice to quench from 1450 to 1550 deg. F., which is well above the critical. The quenching medium is determined largely by the design of the casting and the hardness desired, and is usually either oil or air, although water is sometimes used.

By means of the quenching treatment, unalloyed cast iron with a Brinell hardness of about 400 is readily obtained, while the hardness of alloyed metal runs up to 500 or more. These irons are used for withstanding severe wear and abrasion, and are not commercially machinable.

Balla'y has described a quenching treatment in which good hardness is obtained with machinability. He quenches in oil from about 1500 deg. F., and draws at from 400 deg. F. and 600 deg. F. to relieve quenching stresses. Nickel is used in the iron to improve susceptibility to heat treatment and to lower the critical temperature. The iron is machinable and has a martensitic structure. Brinell hardness is about 350.

As with steel, cast iron is frequently machined in the "as-cast" condition, following which it is quenched, drawn and the machining completed at slow speed or by grinding. The strength of gray cast iron is increased by quenching and drawing, and strength values well over 85,000 lb. per sq. in. are readily obtained with a fair degree of machinability.

White Iron

As its name indicates, white iron is iron of such composition as to produce a white fracture. All the carbon is combined and no graphite exists in the iron as cast.

White iron has been produced for years for abrasion resistant parts and for making malleable iron, but it has limited commercial application. Since white iron is brittle, it sometimes is found necessary to anneal it slightly in order to preclude breakage of the castings in handling. This anneal consists, usually, of holding at 1500 to 1600 deg. F. for three to four hours, which precipitates a small amount of graphite and breaks down some of the massive cementite, thereby increasing the toughness of the castings.

Most white iron poured is converted into malleable iron or some

---

Fig. 5 (upper left)—Iron similar to Fig. 4, annealed with 24-hr. cycle. No pearlite remains. Etched, 125 diameters. Fig. 6 (upper right)—Same iron as Fig. 5, but heat treated to produce high strength with cycle of 8 hr. Etched, 125 diameters. Fig. 7 (lower left)—Same iron as Figs. 3 and 4, but given heat treatment for high strength. Properties illustrated by Fig. 9. Etched, 1500 diameters. Fig. 8 (lower right)—Showing retention of pearlite. The white iron, similar to Fig. 3, was electrically melted and the total annealing cycle was about 15 hr. Etched, 100 diameters.
form similar to malleable iron. Rapid strides have been made during the last year in this field, with attention directed primarily toward shortening the annealing cycle and improving the physical properties of the iron. This activity has developed a series of irons with distinctly new properties.

Malleable Iron

Malleable iron is produced from white cast iron by a suitable annealing process. Schwartz has made this type of iron the subject of a most comprehensive treatment. White iron is primarily an alloy of iron, carbon, and silicon, containing small amounts of other elements. The carbon is entirely combined and no graphite exists, and the structure consists mainly of massive cementite and pearlite. In producing malleable iron from this material, the combined carbon is completely broken down, and the carbon precipitated as graphite in a matrix of ferrite. Since the graphite is very gradually liberated, and since it is liberated at high temperature in solid iron, it assumes a characteristic form, collected in nodules composed of extremely fine individual particles. This graphite is called temper carbon or secondary graphite. Fig. 2 illustrates the structure of malleable iron.

Annealing Stages

Malleable iron is produced from white iron by an annealing process composed of two stages. The first stage consists of heating at a temperature well above the critical (A_c) until the massive cementite has been destroyed. The temperature used commercially ranges from 1600 to 1700 deg. F., and when equilibrium has been reached at this temperature, the structure consists of graphite and solid solution of carbon in iron.

Since the solubility of carbon decreases as temperature decreases, carbon will continue to precipitate as the temperature is lowered. When equilibrium is reached at a temperature just above the critical point, the structure is composed of temper carbon in pearlite.

The second stage of annealing consists of holding at a temperature just below the critical point (A_r) to destroy the pearlite. Carbon continues to precipitate, at the expense of pearlite, and ferrite forms. The temperature used ranges from 1300 to 1350 deg. F., and when equilibrium is reached, the structure is composed of temper carbon in a matrix of ferrite.

The silicon, previously referred to, greatly accelerates this graphitizing process. Silicon is a vigorous graphitizing agent and the malleable foundryman wishes to use as much of it as he can in his iron. He is limited with ordinary melting equipment, however, because, when the silicon is too high, some of the carbon will precipitate out as graphite as the white iron freezes. This graphite, known as primary graphite, is in the form of coarse flakes and deprives malleable iron of strength and ductility.

In commercial malleable practice, the two stages of annealing merge into one another so closely that a distinction is not obvious. After the first stage is completed, the temperature is allowed to drop slowly (10 to 15 F. deg. per hr.) to about 1200 deg. F., when the oven is opened to accelerate cooling for handling. A typical cycle for producing malleable iron in periodic or batch type anneals is as follows:

1. Heat to 1650 deg. F. 20 hr.
2. Hold at 1650 deg. F. 50 hr.
3. Cool to 1350 deg. F. 70 hr.
4. Cool for handling.

The properties of malleable iron are greatly dependent upon the composition of white iron used. This composition, however, has become fairly well standardized for air furnace melting practice, and a typical analysis would be, 2.40 carbon, 1.10 silicon, 0.15 phosphorus, 0.05 sulphur, and 0.25 manganese. Malleable iron, when annealed by the above cycle, can be expected to result in the following physical properties:

- Ultimate tensile strength—50-60,000 lb. per sq. in.
- Yield point—30-45,000 lb. per sq. in.
- Elongation in 2 in.—15-20 per cent
- Impact strength, Charpy—1-10 ft.-lb.

Short Annealing Cycles

Much attention has been directed toward bringing the commercial annealing cycle closer to the theoretical.

Highriter summarizes this procedure very well. Since the tunnel or kiln type of continuous annealer is more controllable than is the periodic, some reduction of annealing time has been made. The tunnel type permits a rapid cooling to the A_r, where an arrest is made and the temperature held at 1300 deg. F. for a sufficient time to complete graphitization.

Attempts to shorten the cycle by changing the composition of the iron (increasing the silicon for its graphitizing action) or by the addition of other graphitizing alloys, have not met with great success, because of the difficulty in preventing primary graphite.

Valentine worked on a different angle and succeeded in shortening the cycle to 30 hours, through the use of an electric annealer, in which time and temperature reactions are closely controlled. Valentine found that manipulation of temperatures, particularly in range of the A_r, increased the rate of graphitization.

The process consists mainly of establishing equilibrium at a temperature above the A_c, in a uniform manner, following which the temperature is manipulated during the cooling to the lower critical point. One major reason for the short duration of this cycle is complete elimination of packing material. The castings are simply piled up on cars and the cars elevated into the annealer. To facilitate the operation, two ovens are used, one for high and one for low temperature. This arrangement permits an air quench during the transfer and, further, conserves heat. The process is said to be thoroughly economical and metallurgically satisfactory.

White and Schneidewind investigated the influence of superheating the molten white iron. They found that white iron superheated to 3200 deg. F. annealed in 40 per cent of the time required to anneal iron superheated to 2800 deg F. These irons were prepared in electric furnaces, and it is probable that temperature is not alone responsible for the results obtained. It is rather apparent from Figs. 3, 4 and 5 that thorough mixing of the iron, simu-
taneous with superheating, distributes the free cementite in such a way as to provide several graphitization centers where only one exists in ordinary white iron. It is also probable that melting and superheating the iron under deoxidizing influences affects the annealing time favorably.

Further, the advantages of superheated, electrically melted, white iron have combined with another phenomenon to reduce further the annealing cycle, and to produce, with extremely short heat treatments, a series of irons related to malleable, but possessing far greater strength. This phenomenon is the ability of white iron, melted under reducing conditions in the rocking indirect furnace, to contain abnormally high quantities of free silicon without the formation of primary graphite. Several foundries have been able to reduce the annealing cycle to 20 hr. by such a process.

Fig. 3 is typical of white iron produced in the above manner. It is free from primary graphite and the massive cementite is uniformly distributed through the pearlite matrix. The iron generally contains less free cementite than do other types of white iron. A typical composition of white iron used in this process for sections up to ½ in. thick is, 2.40 carbon, 1.65 silicon, 0.05 sulphur, 0.05 phosphorus, and 0.25 manganese. A typical annealing cycle for lots ranging from 1500 lb. to five tons would be:

1. Heat to 1750 deg. F. for 3 hr.
2. Hold at 1750 deg. F. for 4 hr.
3. Cool to 1250 deg. F. for 14 hr.

The physical properties resulting from the cycle are:

Ultimate tensile strength—100,000 lb. per sq. in.
Yield point—65,000 lb. per sq. in.
Elongation in 2 in.—27 per cent.
Impact strength, Charpy—5 ft.-lb.
Brinell hardness—180.

Other cycles for annealing this white iron are in use in which the temperature is arrested at or near the lower critical, usually at 1350 deg. F. This permits of much more rapid cooling from the high temperature of the first stage of graphitization, but, since the temperature is held at the lower point for 10 to 12 hr., no time is saved.

Figs. 4 and 5 illustrate the structure of representative malleable irons made in the above described manner. In comparing these to Fig. 2, the difference in grain size and in the size of the carbon particles is outstanding. It is readily apparent that when decomposition of the cementite began, graphite nuclei were formed at close intervals. Therefore, as graphitization progressed, the carbon had only short distances to travel to reach nuclei upon which to precipitate.

Many heat treatments are applied to white iron that has been produced by the electric melting furnace process just described. These treatments all start by holding the castings at high temperature to decompose the free cementite, as in all malleable processes. To accomplish this they are held at 1700 to 1800 deg. F. from two to four hr. Following this, the heat treatment may be varied in countless combinations, developing many products that differ metallurgically from steel only in that they contain temper carbon.

Quenching in oil from this point produces a martensitic structure with strength well over 100,000 lb. per sq. in., but the treatment is severe for castings of other than simple design. Equally good properties are obtained with a less severe air quench, followed by a draw. One effective treatment is as follows:

Hold at 1750 deg. F. for 5 hr.
Air quench to 1400 deg. F.
Oil quench.
Draw at 1350 deg. F. for 1 hr.
Air quench for handling.

Fig. 6 illustrates iron made with this cycle. The physical properties of this type average as follows:

Ultimate tensile strength—100,125,000 lb. per sq. in.
Yield point—65,100,000 lb. per sq. in.
Elongation in 2 in.—27 per cent.
Impact strength, Charpy—5 to 7 ft.-lb.
Modulus of elasticity—30,35,000,000.
Brinell hardness—225-275.

Figs. 7 and 9 illustrate another iron of this type, made with a different heat-treating cycle. The cycle was:

Hold at 1725 deg. F. for 4 hr.
Cool in furnace to 1425 deg. F.—4 hr.
Oil quench.
Draw at 1350 deg. F. for 1 hr.
Air quench for handling.

Various heat treatments intermediate between the complete anneal and the quench-draw treatment just described are also in use for this electrically melted white iron. These are designed to produce, in some cases, a pearlitic or sorbitic matrix and, in other cases, a matrix of pearlite and ferrite. It has been found that the relative proportions of pearlite and ferrite can be controlled with accuracy by the applied heat treatment.

The pearlitic matrix is produced by cooling quickly from the high temperature to soak about 1500 deg. F., where an arrest is made long enough to reach equilibrium. This is followed by an air or oil quench. Since the ductility of such iron is low and the strength is somewhat lower than the high strength material just described, it has not found wide application.

Most producers prefer to arrest at the lower critical point long enough to form some ferrite, thus increasing the ductility. Fig. 8 shows such an iron, produced with the following cycle:

Hold at 1750 deg. F. for 3 hr.
Cool in furnace to 1550 deg. F.
Hold at 1550 deg. F. for 5 hr.
Cool in furnace to 1200 deg. F.
Air quench for handling.

Such material has from 70,000 to 80,000 lb. per sq. in. tensile strength with 6 to 12 per cent elongation.

Another process uses electric annealing furnaces for malleableizing, which is followed by various quenching and drawing treatments. One producer of castings by this process claims 70,000 to 75,000 lb. per sq. in. tensile strength, 50,000 to 55,000 lb. per sq. in. yield point with from 15 to 18 per cent elongation in 2 in. The cycle employed is said to consume about 60 hr. for 5-ton lots. It is divided approximately as follows: 5 hr. to reach soaking temperature, 20 hr. at the high temperature soak followed by air quench to the lower critical where it is held for 25 hr. About 10 hr. additional is required to reach the handling temperature. The iron used is of special composition, and the details have not been made public.

Applications

Many parts which heretofore were made of malleable iron or steel are now being made from heat-treated cast-iron with complete satisfaction. Such parts include underground cable brackets and clamps used in power distribution systems, machinery cams, connecting rods, conveyor chains, dies, gear rakes, gears, differential carriers and universal housings for automobiles, and many other similar products. In addition to possessing more than ample shock resistance and elastic limit, these irons are superior to steel in wearing qualities, stress dampening properties, fatigue resistance and machinability.

One very interesting application of heat-treated iron is for street manhole covers. For this application a material of low yield point is not suitable since it permits the cover to bend after which it rattles in its frame as traffic passes over it. When made from gray cast iron failure was 212 to 172 lb. This high yield point (50,000 lb. per sq. in.) and possesses good impact resistance.

Considerable development work has been done on heat-treated cast-iron cam shafts and crank shafts for automobiles, Diesel engines, etc. Cam shafts of this material are already in use in at least two automobiles, and it is probable that when this is read, at least one automobile will be using heat-treated cast-iron crank shafts.