Heat Treatment of Cast Irons

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Iron (Fe), derives it name from the Latin word ferrum. In its pure form iron is lustrous, silvery, soft, and ductile. However, pure iron is a poor engineering material, generally not as strong as most plastics. Cast irons are based on the Fe-C system, and the solid-state transformations on which cast iron heat treatments are based are similar to those applied to steels.

Iron is the fourth most abundant element on Earth and is one of the most widely disbursed elements in the Earth's crust. In nature it is found combined in various compounds with oxygen, sulfur, or more complicated ores such as carbonates and silicates (Table 1). Because iron is so abundant, combines readily with other elements (such as manganese to form steel) and requires relatively little energy to extract it from ore, it is one of the most attractive elements to use for the products we require in everyday life (Fig. 1).

Cast Irons

Cast iron is a generic term used to designate a family of metals with a wide variety of properties. All cast irons contain more than 2% carbon and an appreciable amount of silicon (usually 1-3%). The high carbon and silicon content means that they are easily melted, have good fluidity in the liquid state and have excellent pouring properties. The basic types of cast iron are best differentiated by their microstructure as opposed to their chemical analysis because the various types overlap (Table 2).

The metallurgy of cast iron is more complex than its economics and, in fact, is one of the more complex metallurgical systems [Fig 2]. Iron-carbon alloys with less than 2% carbon are metastable; the true stable system being iron-graphite (Fe-C). The general term cast iron includes pig iron, gray iron, malleable iron, chilled iron, white iron, and nodular or ductile iron.

If an iron alloy exceeds about 2% carbon, the carbon does not have to nucleate from decomposition of austenite, but instead, it can form directly from the melt by a eutectic reaction. Note that cementite (Fe_3C) can still nucleate at the eutectic more readily than graphite, but on sufficiently slow cooling, graphite itself is able to form and grow.

Consider the solidification of a 3% carbon cast iron (Fig. 3). At a rapid cooling rate, dendrites of austenite form as the alloy cools below the liquidus and grow until the eutectic temperature is reached. At the eutectic, graphite formation is suppressed, but austenite and cementite precipitate to form ledeburite, a form of eutectic that consists of spheres of austenite embedded in cementite. Ledeburite forms at the Fe-Fe_3C eutectic (solid line "nm"). On further cooling, the cementite grows as the austenite decreases in carbon content (along the solid line "no") At the eutectic (point "o"), the remaining austenite transforms to pearlite. At room temperature, the iron is hard and brittle and is called white iron because the surface of a fractured piece of iron is white and (somewhat) lustrous.

Upon slow cooling of a 3% carbon cast iron, austenite forms from the melt, but eutectic freezing is now slow enough so the products of the eutectic reaction are

Table 1 Common Iron Ores [1]

Mineralogical name	Chemical formula	Chemical composition	Class
Magnetite	Fe_3O_4	72.36% Fe, 27.64% O_2	Oxide
Hematite	Fe_2O_3	69.94% Fe, 30.06% O_2	Oxide
Ilmenite	$FeTiO_3$	36.80% Fe, 31.63% O_2, 31.57% Ti	Oxide
Limonite	$HFeO_2$ FeO(OH)	62.85% Fe, 27.01% O_2, 10.14% H_2O	Oxide
Pyrite	FeS_2	46.55% Fe, 53.45% S	Sulfide
Siderite	$FeCO_3$	48.20% Fe, 37.99% CO_2, 13.81% O_2	Carbonate

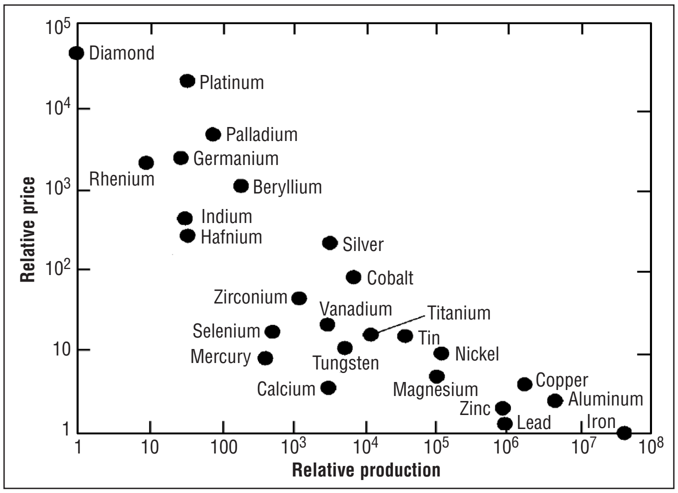

Fig 1 (right). Cost of materials versus their relative use [2] austenite and graphite (the reaction takes place at the dotted line "nm"). The eutectic graphite tends to form flakes surrounded by eutectic austenite. As cooling continues, the austenite decreases in carbon content (along the dotted line "no"), while the remaining austentite transforms to pearlite. Because the fracture surface appears dull gray the material is known as gray iron (or pearlitic gray iron).

Cooling at an extremely slow rate results in phase changes similar to those of a slow cooled component, except the eutectoid cooling is sufficiently slow to permit graphite to precipitate rather than pearlite. No new graphite flakes will form, but the ones present will increase in size. The final microstructure consists of graphite flakes embedded in a ferrite matrix. The resultant material is called ferritic gray iron (cooling of actual castings cooling is seldom slow enough to obtain this structure).

The cooling rate of a portion of a casting sometimes may vary, resulting in a structure containing patches of both white and gray iron, called mottled iron [4].

Graphite forms in cast iron in several different shapes including flakes, nodules and spheroids (Fig. 4). Because graphite has very little (cohesive) strength and reduces the effective metallic cross section of the casting, both strength and ductility are affected.

Types of iron

Pig Iron is the term that is generally applied to a metallic product that contains over 90% iron. Typically it contains approximately 3% carbon, 1.5% silicon and lesser amounts of manganese, sulfur and phosphorus. Pig iron along with scarp metal is the base material for both cast iron and cast steel.

Gray irons are alloys of iron, carbon and silicon, in which more carbon is present than can be retained in solid solution in austenite at the eutectic temperature. The carbon precipitates as graphite flakes. The gray irons typically contain from 1.7% - 4.5% carbon and 1% - 3% silicon as major constituents.

The most common heat treatments applied to gray cast irons are stress relief because of nonuniform cooling of castings and annealing to improve machinability. Subcritical heating is used for both. Stress relief is done at temperatures between 1020 and 1200°F (550 and 650°C) without significantly lowering strength and hardness. Heating at temperatures between 1290 and 1400°F (700 and 760°C) lowers the hardness for improved machinability.

Nodular iron, also known as ductile iron or spheroidal graphite iron, is cast iron in which the graphite is present as tiny balls, or spherulites, instead of graphite flakes (as in gray iron), or compacted aggregates (as in malleable iron). The nodular irons typically contain from 3.2-4.1% C, 1.8-2.8% Si and up to 0.80% Mn as major constituents. Several types of matrix structures (including ferritic and pearlitic) can be developed by alloying and heat treatment. The various grades of regular, unalloyed ductile iron are designated by their tensile properties (Table 3).

Heat treatment of ductile cast iron includes stress relief and annealing, as well as heat treatments used for steels including normalize and temper (for higher strength and wear-resistance), quench and temper (for the highest strength), and austempering. Ferritizing (for the most ductile microstructure) is done by austenitizing at 1650°F (900°C), followed by holding at 1290°F (700°C) to completely transform

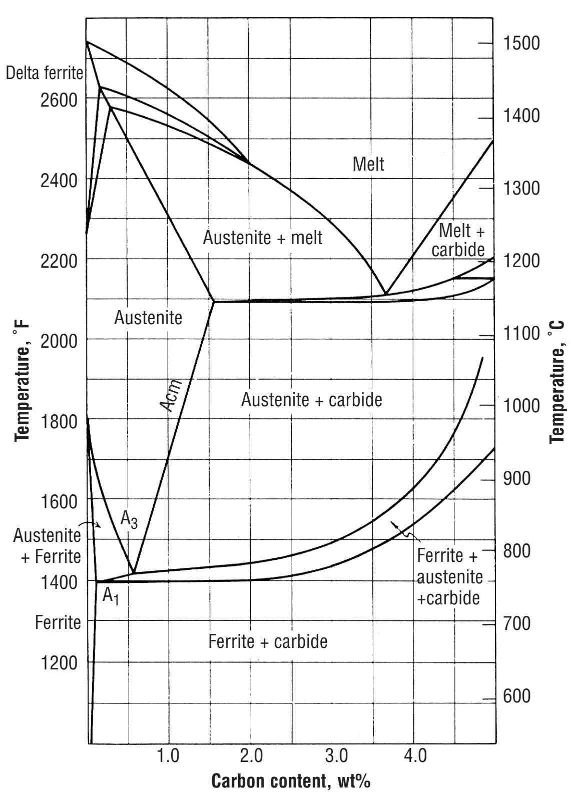

Fig 2. Fe-C-Si diagram at 2% silicon. Silicon strongly promotes graphite formation.

Table 2 Typical Composition of Unalloyed Cast Irons [3]

Element	Gray iron, %	Malleable iron, %	White iron, %	Nodular iron, %
Carbon	2.5-4.0	2.00-2.60	1.8-3.6	3.0-4.0
Silicon	1.0-3.0	1.10-1.60	0.5-1.9	1.8-2.8
Manganese	0.25-1.0	0.20-1.00	0.25-0.80	0.10-1.00
Sulfur	0.02-0.25	0.04-0.18	0.06-0.20	0.03 max
Phosphorous	0.05-1.0	0.18 max	0.06-0.18	0.10 max

Table 3 Common Grades of Ductile Iron [3]

Type (TS-YS-%EL)	Tensile strength, ksi	Yield strength, ksi	Elong., %	Hardness, BHN	Heat treatment	Typical micro-structure
60-40-18	60	40	18	137-170	Annealed	All ferrite
65-45-12	65	45	12	149-229	-	Ferritic
80-55-06	85	55	6	179-255	-	Ferrite & pearlite
100-70-03	100	70	3	229-302	Normal-ized	All pearlite
120-90-02	120	90	2	250-350	Quench & Tempered	Tempered martensite

austenite to ferrite and graphite.

Malleable irons are relatively soft and can be bent without breaking. They include ferritic (or standard) malleable iron and pearlitic malleable iron. Malleable iron is obtained by the heat treatment of white iron so the hard iron carbide structure of ledeburite is converted to a matrix of ferrite or pearlite and graphite is precipitated within the iron. This form of graphite is sometimes referred to as tempered carbon. A wide range of mechanical properties can be obtained in malleable iron with different matrix structures around the graphite.

Ferritic malleable iron has a ferrite matrix with interspersed nodules of tempered carbon and, depending on how it is produced, some combined carbon. Pearlitic malleable iron is designed to have combined carbon in the matrix, resulting in higher strength and hardness than ferritic malleable iron. The malleable irons typically contain from 2.0-2.65% C, 0.90-1.65% Si and 0.25-0.55% Mn as major constituents.

Malleable cast iron can be heat treated to the same microstructures as ductile cast irons.

Chilled cast iron is produced by casting the molten metal in such a way as to produce a surface virtually free of graphitic

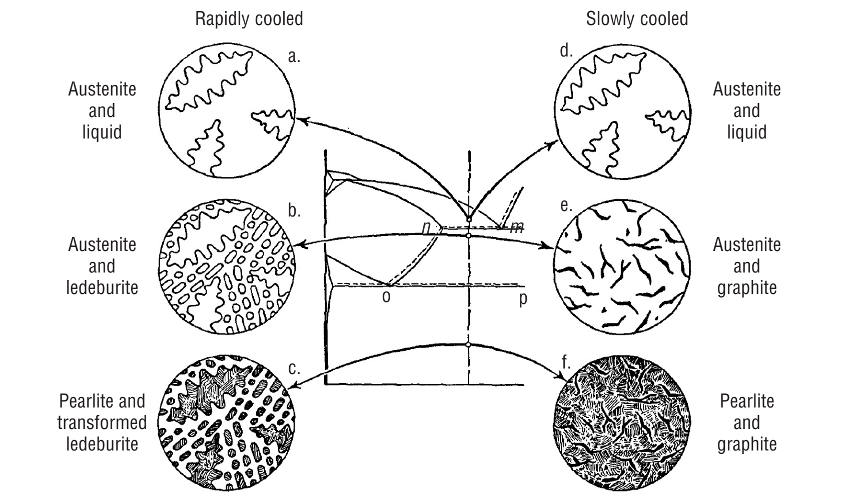

Fig 3. Iron-graphite phase diagram [4]. Microstructures obtained by cooling and solidification of cast iron; white iron (left) and gray iron (right).

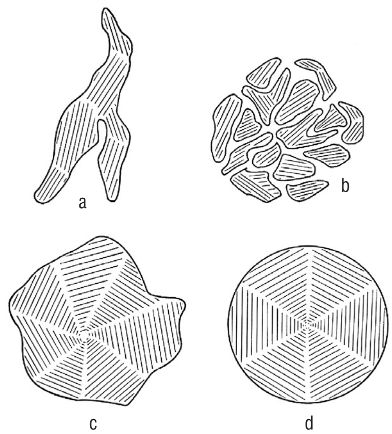

Fig 4. Forms of graphite in cast iron [4]; flakes (a), random orientation (b), nodule (c) and spheroidal (d)

carbon. The surface of chilled iron castings is extremely hard. The depth and hardness of the chilled portion may be controlled by adjusting the composition of the metal.

White iron is a type of chilled cast iron that is virtually free of graphitic carbon, which is achieved by selecting a specific chemical composition to inhibit graphitization for a given section size. The hardness of the casting may be controlled by selection of composition.

In both chilled and white irons, the depth of chill decreases and the hardness increases with increasing carbon content. Carbon varies from 2.5% to above 3.5%. It also is necessary to control silicon content; the chill is reduced by increasing the silicon content. The range of silicon content for white irons is governed by the section size. Silicon content varies from 0.6-1.5%. Alloying elements such as nickel, chromium, and molybdenum are used to improve wear resistance.

References

1. McGannon, H. E. (ed), *The Making, Shaping and Treating of Steel,* US Steel Co., 9th Ed., 1971
2. German, R.M., *Powder Metallurgy of Iron and Steel,* John Wiley & Sons Inc., 1998
3. Walton, C. F. (ed.), *Gray and Ductile Iron Castings Handbook,* Gray and Ductile Iron Founders' Society Inc., 1971
4. Taylor, H.F, Flemings, M.C. and Wulff, J., *Foundry Engineering,* John Wiley & Sons Inc., 1959

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