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Classification and Basic Metallurgy of Cast Irons

THE TERM CAST IRON, like the term steel, identifies a large family of ferrous alloys. Cast irons are multicomponent ferrous alloys, which solidify with a eutectic. They contain major (iron, carbon, silicon), minor (<0.1%), and often alloying (>0.1%) elements. Cast iron has higher carbon and silicon contents than steel. Because of the higher carbon content, the structure of cast iron exhibits a richer carbon phase than that of steel. Depending primarily on composition, cooling rate, and melt treatment, cast iron can solidify according to the thermodynamically metastable

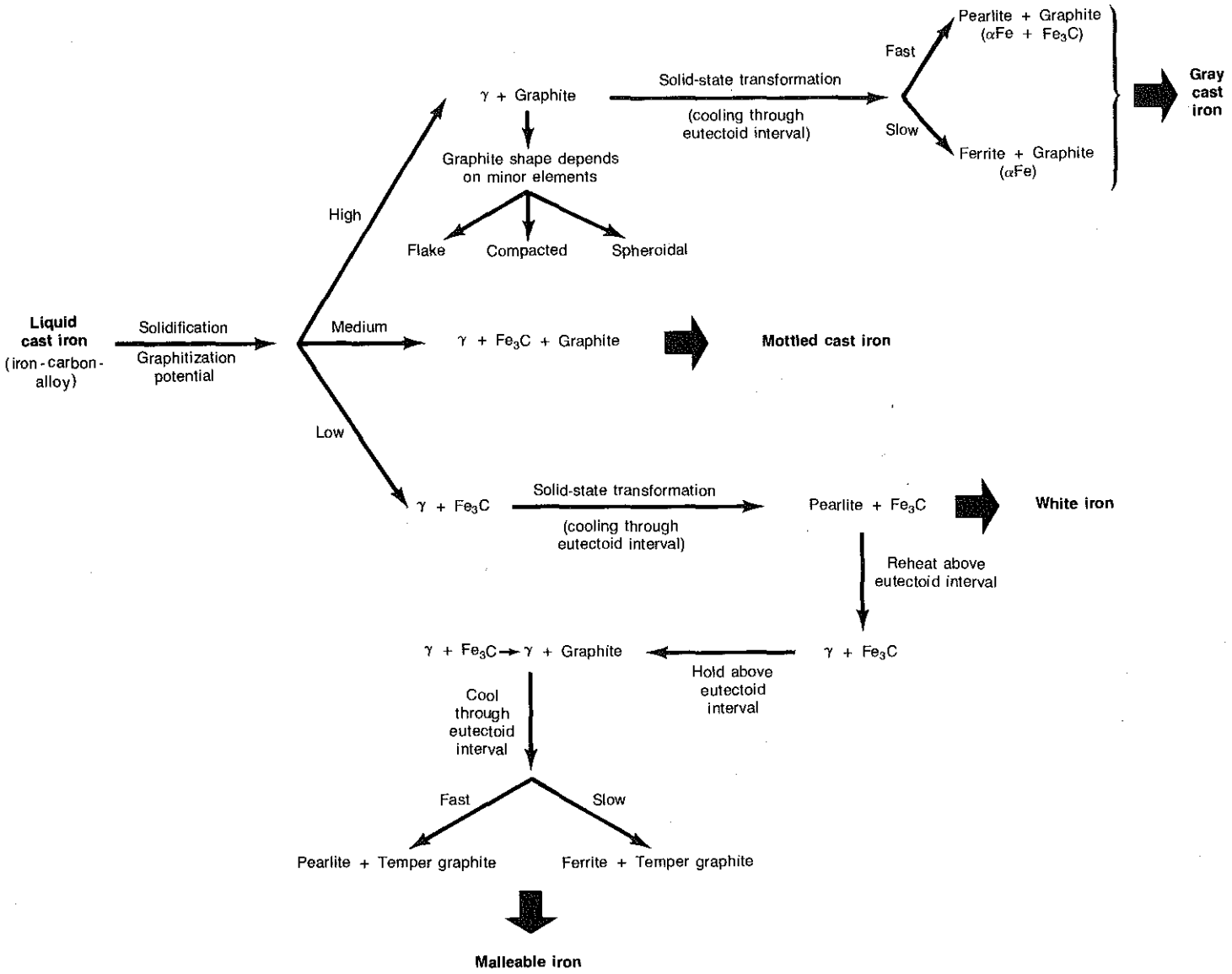


Fig. 1 Basic microstructures and processing for obtaining common commercial cast irons

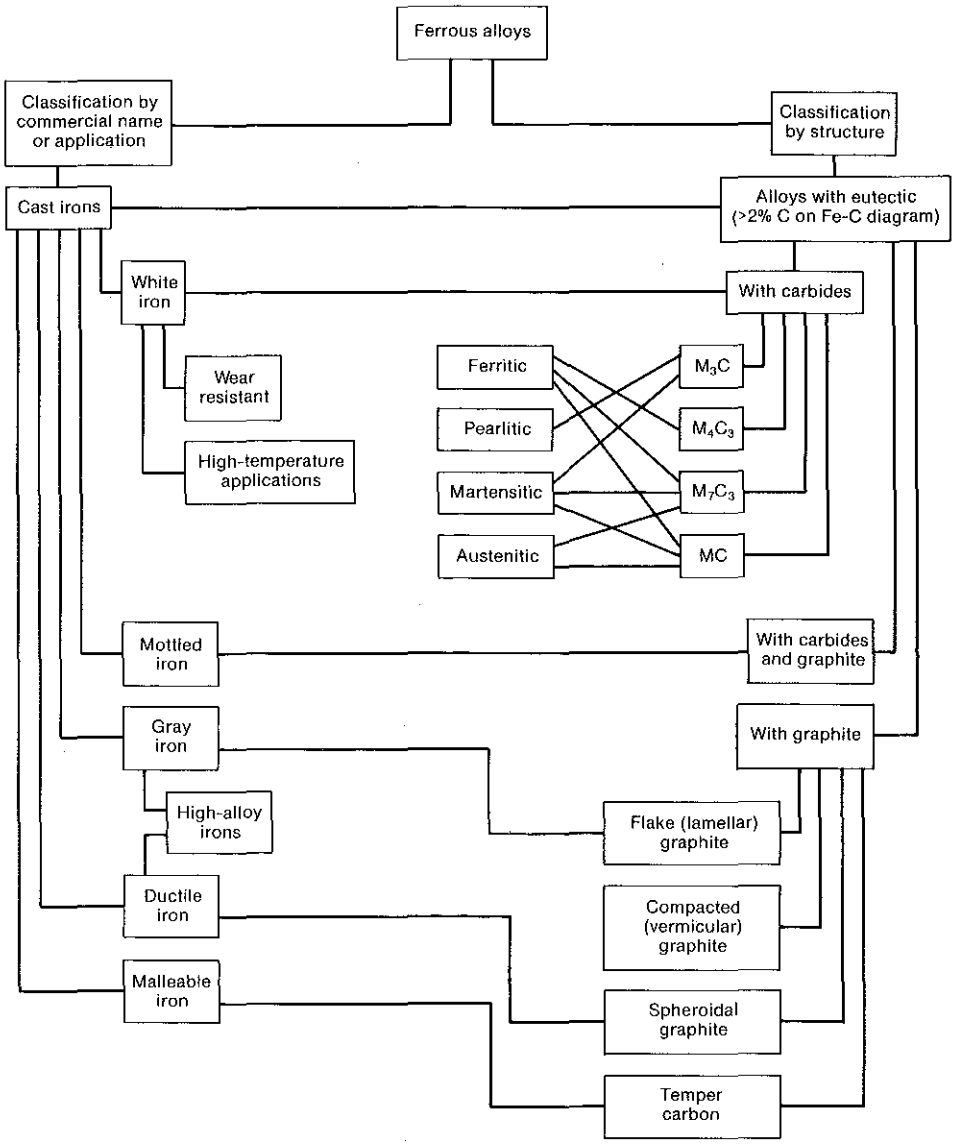


Fig. 2 Classification of cast irons

Table 1 Classification of cast iron by commercial designation, microstructure, and fracture

Commercial designation	Carbon-rich phase	Matrix(a)	Fracture	Final structure after
Gray iron	Lamellar graphite	P	Gray	Solidification
Ductile iron	Spheroidal graphite	F, P, A	Silver-gray	Solidification or heat treatment
Compacted graphite iron	Compacted (vermicular) graphite	F, P	Gray	Solidification
White iron	Fe_3C	P, M	White	Solidification and heat treatment(b)
Mottled iron	Lamellar Gr + Fe_3C	P	Mottled	Solidification
Malleable iron	Temper graphite	F, P	Silver-gray	Heat treatment
Austempered ductile iron	Spheroidal graphite	At	Silver-gray	Heat treatment

(a) F, ferrite; P, pearlite; A, austenite; M, martensite; At, austempered (bainite). (b) White irons are not usually heat treated, except for stress relief and to continue austenite transformation.

Fe-Fe_3C system or the stable iron-graphite system. When the metastable path is followed, the rich carbon phase in the eutectic is the iron carbide; when the stable solidification path is followed, the rich carbon phase is graphite. Referring only to the binary Fe-Fe_3C or iron-graphite system, cast iron can be defined as an iron-carbon alloy with more than 2% C. The reader is cautioned that silicon and other alloying elements may considerably change the maximum solubility of carbon in austenite (γ). Therefore, in exceptional cases, alloys with less than 2% C can solidify with a eutectic structure and therefore still belong to the family of cast iron.

The formation of stable or metastable eutectic is a function of many factors, including the nucleation potential of the liquid, chemical composition, and cooling rate. The first two factors determine the graphitization potential of the iron. A high graphitization potential will result in irons with graphite as the rich carbon phase, while a low graphitization potential will result in irons with iron carbide. A schematic of the structure of the common (unalloyed or low-alloy) types of commercial cast irons, as well as the processing required to obtain them, is shown in Fig. 1.

The two basic types of eutectics, the stable austenite-graphite and the metastable austenite-iron carbide (Fe_3C), have wide differences in their mechanical properties, such as strength, hardness, toughness, and ductility. Therefore, the basic purpose of the metallurgical processing of cast iron is to manipulate the type, amount, and morphology of the eutectic in order to achieve the desired mechanical properties.

Classification

Historically, the first classification of cast iron was based on its fracture. Two types of iron were initially recognized:

- *White iron* exhibits a white, crystalline fracture surface because fracture occurs along the iron carbide plates; it is the result of metastable solidification (Fe_3C eutectic).
- *Gray iron* exhibits a gray fracture surface because fracture occurs along the graphite plates (flakes); it is the result of stable solidification (Gr eutectic).

With the advent of metallography, and as the body of knowledge pertinent to cast iron increased, other classifications based on microstructural features became possible:

- *Graphite shape:* Lamellar (flake) graphite (FG), spheroidal (nodular) graphite (SG), compacted (vermicular) graphite (CG), and temper graphite (TG). Temper graphite results from a solid-state reaction (malleabilization).
- *Matrix:* Ferritic, pearlitic, austenitic, martensitic, and bainitic (austempered).

Another common classification scheme divides cast irons into four basic types: white iron, gray iron, ductile iron, and malleable iron. As indicated above, white iron and gray iron derive their names from the appearance of their respective fracture surfaces. Ductile iron derives its name from the fact that, in the as-cast form, it exhibits measurable ductility. By contrast, neither white nor gray iron exhibits significant ductility in a standard tensile test. Malleable iron is cast as white iron, then "malleabilized" (i.e., heat treated to impart ductility to an otherwise brittle material).

Besides the four basic types, there are other specific forms of cast iron to which special names have been applied.

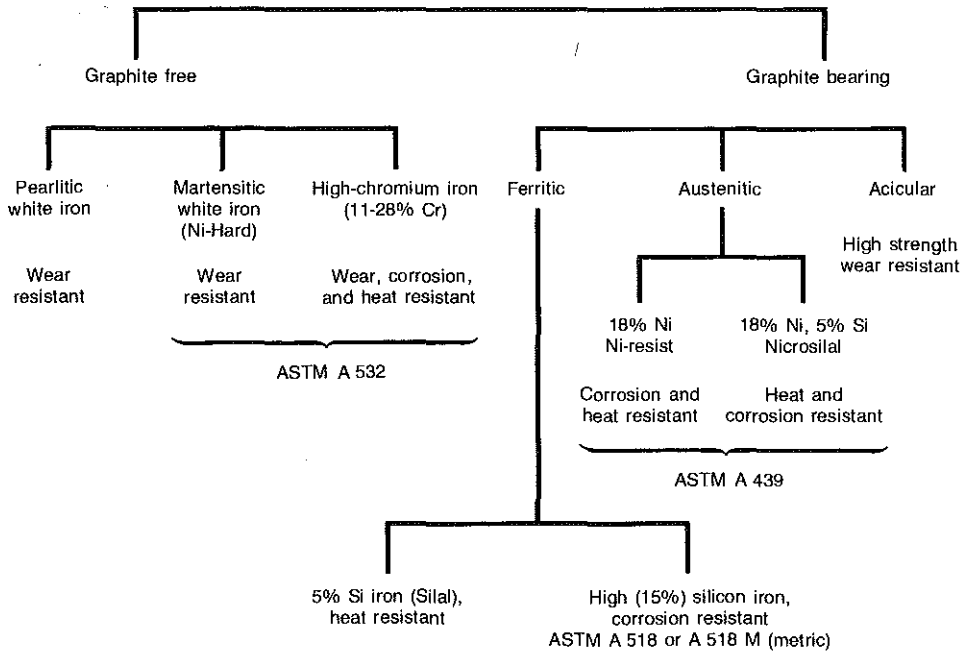


Fig. 3 Classification of special high-alloy cast irons. Source: Ref 1

- *Chilled iron* is white iron that has been produced by cooling very rapidly through the solidification temperature range.
- *Mottled iron* is an area of the casting that solidifies at a rate intermediate between those for chilled and gray iron, and which exhibits microstructural and fracture-surface features of both types.
- *Compacted graphite cast iron* (also known as vermicular iron) is characterized by graphite that is interconnected within eutectic cells, as is the flake graphite in gray iron. Compared with the graphite in gray iron, however, the graphite in CG iron is coarser and more rounded, i.e., its structure is intermediate between the structures of gray iron and ductile iron.
- *High-alloy graphitic irons* are used primarily for applications requiring corrosion resistance or a combination of strength and oxidation resistance. They are produced in both flake graphite (gray iron) or spheroidal graphite (ductile iron).

Figure 2 classifies cast irons according to their commercial names, applications, and structures.

Lastly, a classification used frequently by the floor foundry worker divides cast irons into two categories:

- *Common cast irons:* For general-purpose applications, unalloyed or low alloy
- *Special cast irons:* For special applications, generally high alloy

Table 1 gives the correspondence between commercial and microstructural classification, as well as the final processing stage in obtaining common cast irons. Special cast irons differ from common cast irons mainly in the higher content of alloying elements (>3%), which promote microstructures having special properties for elevated-temperature applications, corrosion resistance, and wear resistance. A classification of the main types of special high-alloy cast irons is shown in Fig. 3.

The Iron-Carbon-Silicon System

The metallurgy of cast irons has many similarities to that of steel, but the differences are important to the metallurgist who works with cast irons (Ref 2). The amount of alloying elements present in the most common grades of steel is relatively low, so these steels can basically be considered as binary iron-carbon alloys. Thus the iron-carbon diagram (Fig. 4) can be used to interpret their structures under conditions of slow or near-equilibrium transformation. The cast irons, however, contain appreciable amounts of silicon in addition to higher carbon contents, and they must be considered ternary Fe-C-Si alloys (Fig. 5). The introduction of this additional constituent, silicon, changes the iron-carbon diagram.

A section through the ternary Fe-Fe_3C-Si diagram at 2% Si (which approximates the silicon content of many cast irons) provides a convenient reference for discussing the metallurgy of cast iron. The diagram in Fig. 5 resembles the binary Fe-Fe_3C diagram in Fig. 4, but it exhibits important differences characteristic of ternary systems. Eutectic and eutectoid temperatures change from single values in the Fe-Fe_3C system to temperature ranges in the Fe-Fe_3C-Si system; the eutectic and eutectoid points shift to lower carbon contents.

Figure 5 represents the metastable equilibrium between iron and iron carbide (cementite), a metastable system. The silicon that is present remains in solid solution in the iron, in both ferrite and austenite, so it affects only the conditions and the kinetics of carbide formation on cooling, not the composition of the carbide phase. The designations α, γ, and Fe_3C, therefore, are used in the ternary system to identify the same phases that occur in the Fe-Fe_3C binary system. Some of the silicon may precipitate along with the carbide, but it cannot be distinguished as a different phase. The solidification of certain compositions occurs not in the metastable system, but rather in the stable system, where the products are iron and graphite rather than iron and carbide. These compositions encompass the gray, ductile, and compacted graphite cast irons.

To justify the use of the ternary diagram at 2% Si to trace phase changes, it must be assumed that the silicon concentration remains at 2% in all parts of the alloy under all conditions. This obviously is not strictly true, but there is little evidence that silicon segregates to any marked degree in cast iron. Thus it is only slightly inaccurate to use the constant-silicon section through the ternary diagram in the same manner as one would apply the Fe-Fe_3C diagram to carbon steel.

In summary, the addition of silicon to a binary iron-carbon alloy decreases the stability of Fe_3C, which is already metastable, and increases the stability of ferrite (the α field is enlarged, and the γ is constricted). The equilibrium diagrams in Fig. 6 show that as the silicon content in the Fe-C-Si system increases, the carbon contents of the eutectic and eutectoid decrease, while the eutectic and eutectoid temperatures increase.

Carbon Equivalent (Ref 2)

The upper dashed line in Fig. 7 indicates the eutectic composition for Fe-C-Si alloys. Without silicon the eutectic is at 4.3%. As the silicon content of iron is increased, the carbon content of the eutectic is decreased. This is a linear relation and can be expressed as a simple equation:

$$\%\,C + \tfrac{1}{3}\%\,Si = 4.3 \qquad \text{(Eq 1)}$$

It is convenient to combine the effect of the silicon with that of the carbon into a single factor, which is called the carbon equivalent (CE):

$$CE = \%\,C + \tfrac{1}{3}\%\,Si \qquad \text{(Eq 2)}$$

The CE of a cast iron describes how close a given analysis is to that of the eutectic composition. When the CE is 4.3, the alloy is eutectic. A CE of 3.9 represents an alloy of lower carbon and silicon content (hypoeutectic) than the eutectic composition, and a CE of 4.6 represents an alloy

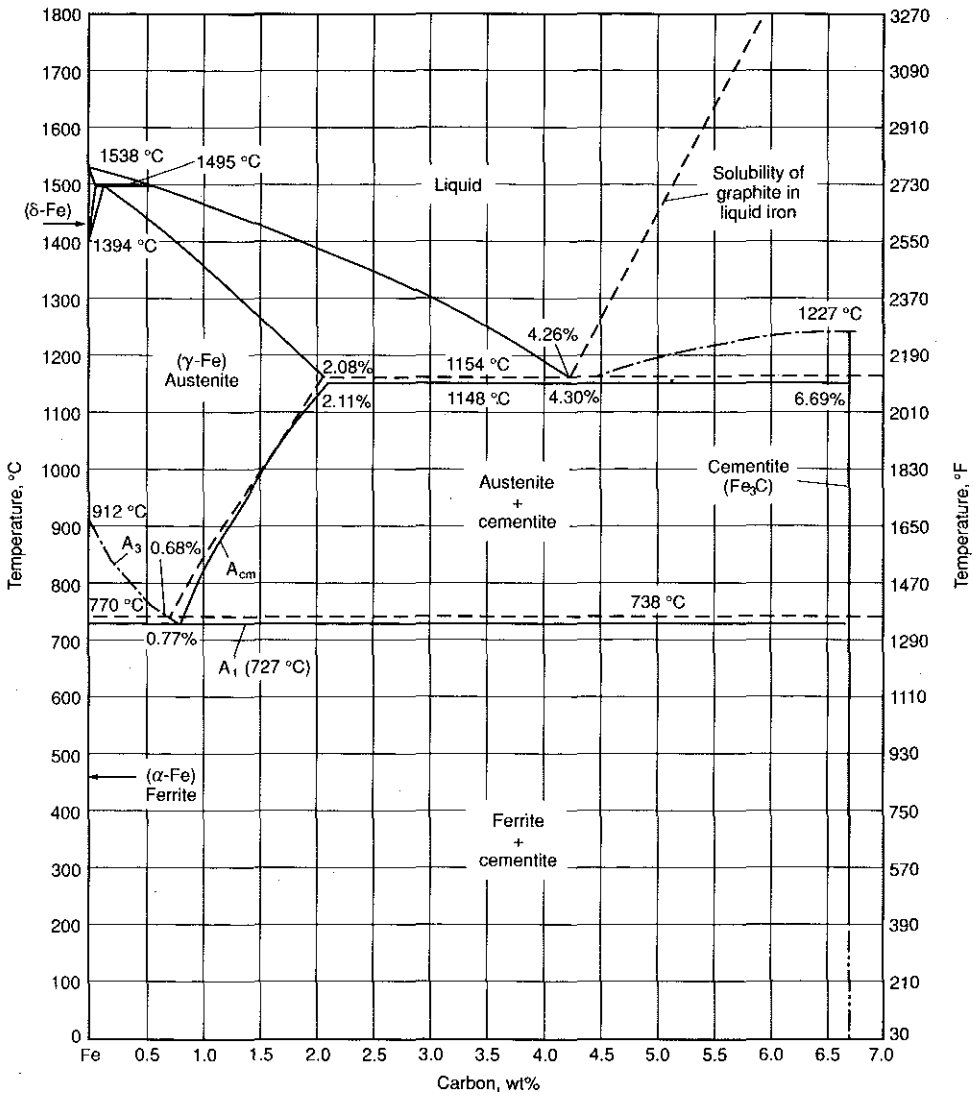


Fig. 4 Iron-carbon diagram, where solid curves represent the metastable system Fe-Fe_3C and dashed curves represent the stable system iron-graphite

of greater carbon and silicon content (hypereutectic) than the eutectic composition. Irons of the same CE value may be obtained with different carbon and silicon values.

Other values representing the CE of cast irons have also been suggested. When appreciable amounts of phosphorus are present in the iron, the phosphorus content of the iron is included:

$$\text{CE} = \%\,\text{C} + \frac{\%\,\text{Si} + \%\,\text{P}}{3} \qquad \text{(Eq 3)}$$

Thus, an iron with 3.2% C, 2% Si, and 0.4% P has a CE value of 4.0 and is hypoeutectic. An iron with 3.2% C, 2% Si, and 1.3% P has a CE value of 4.3 and is eutectic. An iron with 3.2% C, 2.9% Si, and 1.3% P has a CE value of 4.6 and is hypereutectic.

The total carbon and silicon contents of the alloy, as related in the CE value, not only establish the solidification temperature range of the alloy, but are also related to the foundry characteristics of the alloy and its properties. It should be noted, however, that irons of constant CE, but with appreciably different carbon and silicon contents, will not have similar casting properties. For example, carbon is more than twice as effective in preventing solidification shrinkage than the CE equation indicates. However, silicon is more effective in keeping thin sections from becoming hard. There are similar differences in some of the use properties, and these limit the value of CE in specifications.

Principles of the Metallurgy of Cast Irons

The goal of the metallurgist is to design a process that will produce a structure that will yield the expected mechanical properties. This requires knowledge of the structure-properties correlation for the particular alloy under consideration, as well as knowledge of the factors that affect the structure. When discussing the metallurgy of cast iron, the main factors of influence on the structure that one needs to address are:

- Chemical composition
- Cooling rate
- Liquid treatment
- Heat treatment

In addition, the following aspects of combined carbon in cast irons should be considered:

- In the original cooling or through subsequent heat treatment, a matrix can be internally decarburized or carburized by depositing graphite on existing sites or by dissolving carbon from them.
- Depending on the silicon content and the cooling rate, the pearlite in iron can vary in carbon content. This is a ternary system, and the carbon content of pearlite can be as low as 0.50% with 2.5% Si.
- The measured hardness of graphitic irons is influenced by the graphite, especially in gray iron. Martensite microhardness may be as high as 66 HRC or as low as 54 HRC in gray iron (58 HRC in ductile).
- The critical temperature of iron is influenced (raised) by silicon content, not carbon content.

The following sections in this article discuss some of the basic principles of cast iron metallurgy. More detailed descriptions of the metallurgy of cast irons are available in the articles in this Volume that describe specific types of cast irons.

Gray Iron (Flake Graphite Iron)

The composition of gray iron must be selected in such a way as to satisfy three basic structural requirements:

- The required graphite shape and distribution
- The carbide-free (chill-free) structure
- The required matrix

For common cast iron, the main elements of the chemical composition are carbon and silicon. Figure 7 shows the range of carbon and silicon for common cast irons as compared with steel. It is apparent that irons have carbon in excess of the maximum solubility of carbon in austenite, which is shown by the lower dashed line. A high carbon content increases the amount of graphite or Fe_3C. High carbon and silicon contents increase the graphitization potential of the iron as well as its castability. Although increasing the carbon and silicon contents improves the graphitization potential and therefore decreases the chilling tendency, the strength is adversely affected (Fig. 8). This is due to ferrite promotion and the coarsening of pearlite.

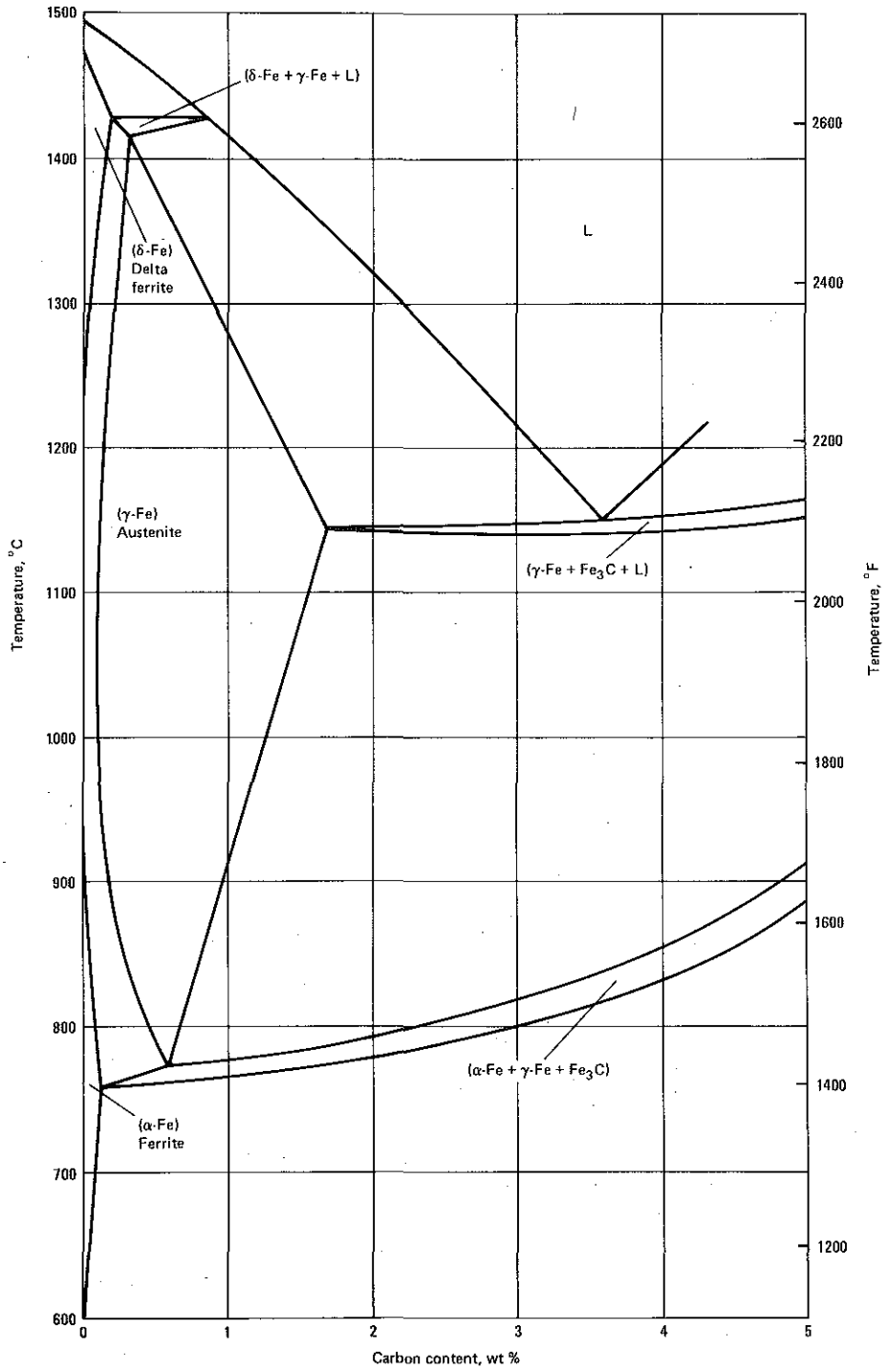


Fig. 5 Section through the Fe-Fe_3C-Si ternary equilibrium diagram at 2% Si

The manganese content varies as a function of the desired matrix. Typically, it can be as low as 0.1% for ferritic irons and as high as 1.2% for pearlitic irons, because manganese is a strong pearlite promoter.

From the minor elements, phosphorus and sulfur are the most common and are always present in the composition. They can be as high as 0.15% for low-quality iron and are considerably less for high-quality iron, such as ductile iron or compacted graphite iron. The effect of sulfur must be balanced by the effect of manganese. Without manganese in the iron, undesired iron sulfide (FeS) will form at grain boundaries. If the sulfur content is balanced by manganese, manganese sulfide (MnS) will form, but this is harmless because it is distributed within the grains. The optimum ratio between manganese and sulfur for an FeS-free structure and maximum amount of ferrite is:

$$\%\,Mn = 1.7\,(\%\,S) + 0.15 \qquad \text{(Eq 4)}$$

Other minor elements, such as aluminum, antimony, arsenic, bismuth, lead, magnesium, cerium, and calcium, can significantly alter both the graphite morphology and the microstructure of the matrix.

The range of composition for typical unalloyed common cast irons is given in Table 2. The typical composition range for low- and high-grade unalloyed gray iron (flake graphite iron) cast in sand molds is given in Table 3.

Both major and minor elements have a direct influence on the morphology of flake graphite. The typical graphite shapes for flake graphite are shown in Fig. 9. Type A graphite is found in inoculated irons cooled with moderate rates. In general, it is associated with the best mechanical properties, and cast irons with this type of graphite exhibit moderate undercooling during solidification (Fig. 10). Type B graphite is found in irons of near-eutectic composition, solidifying on a limited number of nuclei. Large eutectic cell size and low undercoolings are common in cast irons exhibiting this type of graphite. Type C graphite occurs in hypereutectic irons as a result of solidification with minimum undercooling. Type D graphite is found in hypoeutectic or eutectic irons solidified at rather high cooling rates, while type E graphite is characteristic for strongly hypoeutectic irons. Types D and E are both associated with high undercoolings during solidification. Not only graphite shape but also graphite size is important, because it is directly related to strength (Fig. 11).

Alloying elements can be added in common cast iron to enhance some mechanical properties. They influence both the graphitization potential and the structure and properties of the matrix. The main elements are listed below in terms of their graphitization potential:

High positive graphitization potential (decreasing positive potential from top to bottom)
Carbon
Tin
Phosphorus
Silicon
Aluminum
Copper
Nickel
Neutral
Iron
High negative graphitization potential (increasing negative potential from top to bottom)
Manganese
Chromium
Molybdenum
Vanadium

This classification is based on the thermodynamic analysis of the influence of a third element on carbon solubility in the Fe-C-*X* system, where *X* is a third element (Ref 6). Although phosphorus is listed as a graphitizer (which may be true thermodynamically), it also acts as a matrix hardener. Above its solubility level (probably about 0.08%), phosphorus forms a very hard ternary eutectic. The above classification should also in-

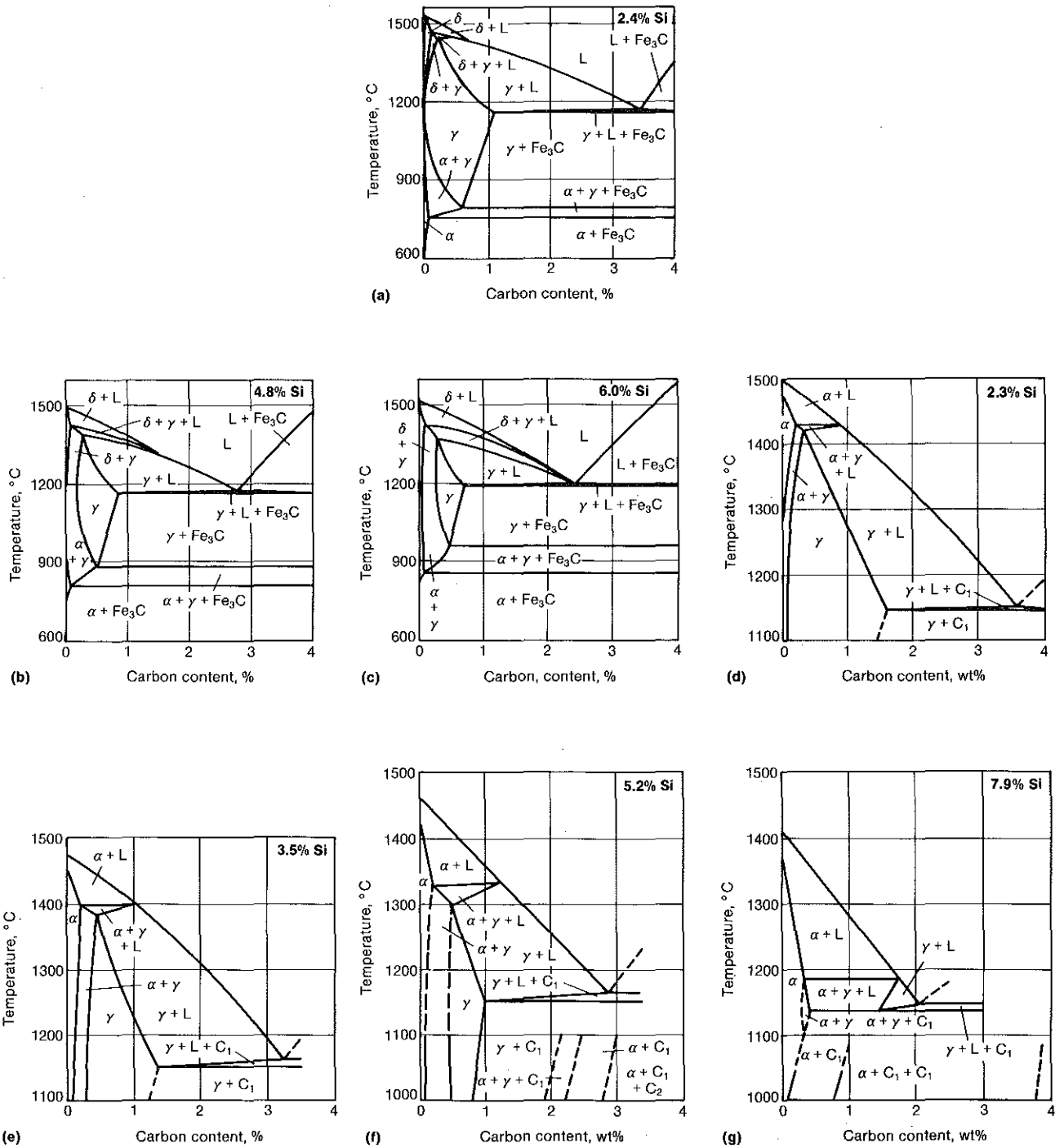


Fig. 6 Influence of silicon content on the solubility lines and equilibrium temperatures of the iron-carbon system. (a) to (c) Source: Ref 3. (d) to (g) Source: Ref 4

clude sulfur as a carbide former, although manganese and sulfur can combine and neutralize each other. The resultant MnS also acts as nuclei for flake graphite. In industrial processes, nucleation phenomena may sometimes override solubility considerations.

In general, alloying elements can be classified into three categories, discussed below.

Silicon and aluminum increase the graphitization potential for both the eutectic and eutectoid transformations and increase the number of graphite particles. They form solid solutions in the matrix. Because they increase the ferrite-pearlite ratio, they lower strength and hardness.

Nickel, copper, and tin increase the graphitization potential during the eutectic transformation but decrease it during the eutectoid transformation, thus raising the pearlite-ferrite ratio. This second effect is due to the retardation of carbon diffusion. These elements form solid solution in the matrix. Because they increase the amount of pearlite, they raise strength and hardness.

Chromium, molybdenum, tungsten, and vanadium decrease the graphitization potential at both stages. Thus, they increase the amount of carbides and pearlite. They principally concentrate in the carbides, forming $(FeX)_nC$-type carbides, but also alloy the αFe solid solution. As long as carbide formation does not occur, these elements increase strength and hardness. Above a certain

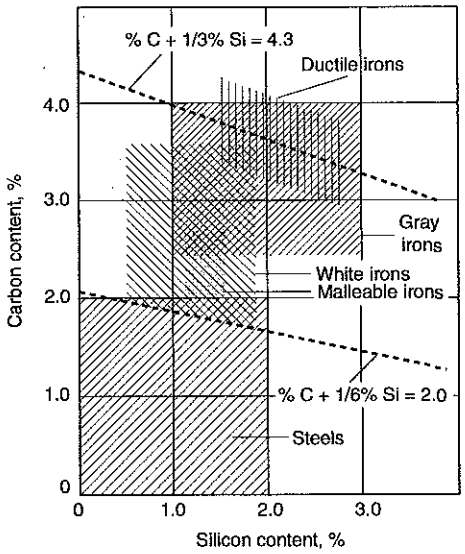


Fig. 7 Approximate ranges of carbon and silicon for steel and various cast irons. Source: Ref 2

level, any of these elements will determine the solidification of a structure with both Gr and Fe_3C (mottled structure), which will have lower strength but higher hardness.

In moderately alloyed gray iron, the typical ranges for the elements discussed above are as follows:

Element	Composition, %
Chromium	0.2-0.6
Molybdenum	0.2-1
Vanadium	0.1-0.2
Nickel	0.6-1
Copper	0.5-1.5
Tin	0.04-0.08

The influence of composition and cooling rate on tensile strength can be estimated using (Ref 5):

$$TS = 162.37 + 16.61/D - 21.78\ (\%\ C) - 61.29\ (\%\ Si) - 10.59\ (\%\ Mn - 1.7\%\ S) + 13.80\ (\%\ Cr) + 2.05\ (\%\ Ni) + 30.66\ (\%\ Cu) + 39.75\ (\%\ Mo) + 14.16\ (\%\ Si)^2 - 26.25\ (\%\ Cu)^2 - 23.83\ (\%\ Mo)^2 \quad \text{(Eq 5)}$$

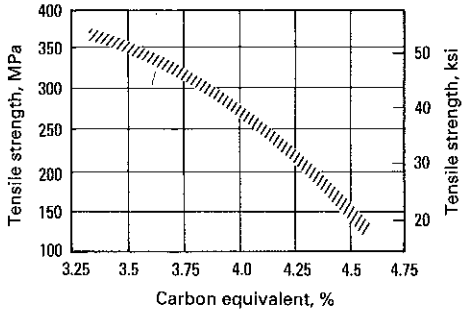


Fig. 8 General influence of carbon equivalent on the tensile strength of gray iron. Source: Ref 2

where TS is the tensile strength and D is the bar diameter (in inches). Equation 5 is valid for bar diameters of 20 to 50 mm (1/8 to 2 in.) and compositions within the following ranges:

Element	Composition, %
Carbon	3.04-3.29
Chromium	0.1-0.55
Molybdenum	0.03-0.78
Silicon	1.6-2.46
Nickel	0.07-1.62
Sulfur	0.089-0.106
Manganese	0.39-0.98
Copper	0.07-0.85

The cooling rate, like the chemical composition, can significantly influence the as-cast structure and therefore the mechanical properties. The cooling rate of a casting is primarily a function of its section size. The dependence of structure and properties on section size is termed section sensitivity. Increasing the cooling rate will:

- Refine both graphite size and matrix structure; this will result in increased strength and hardness
- Increase the chilling tendency; this may result in higher hardness, but will decrease the strength

Consequently, composition must be tailored in such a way as to provide the correct graphitization potential for a given cooling rate. For a given chemical composition and as the section thickness increases, the graphite becomes coarser, and the pearlite/ferrite ratio decreases, which results in lower strength and hardness (Fig. 12). Higher CE has similar effects.

The liquid treatment of cast iron is of paramount importance in the processing of this alloy because it can dramatically change the nucleation and growth conditions during solidification. As a result, graphite morphology, and therefore properties, can be significantly affected. In gray iron practice, the liquid treatment used, termed inoculation, consists of minute additions of minor elements before pouring. Typically, ferrosilicon with additions of aluminum and calcium, or proprietary alloys, are used as inoculants. The main effects of inoculation are:

- An increased graphitization potential because of decreased undercooling during solidification; as a result of this, the chilling tendency is diminished, and graphite shape changes from type D or E to type A
- A finer structure (i.e., higher number of eutectic cells), with a subsequent increase in strength

As shown in Fig. 13, inoculation improves tensile strength. This influence is more pronounced for low-CE cast irons.

Heat treatment can considerably alter the matrix structure, although graphite shape and size remain basically unaffected. A rather low proportion of the total gray iron produced is heat treated.

Table 2 Range of compositions for typical unalloyed common cast irons

Type of iron	Composition, % C	Si	Mn	P	S
Gray	2.5-4.0	1.0-3.0	0.2-1.0	0.002-1.0	0.02-0.25
Compacted graphite	2.5-4.0	1.0-3.0	0.2-1.0	0.01-0.1	0.01-0.03
Ductile	3.0-4.0	1.8-2.8	0.1-1.0	0.01-0.1	0.01-0.03
White	1.8-3.6	0.5-1.9	0.25-0.8	0.06-0.2	0.06-0.2
Malleable	2.2-2.9	0.9-1.9	0.15-1.2	0.02-0.2	0.02-0.2

Source: Ref 2

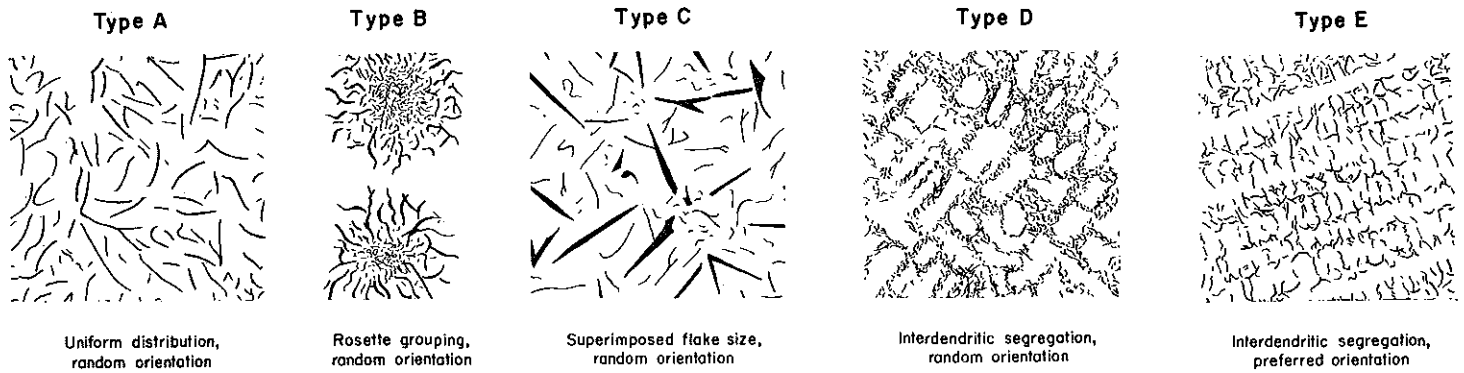


Fig. 9 Types of graphite flakes in gray iron (AFS-ASTM). In the recommended practice (ASTM A 247), these charts are shown at a magnification of 100×. They have been reduced to one-third size for reproduction here.

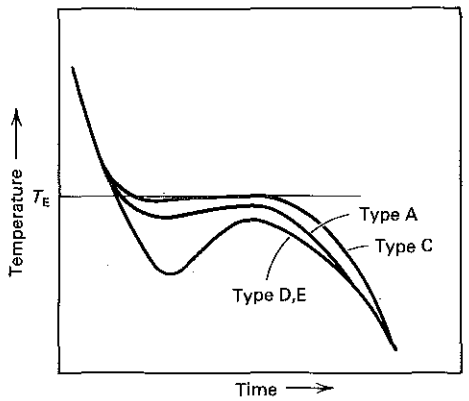


Fig. 10 Characteristic cooling curves associated with different flake graphite shapes. T_E, equilibrium eutectic temperature

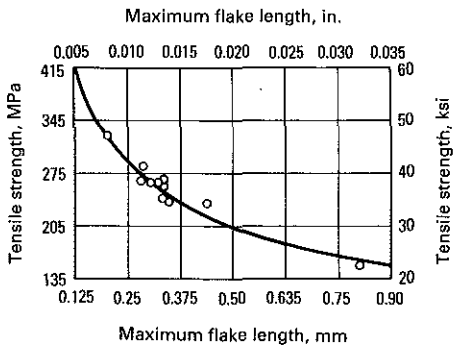


Fig. 11 Effect of maximum graphite flake length on the tensile strength of gray iron. Source: Ref 5

Common heat treatments are stress relieving or annealing to decrease hardness.

Ductile Iron (Spheroidal Graphite Iron)

Composition. The main effects of chemical composition are similar to those described for gray iron, with quantitative differences in the extent of these effects and qualitative differences in the influence on graphite morphology. The CE has only a mild influence on the properties and structure of ductile iron, because it affects graphite shape considerably less than in the case of gray iron. Nevertheless, to prevent excessive shrinkage, high chilling tendency, graphite flotation, or a high-impact transition temperature, optimum amounts of carbon and silicon must be selected. Figure 14 shows the basic guidelines for the selection of appropriate compositions.

As mentioned previously, minor elements can significantly alter the structure in terms of graphite morphology, chilling tendency, and matrix structure. Minor elements can promote the spheroidization of graphite or can have an adverse effect on graphite shape. The minor elements that adversely affect graphite shape are said to degenerate graphite shape. A variety of

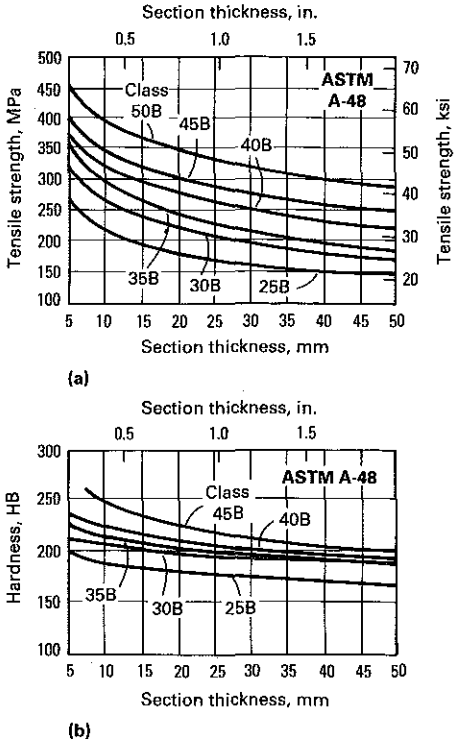


Fig. 12 Influence of section thickness of the casting on (a) tensile strength and (b) hardness for a series of gray irons classified by their strength as-cast in 30 mm (1.2 in.) diam bars. Source: Ref 2

graphite shapes can occur, as illustrated in Fig. 15. Graphite shape is the single most important factor affecting the mechanical properties of cast iron, as shown in Fig. 16.

The generic influence of various elements on graphite shape is given in Table 4. The elements in the first group, the spheroidizing elements, can change graphite shape from flake to compacted to spheroidal. This is illustrated in Fig. 17 for magnesium. The most widely used element for the production of spheroidal graphite is magnesium. The amount of residual magnesium required to produce spheroidal graphite, Mg_{resid}, is generally 0.03 to 0.05%. The precise level depends on the cooling rate. A higher cooling rate requires less magnesium. The amount of magnesium to be added in the iron is a function of the initial sulfur level, S_{in}, and the recovery of magnesium, η, in the particular process used:

$$Mg_{added} = \frac{0.75\ S_{in} + Mg_{resid}}{\eta} \qquad \text{(Eq 6)}$$

A residual magnesium level that is too low results in insufficient nodularity (i.e., a low ratio

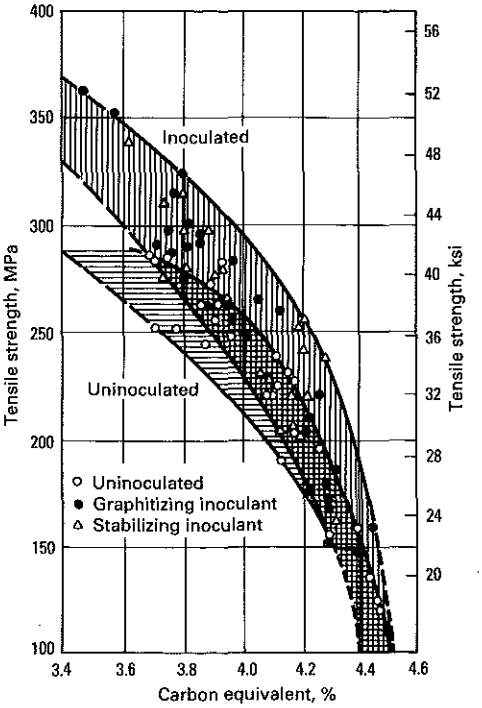


Fig. 13 Influence of inoculation on tensile strength as a function of carbon equivalent for 30 mm (1.2 in.) diam bars. Source: Ref 2

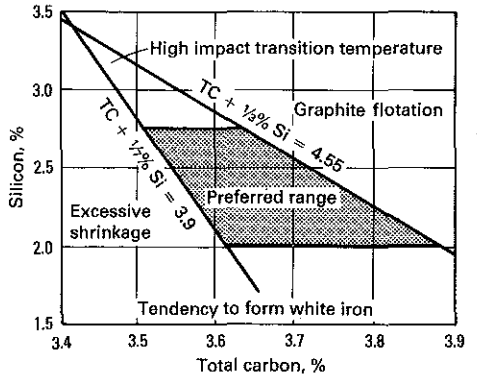


Fig. 14 Typical range for carbon and silicon contents in good-quality ductile iron. TC, total carbon. Source: Ref 2

between the spheroidal graphite and the total amount of graphite in the structure). This in turn results in a deterioration of the mechanical properties of the iron, as illustrated in Fig. 18. If the magnesium content is too high, carbides are promoted.

The presence of antispheroidizing (deleterious) minor elements may result in graphite shape deterioration, up to complete graphite degeneration. Therefore, upper limits are set on the amount of

Table 3 Compositions of unalloyed gray irons

ASTM A 48 class	Carbon equivalent	Composition, % C	Si	Mn	P	S
20B	4.5	3.1-3.4	2.5-2.8	0.5-0.7	0.9	0.15
55B	3.6	≤3.1	1.4-1.6	0.6-0.75	0.1	0.12

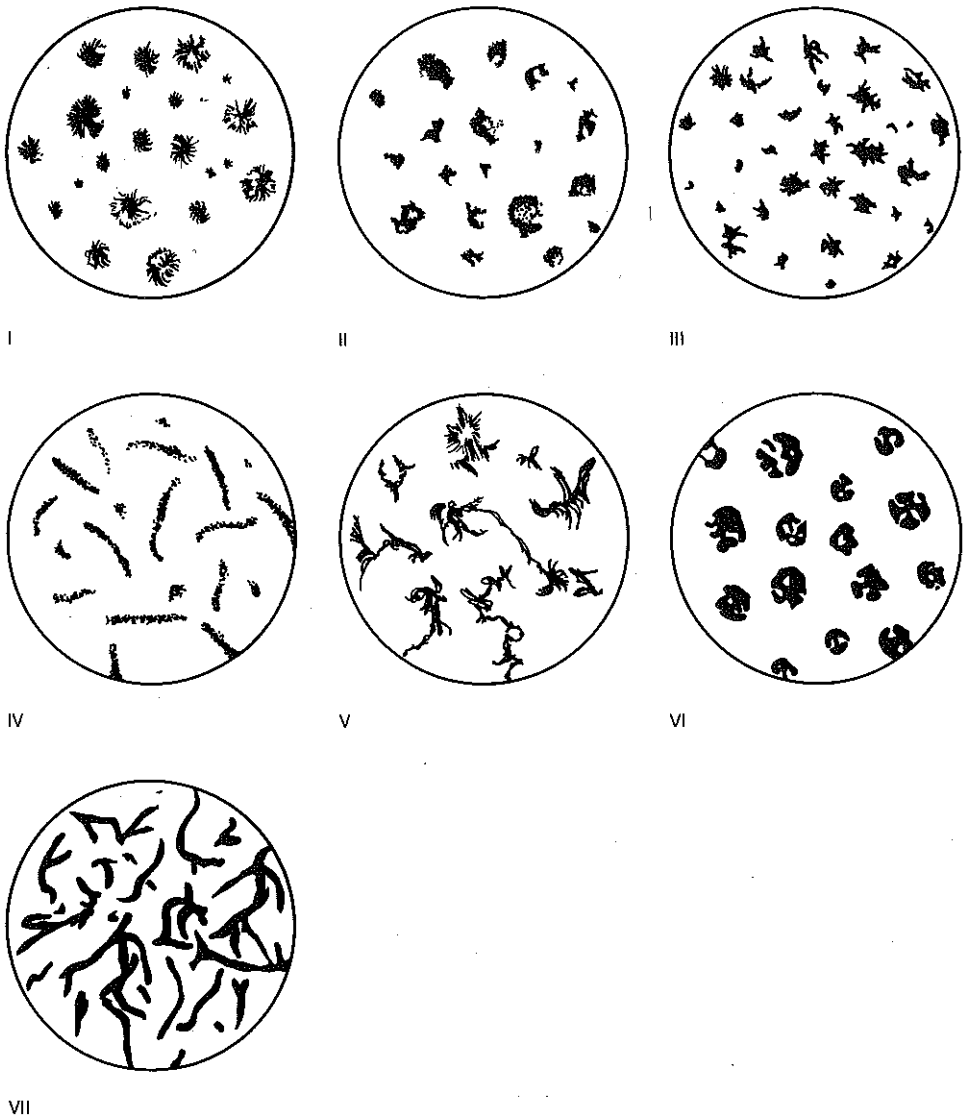


Fig. 15 Typical graphite shapes after ASTM A 247. I, spheroidal graphite; II, imperfect spheroidal graphite; III, temper graphite; IV, compacted graphite; V, crab graphite; VI, exploded graphite; VII, flake graphite

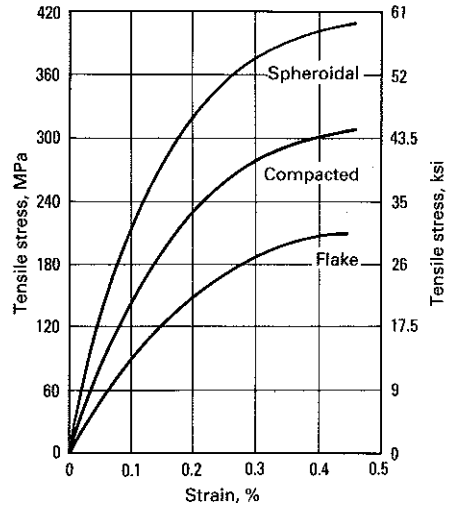


Fig. 16 Influence of graphite morphology on the stress-strain curve of several cast irons

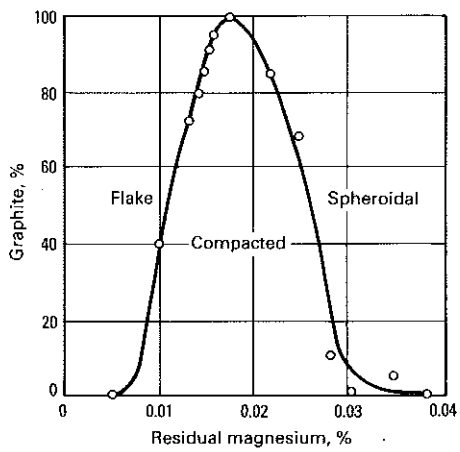


Fig. 17 Influence of residual magnesium on graphite shape

deleterious elements to be accepted in the composition of cast iron. Typical maximum limits are (Ref 9, 10):

Element	Composition, %
Aluminum	0.05
Arsenic	0.02
Bismuth	0.002
Cadmium	0.01
Lead	0.002
Antimony	0.001
Selenium	0.03
Tellurium	0.02
Titanium	0.03
Zirconium	0.10

These values can be influenced by the combination of various elements and by the presence of rare earths in the composition. Furthermore, some of these elements can be deliberately added during liquid processing in order to increase nodule count.

In general, alloying elements have the same influence on structure and properties of ductile iron as for gray iron. A better graphite morphology allows more efficient use of the mechanical properties of the matrix, so alloying is more common in ductile iron than in gray iron.

Cooling Rate. When the cooling rate is changed, effects similar to those discussed for gray iron occur in ductile iron, but the section sensitivity of ductile iron is lower. This is because spheroidal graphite is less affected by cooling rate than flake graphite.

The liquid treatment of ductile iron is more complex than that of gray iron. The two stages for the liquid treatment of ductile iron are:

1. Modification, which consists of magnesium or magnesium alloy treatment of the melt, with the purpose of changing graphite shape from flake to spheroidal
2. Inoculation (normally, postinoculation, i.e., after the magnesium treatment) to increase the nodule count. Increasing the nodule count is an important goal, because a higher nodule count is associated with less chilling tendency (Fig. 19) and a higher as-cast ferrite/pearlite ratio

Table 4 Influence of various elements on graphite shape

Element category	Element
Spheroidizer	Magnesium, calcium, rare earths (cerium, lanthanum, etc.), yttrium
Neutral	Iron, carbon, alloying elements
Antispheroidizer (degenerate shape)	Aluminum, arsenic, bismuth, tellurium, titanium, lead, sulfur, antimony

Heat treatment is extensively used in the processing of ductile iron. Better advantage can be taken of the matrix structure than for gray iron. The heat treatments usually applied are:

- Stress relieving
- Annealing to produce a ferritic matrix
- Normalizing to produce a pearlitic matrix

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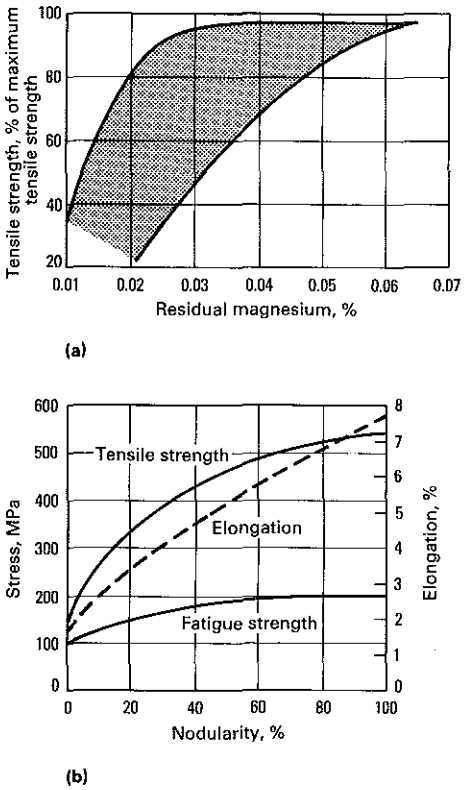


Fig. 18 Influence of (a) residual magnesium and (b) modularity on some mechanical properties of ductile iron. Source: Ref 7, 8

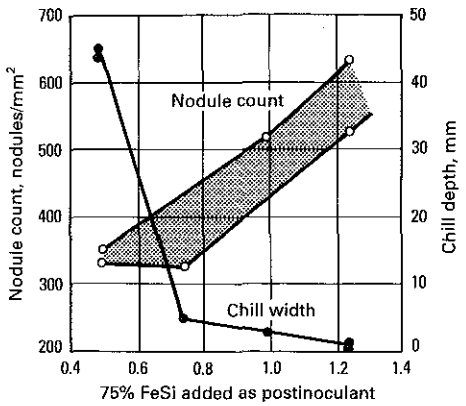


Fig. 19 Influence of the amount of 75% ferrosilicon added as a postinoculant on the nodule count and chill depth of 3 mm (0.12 in.) plates. Source: Ref 11

- Hardening to produce tempering structures
- Austempering to produce a ferritic bainite

Austempering results in ductile irons with twice the tensile strength for the same toughness. A comparison between some mechanical properties of austempered ductile iron and standard ductile iron is shown in Fig. 20.

Compacted Graphite Irons

Compacted graphite (CG) irons have a graphite shape intermediate between spheroidal and flake. Typically, CG looks like type IV graphite (Fig. 15), and most of the properties of CG irons lie in between those of gray and ductile iron.

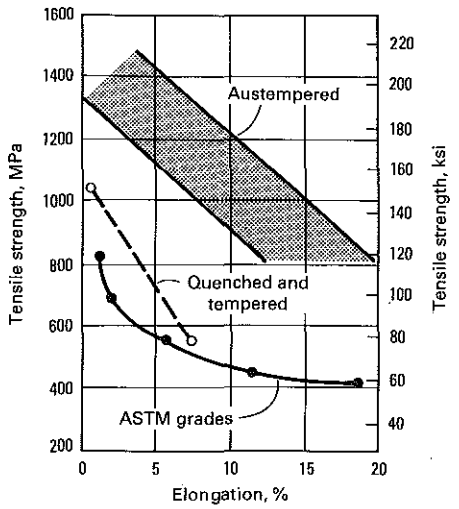


Fig. 20 Properties of some standard and austempere ductile irons. Source: Ref 12

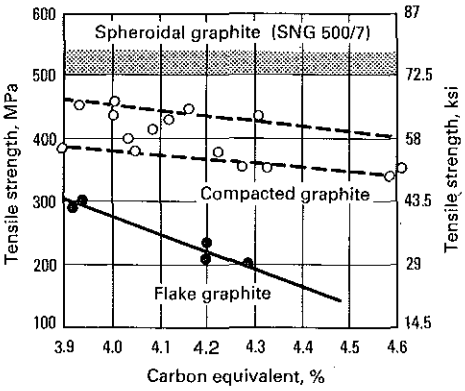


Fig. 21 Effect of carbon equivalent on the tensile strength of flake, compacted, and spheroidal graphite irons cast in 30 mm (1.2 in.) diam bars. Source: Ref 13

The chemical composition effects of CG irons are similar to those described for ductile iron. The CE influences strength less obviously than for the case of gray iron, but more than for ductile iron, as shown in Fig. 21. The graphite shape is controlled, as in the case of ductile iron, through the content of minor elements. When the goal is to produce CG, it is easier from the standpoint of controlling the structure to combine spheroidizing (magnesium, calcium, and/or rare earths) and antispheroidizing (titanium and/or aluminum) elements. Additional information is available in the article "Foundry Practice for Cast Irons" in this Volume.

The cooling rate affects properties of CG irons less for gray iron but more for ductile iron (Fig. 22). In other words, CG iron is less section sensitive than gray iron. However, high cooling rates are to be avoided because of the high propensity of CG iron for chilling and high nodule count in thin sections.

Liquid treatment can have two stages, as for ductile iron. Modification can be achieved with

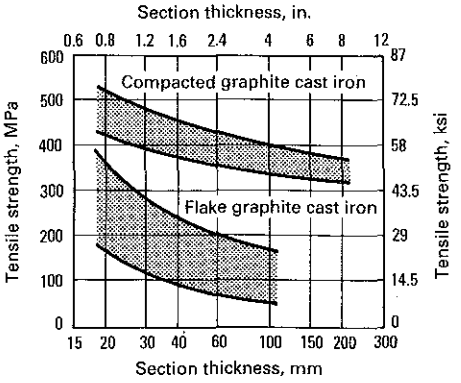


Fig. 22 Influence of section thickness on the tensile strength of compacted graphite irons. Source: Ref 14

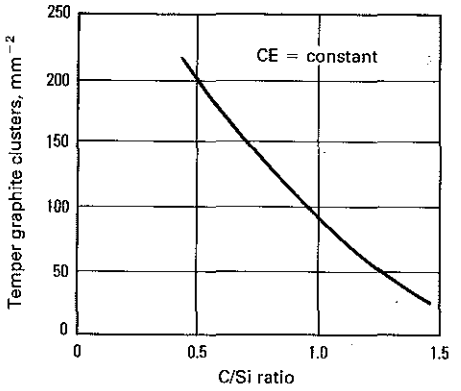


Fig. 23 Influence of C/Si ratio on the number of temper graphite clusters at constant carbon equivalent. Source: Ref 14

magnesium, Mg + Ti, Ce + Ca, and so on. Inoculation must be kept at a low level to avoid excessive nodularity.

Heat treatment is not common for CG irons.

Malleable Irons

Malleable cast irons differ from the types of irons previously discussed in that they have an initial as-cast white structure, that is, a structure consisting of iron carbides in a pearlitic matrix. This white structure is then heat treated (annealing at 800 to 970 °C, or 1470 to 1780 °F), which results in the decomposition of Fe_3C and the formation of temper graphite. The basic solid-state reaction is:

$$Fe_3C \rightarrow \gamma + Gr \qquad \text{(Eq 7)}$$

The final structure consists of graphite and pearlite, pearlite and ferrite, or ferrite. The structure of the matrix is a function of the cooling rate after annealing. Most of the malleable iron is produced by this technique and is called blackheart malleable iron. Some malleable iron, called whiteheart malleable iron, is produced in Europe by decarburization of the white as-cast iron.

The composition of malleable irons must be selected in such a way as to produce a white as-cast structure and to allow for fast annealing