

CHAPTER 11

Cast Irons

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Introduction

Cast irons of different types constitute the largest tonnage of all metal castings produced. Cast irons offer a wide range of properties, namely strength, hardness, machinability, corrosion resistance, abrasion resistance, damping, etc. Foundry properties such as high casting yield, good fluidity, low shrinkage, easily attainable casting soundness, and others make cast irons highly desirable material for engineering and other uses. Recent developments have added to the versatility of cast irons by offering enhanced engineering properties ensuring widespread use in the future. During 2010, a total of 94.1 million tons of castings were produced in the world, as per the *Modern Casting Magazine* (December 2011) World-casting census. All types of iron castings accounted for 73% of total casting production (gray iron 47%, ductile 25%, and malleable 1%). Malleable iron tonnage is decreasing while ductile iron and gray iron tonnage is increasing. For the history of cast iron starting in 2000 BC to the present, students are referred to the review by C. R. Loper Jr. [1, 2].

Examples of Iron Castings

Cast iron is a versatile engineering material, and economical to produce. In Fig. 11.1, a few of the multitude of castings made in different molding processes and meeting different specifications are shown. There is a wide range of sizes, shapes, and applications where iron castings are used.

Various Types of Cast Irons—Definitions

Cast irons can be defined as alloys of iron with carbon and silicon along with other elements depending on type and grade, where $\%C + 1/6\%Si = 2.0\%$ or higher. This represents maximum solubility of carbon in austenite. Above this level, carbon will precipitate as either free carbon (graphite) or as cementite (iron carbide). The term *cast iron* is a generic term that refers to a family of materials differing widely in their properties. Cast iron (unalloyed) is in general an alloy of iron, carbon (up to about 4.0%), and silicon (up to about 4.5%). Alloyed cast irons may contain elements like nickel, chromium, molybdenum, and manganese to varying percentages. Definitions of specific types are given below.



(a)



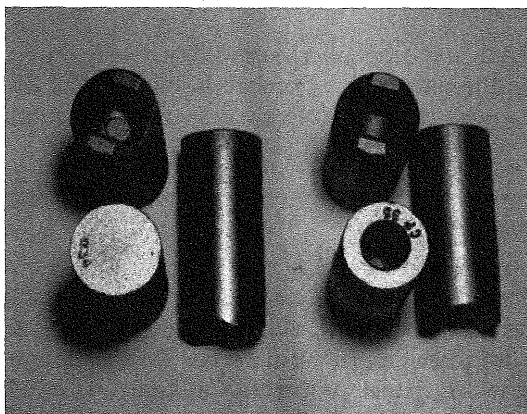
(b)



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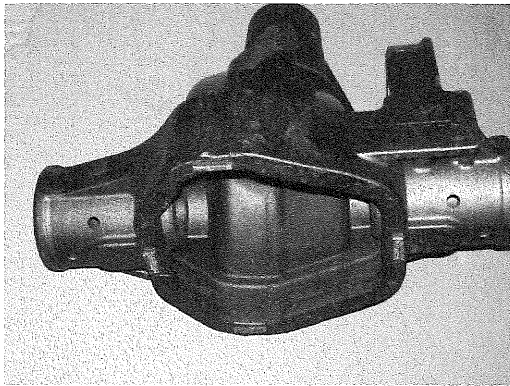


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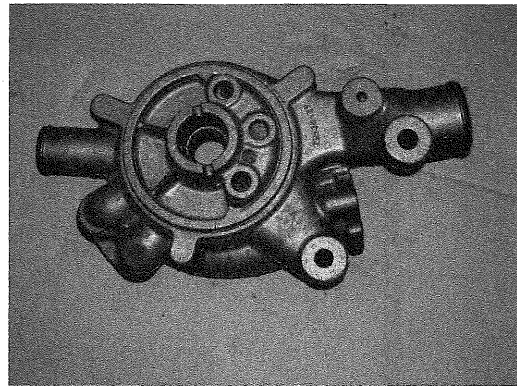


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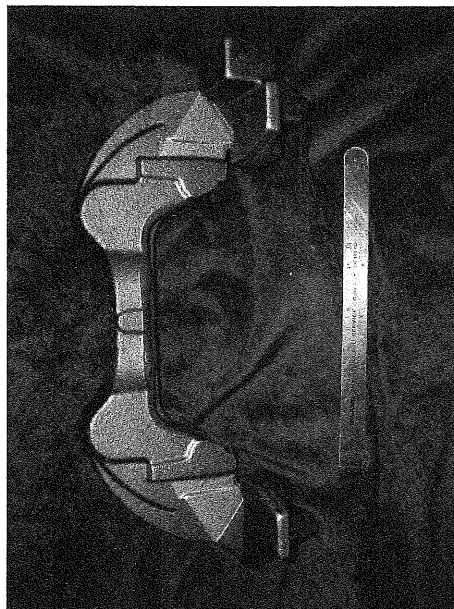
FIGURE 11.1 Typical castings produced in cast iron. (a) Gear shift fork, (b) rocker arm, (c) anchor plate, (d) caliper, and (e) valve lifters, shell moded. (Continued)



(f)



(g)



(h)

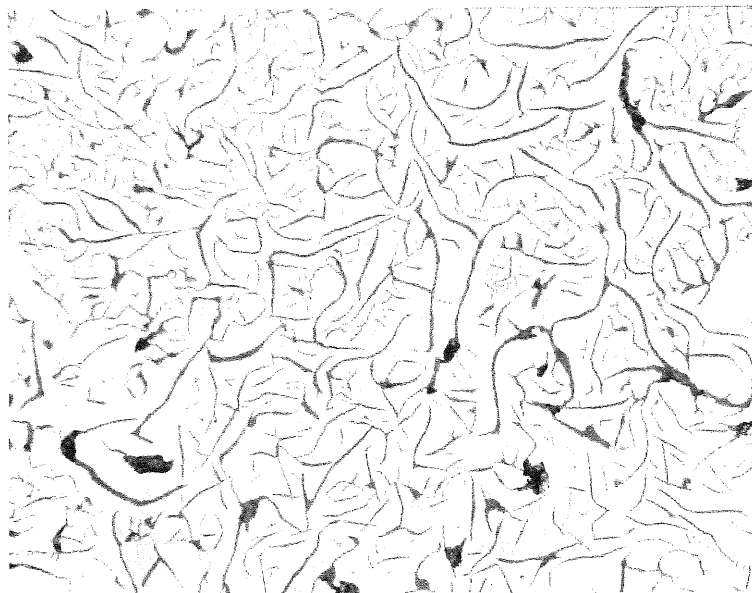
FIGURE 11.1 (Continued) (f) Differential carrier—lost-foam process, (g) fluid circulating pump—lost-foam process, (h) brake anchor. (Private communication a, b, and e from Castwell, Skokie, IL and c, d, f, g, and h from Alagarsamy Consulting.)

Gray Cast Iron

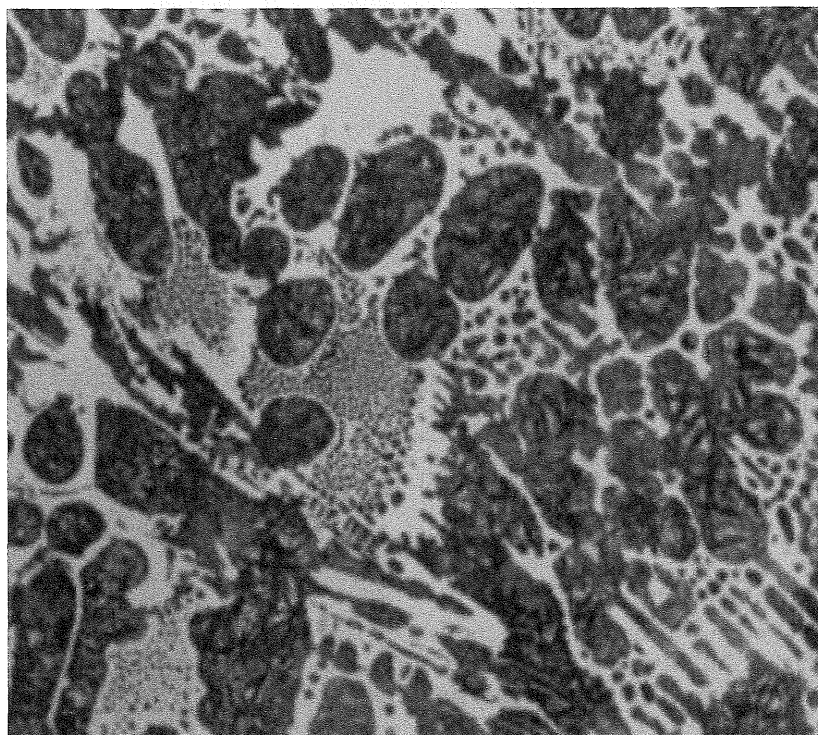
An iron in which most of the carbon appears as free or graphitic carbon in “flake” form (Fig. 11.2a). Matrix is generally pearlitic but could also contain ferrite. Gray cast iron when fractured appears as gray and sooty.

White Cast Iron

An iron having a composition such that after solidification, its carbon is present in combined form as cementite (iron carbide). White iron exhibits a white crystalline fracture (Fig. 11.2b and c).

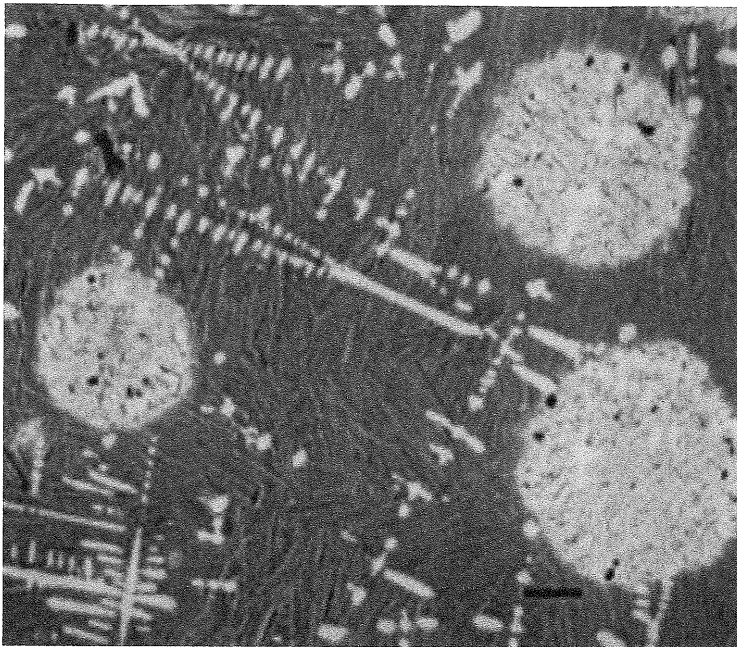


(a)

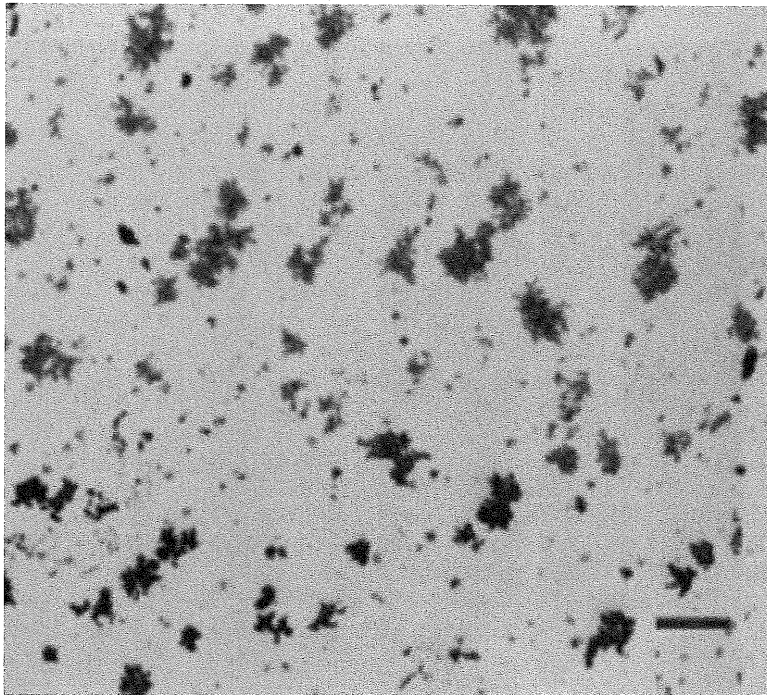


(b)

FIGURE 11.2 Micrographs of various forms of cast irons. (a) flake graphite in gray iron, (b) white iron (Ni-hard), etched. (Continued)

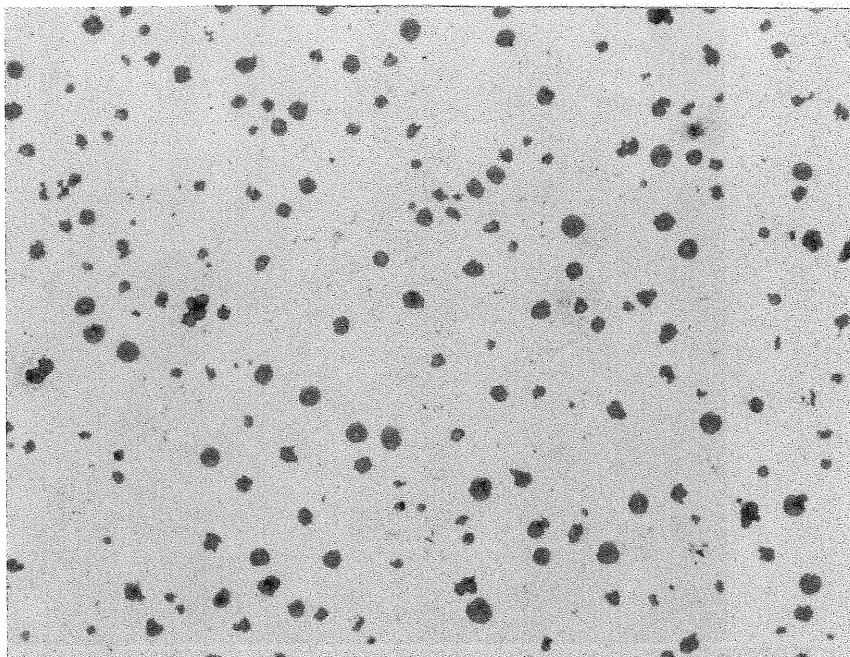


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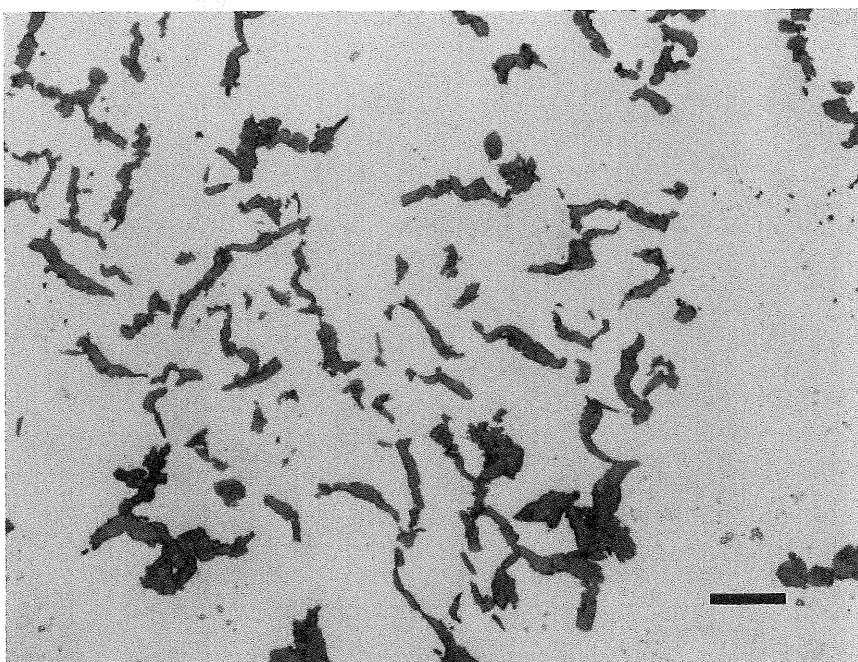


(d)

FIGURE 11.2 (Continued) (c) massive cementite in chill cast iron, etched, (d) temper carbon in malleable iron. (Continued)



(e)



(f)

FIGURE 11.2 (Continued) (e) spheroidal graphite in ductile iron, and (f) vermicular graphite in CG iron. (From Vander Voort [3].)

Chilled Cast Iron

An iron that would freeze normally as gray iron with flake graphite is forced to solidify fast in certain locations by rapid cooling by use of metal or graphite chills. Fractured surfaces of chilled iron show areas of white iron where it cooled fast and areas of gray iron where it solidified slowly.

Malleable Iron

An iron that develops ductility or malleability after heat treating a white iron of suitable chemistry is classified as malleable iron. The carbon in malleable iron is present as nodular-shaped aggregates of graphite (Fig. 11.2*d*).

Ductile Iron (Spheroidal Graphite Cast Iron)

Molten cast iron after special treatment with alloys containing magnesium, cerium, lanthanum, etc., will solidify where most of the carbon will occur as spheroidal-shaped graphite particles (Fig. 11.2*e*) rather than flakes. Because of the shape of graphite, the matrix is interconnected imparting ductility to the iron.

Compacted Graphite Cast Irons

Iron that is melted and treated almost similar to ductile iron, but with much less alloy additions, solidifies with graphite of vermicular shape (shorter, stubbier flakes than flake graphite). This type of cast iron is considered to be in between flake graphite and nodular graphite cast irons with properties falling between the two (Fig. 11.2*f*).

Austenitic Cast Irons

Irons alloyed with nickel, chrome, copper, and molybdenum that could have either flake graphite or nodular graphite but with austenitic matrix at room temperature have special properties and are used in corrosion resistance and high-temperature applications.

The definitions given above illustrate important factors that affect the nature of cast irons. These are chemical composition, melting and conversion conditions, solidification process, cooling rate, and final microstructure. Besides these primary factors, there are other significant factors that affect the quality of cast irons. These are discussed later.

Various types of cast irons can be generally represented in the carbon-silicon diagram [4], modified to reflect the extended range of silicon, as shown in Fig. 11.3, as a broad range. Special irons may have different compositions than those depicted in Fig. 11.3. Table 11.1 shows ranges of key elements for different types of cast irons.

Microstructures of Cast Irons

Various members of the family of cast irons are very sensitive to processing variables, which affect the microstructure and thus the mechanical and other properties. The structural components of cast irons differentiate various types of irons—gray, malleable, white, nodular, and vermicular graphite. The more significant factors are defined below.

Graphite

Carbon in cast iron may precipitate as free or elemental carbon as graphite. In gray irons, this graphite precipitates in the form of flakes. Because of the low density of graphite and depending on the carbon content of the iron, the volume of free graphite

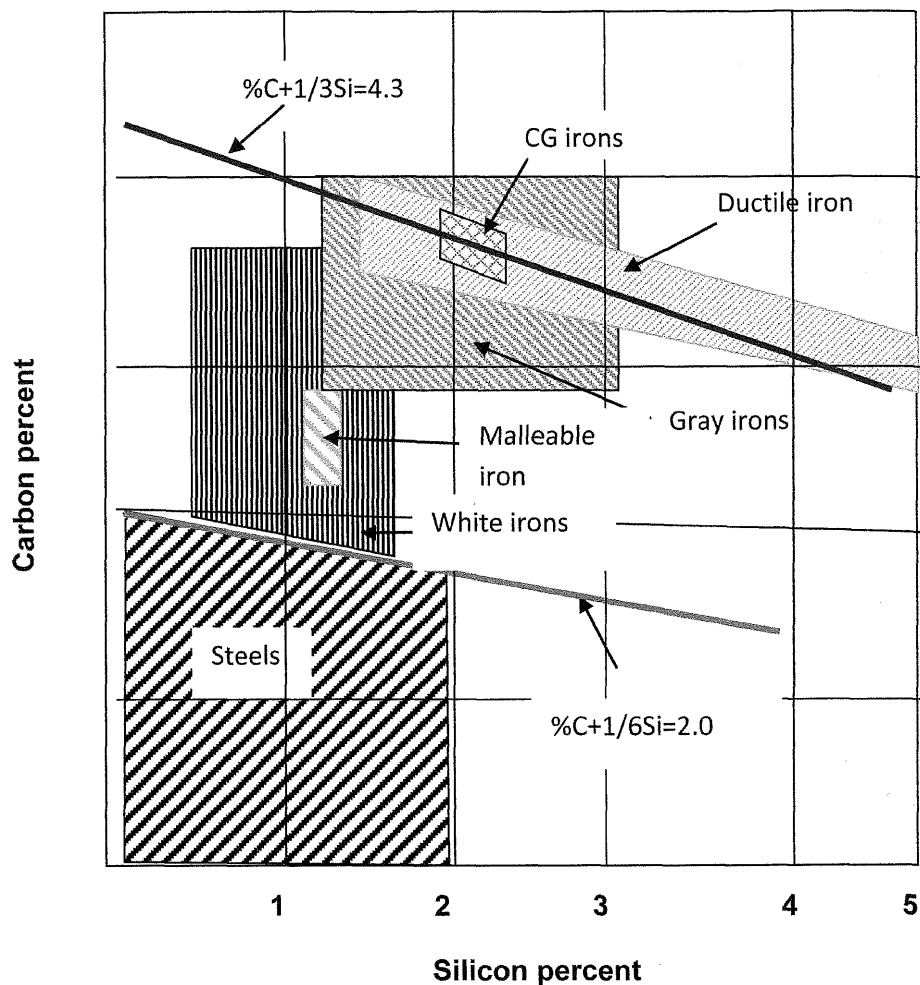


FIGURE 11.3 Carbon and silicon ranges for cast irons and steel. (From Walton [4].)

Element	Gray Iron, %	White Iron*, %	Ductile Iron	CG Iron
Carbon	2.5–4.0	1.8–3.6	3.2–4.0	3.4–3.7
Silicon	1.0–3.0	0.5–1.9	2.0–4.5	1.8–2.4
Manganese	0.4–1.0	0.25–0.8	0.1–0.5	0.1–0.5
Sulfur	0.05–0.25	0.06–0.20	0.004–0.015	0.004–0.015
Phosphorous	0.05–1.0	0.06–0.18	0.01–0.05	0.01–0.05

*Note: Such compositions may be converted from white to malleable iron by heat treatment.

Source: From Heine et al. [1].

TABLE 11.1 Broad Ranges of Composition of Key Elements in Various Cast Irons

may vary from 6 to 16% of the total volume. There are other forms of graphite in cast irons as shown in Fig. 11.2*d, e, and f*. Temper carbon is another form that is present in malleable iron as a result of heat treatment of white iron. Nodular or spherical graphite in ductile iron and vermicular graphite in compacted graphite irons develop when cast iron is treated with small quantities of magnesium and rare earths.

The amount, type, size, shape, and distribution of the graphite in cast irons greatly influence their properties. The type and size characteristics of flake graphite in gray irons have been described in standards adopted by ASTM and AFS (Fig. 11.4). In general, type A graphite has random orientation and is uniformly distributed, and is the desired

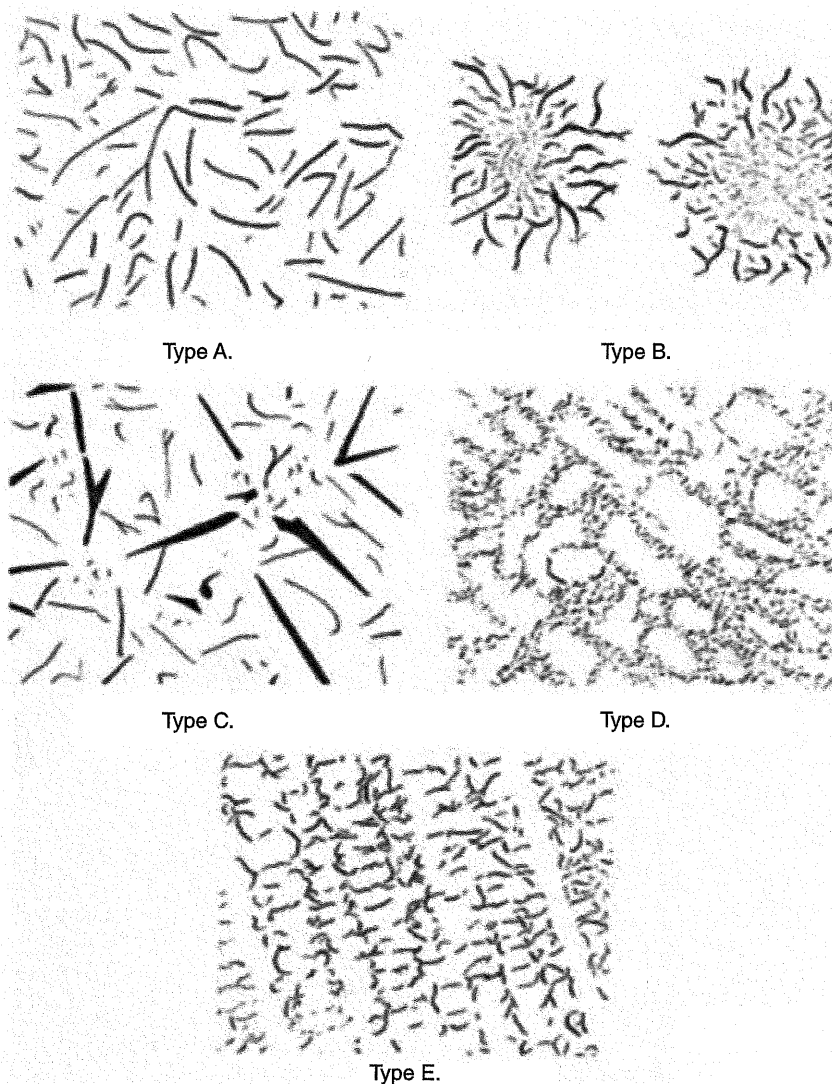


FIGURE 11.4 Types of flake graphite—type A, B, C, D, and E. (From Walton [4].)

type in gray cast irons [5]. Flake graphite breaks up the continuity of the matrix, and is responsible for the lack of ductility observed in tensile testing of gray irons. Temper carbon (spherules) in malleable irons and spheroidal graphite in ductile irons do not reduce ductility, as does the flake graphite. Although vermicular graphite (in CG iron) reduces ductility to some extent, it still has significant ductility in tensile testing.

Cementite

Carbon in cast irons may occur entirely or in part in the chemically combined form as Fe_3C , cementite. Other elements like Mn and Cr will substitute for iron. Free or massive cementite develops during the solidification of white or chilled cast irons (Fig. 11.2*b* and *c*). Cementite is very hard and brittle and influences the properties greatly if present in significant quantities. The weight of Fe_3C is about 15 times the weight of the carbon. If a cast iron containing 2.5% carbon solidifies as white iron, it will contain 37.5% iron carbide and therefore will be very hard and brittle. Cementite is also one of the two constituents of pearlite.

Ferrite

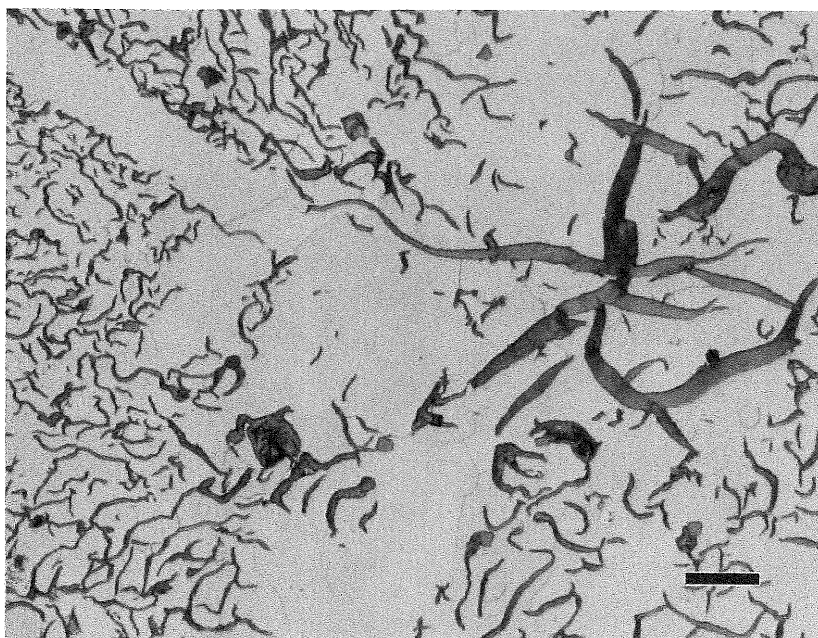
Ferrite may be defined as the normal temperature body-centered cubic crystalline form of iron and as such is relatively soft, ductile, and of moderate strength. In cast irons, the silicon is in ferrite phase (free ferrite and ferrite in pearlite). Silicon and other elements harden and strengthen the ferrite, and the hardness can vary from 140 to over 200 BHN. Mechanical properties of ferrite depend on alloy composition.

Structurally, ferrite in cast irons may occur as free ferrite or as ferrite in pearlite. Free ferrite dominates in malleable irons and other irons of maximum ductility. In gray irons, ferrite occurs mainly as a part of pearlite unless chemistry or heat treatment favors ferrite formation (Fig. 11.5*a* and *b*). In ductile iron, ferrite forms around the graphite nodules first and extends all the way to the grain boundary when favorable graphitizing potential exists (Fig. 11.5*c* and *d*). In compacted graphite irons, ferrite is favored around the graphite particles.

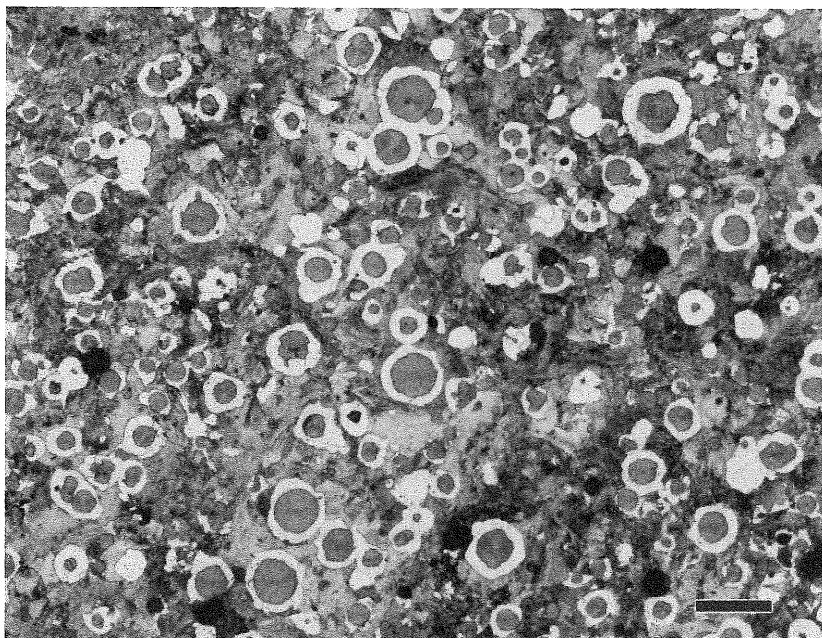


(a)

FIGURE 11.5 Gray and ductile iron morphologies; (a) pearlitic matrix (*Continued*)

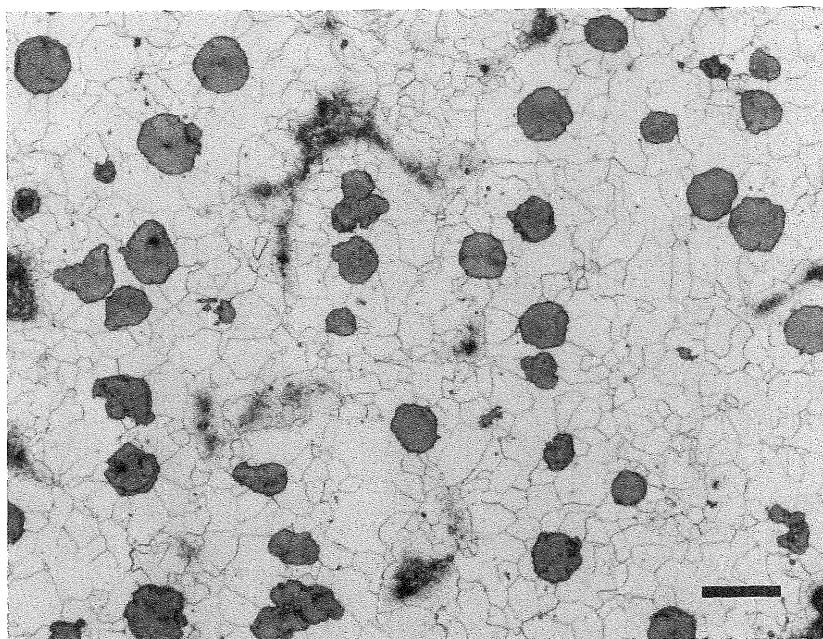


(b)



(c)

FIGURE 11.5 (Continued) (b) ferritic matrix, (c) pearlitic matrix and (Continued)



(d)

FIGURE 11.5 (Continued) (d) ferritic matrix. (From Vander Voort [3].)

Pearlite

Pearlite consists of a mixture of ferrite and cementite arranged in alternate lamellae. Pearlite in cast irons is strong and moderately hard (200 to 300 BHN) and has some ductility. The amount of pearlite present in cast irons depends on the degree of graphitization of the iron (Fig. 11.5a and c). In fully pearlitic iron, carbon is contained in the pearlite as iron carbide (also called combined carbon); it can be 0.5 to 0.9%. In white iron, pearlite is the predominant constituent besides cementite.

Steadite

The phosphorous present in cast irons, especially gray irons, occurs often as steadite, a eutectic of iron and iron-phosphide of low melting point, about 1750 to 1800°F. Phosphorous segregates into areas where the iron solidifies late in the freezing process. Steadite is distributed in grain boundary areas (Fig. 11.6) [3]. Iron phosphide, like iron carbide, is very hard and brittle. Excessive phosphorous content raises the hardness and brittleness of gray iron due to steadite formation.

Austenite

In cast irons, austenite may be defined as a high-temperature face-centered cubic crystalline form of iron occurring during solidification and which, during slow cooling, changes to pearlite, ferrite, or a mixture of the two. Austenite is present as a portion of the microstructure at room temperature in irons especially alloyed with nickel and chromium and in irons that are subjected to specialty heat treatment like austempering.



FIGURE 11.6 Optical micrograph of steadite (iron-iron phosphide eutectic in gray cast pig iron). (From Vander Voort [3].)

Ledeburite

Ledeburite is the eutectic of austenite and cementite. It forms during solidification without graphite and the austenite transforms into pearlite below the austenite transformation temperature while cementite retains its structure.

In addition to the above structural constituents, cast irons may contain nonmetallic inclusions. These are mainly sulfides of manganese due to the presence of sulfur and silicates of iron and manganese formed by the reaction with oxygen. For summary purposes, some properties of microconstituents of cast irons are presented in Table 11.2.

From Table 11.2, it can be seen that structural components of widely varying properties may occur in cast irons. Therefore, the properties of commercial iron castings are largely influenced by the microstructure developed during and after solidification. In this connection, it should be noted that chemical composition is not the only factor determining the microstructure. Cooling rates, freezing mechanism, presence of certain gases in the metal, and a host of other variables in the foundry practice may markedly affect the microstructures formed and consequently the properties. The actual manipulation in the foundry may cause drastic changes in the microstructure and properties of the iron. For example,

Constituent	Specific Gravity, g/cc	Tensile Strength, psi	Elongation, %	Reduction of Area, %	BHN	Remarks
Ferrite	7.86	39,500–42,000	61	30.9	75	
Silicoferrite	–	45,150	50	91.6	–	0.82% Si
Silicoferrite	–	63,500	50	85	–	2.28% Si
Silicoferrite	–	77,400	21	28.7	–	3.4% Si
Cementite	7.66	–	–	–	550	–
Pearlite	7.846	120,000	15	–	240	–
Pearlite	–	125,000	10	15	200	Pearlitic steel
Pearlite	–	105,000–125,000	–	–	–	0–0.8% manganese
Graphite	2.55	–	–	–	–	–
Ledeburite	–	–	–	–	680–840	–
Steadite	7.32	–	–	–	–	–
Manganese sulfide	4	–	–	–	–	–
Iron sulfide	5.02	–	–	–	–	–

Source: From Heine et al. [1].

TABLE 11.2 Selected Properties of Microconstituents in Cast Irons

in gray irons, the type of graphite, whether A, B, C, D, or E, may be greatly altered by many variables in the melting practice, and holding and handling of the molten metal. In malleable irons, the melting practice and heat treatment given to the white irons are major factors affecting the properties. Ductile and CG irons are also very sensitive to the foundry practice with respect to graphite particle number, shape, size, and distribution. In all irons, the influence of section size and cooling rate is very important. With all the factors involved, the family of cast irons can offer widely varying structures and properties for engineering use, each with its own advantages and limitations. It is the job of the trained foundry personnel to produce the kind of microstructure desired in the castings.

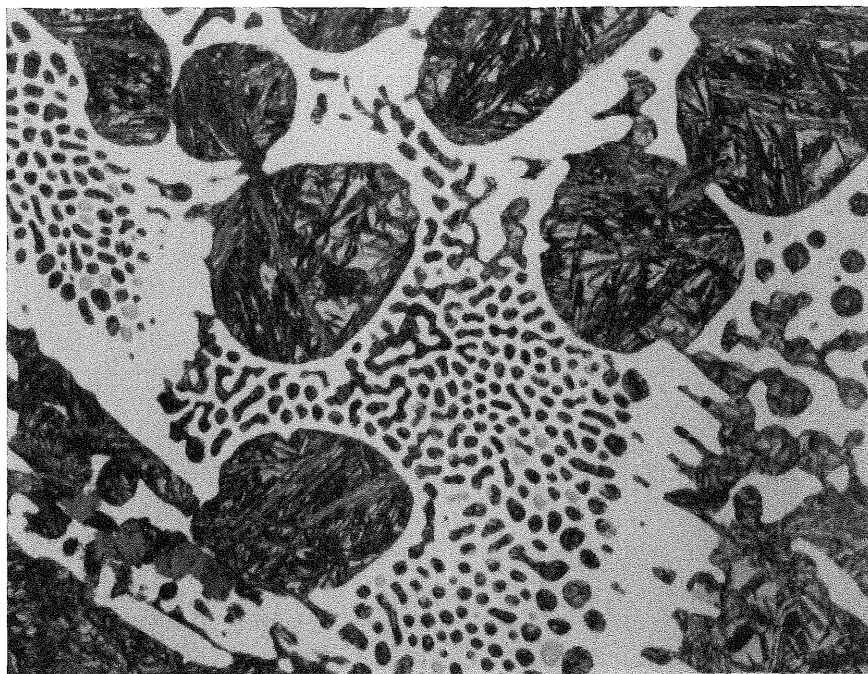


FIGURE 11.20 Microstructure of Ni-hard cast iron (Fe: 3.3%, C: 0.9%, Mn: 0.9%, Si: 1.8%, Cr: 4.4%, Ni: 0.4%, Mo: 0.4%) revealing massive cementite, ledeburite, and patches of plate martensite and retained austenite. Etched with aqueous 10% $\text{Na}_2\text{S}_2\text{O}_5$. Original at 500 \times . Ledeburite is a eutectic of cementite and austenite where, with cooling, the austenite transforms to ferrite and cementite in the form of pearlite. Some graphite is also present. (From Vander Voort [3].)

To stabilize carbides, alloying elements like chromium, manganese, and molybdenum are added to the melt at various concentrations listed later in this chapter. One of the popular commercial white irons produced for wear-resistant applications is “Ni-hard” and its microstructure is shown in Fig. 11.20. Ni-hard is white iron alloyed with nickel and chrome for wear applications such as mill liners.

Graphitic Cast Irons

Graphite Precipitation during Solidification

When cast irons solidify in stable eutectic mode, excess carbon is precipitated in the form of graphite, which can take different shapes. Main classifications for graphite shapes are (1) flake graphite, (2) spheroidal graphite, and (3) compacted or vermicular graphite. Some cases of coral graphite are seen as an anomaly. Various graphite forms and their orientation and growth axis are shown in Fig 11.21.

The shape of graphite affects the strength significantly and cast irons are classified according to the shape. Flake graphite irons are known as gray cast irons; spheroidal graphite irons are known as ductile irons; and vermicular graphite irons are called compacted graphite irons, or CG irons for short. Graphite shapes are determined during solidification and are not altered during subsequent cooling and/or heat treatments.

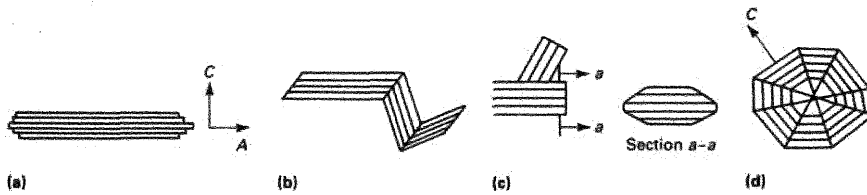


FIGURE 11.21 Schematic of various graphite shapes growing with austenite during eutectic solidification: (a) flake graphite, (b) vermicular graphite, (c) coral graphite, and (d) spheroidal graphite. (From Stefanescu [10].)

Flake Graphite

Flake graphite size and distribution can vary widely depending on the carbon equivalent, cooling rate, and processing variables and thus affect the mechanical properties greatly. Flake graphite irons should be considered as a family with tensile strengths ranging from 20 to 60 Ksi (138 to 413 MPa). Different classes of flake graphite are shown in Fig. 11.4. Type A through type E, classified by AFS and ASTM, show the distribution and shape of the graphite flakes [5].

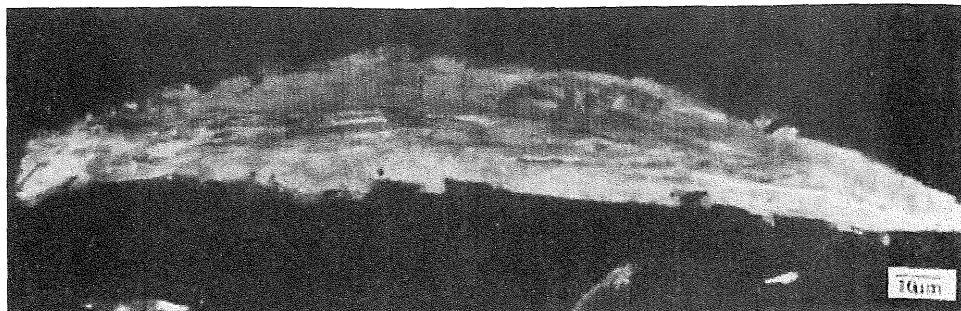
From the evidence presented from the research work [11], using extracted graphite particles by deep etching and examining under SEM and TEM, flake graphite growth patterns can be seen clearly in Fig. 11.22.

Type A has randomly oriented flakes, which are desirable in gray cast irons. Even in type A, the size of graphite varies with carbon equivalent and cooling rate. Long flakes signify higher carbon equivalent and low cell count or larger cell size. When eutectic cells are large, the flakes are longer. It is not easy to distinguish the eutectic cells with type A graphite morphology without special etching or some other techniques such as direct austempering. If carbide stabilizing elements like Cr, Mo, and V are present they will form grain boundary carbides and macro etching can reveal the eutectic cells as shown in Fig. 11.23. Higher cell count, either from inoculation or from faster rate of solidification, decreases the length of the graphite flake. Classification of graphite sizes from 1 through 8 (longest to shortest) is provided in ASTM standards. Graphite flake length has direct correlation to tensile strength. When effective nucleation occurs, austenite-graphite eutectic grows in a cellular manner. Cellular growth continues until cells impinge on one another, or until the composition of the melt changes due to segregation of certain elements (Cr, Mn, Mo, V, P) so that other phases form in the intercellular areas.

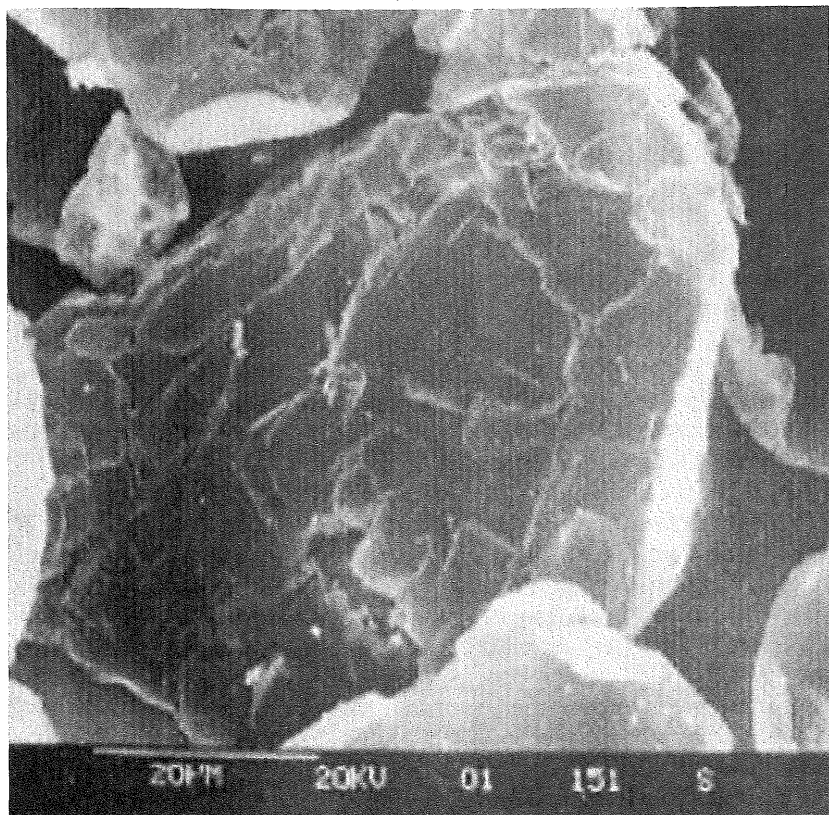
Failure to nucleate austenite-graphite eutectic early in eutectic solidification results in eutectic undercooling, and eutectic nucleation at a lower temperature. At this lower temperature diffusion distances between graphite flakes are reduced such that flakes at the center of the eutectic cell are finer and the interflake distance is reduced. Then the heat of fusion raises the melt temperature nearby (recalescence) and continued eutectic growth occurs with coarser flakes and developing type B graphite (rosette graphite).

Type C graphite precipitates from hypereutectic composition surrounded entirely by liquid, so that it grows as a crystalline, blocky morphology prior to the eutectic solidification.

Increased volume fraction of austenite in hypoeutectic irons and faster cooling rates decreases the interdendritic volume of liquid. Development of this proeutectic



(a)

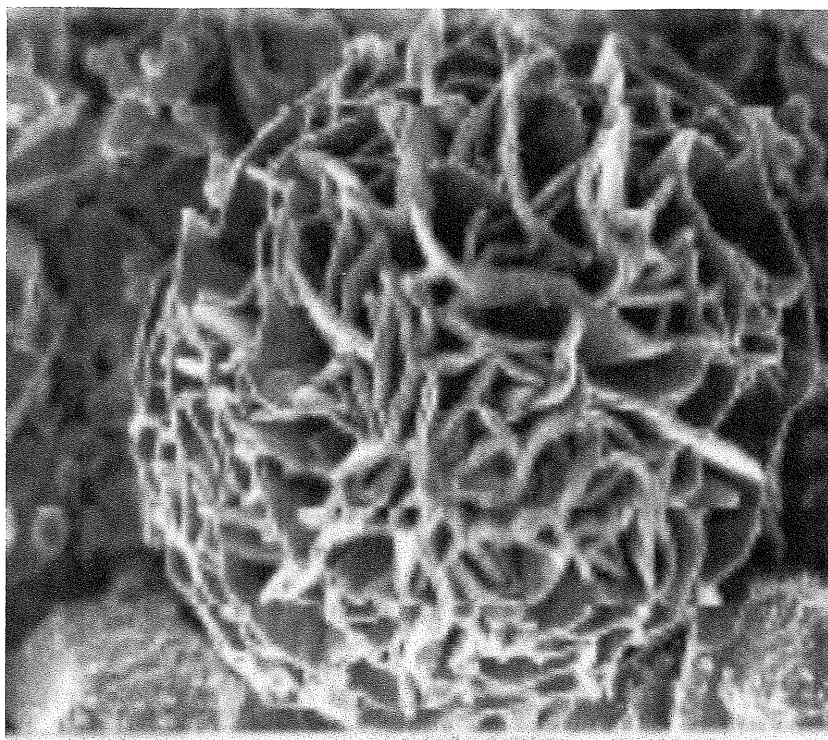


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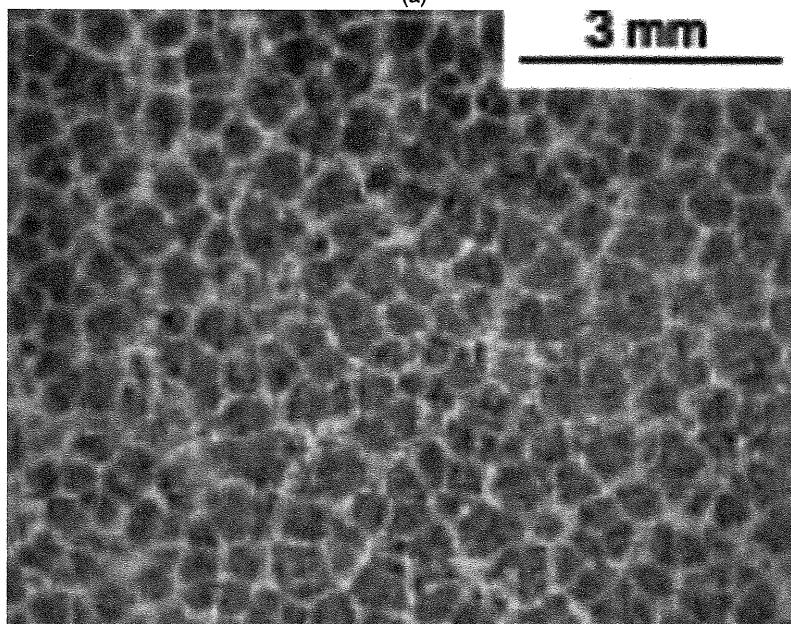
FIGURE 11.22 SEM micrograph of (a) flake graphite removed by deep etching and (b) details of the surface structure of the flake graphite. (From Loper [11].)

austenite is associated with delayed eutectic nucleation. Eutectic graphite flakes tend to be finer (similar to the core of the type B graphite) and grow in a cellular manner similar to type A graphite. Thus, the undercooled graphite is classified as type D graphite and has randomly oriented graphite flakes.

Type E graphite is an extreme form of type D graphite where the interdendritic areas are severely restricted by the development of proeutectic austenite dendrites. This

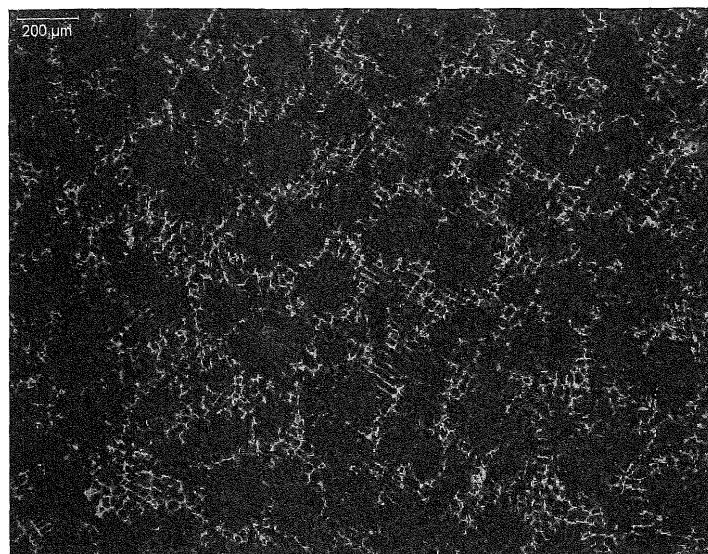


(a)



(b)

FIGURE 11.23 (a) One deep-etched single cell [12], (b) eutectic cells revealed by etching with Steads reagent [Alagarsamy Consulting], (Continued)



(c)

FIGURE 11.23 (Continued) (c) macro-etched to reveal grain boundary carbides. (From Gundlach, private communication [13].)

results in a more divorced eutectic formation so that the resulting graphite flakes are oriented within the austenite dendrites. Figure 11.24 shows type A through E graphites, discussed above. Anomalous graphite morphology known as “Widmanstätten” graphite is also shown in Fig. 11.24 [5].

Spheroidal or Nodular Graphite (SG) Cast Irons

Graphite shape is dramatically changed from flake graphite when sulfur and oxygen in the cast iron melt is tied up by shape-active elements like Mg, rare earths, and Ca. After the sulfur and oxygen are tied up as sulfides and oxides, a small amount of excess Mg will cause the graphite to precipitate in nodular (spheroidal) form. It may not be enough to have sufficient Mg to promote fully nodular graphite without some form of postinoculation to provide nuclei for graphite precipitation. Without the postinoculation, iron may solidify with carbides due to lack of graphite nucleation and growth resulting in the eutectic solidifying at lower temperature [below 1950°F (1066°C)]. In contrast to gray irons, most ductile iron castings are produced in the hypereutectic range. Within the narrow CE range, ductile iron strengths are not affected by small changes in carbon equivalent, as is the case with flake graphite irons.

Properties in ductile iron casting are mainly varied by controlling relative volumes of various components of the matrix such as ferrite, pearlite, and martensite by the use of alloying elements and to a lesser extent by the rate of cooling in the molds and outside the molds.

Spheroidal Graphite Development

Spheroidal graphite nucleates around inclusions introduced during melt conversion and inoculation steps in contact with liquid. As most ductile irons are of hypereutectic composition graphite grows in contact with liquid prior to encapsulation by austenite

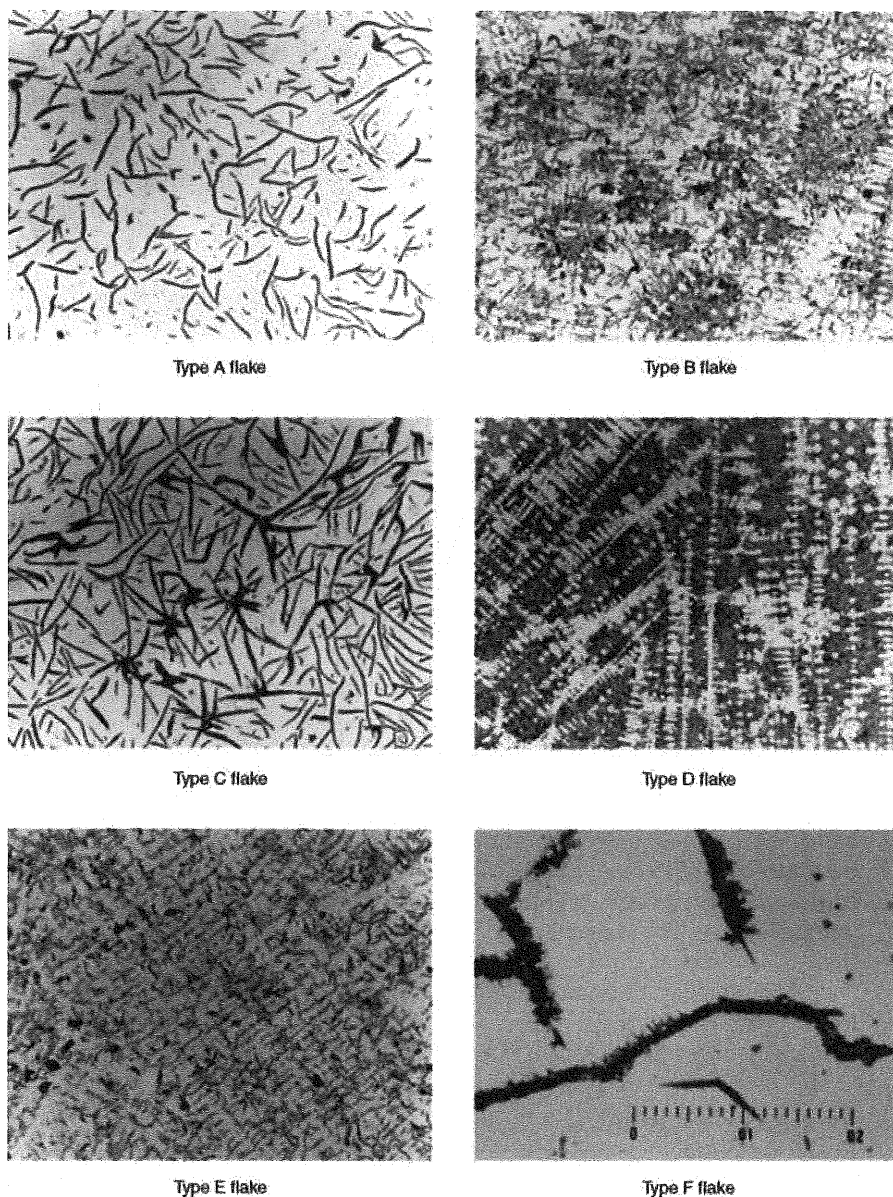


FIGURE 11.24 Flake graphite forms A through E and Widmanstätten graphite F. (From Goodrich [5].)

shell. Further growth occurs as divorced eutectic, carbon diffusing through austenite shell, and depositing on to the nodule surface. Spheroidal graphite development can be seen clearly as growth in three stages, the nuclei dark spot in the center, growth of spheroid in contact with liquid as dense graphite in the center, and then growth by diffusion of carbon through austenite in Figs. 11.25*a* and *b*. Radial and circumferential growth details can also be seen in Fig. 11.25.

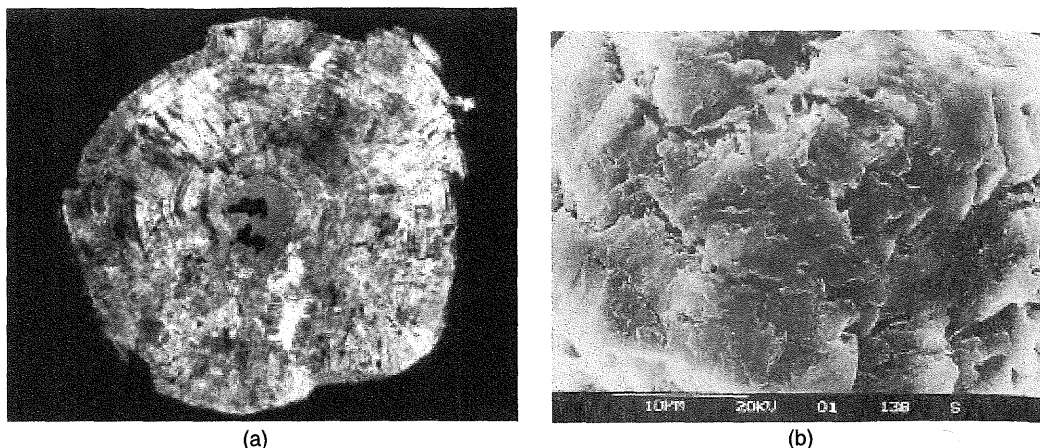


FIGURE 11.25 (a) Cross section of a spheroidal graphite removed by deep etching showing the radial and angular crystallographic planes, and (b) detail of the surface structure of the nodule. (From Loper and Fang [14].)

Vermicular Graphite

When the graphite shape is thicker than typical flake graphite and shorter in length as shown in Fig 11.2f, it is classified as vermicular graphite. Castings produced with this type of graphite are called *compacted graphite* (CG) cast irons. The aspect ratio (ratio of length of graphite particle to width) may vary between 3 and 8. This type of graphite results from treating the melt with magnesium and/or rare earths, and keeping the residual magnesium low (around 0.01 to 0.02%). This graphite morphology allows for better use of the matrix, yielding higher strength and ductility than flake graphite cast iron. Similarities between the solidification patterns of flake and compacted graphite iron explain the good castability of the later compared to ductile iron. In addition, the interconnected graphite provides better thermal conductivity and damping capacity than spheroidal graphite.

Vermicular graphite nucleates as spheroidal graphite but grows differently due to lower magnesium and/or higher sulfur, titanium, and oxygen levels. Figure 11.26 depicts the three-dimensional view of a deep-etched graphite particle.

Coral or Chunk Graphite

Even though this type of graphite is not desired, it can be seen in castings when processes are out of control. When excess rare earths are present, especially in heavier sections, chunk graphite can form. Growth of this type of graphite is shown in Fig. 11.27.

Factors Affecting Solidification of Cast Irons

Solidification of Gray Iron

In a hypereutectic gray iron, solidification begins with the precipitation of kish graphite in the melt. Kish grows as large, straight, undistorted flakes or as very thick, lumpy flakes that tend to rise to the surface of the melt because of their low relative density. When the temperature has been lowered sufficiently, the remaining liquid solidifies as a eutectic structure of austenite and graphite. Generally, eutectic graphite is finer than kish graphite.

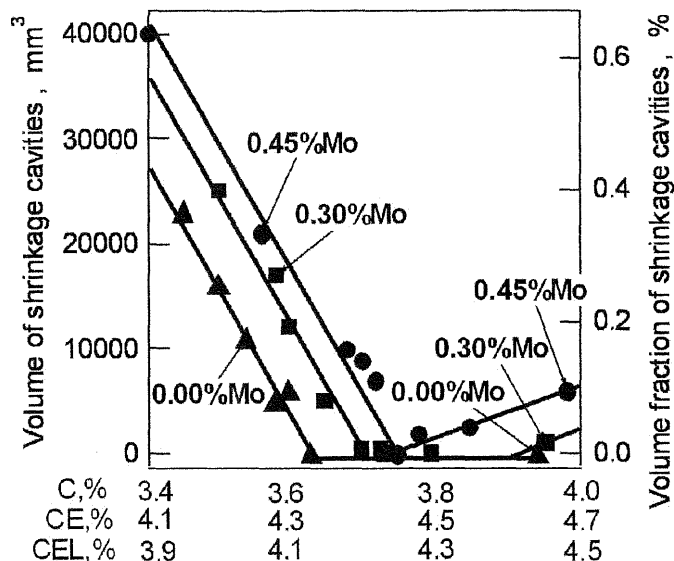


FIGURE 11.37 Effect of CE and segregating elements on shrinkage of ductile iron castings. CE = C + 1/3 Si, CEL = C + 0.25 Si. (From Kanno et al. [19].)

Compacted Graphite Cast Irons

Early production of compacted graphite iron involved the use of titanium containing magnesium ferrosilicon alloys. Titanium was used to reduce the nodularity in otherwise good ductile iron. Recent production practices use rare earth containing magnesium ferrosilicon alloys. A patented process called *SinterCast* uses thermal analysis techniques to control the nodularity below 20%, by “undertreating” the iron first and then adding just the right amount of active elements based on the test results. Inoculation requirement for CG iron is less than that for ductile iron. Too much inoculation will increase the nodularity. Figure 11.38 shows the relationship between Mg and sulfur for ductile and CG irons. Measured magnesium by spectrometers is total magnesium (MgS + MgO + Mg), hence, if final sulfur is high it will be combined with magnesium and thus the need for higher analyzed Mg residual to maintain the same nodularity [20, 21].

Process parameters to produce CG iron with low nodularity and free of carbides in thin sections down to 3 mm by both in-mold and in-ladle treatment processes have been established [22,23]. The best results in 6-mm-thick samples were obtained from base iron with 0.01% S and 0.028% Mg when insulating sand inserts were used. Fifty-seven percent compactness was obtained in 6-mm-thick sections with typical silica sand molds for 0.01% S in base iron and 0.028% residual Mg. The compactness could be increased to 66% in 6-mm-thick sections with relatively high S (0.02%) in base iron following in-mold treatment without sand inserts.

Key Elements and Their Effects on Cast Irons

All the elements normally present in the cast iron exert some influence on the microstructure of the iron. Carbon and silicon, of course, are fundamental and most important

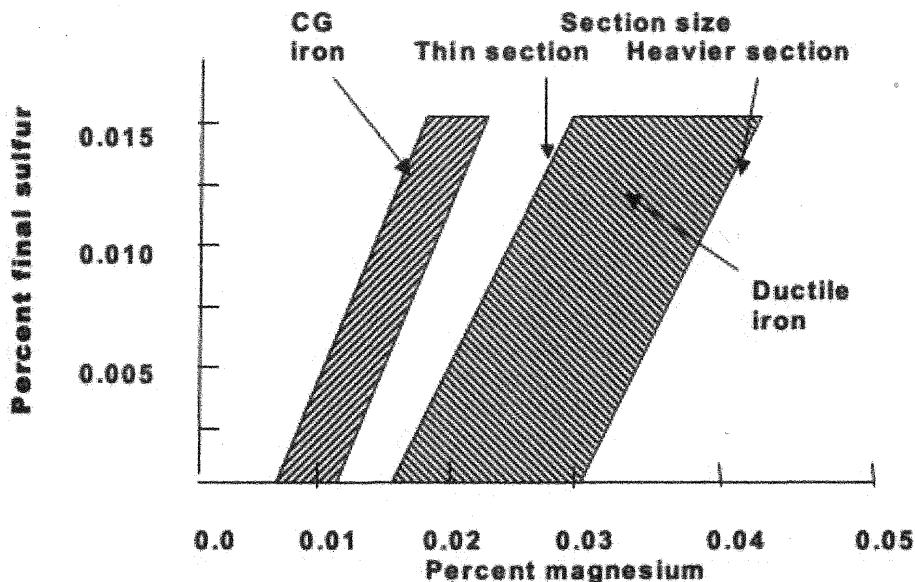


FIGURE 11.38 Relationship between final iron sulfur and magnesium residual on the graphite shape control. (From Heine [20], Alagarsamy [21].)

with respect to affecting the microstructure and mechanical properties of cast irons, and may be considered first.

Carbon

Carbon in graphitic cast iron is present from about 2.5 to 4.5% by weight. Two phases containing carbon occur: elemental carbon in the form of graphite and combined carbon as Fe_3C . Chemical analysis usually reports the total carbon percentage in the iron. Since the two forms may be determined separately by chemical analysis, the degree of graphitization may be assessed by the following relationships:

$$\% \text{ total carbon} = \% \text{ graphitic carbon} + \% \text{ combined carbon} \quad (11.11)$$

and degree of saturation (Sc)

$$Sc = \% \text{ graphitic carbon} / \% \text{ total carbon} \quad (11.12)$$

If graphitization is complete, there will not be any combined carbon, and the total carbon and graphitic carbon are the same. In pearlitic irons, the combined carbon content may vary from 0.5 to 0.8%.

Silicon

Silicon level varies in cast irons from 1.0 to 5.0%. The most important effect of silicon is on graphitization. It may be noted from Fig. 11.18 that increasing silicon shifts the carbon content at the eutectic point of the iron-carbon diagram to the left (from around 4.25 to 3.6%). The eutectic shift is often described by the following relationship:

$$\text{Eutectic carbon percentage (in Fe-C-Si alloy)} = 4.3 - \frac{1}{3} (\% \text{ Si}) \quad (11.13)$$

The combined effect of carbon, silicon and phosphorous on the phase diagram can be expressed as carbon equivalent (CE). Several different formulae are used in different applications. To estimate the chemistry (C and Si) quickly in the melt shop by thermal analysis by determining the austenite-liquidus temperature (TAL), carbon equivalent liquidus (CEL) is used. $CEL = C + 1/4Si + 1/2P$ is used generally for chemistry evaluation. It should be emphasized that melting variables affect the TAL for the same chemical composition. CE at the eutectic point is commonly given as

$$CE = C + 1/3Si + 1/2P \quad (11.14)$$

In ductile and CG irons, the phosphorous term is omitted as its levels are very low. If the carbon equivalent of an iron is calculated to be 4.3%, then the iron corresponds roughly to a eutectic alloy. Hypoeutectic and hypereutectic irons correspond to CE less than and higher than 4.3%, respectively. In very high hypereutectic irons, the freezing process may begin with the precipitation of graphite, and is said to form *kish in gray cast irons*. Because of its buoyancy, kish pops out of the melt into the air and can be observed as sparkly graphite flakes floating on the surface of the iron or in the air above the iron.

Not only does silicon shift the eutectic point to the left, but it also shifts the solubility limits of carbon in austenite to the left of equivalent points in the Fe-C system. At 2.0% Si solubility of carbon in austenite is only about 0.6% compared to 0.76% for 0% Si.

Microstructurally, silicon dissolves in ferrite and as a result, hardens and strengthens the ferrite. Ferrite in pure iron will have a hardness of 80 to 90 BHN, whereas with 2.0% Si, the hardness increases to 120 to 130 BHN.

Sulfur and Manganese

Sulfur, which may be present up to 0.25%, is an important modifying element in flake graphite cast irons. Sulfur content below 0.01% enables full graphitization. At higher sulfur levels (above 0.25%) pearlite will be the final microstructure and the iron is harder to machine.

The influence of sulfur needs to be considered relative to its reaction with manganese in the iron. Sulfur will form FeS and segregate to the grain boundaries during freezing. When manganese is present, MnS and complex manganese-iron sulfides are formed, depending on the manganese content. The manganese sulfides begin to precipitate early, and continue to do so during the entire freezing process and are therefore randomly distributed. When the sulfur is combined with Mn as MnS, the effect of sulfur on pearlite formation is lost. Manganese in excess of that which is combined with sulfur may promote pearlite. The following rules are advanced to express the Mn and S relationship:

1. $1.7 \times \%S = \text{Mn}$; theoretical value of Mn to react with S.
2. $1.7 \times S + 0.15 = \%Mn$; the manganese percentage for maximum ferrite and a minimum of pearlite.
3. $3 \times \%S + 0.35\%$; the manganese level to promote pearlitic microstructure.

Phosphorous

Formation of steadite (iron-iron phosphide eutectic) by phosphorous in cast iron has been mentioned earlier. Segregation of P may result in lowering of the temperature of final solidification to 1800°F (982°C). The percentage of steadite present in the final structure may amount to 10 times the P content in the iron. Because of segregation, the steadite is usually found in cell boundaries. Because P forms a eutectic as it segregates, P is often included in the carbon equivalent calculation as shown:

$$CE = \%C + \frac{1}{3}(\%Si + \%P) \quad (11.15)$$

The iron phosphide is hard and brittle as is the carbide. Increasing P increases hardness and brittleness, especially above 0.3%. To a limited degree, increasing P contributes to increased fluidity and is recommended in very thin section castings to avoid misruns.

Influence of Melting and Melt Handling Procedures on Solidification

Solidification of cast irons are affected by many factors involved in melting and melt handling, including the presence of minor elements, superheating, holding time, and cleanliness of charge materials. This also affects the shrinkage development during solidification and risering techniques used to produce sound castings [22–25].

Superheating above 2730°F (1500°C) reduces nucleation potential and graphite precipitation is retarded. In gray irons undercooled graphite (type E and D) may form if the nucleation of graphite is not enhanced during melting and holding. One of the main reasons for inverse chill in ductile iron solidification is superheating the iron above this temperature. The term “Monday morning iron” is used to describe cast irons that have low nucleation potential and thus require special techniques such as addition of silicon carbide to the melt to avoid problems such as inverse chill, low nodule count, chill carbides, and shrinkage [26]. Graphite nucleation and growth should be able to keep up with the cooling rate of liquid iron. If the cooling rate is faster than the graphite precipitation rate, iron undercools below the carbide eutectic and solidifies as carbide eutectic.

Gray Iron Cell Counts with Superheating

When the iron is superheated, graphite nucleation and cell formation are delayed with increased undercooling. This will result in lower cell count and larger eutectic cells. When cell size is larger, graphite flake length is increased with lower hardness and tensile strength [4]. Figure 11.31 illustrates the effect of undercooling on cell count as a result of superheating.

High Carbon Equivalents

Gray iron is section sensitive; that is, when it is cooled slowly, graphite flakes grow longer with resultant low strength and hardness.

In ductile irons, when CE is higher than 4.6, and conditions are favorable for graphite precipitation and growth, such as higher pouring temperatures, larger casting sections, and well-inoculated iron, graphite will grow to a large size before austenite envelops the nodule. If the graphite size is large enough, the buoyancy forces will lift the nodules to the upper levels of castings. This movement of graphite nodules will result in what is called *graphite flotation* (Fig. 11.39). In extreme cases, nodules will not be compact and will look like they have exploded. When these events occur, the cope surface will be much higher in carbon and lower in hardness with inferior mechanical properties. Different forms of deformed graphite are discussed later in this chapter. Even when the cope surface exhibits exploded graphite (Fig. 11.40), lower levels (drag) of castings will be of typical microstructure similar to that of eutectic composition [9, 27].

Graphite Shape-Active Elements

Key elements that significantly advance the solidification of carbon as graphite in nodular form are magnesium, rare earths (cerium, lanthanum, neodymium, etc.), calcium, and barium. They combine with sulfur and oxygen in the iron and provide some nuclei for the precipitation of graphite in the spheroidal form. The amount of these elements needed to convert to ductile iron is very small. Calcium and barium are used as supplemental elements and are not used as main elements for control. Even though rare earths could precipitate carbon as nodular graphite, they are not used alone in ductile iron production. Magnesium is the element of choice in the production of ductile iron.

Chunk Graphite	Intercellular Flake Graphite	Deleterious Graphite
Ce, Ca, Si, Ni, C	Bi, Cu, Al, Pb, Sb, Sn, As, As, Cd	Zr, Zn, Se, Ti, N, S, O

Source: From AFS [8].

TABLE 11.8 Classification of Subversive Elements

When the residuals are in excess of that required for spheroidization, various negative effects are observed. Some of these effects are (1) shrinkage porosity, (2) carbide formation, (3) graphite flotation, and (4) exploded graphite.

Graphite morphology is also affected by trace elements and alloying elements that may be present from the raw materials and alloys used in melting and conditioning the iron. Elements which are present in small quantities but interfere with the normal spheroidal graphite growth are called subversive elements, and the resulting shape can seriously affect mechanical properties. These elements are very highly surface-active and exert significant effect on graphite morphology. Some of these elements are beneficial at certain levels and harmful at other levels. Table 11.8 shows three classifications of these elements as to their effect on graphite shape.

Exact mechanism of chunk graphite formation is not yet clear. Elements in the first column either increase the carbon equivalent or promote undercooling. Some of the elements in column 2 tend to segregate to cell boundaries, and achieve local concentrations high enough to form flake graphite. The undesirable effect of elements in column 2 can be neutralized by the addition of elements from column 1 and vice versa.

Elements in column 3 influence the graphite shape directly by interfering with the nodularizing effect of magnesium. They must be controlled to a low level either by controlling charge materials or by adding extra magnesium to neutralize their effect. Rare earths are very effective in neutralizing the effect of elements in column 2, that are prone to flake graphite formation, but Mg by itself is ineffective in doing so.

Deleterious Graphite Shapes

Graphite Flotation

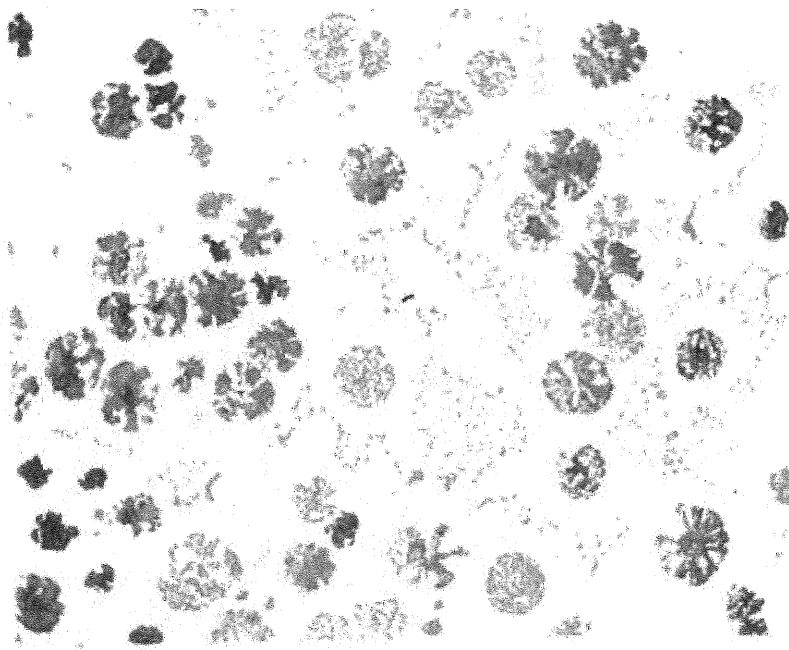
When the CE is too high and iron is well inoculated, graphite precipitates at a higher temperature (above the graphite eutectic temperature), and has time to grow before the composition reaches eutectic. When the size of graphite nodules is large enough they tend to float in the liquid and will concentrate near the cope surface of the casting (Figs. 11.39 and 11.40). Convection currents may move the graphite nodules, as shown in Fig. 11.39a.

Exploded Graphite

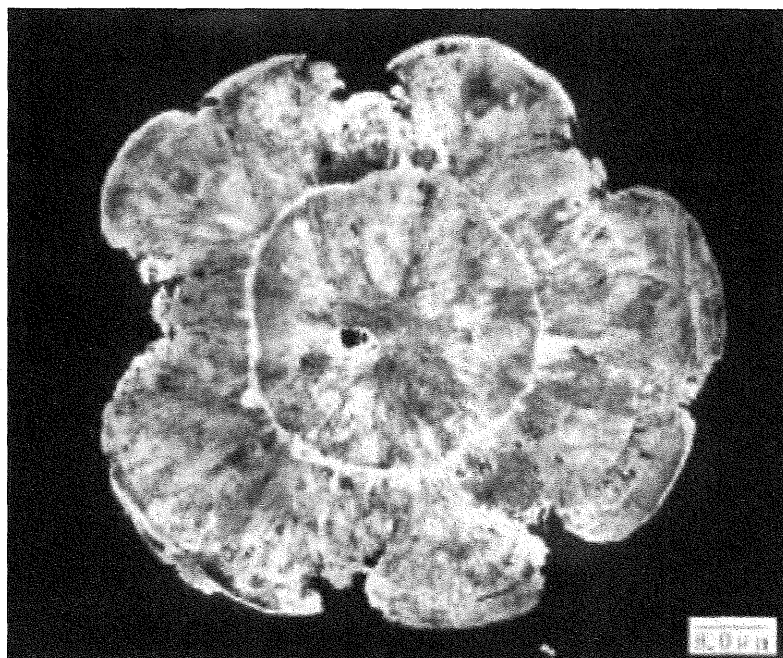
When CE is too high (above 4.6%), and Mg and Ce levels are too high, graphite grows discontinuously and appears like a broken up nodule, as shown in Fig. 11.41. It is important to control Mg and rare earth levels with section thickness of casting produced.

Chunky Graphite

When the rare earth levels are too high for the section thickness, spheroidal graphite degenerates into chunky graphite (Fig. 11.42a). Addition of antimony and or bismuth may neutralize the effect of excess rare earths and minimize the formation of chunky graphite. A SEM micrograph of a chunk graphite cell is shown in Fig 11.42b.

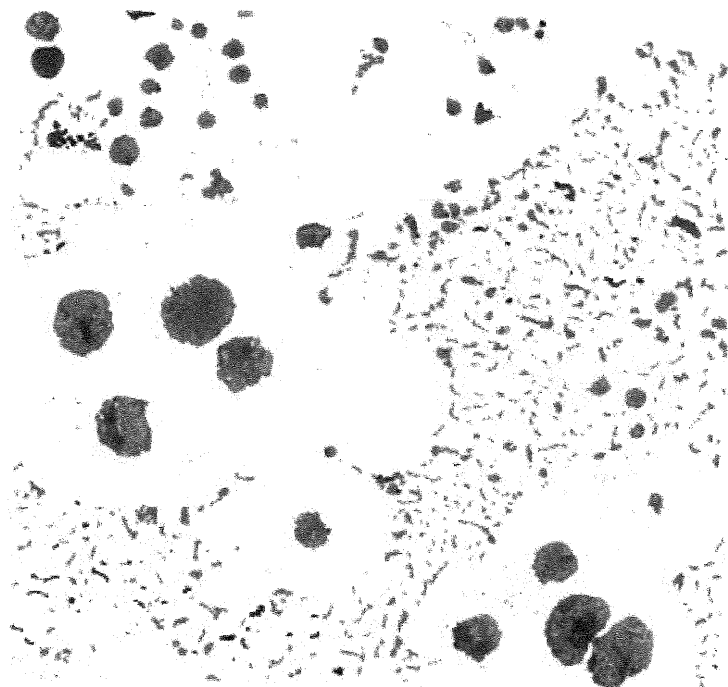


(a)

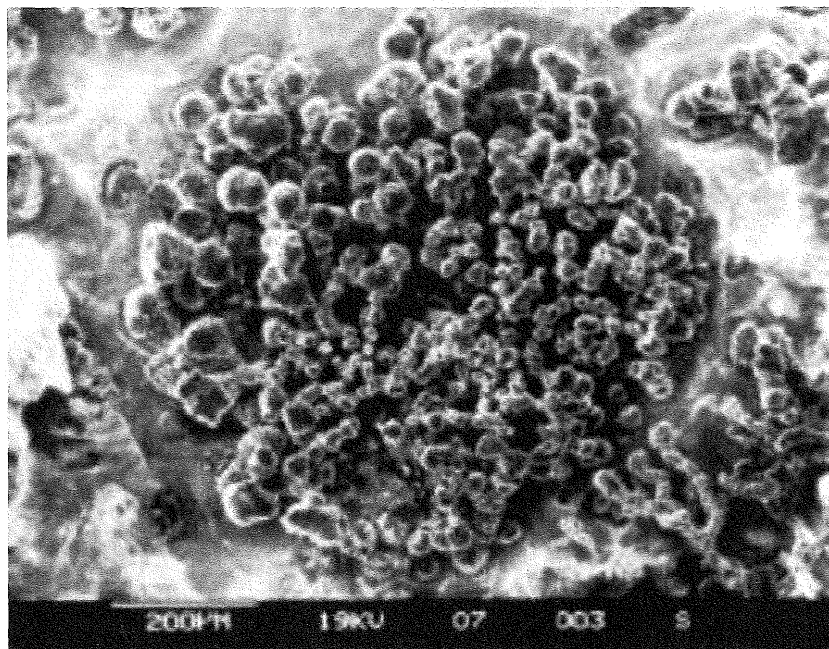


(b)

FIGURE 11.41 (a) Exploded graphite distribution in casting cope surface [9]. (b) Single nodule showing good spherical growth in the center and cauliflower-type growth on the outside. (From Loper and Fang [14].)



(a)



(b)

FIGURE 11.42 Chunk graphite (a) distribution [9] and (b) a SEM micrograph of a deep-etched chunk graphite cell. (From Loper and Fang [14].)

Vermicular Graphite

For the ductile iron, vermicular graphite is considered as faded ductile iron. As the magnesium residual is reduced, more and more vermicular graphite is formed.

A SEM micrograph and optical vermicular microstructures are shown in Fig. 11.43.

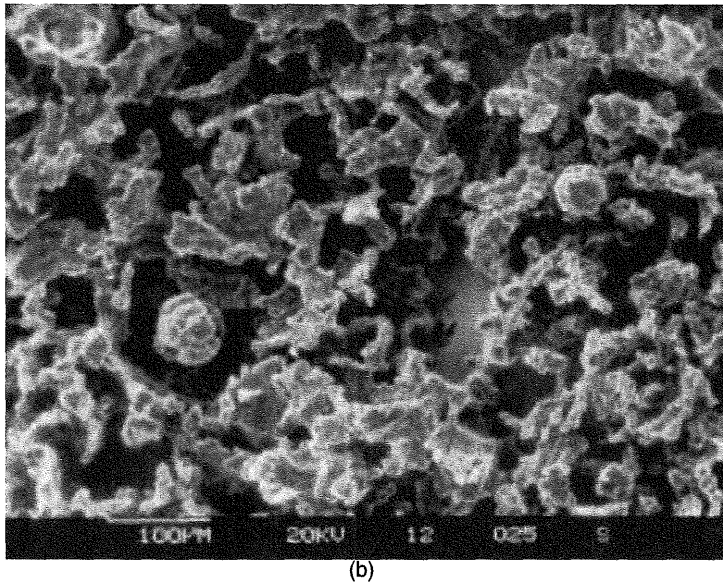
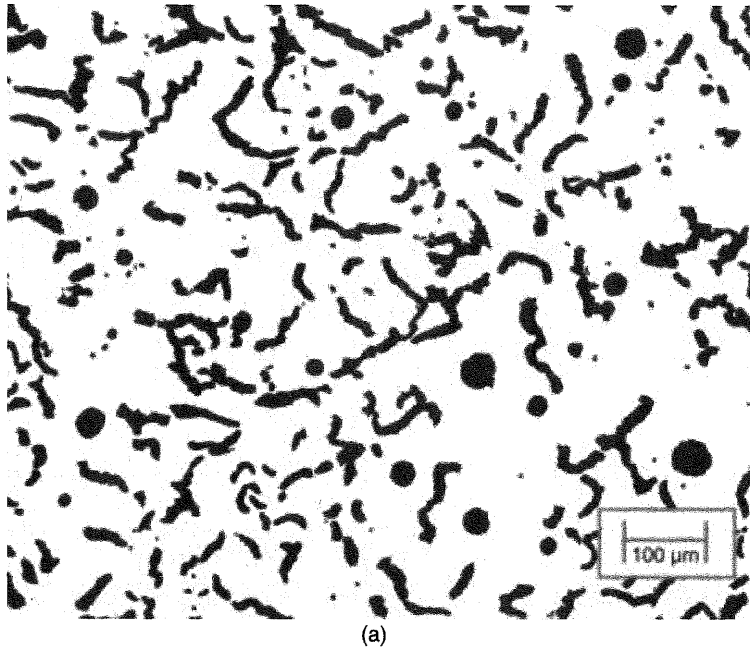


FIGURE 11.43 (a) Vermicular graphite distribution [3] and (b) a SEM micrograph of a deep-etched vermicular graphite cell. (Loper and Fang [14].)

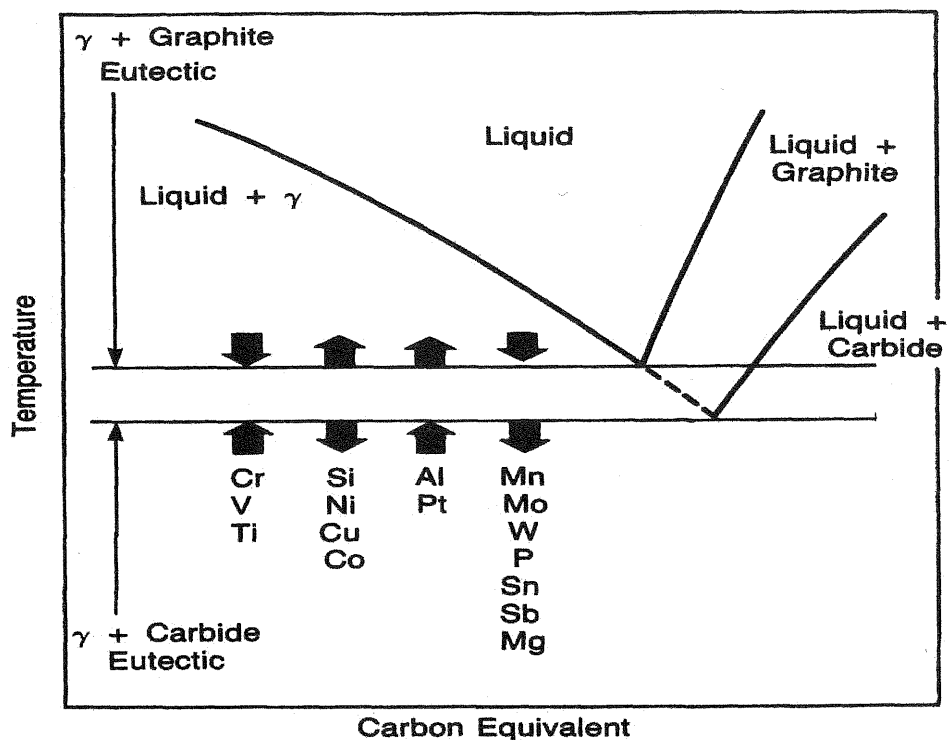


FIGURE 11.44 Effect of key elements on eutectic solidification temperatures. (From Janowak and Gundlach [28].)

Key Elements and Their Effects on Ductile Iron

Many of the elements in cast iron affect two areas of cast iron metallurgy: (1) the stable and metastable eutectic temperatures, and (2) the eutectoid transformation temperatures. Key elements affecting the eutectic temperatures are shown in Fig. 11.44. Some raise the stable eutectic and lower the metastable eutectic temperatures, and they are considered strong graphitizers. The ones that lower the graphite eutectic temperature and increase the carbide eutectic temperature are considered strong carbide formers.

Carbon

Next to iron, carbon is the most important element in ductile iron and affects many characteristics. The expansion resulting from precipitation of graphite as nodules counteracts the solidification shrinkage associated with the precipitation of austenite. This helps mold yield compared with steel castings and makes production of sound castings much easier. Carbon level varies from 3.3 to 4.0%, mainly depending on silicon level and casting section thickness. Carbon equivalent is controlled about the eutectic point, slightly higher than the eutectic. This ensures the least amount of shrinkage in the castings. Lower carbon is prone to shrinkage and carbide formation in thin sections. Higher carbons favor graphite flotation, exploded graphite, and even shrinkage. Carbon is considered a ferritizer. The presence of free graphite in the matrix causes the elastic modulus to decrease and thus, ultrasonic velocity. Increasing graphite content reduces dynamic properties.

Silicon

Silicon levels vary from 2.0 to 3.0% in regular ductile iron castings and 3.8 to 4.5% in high-silicon irons used at high temperatures. Silicon is a strong ferritizer and increases the hardness and yield strength of ferrite by solid-solution hardening. Increasing silicon increases shrinkage propensity in castings. Silicon increases oxidation resistance and is used up to 4.5% for castings such as exhaust manifolds. Silicon also increases the nil ductility temperature. Silicon is added in the melt as ferrosilicon alloys or silicon carbides. Silicon is also added through magnesium ferrosilicon during conversion to ductile iron and during postinoculation. A higher silicon level reduces chill carbide forming tendency.

Sulfur

Free sulfur is detrimental to graphite nodule shape. Base iron sulfur level is carefully controlled to a low level of 0.08 to 0.15%. High sulfur irons can be desulfurized prior to treatment, or special techniques need to be used to convert them to ductile iron. After magnesium treatment, sulfur in the final iron usually varies from 0.005 to 0.015%. Higher sulfur after treatment may lead to sulfur reversal and eventual deterioration of graphite nodules to vermicular and flake graphite. Measured magnesium residual in ductile iron depends on the sulfur residual as some of the magnesium is tied up with sulfur as sulfides.

Oxygen

There is a very low level of dissolved oxygen (<10 ppm) gas in ductile irons, especially after magnesium treatment. But oxygen is present as oxides of metals. Carbon and other elements combine with oxygen to form various oxides and gases that tend to exit through the molten iron. During melting, oxides of iron, manganese, and silicon are dispersed due to violent mixing and turbulence. These oxides can be neutralized by carbon and other elements like aluminum. These de-oxidation reactions are temperature and time dependent. In high production shops, oxides are present throughout the melt treatment and pouring operations to varying degrees depending on charge materials, melt practice, and other variables. Increased oxide content in the iron increases the chances for formation of defects such as pinholes, dross, and slag.

Alloying Elements

Special elements are added to ductile and other graphitic irons mainly to control the matrix during cooling through the eutectoid region as well as during various heat-treatment practices. Alloying elements enable the control of the matrix, independent of the cooling rate. Small amounts of alloys can be added to the treatment ladles to ensure good mixing. Larger additions of alloys are added in the melting furnaces to get better mixing. Elements that have high melting points should be added in the furnace. Many elements may have the same effect on the matrix and the cumulative effect should be considered when calculating additions. Some elements counteract the effect of others. When calculating the actual addition for a certain level of pearlite in the matrix, the cumulative effect of all pearlite-promoting elements should be considered together by giving a weighting factor for each of the elements [29]. Silicon effect is negative since it promotes ferrite.

Copper

This is the preferred element for stabilizing pearlite in the matrix. Copper does not segregate to grain boundaries and does not promote carbides. In many cases, copper is

added in the treatment ladles as cover material for magnesium alloy, and thus improves magnesium recovery. Like silicon, copper also increases magnesium solubility. Many have observed that copper increases shrinkage tendency. Generally, copper is limited to 1.0% for pearlitic castings. If copper alone is inadequate to yield the pearlite content desired, either due to heavy section or when boron is present, then materials such as tin and manganese can be added to complement copper.

Manganese

Manganese affects cast irons during solidification as well as during eutectoid transformation. It segregates to the austenite grain boundaries increasing carbon solubility at the end of solidification, increasing the carbide-forming tendency, and increasing shrinkage porosity. Manganese strengthens the matrix along with copper to increase yield strength. Manganese also increases hardenability and austemperability. Due to segregation, it is usually limited to less than 0.5%, especially for austempered ductile irons. Manganese decreases machinability in pearlitic ductile iron.

Nickel

Nickel is a mild pearlite promoter. It increases yield strength even in ferritic irons. For low-temperature impact grade irons, where silicon level is low, nickel is added to increase yield strength. Addition of 2 to 4.0% nickel may produce as-cast acicular matrix. Higher levels of nickel, 18 to 35%, are used to get as-cast austenitic irons for high temperature and corrosion-resistant applications.

Molybdenum

Molybdenum is added in small quantities, less than 0.4%, to improve hardenability during austempering. It is also added (0.6 to 1.0%) for improving creep resistance for exhaust manifolds that operate at high temperatures. Molybdenum does not promote pearlite, but segregates to grain boundaries and stabilizes complex carbides.

Tin

Tin is a strong pearlite promoter and is considered to be 10 times stronger than copper. It is used only when necessary to stabilize pearlite if it cannot be done by copper alone, and the level of addition is limited to 0.025%. At higher levels of tin (>0.04%) ductile iron becomes increasingly brittle.

Chromium

Chromium is not added to ductile iron and is considered detrimental to ductility as it forms stable carbides in the grain boundary areas. Taking advantage of this fact, castings are produced with carbides to improve wear resistance. For carbidic austempered iron, castings are produced by a carbide stabilizer such as chromium, and by reducing inoculation and thus promoting stable carbides [30]. Stable carbides are not dissolved during the austenitizing step in the austempering process. Chromium is also added with nickel for different grades of austenitic gray and ductile irons.

Residual Elements (Trace Elements and Deleterious Elements)

Many elements are present in small quantities that are not added intentionally but are introduced from scrap steel, pig iron, and alloys. Some elements, even in small

quantities, can be harmful to the graphite shape, and others may affect mechanical properties. Effects of many of these elements are known and can be compensated in most cases.

Aluminum—introduced mainly from ferrosilicon alloys. Aluminum easily oxidizes in the melting operation. About 0.03% aluminum has been shown to produce pinholes. Aluminum is used in steel as a deoxidizer and similar effects can be seen in irons also. With reduced alloy additions, aluminum has not been a significant element affecting ductile iron solidification and casting defects.

Antimony—is a strong pearlite promoter and also forms intercellular flake graphite above 0.004%. Sb is usually used in heavy sections to counteract the chunky graphite forming effect of rare earths and to improve nodule count.

Bismuth—promotes flake graphite even at levels around 0.003%. It is used in heavy section casting production to increase nodule count and is balanced by rare earths.

Boron—even in low levels (0.003%) affects pearlite formation. In normally pearlitic irons, excess boron will reduce the amount of pearlite, hardness, and tensile strength. Boron can come from steel scrap and from leaching out of silica lining bonded with boric acid in induction furnaces.

Lead—introduced from contaminated steel scrap with wheel weights, brass, and other leaded steels. Lead forms flake graphite even at 0.002% levels and magnesium itself is not adequate to neutralize the adverse effect of lead. Rare earths are, however, effective in neutralizing the effects of lead.

Phosphorous—forms grain boundary iron-phosphide eutectic carbides at higher levels and thus is limited to less than 0.05% in most specifications. For low-temperature impact requirements it is limited to less than 0.03%.

Titanium—is introduced from ferrous scrap and from alloying elements. Titanium forms flake graphite and is seen as having a poisoning effect in ductile iron. In heavy sections, Ti may segregate and may cause problems. It reduces the spheroidizing effect of magnesium and is added with magnesium to produce vermicular graphite irons. Titanium can be counteracted by rare earths to avoid flake graphite. Titanium can reduce machinability when present as titanium carbo-nitrides.

Zinc—comes from coating on ferrous metals and from contaminants in scrap. Zinc evaporates during melting.

Conversion from Flake Graphite to Nodular Graphite

In the beginning, ductile iron production was licensed by the International Nickel Company and the alloy used at that period was nickel magnesium alloy. Magnesium is easily soluble in nickel and was easy to introduce into molten iron without violent reactions.

Even though rare earths alone can be used to produce spheroidal graphite, magnesium- and magnesium-containing alloys are the preferred way to make ductile iron castings. Due to cost and the sensitivity to form carbides and other forms of graphite, rare earths are generally used to augment magnesium in designing treatment systems.

The high cost of nickel necessitated the development of magnesium ferrosilicon alloys for reducing the cost of ductile iron treatment. High volatility, reactivity, and low density of magnesium and differing base iron chemistries necessitated the development of various treatment methods to convert base iron to ductile iron. If pure magnesium is used for the conversion, special ladles and procedures need to be used for safety and efficiency of alloy usage [9].

Physical and Mechanical Properties of Cast Irons

Physical Properties

Important physical properties such as thermal conductivity and damping capacity of cast irons are given in Tables 11.10 to 11.12. Thermal conductivity is influenced by the microstructure of cast irons. Since graphite exhibits the highest thermal conductivity of all phases, gray iron has the better thermal conductivity in the family of cast irons. Again, in gray irons, thermal conductivity of graphite parallel to the basal plane is approximately four times that perpendicular to the basal plane. As shown in Table 11.10, thermal conductivity of gray iron increases with the carbon equivalent. The higher the thermal conductivity, the lower is the thermal gradients throughout the casting, and hence, lower thermal stresses in the component subjected to thermal stress in service. In general, thermal conductivity decreases with temperature.

Thermal conductivity of different cast irons are compared in Table 11.11; alloyed cast irons have lower thermal conductivity than ductile iron.

Gray iron possesses the highest damping capacity which is the ability to stop vibrations and ringing. This is shown in Table 11.12 for different ferrous and nonferrous common structural alloys. Because of its high damping capacity, gray iron is used for structures where vibration can cause stresses. Other examples are bases and supports, as well as moving parts.

Thermal Conductivity at Different Test Temperatures, W/m-K					
C, %	Si, %	Carbon Equivalent, %	200°F (95°C)	400°F (205°C)	800°F (425°C)
3.50	2.25	4.25	57.1	51.9	
3.93	1.40	4.40	55.4	51.9	46.7
3.58	1.90	4.21	48.5		
3.16	1.54	3.67	46.7		41.5
2.92	1.75	3.50	36.3		
2.90	1.51	3.40 (Alloyed)	36.3	36.3	36.3

Source: From Davis [15].

TABLE 11.10 Thermal Conductivity of Gray Irons for Different C and Si Contents

	200°F (95°C)	400°F (205°C)	800°F (425°C)
Ductile irons			
Ferritic ductile iron	41.5	38.1	32.9
Pearlitic and alloyed	26	27.7	
High alloy irons			
36% Ni steel invar	10.4		
36% Ni cast irons	39.8		

Source: From Davis [15].

TABLE 11.11 Thermal Conductivity of Different Types of Cast Irons, W/m-K

Material	Relative Damping Capacity
Coarse flake gray iron	100–500
Fine flake gray iron	20–100
Malleable iron	8–15
Ductile iron	5–20
Pure iron	5
White iron	2–4
Eutectoid steel	4
Aluminum	0.4

Source: From Davis [15, p. 854].

TABLE 11.12 Relative Damping Capacities of Some Common Structural Alloys

Thermal Expansion

For the temperature range from room temperature to 1070°C (1960°F), the coefficient of thermal expansion varies from 9.2 to 16.9 $\mu\text{m}/\text{m}\cdot^\circ\text{C}$ (5.1 to 9.4 $\mu\text{in}/\text{in}\cdot^\circ\text{F}$). At room temperature, the commonly used figure of 10 $\mu\text{m}/\text{m}\cdot^\circ\text{C}$ (5.5 $\mu\text{in}/\text{in}\cdot^\circ\text{F}$) is accurate enough for moderate changes in temperature.

Density

Density of gray irons at room temperature varies from about 6.95 g/cm^3 for open-grained high-carbon irons to 7.35 g/cm^3 for close-grained low-carbon irons. The density of white iron is about 7.70 g/cm^3 .

Shrink Rule

Patternmakers' rules (shrink rules) allow 1% linear contraction upon solidification and cooling of gray iron, 0% for annealed ductile iron, 0.7% for as-cast ductile iron, and 1 to 2% for white iron.

Mechanical Properties and Specifications

The single most important factor affecting the strength of graphitic iron castings is graphite shape, size, and distribution. The strength of irons similar in chemistry can vary from 20,000 to 120,000 psi in the as-cast condition just by modifying the graphite shape from flake to nodular. Strength can also be affected by manipulating the matrix for the same graphite structure. All of this can be seen in the various specifications as shown later in the chapter.

All cast irons are section sensitive (properties are dependent on section thickness), as shown in Fig. 11.50 [4]. Many properties and microstructures are affected by the cooling rate of the castings both during solidification and during solid-state transformation. Gray irons are more sensitive to variations in section size compared to malleable and ductile irons. During solidification thicker sections cool slower resulting in large cell size (large graphite flakes) in gray irons and lower nodule count in ductile irons. Low solidification rates increase segregation tendency of carbide-forming elements. At the eutectoid transformation region, heavier sections cool slowly resulting in more ferrite and less pearlite for the same chemistry. Even if the matrix stays pearlitic in gray irons, due to the coarseness of graphite flakes and pearlite lamellae, tensile strengths, and

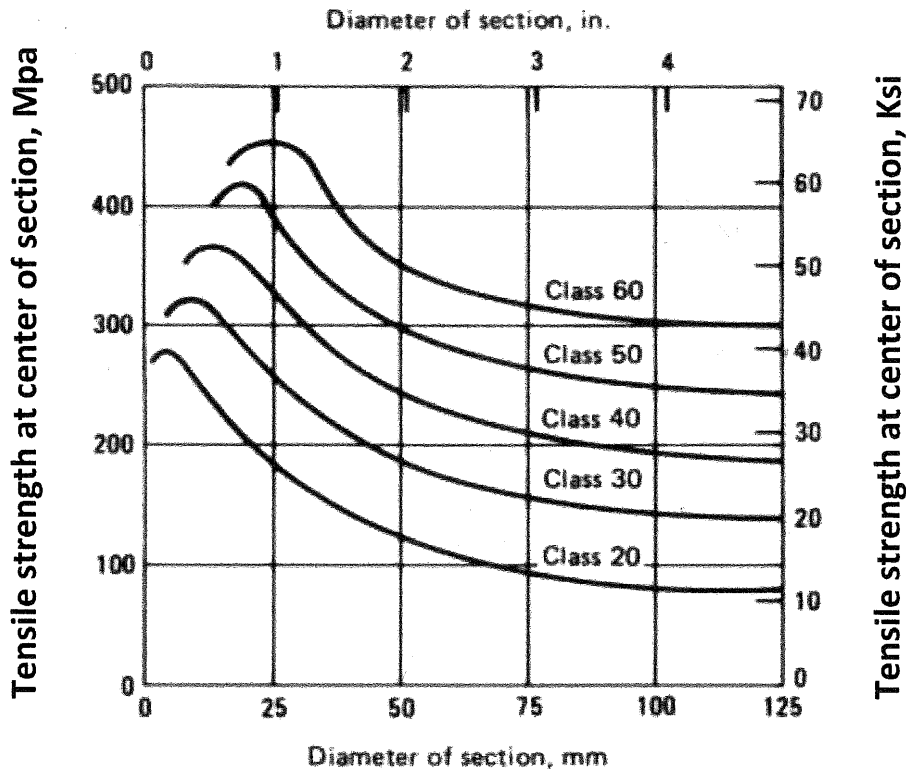


FIGURE 11.50 Decreasing tensile strength with increasing section thickness, illustrating the section sensitivity of gray irons. (From Walton [4].)

hardness are lower in heavier sections than in thinner sections. In ductile irons, heavier sections cooling slowly will have an increased amount of ferrite, unless castings are above the upper critical temperature during mold shakeout.

Different specifying bodies have issued property standards to be met by casting producers. It is not the intent of this book to provide the exact requirements for different grades of materials. Usually, casting producers and buyers agree upon the minimum properties expected from the castings, whether they are from separately cast test bars or from the casting themselves. The tables given here are for reference only and not for strict enforcement of the standards. There are many other details in standards that are not shown here and should be obtained from the specifying bodies to get the latest information. Mechanical properties of SAE J431 automotive gray irons and ISO 185 specifications for gray irons are given in Tables 11.13 and 11.14, respectively. Their graphite size chart, as in ISO 945, is shown in Table 11.15.

Malleable Iron

Mechanical properties of malleable irons are given in Table 11.16, where similar standards are grouped together with class or grade. Automotive grade malleable irons are also included in this table. (See *ASM Handbook*, p. 889.) Typical applications include

SAE Grade	Hardness, HB	Minimum Transverse Load		Minimum Deflection		Minimum Tensile Strength	
		kg	lb	mm	in	MPa	Ksi
G1800	187 max	780	1720	3.6	0.14	124	18
G2500	170–229	910	2000	4.3	0.17	173	25
G3000	187–241	1000	2200	5.1	0.20	207	30
G3500	207–255	1110	2450	6.1	0.24	241	35
G4000	217–269	1180	2600	6.9	0.27	276	40

Note: Properties determined from as-cast test bar (30.5 mm, or 1.2 in, diam).

TABLE 11.13 Mechanical Properties of SAE J431 Automotive Gray Cast Irons

Grade	Tensile Strength, Separately Cast Test Bars, MPa/Ksi
100	100/14.5
150	150/21.75
200	200/29
250	250/36.25
300	300/43.5
350	350/50.75

TABLE 11.14 ISO 185-2005 Gray Cast Iron Classification

Reference Number	Dimension of Graphite Particle Observed at 100 Magnification, mm
1	>100
2	50–100
3	25–50
4	12–25
5	6–12
6	3–6
7	1.5–3
8	<1.5

TABLE 11.15 ISO 945-2008 Graphite Size Chart 1 through 8

pistons, transmission gears, connecting rods, compressor crank shafts and hubs, flanges, pipe fittings, etc.

White Iron (Abrasion-Resistant Cast Iron)

To make the iron-iron carbide system stable or to increase the amount of carbides present, different elements such as Cr, Mo, V, etc., are added to the alloy during melting and treatment. The high-alloyed white cast irons fall into two major groups: (1) Nickel-chromium white irons, which are low-chromium alloys containing 3 to 5% Ni and 1 to 4% Cr, with

Specification No.	Class or Grade	Tensile Strength		Yield Strength		Hardness, HB	Elongation, %
		MPa	Ksi	MPa	Ksi		
Ferritic							
ASTM A 47 and A 338, ANSI G48.1, FED QQ-1-666c	32510	345	50	224	32	156 max	10
	35018	365	53	241	35	156 max	18
ASTM A 197	—	276	40	207	30	156 max	5
Pearlitic and Martensitic							
ASTM A 220, ANSI G48.2, MIL-11444B	40010	414	60	276	40	149–197	10
	45008	448	65	310	45	156–197	8
	45006	448	65	310	45	156–207	6
	50005	483	70	345	50	179–229	5
	60004	552	80	414	60	197–241	4
	70003	586	85	483	70	217–269	3
	80002	655	95	552	80	241–285	2
	90001	724	105	621	90	269–321	1
Automotive							
ASTM A 602, SAE J158	M3210	345	50	224	32	156 max	10
	M4504	448	65	310	45	163–217	4
	M5003	517	75	345	50	187–241	3
	M5503	517	75	379	55	187–241	3
	M7002	621	9	483	70	229–269	2
	M8501	724	105	586	85	269-302	1

Source: Courtesy of ASTM.

TABLE 11.16 Properties of Malleable Iron Castings

one alloy modification that contains 7 to 11% Cr. The nickel-chromium irons are also commonly identified as Ni-hard types 1 to 4. (2) The chromium-molybdenum irons contain 11 to 23% Cr, with up to 3% Mo and are often additionally alloyed with nickel or copper.

A third group comprises the 25 or 28% Cr white irons, which may contain other alloying additions of molybdenum and/or nickel up to 1.5%.

Carbide cast irons such as Ni-hard, are used in wear-resistant or abrasion-resistant applications. Some Ni-hard microstructures are shown in Fig. 11.20. For further reading on abrasion-resistant irons, see Ref. 13.

Compositions and mechanical properties of abrasion-resistant cast irons or white irons are given in Tables 11.17 and 11.18, respectively, in accordance with ASTM A532/A532M

Ductile Iron

Ductile iron tensile properties are ensured by proper microstructure. Once the graphite shape is ensured to be at least 85% nodularity, there is very little change from the graphite

Class	Type	Designation	Composition, %				
			C	Si	Ni	Cr	Mo
I	A	Ni-Cr-HC	2.8–3.6	0.8 max	3.3–5.0	1.4–4.0	1.0 max
I	B	Ni-Cr-LC	2.4–3.0	0.8 max	3.3–5.0	1.4–4.4	1.0 max
I	C	Ni-Cr-GB	2.5–3.7	0.8 max	4.0 max	1.0–2.5	1.0 max
I	D	Ni-HiCr	2.5–3.6	2.0 max	4.5–7.0	7.0–11.0	1.5 max
II	A	121%Cr	2.0–3.3	1.5 max	2.5 max	11.0–14.0	3.0 max
II	B	15%Cr-Mo	2.0–3.3	1.5 max	2.5 max	14.0–18.0	3.0 max
II	D	20%Cr-Mo	2.0–3.3	1.0–2.2	2.5 max	18.0–23.0	3.0 max
III	A	25%Cr	2.0–3.3	1.5 max	2.5 max	23.0–30.0	3.0 max

Source: Courtesy of ASTM.

TABLE 11.17 Compositions of Abrasion-Resistant Cast Irons in Accordance with ASTM A 532/A 532M

Class	Type	Designation	Hardness, HB				Typical Section Thickness	
			Sand Cast, min.	Chill Cast, min.	Hardened, min.	Softened, max.	in	mm
I	A	Ni-Cr-HC	550	600	600	–	8	200
I	B	Ni-Cr-LC	550	600	600	–	8	200
I	C	Ni-Cr-GB	550	600	600	400		
I	D	Ni-HiCr	550	550	600	–	12	300
II	A	121%Cr	550	550	600	400		
II	B	15%Cr-Mo	450	–	600	400	4	100
II	D	20%Cr-Mo	450	–	600	400	8	200
III	A	25%Cr	450	–	600	400	8	200

Source: Courtesy of ASTM.

TABLE 11.18 Mechanical Property Requirements for Abrasion-Resistant Cast Irons in Accordance with ASTM A 532/A 532M

morphology, unlike the gray iron, where the tensile properties are greatly affected by graphite size and distribution. Strength and ductility are significantly affected by the matrix microstructure. When the matrix is predominantly pearlitic both yield and tensile strengths are higher and elongation is lower. On the other hand, when the matrix is ferritic, the strengths are lower and ductility is higher. This is shown clearly in the minimum requirements of these properties in published specifications (Tables 11.19 and 11.20).

Properties of all the regular ASTM A536 grades except 120-90-02 grade can be met in the as-cast condition when the chemistry is closely controlled. Casting users may require heat treatment for grades 60-40-18 and quench and temper heat treatment is normally used to get 120-90-02 grade. The ASTM standards were developed during the early production period of ductile iron, when it was common to use nickel-magnesium alloys. Current practice is without nickel except in special circumstances and hence, the mechanical properties may be different and customers may expect properties in the castings to meet their specifications, which may be different from the standards shown in Table 11.19.

ASTM A536-84 (2004) Ductile Iron			
	UTS, Ksi (MPa)	YS, Ksi (MPa)	E, %
60-40-18	60(414)	40(276)	18
65-45-12	65(448)	45(310)	12
80-55-06	80(552)	55(379)	6
100-70-03	100(689)	70(482)	3
120-90-02	120(827)	90(620)	2

Source: Courtesy of ASTM.

TABLE 11.19 ASTM Grades for Standard Ductile Irons

ISO1083-2004 Ductile Iron			
Grade/JS/S	UTS, MPa	YS, MPa	E, %
350-22	350	220	22
400-18	400	250	18
400-15	400	250	15
450-10	450	310	10
500-7	500	320	7
550-5	550	350	5
600-3	600	370	3
700-2	700	420	2
800-2	800	480	2
900-2	900	600	2
Impact Specifications, minimum Joules, Mean value of three tests (individual test)			
Temp °C	23	-20	-40
350-22-LT			12(9)
350-22-RT	17(14)		
400-18-RT		12(9)	
400-18-LT	14(11)		

TABLE 11.20 International Standard Grades for Ductile Iron

Table 11.19 shows the ASTM grades for as-cast and heat-treated ductile iron castings, properties measured in separately cast test bars. Table 11.20 lists the grades including low-temperature impact properties as per the International Standards Organization (ISO).

It may be necessary to keep the silicon and phosphorous content low to meet the impact specifications.

Austempered Ductile Iron

Mechanical properties of austempered ductile iron are given in Table 11.21 according to ASTM A897 and A897M-06 grades. It is important to ensure that austempered castings are free of carbides, inclusions, and nodule degenerations as they impair properties

Grade	Tensile Strength, MPa/Ksi	Yield Strength, MPa/Ksi	Elongation, %	Impact Energy,* J/ft-lb	Typical Hardness, BHN
750	750/110	500/70	11	110/80	241–302
1	900/130	550/90	9	100/75	269–341
2	1050/150	750/110	7	80/60	302–375
3	1200/175	850/125	4	60/45	341–444
4	1400/200	1100/155	2	35/25	388–477
5	1600/230	1300/185	1	20/15	402–512

*Note: Impact testing is at room temperature, unnotched.

Source: Courtesy of ASTM.

TABLE 11.21 ASTM A897 and A897M-06 Grades for Austempered Ductile Irons

significantly more than in as-cast condition. Nodule count may be maximized to reduce the effect of segregation.

Quality of ductile iron can be evaluated by looking at the relative elongation for tensile or yield strength [36]. One easy way is to plot the yield strength against elongation superimposed on the ASTM minimum properties curve, as shown in Fig. 11.51. When the test points fall below the ASTM minimum curve, as is the case with point A,

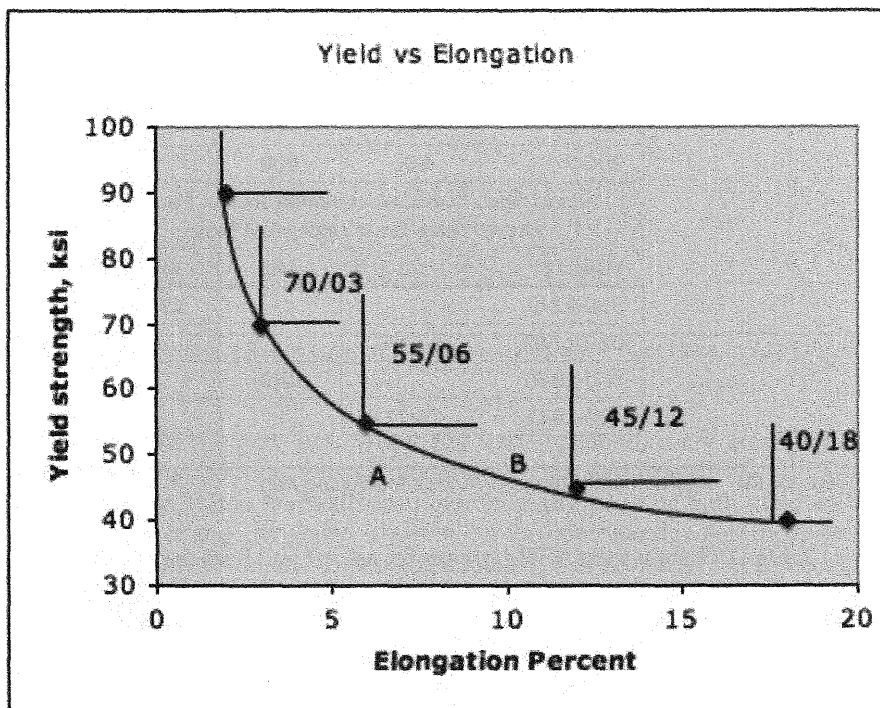


FIGURE 11.51 Yield strength versus elongation as per ASTM minimum properties for different grades. Test point A is inferior ductile, whereas point B is considered good-quality ductile iron even as it does not fall within one of the standard grades. (From Loper and Kotschi [36].)

there could be shortfall in the control of ductile iron production. When carbides, either chill or inverse chill, shrinkage porosity, nonmetallic inclusions and deformed graphite nodules are present in the microstructure, the test point may fall below the curve. When the test points are above the curve, ductile iron quality is above par even if it did not meet a given minimum yield or elongation, represented by point B in Fig. 11.51.

Compacted Graphite Iron

Factors influencing the mechanical properties at room and elevated temperatures of CG irons are composition, structure (nodularity and matrix), and section size. Structure is also affected by type of raw materials, preprocessing variables (superheat, holding time, desulfurization), melt processing (graphite compaction and postinoculation), and postsolidification processing (cooling rate, shakeout time, and heat treatment). Typical mechanical properties according to ASTM A842 are given in Table 11.22. Their strength properties are comparable to those of ductile irons. Elongation values are significantly higher than those of flake graphite irons.

Customers may specify upper limit on nodularity in the microstructure to ensure damping and other properties to meet their needs.

Tensile/Hardness Ratio

Tensile/hardness (T/H) ratio is a nondimensional number, which indicates the quality of irons. Brinell hardness number is converted to compressive strength by multiplying it by 9.81, where the units are in MPa. In ductile iron, this ratio ranges from 0.27 to 0.33. This means the tensile strength is about 30% of compressive strength. A higher ratio indicates a better-quality ductile iron. In gray irons, ratio depends on the CE, and the strength of the irons. Ratio is lower with higher CE and low-strength irons with longer flakes.

Design Considerations

Castings are designed for easier production of molds, with minimal or no coring. Castings should be easily parted and placed in separate halves of the mold. Considerations should be given to ensure ease of placement of the cores in the molds and to remove the residual core sand after the castings are shaken out.

Generous draft (taper) should be provided for easy release of the pattern from the mold.

Plate castings of uniform thickness are harder to fill without misruns. Casting section could be tapered or ribs can be provided for easy and even filling of the mold cavity.

There are some special considerations apart from general design guidelines when designing iron castings. Cast irons have excellent fluidity during mold filling and thus thin sections can be cast. However, there is a minimum wall thickness for different grades

Grade	250	300	350	400	450
Min. tensile strength, MPa	250	300	350	400	450
Min. yield strength, MPa	175	210	245	280	315
Elongation, %	3	2	1	1	1

Source: Courtesy of ASTM.

TABLE 11.22 ASTM A842 CG Iron Specification Grades

depending on the chilling tendency of the irons. As gray and white cast irons are brittle, thin, unprotected sections could break during shakeout and processing in the foundry.

Gray Iron

Chill carbides tend to form at tips of thin sections, hence, wedge-type ends should be avoided. Unsupported thin sections like fins will be susceptible to breakage during normal shakeout operations unless special handling is available.

As gray irons are section sensitive, thin sections will be harder than thick sections, and tensile properties will vary according to cooling rate in the mold. Hence, it is preferable to have uniform sections in the castings.

Interrupted casting sections are susceptible to chipping during machining operations.

Even as gray iron has very minimal shrinkage during eutectic solidification, isolated sections may have shrinkage if intermediate sections are too thin.

Malleable Iron

Malleable iron castings are cast as white iron. White irons shrink more and require risering to eliminate shrinkage porosity. Directional solidification toward riser is beneficial to ensure solid castings. Thin wall castings can easily be made into white iron. If the casting sections are too big, iron can solidify as mottled or even gray, which will not meet the mechanical property requirements. Hence, the largest section that can be cast as white iron is limited.

Ductile and Compacted Graphite Iron

Ductile irons can be cast in thin as well as thick sections. Even though the solidification could be slower for thick sections, which will result in lower nodule count, strength is not reduced significantly as in gray iron castings with heavier sections. Similar to gray iron isolated heavy sections should be avoided to minimize shrinkage porosity. Reentrant corners with sharp radii can cause shrinkage porosity close to the mold surface, which might open up during machining. Mold density at these locations will be lower, which could reduce heat transfer. Special consideration is also given for inspection of ductile iron castings using ultrasonic method. Parallel surfaces are needed for effective testing of nodularity with ultrasonic systems. For the production of ferritic castings, shakeout time is important. If the shakeout time is short or the casting section is too big for the mold line, temperature at shakeout may be above the eutectoid transformation temperature. When castings are shaken out above the transformation temperature, hardness of castings will increase as pearlite formation is favored when the cooling rate is high. In compacted graphite iron castings, nodularity is dependent on cooling rate. Faster cooling rates increase nodularity, and slower cooling rates may favor flake graphite formation. Hence, uniform size is favorable to maintain vermicular graphite in all sections of the casting.