

# Cast Irons<sup>☆</sup>

**KB Rundman**, Michigan Technological University, Houghton, MI, USA

**F Iacoviello**, Università di Cassino e del Lazio Meridionale, DICEM, Cassino (FR), Italy

© 2016 Elsevier Inc. All rights reserved.

1	<b>Metallurgy of Cast Iron</b>	1
2	<b>Solidification of a Hypoeutectic Gray Iron Alloy With CE=4.0</b>	3
3	<b>Matrix Microstructures in Graphitic Cast Irons – Cooling Below the Eutectic</b>	3
4	<b>Microstructure and Mechanical Properties of Gray Cast Iron</b>	4
5	<b>Effect of Carbon Equivalent</b>	5
6	<b>Effect of Matrix Microstructure</b>	5
7	<b>Effect of Alloying Elements</b>	5
8	<b>Classes of Gray Cast Irons and Brinell Hardness</b>	5
9	<b>Ductile Cast Iron</b>	5
10	<b>Production of Ductile Iron</b>	6
11	<b>Solidification and Microstructures of Hypereutectic Ductile Cast Irons</b>	6
12	<b>Mechanical Properties of Ductile Cast Iron</b>	7
13	<b>As-cast and Quenched and Tempered Grades of Ductile Iron</b>	8
14	<b>Malleable Cast Iron, Processing, Microstructure, and Mechanical Properties</b>	8
15	<b>Compacted Graphite Iron</b>	9
16	<b>Austempered Ductile Cast Iron</b>	9
17	<b>The Metastable Phase Diagram and Stabilized Austenite</b>	9
18	<b>Control of Mechanical Properties of ADI</b>	10
19	<b>Conclusion</b>	10
	<b>References</b>	11
	<b>Further Reading</b>	11

Cast irons have played an important role in the development of the human species. They have been produced in various compositions for thousands of years. Most often they have been used in the as-cast form to satisfy structural and shape requirements. The mechanical and physical properties of cast irons have been enhanced through understanding of the fundamental relationships between microstructure (phases, microconstituents, and the distribution of those constituents) and the process variables of iron composition, heat treatment, and the introduction of significant additives in molten metal processing. The interested reader is referred to compilations of micrographs of all of the many different types of cast iron (Davis, 1996, pp. 356–381). Some examples are shown in Figure 1. Graphite elements (black) with different shape are embedded in a metal matrix with a microstructure that depends on the alloy chemical composition, the casting conditions and the heat treatments.

This article examines the relationships between microstructure, processing, and properties of graphitic cast irons. Abrasion-, corrosion-, and heat-resistant irons are specialty grades which are not discussed here. Information about these grades can be found in specialty handbooks (e.g., Davis, 1996).

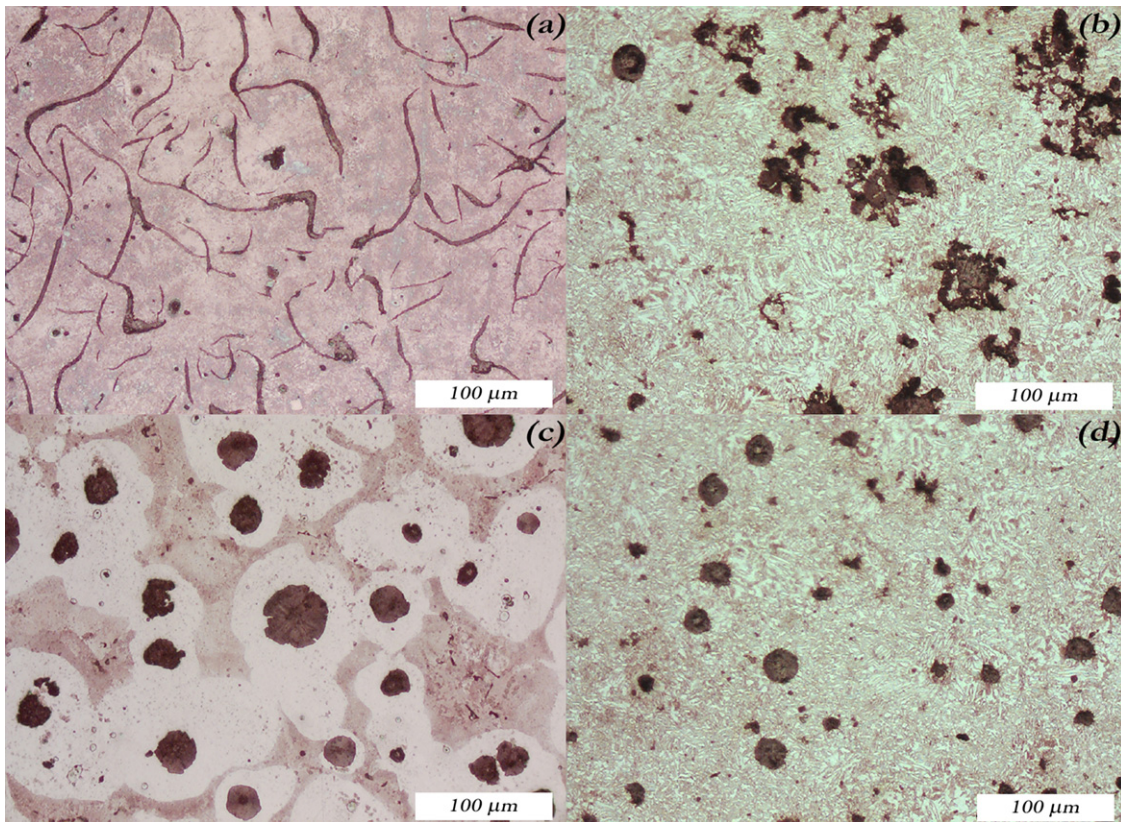
## 1 Metallurgy of Cast Iron

Cast irons, alloys of iron, carbon, and silicon, contain carbon as graphite (pure carbon), as carbide ( $\text{Fe}_3\text{C}$ ), or in solid solution in austenite (austempered ductile iron (ADI), matrix austenite with 1.7–2.1% carbon). The evolution of the total casting tonnage by alloy in the last ten years confirms that cast irons represent the largest tonnage of cast-to-shape products produced worldwide (Figure 2), with the worldwide economical crisis effect that is evident in years 2008–10 (Modern Casting Staff Report, 2014, pp. 17–21).

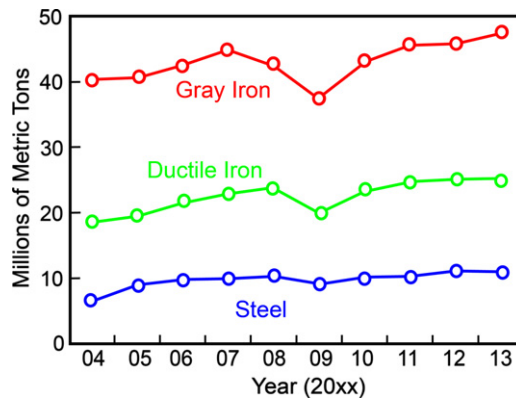
Table 1 lists compositions and distinctive microstructural features for common cast irons. Ferrite and pearlite are defined identically to steel, and ausferrite is a two-phase, high-carbon austenite matrix with embedded ferrite lathes.

The composition of cast irons is defined by the carbon equivalent,  $\text{CE} = \% \text{ carbon} + 1/3\% \text{ silicon}$ , where  $\text{CE} = 4.3$  is the eutectic composition (Walton and Opar, 1981). The usual composition, hypo- or hypereutectic, is given in Table 1 for each iron. Carbon

<sup>☆</sup>Change History: July 2015. F. Iacoviello modified the Abstract, Section 'Metallurgy of Cast Iron,' and Section 'Ductile Cast Iron'. One new reference (Modern Casting Staff Report, 2014) and two new figures (Figures 1 and 2) were added. Figures 3–10 were modified.



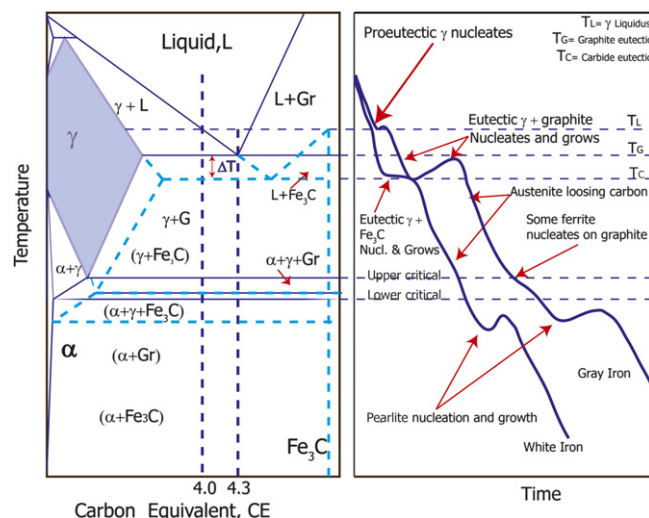
**Figure 1** Different cast irons: (a) pearlitic lamellar cast iron; (b) Exploded graphite in ductile cast iron; (c) Ferritic-pearlitic ductile cast iron; (d) Austempered ductile cast iron.



**Figure 2** Evolution of the total casting tonnage by alloy in the last ten years (Modern Casting Staff Report, 2014).

**Table 1** Cast iron composition ranges and microstructures

Type	C range (wt%)	Si range (wt%)	CE range	Usual composition	Eutectic product	Graphite shape	Common RT matrix microconstituents
Gray	2.5–4.0	1.0–3.0	2.8–5	Hypo	$\gamma$ + graphite	Platelets	Ferrite, pearlite
Ductile	3.0–4.0	1.8–2.8	3.6–4.9	Hyper	$\gamma$ + graphite	Spheres	Ferrite, pearlite, ausferrite
Malleable	2.0–2.6	1.1–1.6	2.4–3.2	Hypo	$\gamma$ + carbide	'Popcorn'	Ferrite, pearlite
White	1.8–3.6	0.5–1.9	2–4.3	Hypo	$\gamma$ + carbide		Ferrite, pearlite
Compacted	3.0–4.0	1.8–2.8	3.6–4.9	Eutectic	$\gamma$ + graphite	Rods	Ferrite, pearlite



**Figure 3** Schematic isopleth showing stable (graphite) and metastable equilibrium ( $\text{Fe}_3\text{C}$ ) in Fe–C–Si alloys. Cooling curves for an alloy of CE = 4.0 are also shown.

and silicon largely determine the microstructure of cast products immediately after solidification. **Figure 3** is a schematic vertical section through the stable and metastable Fe–C–Si phase diagrams (isopleth), where solid lines represent the stable iron–graphite phase diagram and dashed lines represent the metastable iron–cementite phase diagram.

## 2 Solidification of a Hypoeutectic Gray Iron Alloy With CE = 4.0

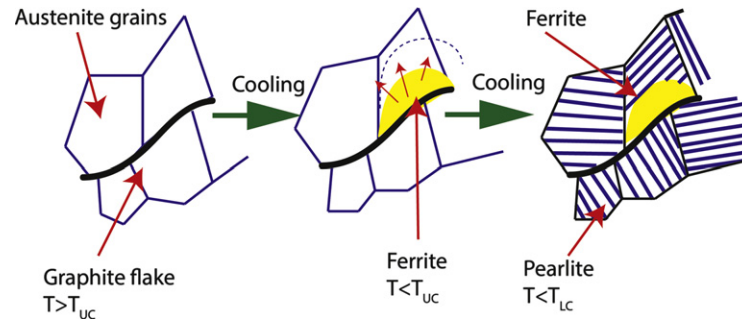
Solidification begins at the austenite liquidus,  $T_L$ , proeutectic austenite dendrites growing into the liquid, enriching it in carbon until the stable eutectic reaction temperature,  $T_G$ , is reached (Merchant, 1968). Cooling below  $T_G$  may result in the equilibrium eutectic reaction  $L \rightarrow \gamma + \text{Gr}$ , a microstructure consisting of austenite dendrites surrounded by a eutectic product (cells) of  $\gamma + \text{Gr}$ , a *gray iron* structure which would be represented by a cooling curve shown in **Figure 3**. However, for higher cooling rates (see the more rapid cooling rate curve in **Figure 3**), and/or a faulty processing history, the iron may supercool below  $T_G$  and satisfy metastable equilibrium between the phases  $\alpha$ ,  $\gamma$ , L, and cementite,  $\text{Fe}_3\text{C}$ . The resulting structure would then be austenite dendrites surrounded by eutectic  $\gamma + \text{Fe}_3\text{C}$ , or *white iron*. The metastable phase diagram is shifted to lower temperatures than the stable diagram by an amount proportional to the amount of silicon. Adding 2% silicon increases the temperature difference,  $\Delta T$ , between the stable and metastable eutectics from 4 to 30 °C. Similar effects are recorded in the eutectoid reaction range. These  $\Delta T$  values are exaggerated in **Figure 3** for illustration. Thus, each iron melted selects either stable or metastable transformation products during solidification. The tendency for iron to solidify white (defined as ‘chill’) in practice is monitored with a ‘chill’ wedge-shaped casting (a standard wedge block, ASTM A367, with thickness varying from 0 to 25 mm (Davis, 1996, pp. 45–46)), where the tendency to form white iron increases as the tip of the wedge casting is approached. Clearly, if the chill wedge has white iron up to and including the 1 cm width, then castings poured from the same iron with section sizes less than 1 cm would also be expected to have white iron present.

The possibility of white iron forming in the fast-cooling sections is cause for concern for foundries producing gray iron castings because of the negative effects of the hard iron carbide. One of the advantages of gray cast iron is its excellent machinability because of its graphite content, but if iron carbide is present it will quickly dull cutting tools. It is necessary to do everything possible to ensure that white iron does not form at any point in the gray iron casting.

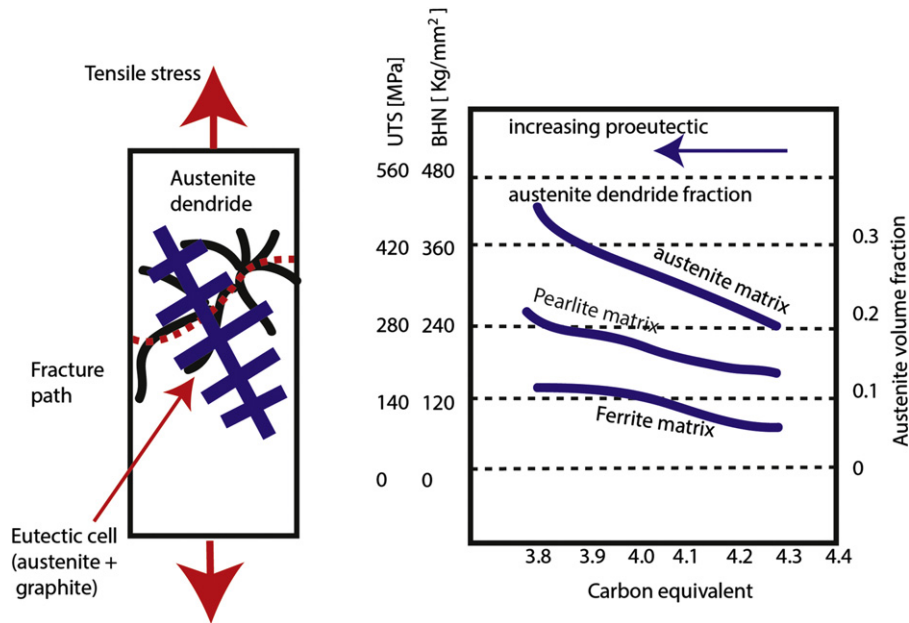
Inoculation is a processing step where an addition (inoculant) is made to the melt just prior to pouring the castings to minimize the possibility of ‘chill.’ Inoculants usually contain reactive elements (calcium, aluminum, barium, strontium) in small amounts (~1%) which react with oxygen and sulfur to form the nuclei for graphite and therefore the graphite–austenite eutectic cells. The most direct result of inoculation is to reduce the amount of carbide in more rapidly cooling sections and to increase the number of eutectic cells (Lownie, 1957).

## 3 Matrix Microstructures in Graphitic Cast Irons – Cooling Below the Eutectic

Matrix microstructures in graphitic irons are determined in a complex way by graphite size and shape, CE, section size, processing history, alloy content, and cooling rate. On cooling below the eutectic temperature (**Figure 3**), austenite carbon content decreases



**Figure 4** Nucleation and growth of ferrite below the upper critical temperature,  $T_{UC}$ , and pearlite below the lower critical temperature,  $T_{LC}$ .



**Figure 5** Schematic illustrating tensile stress fracture along graphite interfaces in gray iron. Schematic relationship is shown between UTS, BHN, and CE for different matrix microstructures.

until below the upper critical temperature, where austenite can begin to transform to stable ferrite + graphite. Ferrite will nucleate on graphite, depositing carbon from austenite that cannot be accepted by the b.c.c. ferrite (see the gray iron microstructure depicted in [Figure 4](#)). In a slowly cooling casting, ferrite nuclei can continue to grow into the austenite. The final structure could be ferrite and graphite as predicted by the stable phase diagram. If the casting was cooled more rapidly, or in the presence of certain alloying elements, the austenite may transform to pearlite. This latter scenario is illustrated in [Figure 4](#) and in the cooling curve of [Figure 3](#).

Factors which favor the formation of ferrite include:

- (i) high graphite surface to volume ratio – giving a high density of nucleation sites for ferrite;
- (ii) high silicon content – silicon raises the upper critical temperature for  $\gamma \rightarrow \alpha$ , giving more rapid carbon diffusion and thereby making the growth of ferrite easier; and
- (iii) slower cooling rates – annealing is used to produce ferritic structures.

Factors favoring the formation of pearlite would be the opposite. In addition certain alloy elements other than silicon would kinetically favor pearlite by lowering the equilibrium phase boundary temperatures.

#### 4 Microstructure and Mechanical Properties of Gray Cast Iron

Gray cast irons have low tensile strengths and almost nonexistent ductilities (and impact strengths) due primarily to the nearly continuous nature (breaks at cell boundaries and at prior austenite dendrites) of the graphite flakes (see [Figure 5](#)). Tensile stresses

propagate cracks along the graphite plates internally. Tensile fracture stresses in gray cast irons are in the range 100–500 MPa (Schneidewind and McElwee, 1950; Krause, 1969). Attempts to determine the fracture toughness of gray irons by fracture mechanics methods yield conservative  $K_{IC}$  measurements in the range 16–22 MPa m<sup>1/2</sup> (Bradley and Srinivasan, 1990).

## 5 Effect of Carbon Equivalent

The carbon equivalence of a gray cast iron affects the strength primarily because of its direct effect upon the amount of the proeutectic austenite dendrites present. This relationship (with a sketch illustrating a dendrite and the eutectic cell) and estimates of tensile strength are given in Figure 5. The tensile strength of a eutectic iron (CE=4.3) is typically around 160 MPa. As the amount of the proeutectic austenite increases with decreasing CE the tensile strength increases in the manner shown. The dendrites act as strengthening entities in much the same manner as adding stiffeners in a composite.

## 6 Effect of Matrix Microstructure

Ferritic irons have lesser strengths than pearlitic irons, which are in turn less than ausferritic irons (see Figure 5). Clearly, the strength of pearlitic irons is greater because of the presence of the fine lamellar plates of iron carbide, which impede crack propagation, and the ausferritic matrix is stronger still because of an even finer dispersion of ferrite in a carbon-stabilized austenite matrix.

## 7 Effect of Alloying Elements

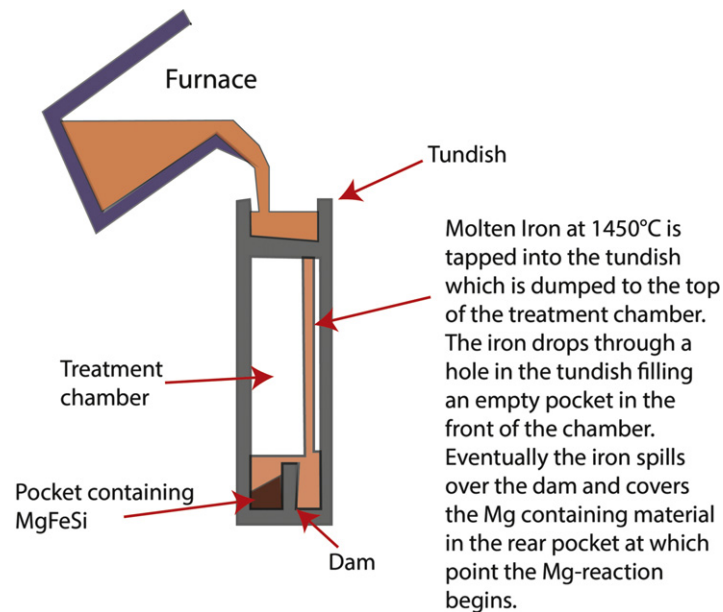
Alloying elements increase the strength of cast irons through their effect on the matrix. Common alloy elements include manganese, copper, nickel, molybdenum, and chromium, elements added primarily to control the matrix microstructure, having only a small effect upon the solidification microstructure. Two important mechanisms contribute to strengthening by alloying in the as-cast grades of gray iron, pearlite refinement (pearlite spacing gets smaller as a result of the alloy depressing the pearlite reaction to lower temperatures) and solid solution strengthening of the ferrite. As an example, an addition of 0.5% molybdenum to gray cast iron will increase the tensile strength by about 35–50 MPa for all values of CE. Transformation to pearlite or ferrite during cooling after casting is observed with cooling curves in much the same way as is done during solidification. A thermal arrest resulting from the latent heat given off during the transformation of austenite is shown in Figure 3 for a gray iron with CE=4.0.

## 8 Classes of Gray Cast Irons and Brinell Hardness

Gray irons are specified by their minimum tensile strength, i.e., a class 20 iron has a minimum tensile strength of 20 ksi (140 MPa), a class 30 iron has a minimum tensile strength of 30 ksi (210 MPa), etc. In most instances the chemical composition is not specified; rather it is the tensile strength and Brinell hardness which are written into specifications for certain applications. For example, automotive disk brake rotors and brake drums are produced from a class 30 Gy iron with a Brinell hardness range of 179–229 kg mm<sup>-2</sup>. It is usually true that alloy elements are not specified, only as needed to meet the minimum tensile specifications and the Brinell hardness range. The Brinell hardness of gray cast irons depends almost entirely upon the microstructure of the matrix material: ferrite (~100 kg mm<sup>-2</sup>), pearlite (~250 kg mm<sup>-2</sup>), and ausferrite (~250–350 kg mm<sup>-2</sup>). Most specifications of matrix microstructures in gray irons call for pearlite, and it is highly desirable for the pearlite to be produced in the as-cast condition.

## 9 Ductile Cast Iron

In late 1940s, Ductile Cast Irons were discovered in the International Nickel Company Research Laboratory (1943, adding Magnesium) and in the British Cast Iron Research Association (1948, adding Cerium). Since their discovery, the annual tonnage of ductile iron produced worldwide increased constantly (Figure 2). This growth is due to the microstructurally important fact that graphite in ductile iron is spheroidal, thereby making the iron-rich matrix constituent continuous. Cracks have no convenient weak path (as in flake graphite iron) through which to propagate, and the material takes on the properties of the ductile matrix, thus giving the name.



**Figure 6** Schematic illustration of the Tundish method to produce ductile iron.

## 10 Production of Ductile Iron

Ductile iron (usually hypereutectic) is produced by ‘treatment’ with magnesium immediately prior to pouring castings (see [Figure 6](#)), followed by inoculation in much the same way as for the production of gray cast iron. Magnesium is added to the melt in the form of a master alloy (~46% silicon, 5% magnesium, balance iron). Dilution of magnesium reduces the violence of the subsequent reaction with molten iron. The castings must be poured within a short time after treatment, usually less than 10 min, because of the high vapor pressure of magnesium.

The reaction produces bubbles of magnesium vapor which rise through the molten iron bath. Successful treatment results when a significant portion of the magnesium dissolves in the molten iron (giving a composition of ~0.03–0.05% magnesium), so that the correct conditions for graphite nodule formation are met in the solidifying melt. Magnesium contents <0.03% will result in vermicular or flake graphite, and contents >0.05% result in the appearance of exploded graphites. Shapes other than spherical contribute to a degradation in ductility. Typical ‘recoveries’ of magnesium for Tundish treatment are in the range 50–60%. It is necessary that the sulfur content be kept <0.01% for successful treatment, because of the affinity of sulfur for magnesium (forming  $Mg_2S$ ), thus removing elemental magnesium from the melt ([Spengler, 1982](#)).

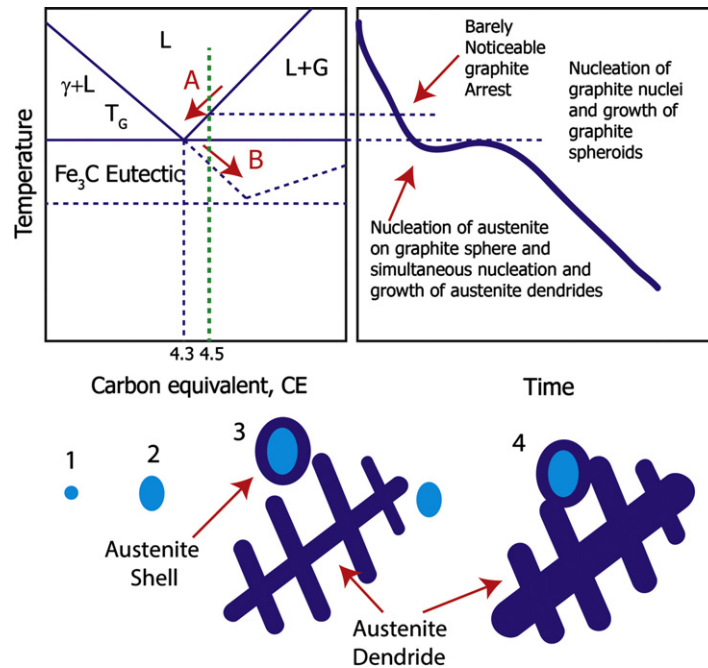
## 11 Solidification and Microstructures of Hypereutectic Ductile Cast Irons

Microstructural evolution during casting of magnesium-treated and properly inoculated irons with CE >4.3 is illustrated in [Figure 7](#). The events shown in [Figure 7](#) are listed below:

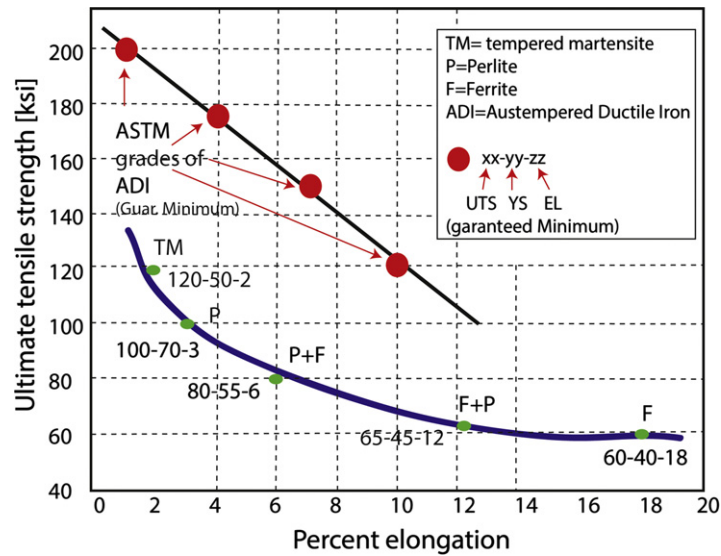
- 1 and 2. Nucleation and growth of graphite nodules, liquid composition following arrow A.
- 3. As the temperature drops below  $T_C$ , austenite nucleates on graphite enclosing the graphite in a shell. Simultaneously, conditions are met for the nucleation of austenite dendrites whose subsequent rejection of carbon moves the liquidus composition along arrow B.
- 4. Supersaturation of carbon in the liquid adjacent to the dendrites can provide conditions allowing nucleation of new graphite nodules, which in turn grow and are enveloped in austenite.

This is a simplified view of a rather complex solidification event. This atypical eutectic reaction is called a neoeutectic, where growth of the graphite occurs by diffusion of carbon across the austenite shell into the graphite. The final as-cast microstructure depends upon the combination of section size, alloy content, and processing history. Measurements made on the plane of polish to characterize the graphite in ductile irons include determining the nodule count and the percentage nodularity.

A typical as-cast microstructure consists of a ‘bull’s-eye’ structure of ferrite surrounding graphite which in turn is surrounded by pearlite. The relative amount of ferrite present depends upon alloy content, nodule count, and the rate at which the casting is



**Figure 7** Phase diagram, cooling curve, and steps describing solidification of ductile cast iron.



**Figure 8** A summary of the tensile properties of various grades of ductile cast iron.

cooled through the transformation where ferrite and pearlite can form and grow, i.e., the same factors as those promoting ferrite in gray cast iron.

## 12 Mechanical Properties of Ductile Cast Iron

The mechanical properties of ductile cast iron depend almost completely upon the microstructure of the continuous matrix, a microstructure which can be controlled by heat treatment. An overview of the tensile properties (UTS vs. % elongation (EL)) of ductile iron is given in **Figure 8**. Impact properties of ductile irons are far superior to gray cast irons, again because of the continuous nature of the matrix. Upper shelf fracture toughness values of 90–100 MPa m<sup>1/2</sup> have been reported for ferritic ductile irons and 60–70 MPa m<sup>1/2</sup> for pearlitic matrices ([Bradley and Srinivasan, 1990](#)).

**Table 2** Typical chemical composition (wt%), matrix microstructure, and Brinell hardness

Element	Grade 60–40–18	Grade 65–45–12	Grade 80–55–6	Grade 100–70–3	Grade 120–90–2
Carbon	3.5–3.9	3.5–3.9	3.5–3.9	3.5–3.8	3.5–3.8
Silicon	2.2–3.0	2.5–2.8	2.2–2.7	2.2–2.7	2.2–2.7
Manganese	0.30 max	0.40 max	0.2–0.5	0.6 max	0.6 max
Chromium	0.06 max	0.10 max	0.10 max	0.10 max	0.10 max
Copper			0.2–0.4	0.2–0.5	0.2–0.5
Microstructure	Ferrite	Mostly ferrite	Mostly pearlite	Pearlite	Tempered martensite
Brinell hardness	130–170	150–220	170–250	241–300	270–550

### 13 As-cast and Quenched and Tempered Grades of Ductile Iron

The UTS vs. % EL diagram of [Figure 8](#) illustrates the range of properties available in the as-cast and quenched and tempered conditions ([Fuller et al., 1980](#); [Davis, 1996](#), pp. 63–76). Grade 60–40–18, with the highest percentage elongation, has a 100% ferritic matrix. Increasing pearlite means increasing strength, with a corresponding decrease in EL, until grade 100–70–3 contains 100% pearlite. The four as-cast grades shown are used in specifications as minimums for design purposes. The actual grade achieved will depend upon alloy content and section size. Grade 120–90–2 is heat treated where the iron has been austenitized, quenched to martensite, and tempered. Note in [Table 2](#) that ferritic grades specify a maximum of the alloy elements copper and manganese, both of which promote the formation of pearlite when the casting is cooling. However, the grades with pearlite commonly have a specification with a minimum of copper. The elements manganese and chromium come from the steel component of the charge. Usually they are not present in quantities too large for the pearlitic grades, but it is becoming increasingly difficult to obtain steel with low enough ‘residuals’ of manganese and chromium to allow the production of ferritic grades of iron in the as-cast condition. Many ferritic matrix castings are obtained by annealing, a heat treatment where the casting is austenitized and then slowly cooled, giving a large amount of time for the formation of ferrite. This heat treatment adds significantly to the cost of production and is not usually desired. Low residuals of manganese and chromium can be achieved by melting larger quantities of pig iron, a charge material which is usually more expensive than scrap steel.

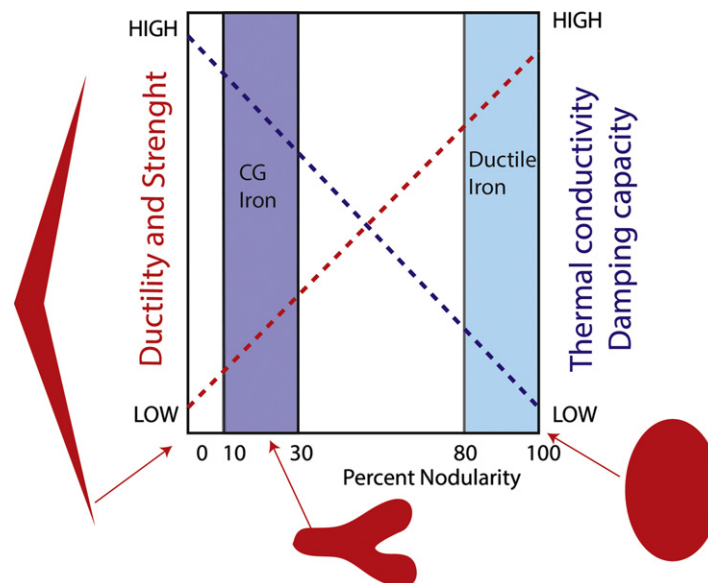
Applications of ductile iron include numerous automotive and construction equipment castings; for example, ferritic ductile cast iron is used to produce impact-resistant spindles (steering knuckles) for wheel applications, and pearlitic grades of ductile iron are a material of choice for automotive crankshafts.

### 14 Malleable Cast Iron, Processing, Microstructure, and Mechanical Properties

Malleable cast iron has lower CE ([Table 1](#)) than gray cast iron, solidifying white. The phase diagram and the cooling curve characteristic of white cast iron are illustrated in [Figure 3](#). It can be seen in the cooling curve that the temperature reached  $T_C$  before nucleation of graphite, thus resulting in white iron. The white iron castings are heated slowly into the  $\gamma + Fe_3C$  two-phase field ([Figure 3](#)) to a temperature in the range 800–1000 °C, and held for up to 24 hours allowing graphite (spheroidal ‘popcorn’-shaped) to nucleate and grow at the expense of the eutectic iron carbide. The final microstructure will be quite similar to ductile cast iron. Like ductile cast iron the matrix is the continuous phase and so the final structure will have similar properties to ductile cast iron, excellent strength, ductility, and toughness. The strength and ductility of malleable irons would overlap the as-cast properties of ductile iron shown in [Figure 8](#). Pearlitic malleable irons would be stronger but less ductile than ferritic malleable cast irons for the same reasons as for ductile iron. Fracture toughness values in the range 60–70 MPa m<sup>1/2</sup> have been reported ([Bradley and Srinivasan, 1990](#)) for ferritic grades, values somewhat less than for a similar ferritic ductile iron. Ferritic malleable iron is produced by slow cooling through the upper critical temperature,  $T_{UC}$ , and pearlitic malleable iron by more rapid cooling, even cooling in air, after the malleablizing treatment ([Gilbert, 1968](#); [Davis, 1996](#), pp. 94–106).

Malleable cast iron has been produced for thousands of years, but it is slowly being replaced by ductile cast iron. Two important reasons why malleable iron is decreasing in favor is cost and limitations on section size that can be produced in the malleable state. Clearly it is less costly to produce nodules in the as-cast condition than to require an additional lengthy heat treatment step. In addition ductile cast iron can be produced in very large section sizes, while the requirement to start with white iron limits malleable iron to practical section sizes of the order of 25–50 mm. Malleable iron section sizes larger than this will solidify with graphite flakes and would therefore have severely reduced ductility. Automotive applications for malleable iron continue to make large use of this material, including driveline yokes, connecting rods, and diesel pistons.





**Figure 9** Variation of physical and mechanical properties of cast irons as a function of the percentage nodularity of the iron.

## 15 Compacted Graphite Iron

Compacted graphite (CG) irons are a form of cast iron recognized since the 1960s (Shellang, 1965) as having unique mechanical and physical properties determined in large part by the shape of the graphite. These irons are produced in much the same way as ductile cast iron, except the objective is to have the molten iron dissolve a lesser amount of magnesium, usually  $\sim 0.01\text{--}0.015$  wt %. This amount of magnesium is enough to guarantee that no flakes are formed, yet not high enough to allow full nodularity (Davis, 1996, pp. 80–93). A typical CG iron might contain 25% nodularity, the rest of the graphite having a twisted rod-shaped structure typical of CG iron.

The mechanical and physical properties of CG iron, for a given matrix microstructure, will reside between the properties of flake graphite iron and spheroidal graphite iron as shown schematically in Figure 9. The more continuous nature of the compacted flakes will have physical properties closer to that of flakes (higher thermal conductivity and damping capacity), yet having tensile properties which are significantly superior to flake graphite irons.

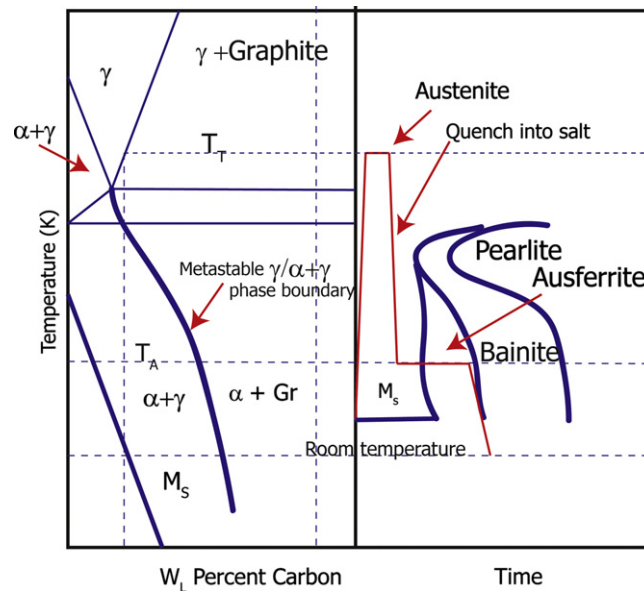
## 16 Austempered Ductile Cast Iron

All as-cast and quenched and tempered grades of ductile iron have a b.c.c. matrix, with properties determined by the distribution of iron carbide within the ferrite matrix. ADI has an austenitic matrix produced by heat treatment which is stable at room temperature (Johansson, 1977). This austenitic matrix is responsible for the attainment of unique mechanical properties. Figure 8 shows ASTM grades of ADI having higher strengths than the as-cast grades, yet retaining excellent ductility, a result of the f.c.c. matrix together with a fine-scale dispersion of ferrite. The ASTM grades represent guaranteed minimums in tensile strength and ductility; the cross-hatched region at higher strengths and ductilities than the ASTM grades represents more typical ADI tensile properties. Clearly, ADI offers an entirely new opportunity for applications of ductile cast iron. Indeed ADI, with comparable strengths and ductilities, is making inroads into markets once dominated by steel forgings and steel castings.

## 17 The Metastable Phase Diagram and Stabilized Austenite

Consider the schematic low-temperature portion of the Fe–C–2.4 Si phase diagram in Figure 10 together with an isothermal transformation diagram for a ductile cast iron austenitized at  $T_\gamma$  and austempered at  $T_A$ . Note that this diagram includes the martensite start temperature ( $M_S$ ) and the metastable extension of the  $(\alpha + \gamma)/\gamma$  phase boundary. The heat treatment used to produce ADI is illustrated in Figure 10 and described as follows:

- (i) Casting heated to and held at  $T_\gamma$  until fully austenitized with the matrix at 0.8 wt% carbon.
- (ii) Cooled to  $T_A$ , the austempering temperature, holding for 1–4 h, allowing the reaction  $\gamma (0.8\text{ C}) \rightarrow \alpha (0\text{ C}) + \gamma (2.0\text{ C})$  (ausferrite).



**Figure 10** Isoleth at 2.4% silicon illustrating the metastable  $\gamma/\alpha+\gamma$  phase boundary. Isothermal transformation diagram for ADI is also shown.

- (iii) Held at  $T_A$  until the ausferrite reaction is complete. Cooled to room temperature before the high-carbon austenite transforms to stable bainite. With the high carbon content present in the austenite, the martensite start temperature has been reduced to near absolute zero kelvin. This allows ADI to be austenitic at room temperature, an accomplishment made in commercial grades of cast iron only by adding large quantities of nickel or manganese (Davis, 1996, pp. 192–204), or in steel by adding large quantities of nickel (austenitic stainless steel) or manganese (Hadfield steel).

Production of ADI to mechanical property specifications requires first producing quality ductile cast iron, and second, careful control of the heat treatment parameters necessary to convert austenite to ausferrite. Clearly, heat-treated products cannot overcome basic deficiencies in the cast state, including porosity (shrinkage and gas), slag, sand, inclusions from impurities, low nodularity, low nodule count, etc. These extrinsic defects can be minimized by good foundry practice and adhering to tight processing schedules. Some 'deficiencies' cannot be overcome by good foundry practice which are intrinsic to the process of solidification. These include microsegregation in the casting and limitations in the nodule count that is attainable, a limitation defined primarily by the cooling rate (section size) of the casting. It has been shown that these intrinsic deficiencies can be minimized by proper selection of heat treatment and even a controlled amount of deformation at the austempering temperature before the ausferrite reaction commences (Rundman, 1997).

## 18 Control of Mechanical Properties of ADI

ASTM grades of ADI illustrated in Figure 8 can be created from the same alloy. The major factor controlling these tensile properties in ADI is the choice of the austempering temperature, the parameter primarily responsible for defining the scale (size and number of ferrite particles in the austenite matrix). High austempering temperatures (400–425 °C) give coarse microstructures (ASTM grade 1 ADI) with relatively low strengths but higher ductility, while low austempering temperatures (275–300 °C) give very fine microstructures (ASTM grades 4 and 5) with high strengths but lower ductility. Fracture toughness values for these materials give results in the range 60–90 MPa m<sup>1/2</sup> (Warda, 1990).

Examples of potential applications for ADI include gears, automotive crankshafts, digger teeth for front-end loader applications, automotive camshafts, railroad car wheels, etc. Many applications require resistance to sliding wear, a property enhanced by the presence of the austenite which transforms to martensite in service.

## 19 Conclusion

This article briefly discusses the development of the microstructure and mechanical properties of cast irons containing graphite as a desired microconstituent. Phase diagrams and cooling curves are used to describe the fundamentals of solidification in gray and ductile cast irons. Important processing steps (inoculation in gray and ductile iron and magnesium treatment in ductile iron) required to produce quality gray and ductile cast irons are discussed. The mechanical properties (primarily tensile properties) of

these irons are described in relationship to their microstructures. Malleable and CG irons are briefly noted and ADI is treated in detail.

## References

- Bradley, W.L., Srinivasan, M.N., 1990. Fracture and fracture toughness of cast irons. *Int. Mater. Rev* 35 (3), 129–159.
- Davis, J.R., 1996. *ASM Specialty Handbook: Cast Irons*. Materials Park, OH: ASM International.
- Fuller, A.G., Emerson, P.J., Sergeant, G.F., 1980. A report on the effect upon mechanical properties of variation in graphite form in irons having varying amounts of ferrite and pearlite in the matrix structure and the use of non-destructive tests in the assessments of mechanical properties of such irons. *AFS Trans* 88, 21–50.
- Gilbert, G.N.J., 1968. *Engineering Data on Malleable Cast Irons*. Birmingham: BCIRA.
- Johansson, M., 1977. Austenitic–bainitic ductile iron. *AFS Trans* 85, 117–122.
- Krause, D.E., 1969. Gy iron – a unique engineering material. *Gray, Ductile, and Malleable Castings – Current Capabilities*, STP 485. Philadelphia: ASTM, pp. 3–28.
- Lownie, H.W., 1957. Theories of gray cast iron solidification. *AFS Trans* 65, 340–351.
- Merchant, H.D., 1968. Solidification of cast irons: A review of literature. In: Merchant, H.D. (Ed.), *Recent Research on Cast Iron*. New York: Gordon and Breach.
- Modern Casting Staff Report, 2014. *Steady Growth in Global Output, Modern Casting*. American Foundry Society, pp. 17–21.
- Rundman K.B., 1997. Segregation of alloying elements in ductile cast iron: The use of chemical, thermal, and mechanical processing to control the effects of segregation in austempered ductile iron. *Honorary Cast Iron Lecture, American Foundrymen's Society*.
- Schneidewind, R., McElwee, R.G., 1950. Composition and properties of gray iron, parts I and II. *AFS Trans* 58, 312–330.
- Shellang, R.D., 1965. Cast iron (with vermicular graphite) 3, 421–886. *US Patent*.
- Spengler, A.F., 1982. *The Ductile Iron Process, Compendium VI*. Chicago, IL: Miller.
- Walton, C.F., Opar, T.J., 1981. *Iron Castings Handbook*. Iron Castings Society.
- Warda, R.D., 1990. *Ductile Iron Data for Design Engineers QIT-Fer et Titane*.

## Further Reading

- Angus, H.T., 1960. *Physical and Engineering Properties of Cast Iron*. BCIRA, p. 21.