CAST IRON:
The Engineered Metal

Gray and ductile iron should be considered for parts that are currently made of steel and other metals, to open up new opportunities for cost and weight reduction as well as better performance.

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Cast iron is a composite material consisting of precipitated graphite particles in a solid metal matrix. The metal matrix is similar to steel, and the properties in the matrix are controlled by the amount of carbon that is combined with the iron.

It is important to understand that not all cast irons are the same. In fact, the properties of a particular cast iron grade are heavily dependent on manufacturing processes. While the properties of steel grades are determined primarily by the chemical composition, cast iron properties are controlled by four factors:

- Chemical composition
- Inoculation
- Solidification rate
- Cooling rate

This article shows how each of these variables plays an equally important role in determining the consistency of mechanical properties and machinability of the cast iron part. It also describes the properties of cast iron grades, explains the meanings of the grade numbers, and shows how the amount and shape of graphite particles affects final properties.

Cast iron composition

When carbon is added to iron, the result is a chemical compound called iron carbide (Fe₃C). Iron without carbon forms a body-centered crystal structure called ferrite. Alternating plates of iron carbide and ferrite make up pearlite; as more carbon is added, a higher percentage of pearlite is formed in the matrix (Fig. 1). Pearlite forms in both steel and cast irons. As you might expect, high-carbon steel has more pearlite than low-carbon steel.

Pearlite is much harder and stronger than ferrite. A steel or cast iron having a high percentage of pearlite is more wear resistant and has a higher tensile strength with lower elongation than a ferrous metal with a high percentage of ferrite. In steel, all of the carbon is combined with iron to form pearlite. The percentage of pearlite may be easily controlled simply by the amount of carbon in the base melt. However, in the cast iron grades, the amount of carbon that remains in solution to combine with iron depends on the rate of cooling and on the addition of small amounts of alloying elements, rather than on the carbon content.

Graphite formation in iron

At 2800°F (1540°C), approximately 6% carbon is soluble in iron. As the iron cools, the solubility limit decreases. At 2050°F (1120°C), only 2% carbon is soluble in iron; and under equilibrium conditions, excess carbon forms graphite as it is forced out of solution. Graphite can take almost any shape imaginable, but for the purpose of making cast iron, only two forms are beneficial: flakes, which are present in gray iron, and nodules, which are present in ductile iron. The American Foundrymen’s Society (AFS) has developed a set of standards for classification of graphite in cast irons.

Graphite precipitates out of solution and nucleates naturally as iron cools in the liquid state, because the solubility limit of graphite decreases with decreasing temperature. Numerous factors that are not easy or economical to control affect the solubility limit, and it would be nearly impossible to
control the exact point at which the graphite nucleates. Therefore, additions called inoculants are used to force graphite out of the melt at a precise time, and they make possible control over the size and shape of the resulting graphite particles. The composition of the base melt and the type of inoculant are two important factors that control the size and shape of the graphite particles.

Under the standards for the classification of graphite in cast iron, the form of the precipitated graphite particle is represented by Roman numerals I to VII. Type I graphite is spheroidal and type VII graphite is in the form of a thin flake. Ductile iron contains types I and II graphite nodules, and gray iron contains type VII flakes. The vast majority of engineered cast irons are either gray or ductile iron, so that types I, II, and VII predominate.

**Gray cast iron**

Gray cast iron grades are typically identified by the ASTM A48 classification system. In that standard, classes range from 20 to 60. Each class represents the tensile strength in ksi of a separately cast test bar poured from the iron that makes the casting. For example, a casting certified to ASTM A48 class 40 is cast with iron that has 40,000 psi tensile strength in a separately cast test bar. The test bar size should represent the controlling section size of the casting, so that it correlates approximately with the strength in the part. Likewise, a class 60 casting is poured from iron with 60,000 psi tensile strength in a separately cast test bar.

Graphite flakes can form in a variety of patterns, which are classified by standards also established by AFS. The most common graphite patterns are types A, D, and E. Type A graphite is defined as flakes arranged in a completely random pattern. Type D graphite has a preferred orientation but a distinct pattern because it forms inside the austenite dendrite arm spacing during solidification of the matrix. In type E graphite, the flakes are random with a dendritic pattern. Type B graphite is in the form of clusters, or rosettes; and type C graphite, also called “kish” graphite, is in the form of thick, coarse flakes.

The size of the graphite particle is also important, and the flake length (or nodule diameter in the case of ductile iron) is measured at 100X magnification. The maximum flake length for each size category under the ASTM A247 designation is listed in Table 1.

The length of the graphite flake has a significant effect on the strength of the casting. With everything else being equal, the strength of a casting having type A graphite with small flakes is higher than that of castings having longer flake lengths. Therefore, the description of graphite should include the form of the particle, the pattern it forms if it is flake graphite, and the size. An analysis of the graphite in gray iron might be “Type VII graphite flakes, type A, size 4 – 6.”

Too many engineers who decide which grade of gray iron to select for a specific application make the mistake of confusing the classes in the A48 gray iron standard.
with a rating of superiority. While it is true that a class 30 iron is lower in tensile strength than a class 40 iron, other factors should be considered. Machinability, wear resistance, vibration damping, response to heat treatments, and fatigue are important properties unique to each grade (Tables 2 and 3). It is important to consider all of those characteristics, rather than just tensile strength alone, when deciding which grade is the best.

**Ductile iron**

The grades of ductile iron generally fall under one of the classes listed in the ASTM A536 material standard. Similar to gray iron, ductile iron is also classified by mechanical properties. Tensile strength, yield strength, and elongation are included as part of the classification. The five most common grades are:

- 120-90-02
- 100-70-03
- 80-55-06
- 65-45-12
- 60-40-18

The first two numbers are the tensile strength and yield strength in ksi. The third number is the elongation in percent. An 80-55-06 ductile iron casting is poured from iron that produced a test bar having 80,000 minimum psi tensile strength, 55,000 psi yield strength, and 6% elongation.

The mechanical property requirements for a specific gray or ductile iron grade are guaranteed minimums. This is unlike the classification of steels, for which the mechanical properties listed in engineering handbooks are designated “typical.” These guaranteed minimum values make designing the part around material strength much easier. As previously mentioned, other engineering properties must be considered, and those values within a particular grade are also readily available.

In ductile iron, unlike gray iron, the graphite nodules do not solidify in specific patterns. Therefore, the nodules are measured and counted. Under AFS guidelines, the graphite nodules in ductile iron are categorized by the nodule size and the number of nodules per square millimeter. For example, one way to describe the nodules in a ductile iron casting would be “the part contains Type I and II nodular graphite, 100 nodules per square millimeter, size 5 or smaller.”

Castings do have areas in the cross-section that solidify and cool faster than others, and for that reason, the graphite size and distribution also vary. It is usually up to the customer and the foundry to agree on the location where the graphite is to be analyzed and on the requirements for graphite morphology in that location.

**The matrix structure**

Cast iron is unique in that the amount of carbon that stays in solution is controllable. All of the carbon can be precipitated out to form a matrix that is ferritic, or up to 2% carbon can be kept in solution to form a matrix that is pearlitic. Matrix structures having a controlled pearlite-to-ferrite ratio are also possible.

The grades within the gray iron family and the grades within the ductile iron family have different levels of pearlite and ferrite. That is how the grades of gray and ductile iron are achieved. Foundries practicing good process controls over the variables that affect cast iron properties are able to provide their customers with engineered cast iron castings that have consistent and predictable material properties.

A gray iron foundry that produces castings under the ASTM A48 standard would be able to meet the classification requirements by targeting a matrix that contains mostly ferrite for castings certified to class 20, and targeting a pearlitic matrix for class 40 castings. Strength increases when the casting is alloyed and heat-treated, just like steel, and a class 60 casting might be produced by quenching and tempering. The size and shape of the graphite flake may also be controlled to produce the required mechanical properties.

Ductile iron foundries generally produce the grades in the ASTM A536 standard by altering the matrix composition. For example, a 65-45-12 ductile iron has a matrix containing mostly ferrite; a 100-70-02 ductile iron contains mostly pearlite (Fig. 2). As strength and wear resistance increase in the pearlitic grades, machinability decreases. A 65-45-12 ductile iron part is much more machinable than a 100-70-02 ductile iron part.

The most important characteristic of cast iron is that it is a composite consisting of solid graphite particles in an iron matrix. As such, it can be tailored to provide a wide variety of mechanical properties and machinability ratings, and it responds very well to heat treatments and surface coatings. Cast iron is 10% lighter than steel, and the graphite damps noise in gears and other vibrating components. It has excellent resistance to wear and good thermal conductivity. Although it may not be as strong as the highest-strength steel, its processing
benefits make it a good choice for many applications in which engineers would like to reduce costs and raise performance.

Continuous casting

The casting process also has a strong influence over the properties in a cast iron casting. In continuous casting, molten iron is held in a refractory-lined steel shell. A water-cooled graphite die is mounted on the bottom of the vessel. Molten iron enters the die, and a solid skin that takes the shape of the bar begins to form. As the bar is pulled out of the die in a series of strokes, the skin becomes thicker until it can sufficiently support the head pressure of the molten iron inside the bar machine. When the bar exits the die, it consists of a thin outer shell with a molten iron core.

The heat from the molten iron core reheats the outer skin, which was rapidly chilled inside the die. The matrix in the rim is transformed to austenite and cools in still air as the bar moves horizontally along a series of rollers. The center of the bar is allowed to solidify and cool in still air. The resulting microstructure in the continuous cast bar is a homogeneous matrix of pearlite and ferrite, or a ratio of the two, depending on the grade.

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Molten iron is continuously added to the bar machine crucible during the production run to maintain head pressure and a sufficient distance between the die opening and the top of the molten metal bath. Impurities float to the top of the bath, well away from the die opening. This eliminates slag, dross, and other tool-wearing inclusions.

Consistency in the matrix structure and elimination of impurities are essential to reducing machining costs. A wide range of microstructures within a particular grade of ductile iron causes variations in machinability. Inclusions can also cause catastrophic failure of the tool insert, and therefore must be eliminated.

The inherent qualities of the process mean that continuous-cast bars are free of shrinkage, porosity, and inclusions and hard spots. Because the bar mostly solidifies and cools in still air outside of the die, only two variables must be considered: the base chemistry and inoculation. Quality systems in continuous casting bar mills in the United States ensure good control over the graphite size, shape, distribution, and the composition of the matrix structure.

Benefits of cast iron

Vibration damping is important in gears and in applications where harmonic vibrations cause failure. For example, in an automotive balance shaft, gear noise reduction resulted directly from the conversion of 1144 steel to 80-55-06 ductile iron — without any change in how the part was manufactured. In another case, the 4140 pistons in an impact hammer were cracking prematurely because of harmonic vibrations. The failures stopped when the part was converted to austempered ductile iron. Although the ductile iron had lower tensile strength, the vibration-damping characteristics reduced harmonic vibrations.

The best way to select a ductile iron grade to replace carbon steel is to pick one that has a similar matrix and hardness, which means matching the matrix structure as closely as possible. Usually, a ferritic ductile iron is the best candidate to replace carbon steels having up to 0.35% carbon. Partially pearlitic ductile irons such as an 80-55-06 are the best candidates for the medium carbon steels. Fully pearlitic ductile irons are best for replacing carbon steels that require heat treatment to improve wear resistance. The machinability of a fully pearlitic ductile iron may be less than that of carbon steel, but the savings from eliminating all the steps associated with heat treatment can offset the cost of additional machining.

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