

Ductile Iron

Special cast irons differ from the common cast irons mainly in the higher content of alloying elements which promote microstructures having special properties for elevated-temperature applications, corrosion resistance, and wear resistance. This article explains how chemical composition, cooling rate, liquid treatment and heat treatment influencing on a structure and the expected mechanical properties of cast irons.

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

- White iron: Exhibits a white, crystalline fracture surface because fracture occurs along the iron carbide plates; it is the result of metastable solidification (Fe-C eutectic)
- Gray iron: Exhibits a gray fracture surface because fracture occurs along the graphite plates (flakes); it is the result of stable solidification (Gr eutectic)

Special cast irons differ from the common cast irons mainly in the higher content of alloying elements which promote microstructures having special properties for elevated-temperature applications, corrosion resistance, and wear resistance.

The goal of the metallurgist is to design a process that will produce a structure that will yield the expected mechanical properties. This requires knowledge of the structure-properties correlation for the particular alloy under consideration as well as of the factors affecting the structure.

When discussing the metallurgy of cast iron, the main factors of influence on the structure that one needs to address are:

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

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

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

For common cast iron, the main elements of the chemical composition are carbon and silicon. High carbon content increases the amount of graphite or Fe₃C. High carbon and silicon contents increase the graphitization potential of the iron as well as its castability.

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

From the minor elements, phosphorus and sulfur are the most common and are always present in the composition. They can be as high as 0.15% for low-quality iron and are considerably less for high-quality iron, such as ductile iron or compacted graphite iron.

The main effects of chemical composition to nodular (ductile) iron are similar to those described for gray iron, with quantitative differences in the extent of these effects and qualitative differences in the influence on graphite morphology. The carbon equivalent has only a mild influence on the properties and structure of ductile iron, because it affects graphite shape considerably less than in the case of gray iron. Nevertheless, to prevent excessive shrinkage, high chilling tendency, graphite flotation or a high impact transition temperature, optimum amounts of carbon and silicon must be selected. Minor elements can significantly alter the structure in terms of graphite morphology, chilling tendency, and matrix structure. Minor elements can promote the spheroidization of graphite or can have an adverse effect on graphite shape.

The general influence of various elements on graphite shape. The elements in the first group - the spheroidizing elements - can change graphite shape from flake through compacted to spheroidal. The most widely used element for the production of spheroidal graphite is magnesium. The amount of residual magnesium required to produce spheroidal graphite is generally 0.03 to 0.05%. The precise level depends on the cooling rate. A higher cooling rate requires less magnesium. The amount of magnesium to be added in the iron is a function of the initial sulfur level. A residual magnesium level that is too low results in insufficient nodularity. This in turn results in a deterioration of the mechanical properties of the iron. If the magnesium content is too high, carbides are promoted.

The presence of antispheroidizing minor elements may result in graphite shape deterioration, up to complete graphite degeneration. Therefore, upper limits are set on the amount of deleterious elements to be accepted in the composition of cast iron. These values can be influenced by the combination of various elements and by the presence of rare earths in the composition. Furthermore, some of these elements can be deliberately added during liquid processing in order to increase nodule count.

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

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

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

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

Heat treatment is extensively applied on ductile iron because better advantage can be taken of the matrix structure than for gray iron. The heat treatments usually applied are as follows:

- Stress relieving
- Annealing to produce a ferritic matrix
- Normalizing to produce a pearlitic matrix
- Hardening to produce tempering structures
- Austempering to produce a ferritic bainite.

The advantage of austempering is that it results in ductile irons with twice the tensile strength for the same toughness. Compacted graphite (CG) irons have a graphite shape intermediate between spheroidal and flake. Typically, compacted graphite looks like type IV graphite.

The chemical composition effects are similar to those described for ductile iron. Carbon equivalent influences strength less obviously than for the case of gray iron, but than for ductile iron. The graphite shape is controlled, as in the case of ductile iron, through the content of minor elements. When the goal is to produce compacted graphite, it is easier from the stand point of controlling the structure to combine spheroidizing (magnesium, calcium, and/ or rare earths) and antispheroidizing (titanium and/or aluminum) elements.

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

The usual microstructure of gray iron is a matrix of pearlite with graphite (flakes dispersed throughout). Foundry practice can be varied so that nucleation and growth of graphite flakes occur in a pattern that enhances the desired properties. The amount, size, and distribution of graphite are important.

Cooling that is too rapid may produce so-called chilled iron, in which the excess carbon is found in the form of massive-carbides. Cooling at intermediate rates can produce mottled iron, in which carbon is present in the form of both primary cementite (iron carbide) and graphite. Very slow cooling of irons that contain large percentages silicon and carbon is likely to produce considerable ferrite and pearlite throughout the matrix, together with coarse graphite flakes.

Flake graphite is one of seven types (shapes or forms) of graphite established in ASTM A 247. Flake graphite is subdivided into five types (patterns), which are designated by the letters A through E. Graphite size is established by comparison with an ASTM size chart, which shows the typical appearances of flakes of eight different sizes at 100x magnification.

Type A flake graphite (random orientation) is preferred for most applications. In the intermediate flake sizes, type A flake graphite is superior to other types in certain wear applications such as the cylinders of internal combustion engines.

Type B flake graphite (rosette pattern) is typical of fairly rapid cooling, such as is common with moderately thin sections (about 10 mm) and along the surfaces of thicker sections, and sometimes results from poor inoculation.

The large flakes of type C flake graphite are typical of kish graphite that is formed in hypereutectic irons. These large flakes enhance resistance to thermal shock by increasing thermal conductivity and decreasing elastic modulus. On the other hand, large flakes are not conducive to good surface finishes on machined parts or to high strength or good impact resistance.

The small, randomly oriented interdendritic flakes in type D flake graphite promote a fine machined finish by minimizing surface pitting, but it is difficult to obtain a pearlitic matrix with this type of graphite. Type D flake graphite may be formed near rapidly cooled surfaces or in thin sections. Frequently, such graphite is surrounded by a ferrite matrix, resulting in soft spots in the casting.

Type E flake graphite is an interdendritic form, which has a preferred rather than a random orientation. Unlike type D graphite, type E graphite can be associated with a pearlitic matrix and thus can produce a casting whose wear properties are as good as those of a casting containing only type A graphite in a pearlitic matrix.

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.