Cast Iron Metallurgy

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Cast iron (CI) is one of the oldest materials in commercial use. It has excellent compressive strength and is commonly used for structures that require this property, as well as for water and sewer lines. This article explains CI metallurgy and why the understanding of this metallurgy is key to understanding other ferrous materials and alloys.

The composition of cast iron (CI) varies significantly depending upon the grade of pig iron used in its manufacture. CI contains carbon in the range of ~2 to 4 wt%. The mode and concentration of carbon in the CI is controlled to produce various grades of CI, which differ significantly in their mechanical properties and weldability.

The carbon equivalent (CE) of a CI helps to distinguish the gray irons, which cool into a microstructure containing graphite, and the white irons, where the carbon is present mainly as cementite. The CE is defined in Equation (1).

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CE (\text{wt}%) = C + \frac{Si + P}{3}
\]  
(1)

A high cooling rate and a low CE favor the formation of white CI whereas a low cooling rate or a high CE promotes gray CI.

During solidification, the major proportion of the carbon precipitates in the form of graphite or cementite. When solidification is just complete, the precipitated phase is embedded in a matrix of austenite that has an equilibrium carbon concentration of ~2 wt%. On further cooling, the carbon concentration of the austenite decreases as more cementite or graphite precipitates from solid solution. For conventional CIs, the austenite then decomposes into pearlite at the eutectoid temperature. In gray CIs, however, if the cooling rate through the eutectoid temperature is sufficiently slow, then a completely ferritic matrix is obtained, with the excess carbon being deposited on the already existing graphite.

White Cast Iron

White CIs are hard and brittle and cannot be machined easily. White CI is the only member of the CI family in which carbon is present only as carbide. Because of the absence of graphite, it has a light appearance. The presence of different carbides makes white CIs
extremely hard and abrasion resistant, but very brittle.

The microstructure of white CI contains massive cementite (white) and pearlite. It contains interdendritic cementite (white), which sometimes has a Widmanstätten (“spiky”) appearance. Austenite forms as the proeutectic constituent before the eutectic reaction (liquid transforms to austenite and cementite) and later transforms to pearlite and cementite upon cooling below the eutectoid temperature, ~723 °C. White CI is named after its white surface. When fractured, cracks pass straight through due to its carbide impurities. An improved form of white CI is chilled CI.

**Chilled Cast Iron**

When a localized area of a gray CI is cooled very rapidly from the melt, CI is formed at the place that has been cooled. This type of white CI is called chilled iron. A chilled iron casting can be produced by adjusting the carbon composition of the white CI, so that the normal cooling rate at the surface is just fast enough to produce white CI while the slower cooling rate below the surface will produce gray iron. The depth of chill decreases and the hardness of the chilled zone increases with increasing carbon content.

Chromium is used in small amounts (1 to 4%) to control chill depth, increase hardness, and improve abrasion resistance. It also stabilizes carbide and suppresses the formation of graphite in heavy sections. When added in amounts of 12 to 35%, chromium will impart resistance to corrosion and oxidation at elevated temperatures.

**Gray Cast Iron**

Gray CI is named for its gray fractured surface, which occurs because the graphitic flakes deflect a passing crack and initiate countless new cracks as the material breaks. Gray CIs are softer than white CIs, and have a microstructure of graphite in a transformed-austenite and cementite matrix. The graphite flakes, which are rosettes in three dimensions, have a low density and hence compensate for the freezing contraction, thus giving good castings that are free from porosity. The flakes of graphite have good damping characteristics and good machinability because the graphite acts as a chip breaker and lubricates the cutting tools. In applications involving wear, the graphite is beneficial because it helps retain lubricants. The flakes of graphite also are stress concentrators, however, and lead to poor toughness. The recommended applied tensile stress is therefore only a quarter of the actual ultimate tensile strength.

Gray CI is the oldest and most common form of CI. As a result, many people assume it is the only form of CI and the terms “cast iron” and “gray iron” are used interchangeably. Unfortunately, the property of gray-iron brittleness is also assigned to all CIs.

The fluidity of liquid gray iron, and its expansion during solidification from the formation of graphite, has made this metal ideal for the production of shrinkage-free, intricate castings such as engine blocks.

The flake-like shape of graphite in gray iron (Figures 1 and 2) exerts a dominant influence on its mechanical properties. The graphite flakes act as stress raisers, which may prematurely cause localized plastic flow at low stresses, and initiate fracture in the matrix at higher stresses. Consequently, gray iron exhibits no elastic behavior, but has excellent damping characteristics, and fails in tension without significant plastic deformation.
Pipes with diameters from 1.5 to 5 in (38 to 127 mm) with wall thicknesses ranging from 0.138 to 0.25 in (3.5 to 6.4 mm) are readily produced by continuous casting, using tubular blanks as molds. Centrifugal casting is also used to produce pipes as this process permits good dimensional control. Other gray CI products are packer parts, valve bodies, valve parts, and boilers.

**Spheroidal Graphite Cast Iron**

Sulfur in CIs is known to favor the formation of graphite flakes. The graphite can be induced to precipitate in a spheroidal shape by removing the sulfur from the melt using a small quantity of calcium carbide (CaC₂). This is followed by a minute addition of magnesium or cerium, which poisons the preferred growth directions and hence leads to isotropic growth resulting in spheroids of graphite. The calcium treatment is necessary before the addition of magnesium since the latter also has an affinity for both sulfur and oxygen, whereas graphite’s spheroidizing ability depends on the presence of magnesium in solution in the liquid iron. The magnesium is frequently added as an alloy with iron and silicon (Fe-Si-Mg) rather than as pure magnesium. Magnesium tends to encourage the precipitation of cementite, however, so silicon is also added as ferro-silicon inoculant to ensure the precipitation of carbon as graphite. Spheroidal graphite CI has excellent toughness and is widely used in crankshafts.

The latest breakthrough in CIs is where the matrix of spheroidal graphite CI is not pearlite, but bainite (Figure 3). The chemical composition of the spheroidal graphite CI is similar to that of gray CI but with 0.05 wt% of magnesium. This creates a major improvement in toughness and strength. The bainite is obtained by isothermal transformation of the austenite at temperatures below that at which pearlite forms.

**Heat-Treated Spheroidal Graphite Cast Iron**

Spheroidal graphite CI usually has a pearlitic matrix. Annealing, however, causes the carbon in the pearlite to precipitate onto the existing graphite or to form further small graphite particles, leaving behind a ferritic matrix. This gives the iron even greater ductility.

**Austempered Ductile Cast Iron**

The chemical composition of this CI is Fe, 3.52 C, 2.51 Si, 0.49 Mn, 0.15 Mo,
and 0.31 Cu wt% (Figures 4 and 5).

The automobile industry has made good use of austempered ductile CI. It is used for crankshafts in some sports cars. To avoid distortion, the crankshaft is rough-machined after casting, heat-treated to produce the bainitic microstructure, and then finish machined. It is reported to have excellent fatigue properties and its damping characteristics reduce engine noise.

**Wear-Resistant High-Chromium Cast Iron**

This CI is used in circumstances where a very high wear resistance is desirable, such as during the crushing of rocks and minerals. The iron contains a combination of very strong carbide-forming alloying elements. Its chemical composition is, therefore, Fe, 2.6 C, 17 Cr, 2 Mo, and 2 Ni wt%.

**Welding of Cast Irons**

Most of the welding of CI is repair welding. Carbon pickup and resulting cracks are the main concerns when welding CI. The casting process is never perfect, especially when dealing with large components. Instead of scrapping defective castings, they can often be repaired by welding. Naturally, the very high carbon concentration of typical CIs causes difficulties by introducing brittle martensite in the heat-affected zone of the weld. It is therefore necessary to preheat to a temperature of ~450 °C, followed by slow cooling after welding, to avoid cracking.

When color matching is not an issue, filler material with large nickel content is often used. The presence of nickel in the weld metal yields austenitic weld metal, which is not sensitive to the carbon pickup from the CI. The deposits are soft and can be machined to provide the necessary shape and finish. For larger repairs, the cost of nickel electrodes often constrains the extent of welding. To avoid too-costly repairs, the faces of the bevel are buttered with nickel-rich electrodes and then matched for the rest of the welding with suitably matched and less expensive carbon steel electrodes.

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