PDHonline Course M568 (2 PDH)

Cast Irons; Types, Properties, Applications & Weldability

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Course Content

Cast irons, like steels, are essentially alloys of iron and carbon, but whereas the carbon content of steel is limited to a maximum of 2%, cast irons generally contain more than 2% carbon.

To achieve the best casting for a particular application at the lowest cost consistent with the component's requirements, it is necessary to have an understanding of the types of cast iron. The general designation of cast iron is meaningless, except in the sense of an iron-carbon alloy containing relatively large amounts of carbon either as graphite or as iron carbide. Therefore, it is necessary to make a more specific designation. They can be divided into five groups, based on composition and metallurgical structure: white cast iron, malleable cast iron, gray cast iron, ductile cast iron, compacted graphite iron and alloy cast iron.

Because of their relatively high silicon content, cast irons inherently resist oxidation and corrosion by developing a tightly adhering oxide and subscale to repel further attack. Iron castings are used in applications where this resistance provides long life. Resistance to heat, oxidation and corrosion are appreciably enhanced with alloyed irons. However, since cast irons contain more than 2% carbon, 1 to 3% silicon and up to 1% manganese, their weldability is poor. As cast irons are relatively inexpensive, very easily cast into complex shapes and readily machined, they are an important engineering and structural group of materials. Unfortunately not all grades are weldable and special precautions are normally required even with the so-called weldable grades.

One reason for the widely use of iron castings is the high ratio of performance to cost that they offer the designer and end user. This high value results from many factors, one of which is the control of microstructure and properties that can be achieved in the as-cast condition, enabling a high percentage of ferritic and pearlitic iron castings to be produced without the extra cost of heat treatment. To obtain the advantage of producing high quality castings as-cast requires the use of consistent charge materials and the implementation of consistent and effective practices for melting, holding, treating, inoculation and cooling in the mold.

However heat treatment is a valuable and versatile tool for extending both the consistency and range of properties of iron castings beyond the limits of those produced in the as-cast condition. Thus, to fully utilize their potential, the designer should be aware of the wide range of heat treatments available, and their response to these heat treatments.

Cast iron has been used extensively in many industrial applications, such as water industry, for more than 150 years. As a result, a large proportion of water transport and distribution pipes were predominantly made of cast iron in the past although they are being phased out by the introduction of new materials. Buried cast iron pipes age and deteriorate during the service due to various aggressive environments surrounding the pipes. Depending on a variety of factors, including the type of cast iron materials, local geology, and operation conditions, cast iron pipes deteriorate at different rate. The problem can be further complicated by the diversity in production quality in both cast iron material and pipes and the wide range in the diameter and wall thickness of the pipes. However, it is also known that corrosion rates of buried pipes decrease over time. This is largely attributable to the formation of graphite-containing corrosion products that adhere firmly to the unattacked metal substrate, providing a barrier and limiting the rate at which further corrosion attacks can occur.

INTRODUCTION

Cast iron is one of the oldest ferrous metals in commercial use. It is primarily composed of iron (Fe), carbon (C) and silicon (Si), but may also contain traces of sulfur (S), manganese (Mn) and phosphorus (P). It has a relatively high carbon content of 2% to 5%. It is typically brittle and nonmalleable (i.e. it cannot be bent, stretched or hammered into shape) and relatively weak in tension. Cast iron members fracture under excessive tensile loading with little prior distortion. Cast iron, however, has excellent compressive strength and is commonly used for structures that require this property, as well as for water and sewer lines. The composition of cast iron and the method of manufacture are critical in determining its characteristics.

The composition of cast iron (CI) varies significantly depending upon the grade of pig iron used in its manufacture. 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 (carbide).

The CE is defined as below;

CE (wt%)=C+ (Si+P)/3

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%. 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.
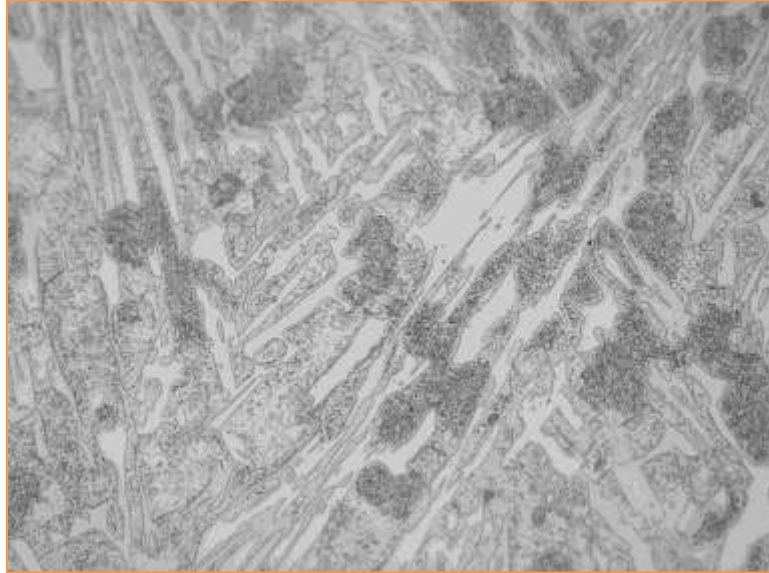

Gray Cast Iron Structure

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, which sometimes has a Widmanstatten ("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 cast iron derives its name from the white, crystalline crack surface observed when a casting fractures. Most white cast irons contain <4,3% carbon, with low silicon contents to inhibit the precipitation of carbon as graphite.

It is used in applications where abrasion resistance is important and ductility not required, such as liners for cement mixers, ball mills, certain types of drawing dies and extrusion nozzles. White cast iron is generally

considered unweldable. The absence of any ductility that can accommodate welding-induced stresses in the base metal and heat affected zone adjacent to the weld results in cracking during cooling after welding.

White Cast Iron Structure

MALLEABLE CAST IRON

Malleable irons are a class of cast irons with mechanical strength properties that are intermediate to those of gray or ductile cast irons. The microstructure provides properties that make malleable irons ideal for applications where toughness and machinability are required, and for components that are required to have some ductility or be malleable so that they can be bent or flexed into position without cracking.

They are often used as the material of choice for small castings or castings with thin cross sections which, in other irons, would tend to have chill (carbides in the surface layers due to the rapid cooling rates in thin sections). Castings of less than a gram in weight are successfully sand cast in malleable iron. Another significant aspect is that the malleable properties can exist to the surface of the casting as opposed to in ductile (also called spheroidal graphite, SG) irons where the cast surface can contain flake graphite, creating a situation where thin malleable iron castings can be stronger than SG.

The lower silicon gives malleable iron better fracture toughness properties in low temperature environments than the standard nodular iron grades because the ductile to brittle transformation temperature is lower than many other ductile iron alloys.

Malleable cast iron is produced by heat treating white cast iron of a suitable composition. Iron carbide can decompose into iron and carbon under certain conditions. This reaction is favored by high temperatures, slow cooling rates and high carbon and silicon contents. At room temperature, the microstructure therefore consists of temper carbon nodules in a ferrite matrix, generally known as ferritic malleable cast iron. The compact nodules of temper carbon do not break up the continuity of the tough ferritic matrix, resulting in high strength and improved ductility. The graphite nodules also serve to lubricate cutting tools, which accounts for the very high machinability of malleable cast iron.

Ferritic malleable cast iron has been widely used for automotive, agricultural and railroad equipment; expansion joints and railing castings on bridges; chain-hoist assemblies; industrial casters; pipe fittings; and many applications in general hardware.

If full graphitization is prevented and a controlled amount of carbon remains in the iron during cooling, finely distributed iron carbide plates nucleate in the iron at lower temperatures. This can be achieved by alloying with manganese, or by replacing the second-stage anneal by a quench (usually in air or oil). Due to the presence of

iron carbide in the microstructure, the strength and hardness of these castings are increased over those of ferritic malleable cast iron.

COMPACTED (VERMICULAR) GRAPHITE CAST IRON

Compacted graphite irons (CG-irons) are a range of cast irons having mechanical and physical properties intermediate between those of flake graphite and nodular graphite cast irons. They are of interest to engineers because of their useful combination of strength, thermal conductivity and other properties. They have good founding characteristics and their production requires controls similar to those applied in the manufacture of ductile iron castings.

It is recommended to add a high efficiency inoculant for production of CG-irons. Barium and Strontium containing ferrosilicon inoculants are found to give good results. Inoculant addition rate should be similar to that for ductile irons, i.e. between 0.3 and 0.8 wt percentage. The higher levels giving a fine distribution of compacted graphite throughout castings and less sensitivity to carbide (cementite) formation.

The Figure below shows typical microstructure obtained for a CG-iron casting produced from a high Rare Earth-containing MgFeSi-alloy. Homogeneous CG-structures throughout all section sizes are a characteristic feature obtained by the high RE-containing alloy in comparison to an ordinary lower RE-containing MgFeSi-alloys.

CG Iron Structure

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 cast iron is one of the most widely used casting alloys and typically contains between 2,5% and 4%

carbon, and between 1% and 3% silicon. With proper control of the carbon and silicon contents and the cooling rate, the formation of iron carbide during solidification is suppressed entirely, and graphite precipitates directly from the melt as irregular, generally elongated and curved flakes in an iron matrix saturated with carbon.
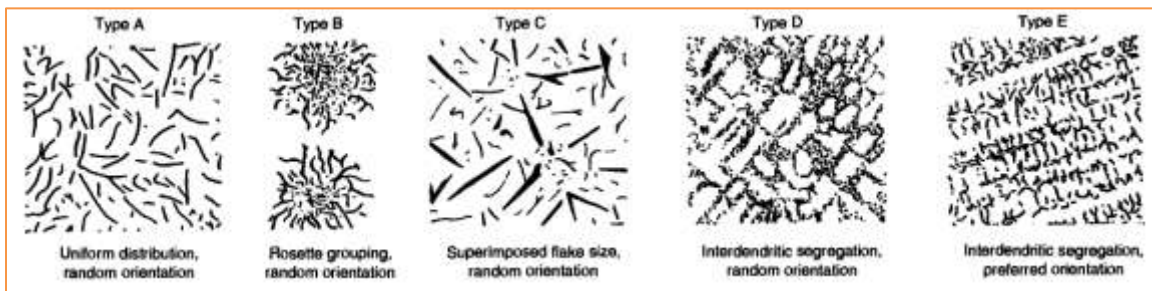
When a gray iron casting fractures, the crack path follows these graphite flakes and the fracture surface appears gray because of the presence of exposed graphite. Gray CIs are softer than white CIs, and have a microstructure of graphite in a transformed-austenite and cementite matrix. The graphite flakes, 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.
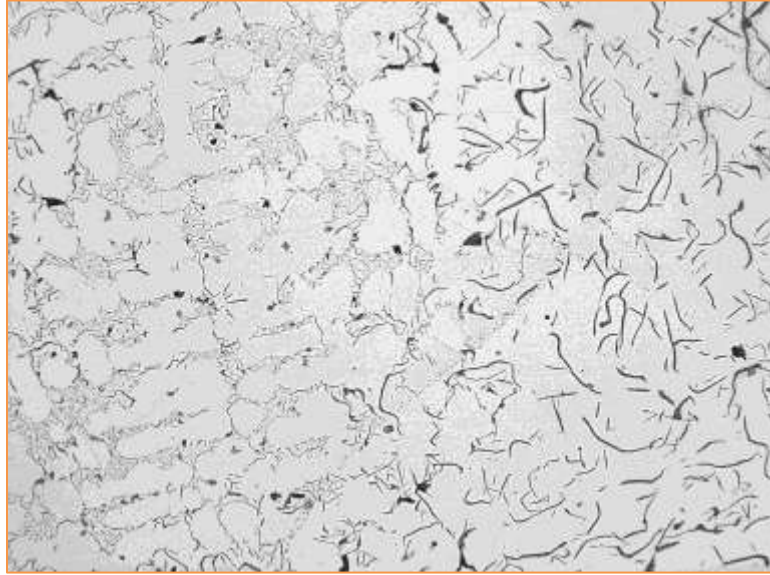
The fluidity of liquid gray iron, and its expansion during solidification from the formation of graphite, has made this metal ideal for the production of shrinkage-free, intricate castings such as engine blocks. The flake-like shape of graphite in gray iron exerts a dominant influence on its mechanical 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.

The strength of gray cast iron depends almost entirely on the matrix in which these graphite flakes are embedded. Slow cooling rates and high carbon and silicon contents promote full graphitization, and the majority of the carbon dissolved in the iron at high temperatures is deposited as graphite on the existing flakes during cooling. The structure then consists of graphite flakes in a ferrite matrix, referred to as ferritic gray cast iron. If graphitization of the carbon dissolved in the iron at high temperatures is prevented during cooling, iron carbide precipitates out and the matrix is pearlitic (referred to as pearlitic grey cast iron). Ferritic gray cast iron is normally soft and weak.

Pipes with diameters from1.5 to 5in (38 to 127 mm) with wall thicknesses ranging from 0.138 to 0.25in (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 valve bodies, valve parts, machine tool housings, and brake drums.

Type A	Type B	Type C	Type D	Type E
Uniform distribution, random orientation	Rosette grouping, random orientation	Superimposed flake size, random orientation	Interdendritic segregation, random orientation	Interdendritic segregation, preferred orientation

Classification of Graphite Flake Morphology

Ferritic Gray Cast Iron Structure

Pearlitic Gray Iron Structure

SPHEROIDAL GRAPHITE (DUCTILE) CAST IRON

Ductile cast iron, also known as nodular iron or spheroidal graphite (SG) iron, is very similar in composition to gray cast iron, but the free graphite in these alloys precipitates from the melt   as spherical particles rather than flakes. This is accomplished through the addition of small amounts of magnesium or cerium to the ladle just before casting. The spherical graphite particles do not disrupt the continuity of the matrix to the same extent as graphite flakes, resulting in higher strength and toughness compared with gray cast iron of similar composition.

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. 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.

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.

Typical applications are agricultural (tractor and implement parts); automotive and diesel (crankshafts, pistons and cylinder heads); electrical fittings, switch boxes, motor frames and circuit breaker parts; mining (hoist drums, drive pulleys, flywheels and elevator buckets); steel mill (work rolls, furnace doors, table rolls and bearings); and tool and die (wrenches, levers, clamp frames, chuck bodies and dies for shaping steel, aluminum, brass, bronze and titanium).
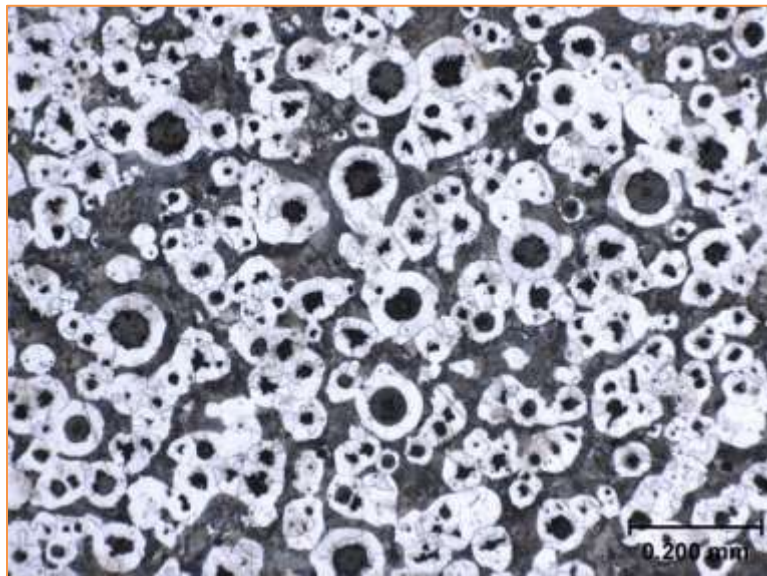
Ductile Iron
As-cast bulls-eye structure in a pearlitic matrix

AUSTEMPERED DUCTILE CAST IRON

The high-strength grades of ductile iron can be quenched and tempered to form a bainite-like matrix produced by austempering. Austempered ductile iron (ADI) provides twice the strength of conventional ductile iron at a given level of ductility. ADI can have strength in excess of 230 ksi (1,586 MPa); however, its modulus is 20% lower than steel with a comparable strength.

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.

The austempering heat treatment converts ductile iron to ADI, bringing about excellent strength, toughness, and fatigue characteristics. ADI is stronger per unit weight than aluminum, as wear resistant as steel and has the potential for up to 50% cost savings.

For the designer ADI is a most versatile material, enabling innovative solutions to new and current problems. By selecting precise heat treatment parameters a specific set of properties can be achieved. The lower hardness ductile iron castings are used in structural applications, often where weight and cost reduction are important. Wear resistance is superior to steel at any given hardness level, making the higher hardness grades ideal for mining, construction, agricultural and similar high abrasion applications.

In order to produce ADI, ductile iron must undergo a heat treat process called Austempering. Austempering was developed in the 1930's and has subsequently been applied to steel to produce a microstructure called Bainite. While the steps for Austempering ductile iron are essentially the same as those for steel, the resultant microstructure is different. It is called Ausferrite and consists of a mixture of high carbon Austenite and ferrite. Austempering, in general, consists of the following:
1. Heating to a temperature to produce Austenite;
2. Quenching rapidly to avoid the formation of pearlite or other microconstituents to a temperature above the Martensite start (Ms). This quench temperature is referred to as the Austempering temperature;
3. Holding at the selected Austempering temperature for a time sufficient to transform the Austenite to the desired end product; Bainite for steel and Ausferrite for ductile iron.

ALLOYED CAST IRON

These irons are classified as two types: corrosion-resistant and elevated-temperature service. Corrosion-resistant alloyed cast iron is used to produce parts for engineering applications that operate in an environment such as sea water, sour well oils, commercial organic and inorganic acids and alkalis. Elevated-temperature service alloyed iron resists formation and fracture under service loads, oxidation by the ambient atmosphere, growth and instability in structure up to 1,100°F (600°C). The ability to cast complex shapes and machine alloyed irons makes them an attractive material for the production of components in chemical processing plants, petroleum refining, food handling and marine service.

The high chromium containing 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, such as Cr, Mo and Ni.

PROPERTIES and SPECIFICATIONS OF CAST IRONS

The properties of all metals are influenced by the manner in which they solidify and cool. The individual design of a casting (the molding process, the way the molten metal is introduced into the cavity and the pouring temperature) determines the rate of cooling in the various parts of a casting. The cooling rate in any particular section factors heavily into the mechanical properties of the iron.

When mechanical properties are important, the most common procedure to qualify iron is to use a standard test bar poured separately with the specified lot of general engineered castings. Most specifications of the American Society for Testing and Materials (ASTM) apply this method to qualify the iron used to pour the castings. The actual properties of the metal in the casting will depend upon its characteristics and the cooling rate of the metal in the various sections of the casting.
Most common characteristics and applications for the various types of CIs are given below with their corresponding industry specifications.

	Standard Specifications	Characteristics	Applications
Gray Iron	• ASTM A48: gray iron castings • ASTM A74: cast iron soil & pipe fittings • ASTM A126: gray iron castings for valves, flanges & pipe fittings • ASTM A159: automotive gray iron castings • SAE J431: automotive gray iron castings • ASTM A278 & ASME SA278: gray iron castings for pressure-containing parts for temperatures up to 650F (343C) • ASTM A319: gray iron castings for elevated temperatures for non-pressure-containing parts • ASTM A823: statically cast permanent mold castings • ASTM A834: common requirements for iron castings for general industrial use	Several strength grades; vibration damping; low rate of thermal expansion & resistance to thermal fatigue; lubrication retention; and good machinability.	Automobile engine blocks & heads; manifolds for internal combustion engines; gas burners; machine tool bases; dimensionally stable tooling subjected to temperature variations, such as gear blanks & forming die covers; cylinder liners for internal combustion engines; intake manifolds; soil pipes; counterweights; and enclosures & housings.
Ductile Iron	• ASTM A395 & ASME SA395: ferritic ductile iron pressure-retaining castings for use at elevated temperatures • ASTM A439: austenitic ductile iron castings • ASTM A476 & ASME SA476: ductile iron castings for paper mill dryer rolls • ASTM A536 & SAE J434: ductile iron castings • ASTM A571 & ASME SA571: austenitic ductile iron castings for pressure-containing parts suitable for low-temperature service • ASTM A874: ferritic ductile iron castings suitable for low-temperature service • ASTM A897: austempered ductile iron castings	Several grades for both strength & ductility; high strength; ductility & wear resistance; contact fatigue resistance; ability to withstand thermal cycling; and production of fracture-critical components.	Steering knuckles; plow shares; gears; automotive & truck suspension components; brake components; valves; pumps; linkages; hydraulic components; and wind turbine housings.
CGI	• ASTM A842: CGI castings	A compromise of properties between gray & ductile iron.	Diesel engine blocks & frames; cylinder liners; brake discs for trains; power generators; exhaust manifolds; pump housings; and brackets.
White Iron	• ASTM A532: abrasion-resistant white iron castings	Extremely hard & wear-resistant.	Crushing & grinding applications; and grinding balls.
Malleable Iron	• ASTM A47 & ASME SA47: ferritic malleable iron castings • ASTM A197: cupola malleable iron • ASTM A220: pearlitic malleable iron • ASTM A338: malleable iron flanges, pipe fittings & valve parts for railroad, marine & other heavy-duty service up to 650F (343C) • ASTM A602 & SAE J158: automotive malleable iron castings	Soft & extremely ductile.	Chains; sprockets; tool parts & hardware; connecting rods; drive train & axle components; and spring suspensions.
Alloyed Iron	• ASTM A436: austenitic gray iron castings • ASTM A518: corrosion-resistant high-silicon iron castings	Corrosion resistant; retains strength & dimensions during elevated-temperature exposure; and ability to withstand thermal cycling.	Parts for chemical processing plants; petroleum refining; food handling & marine service; control of corrosive fluids; and pressure valves.

Specifications, Characteristics and Typical Applications

MECHANICAL PROPERTIES OF CAST IRONS

Due to the low toughness and ductility of cast iron (especially white and gray cast iron), standard tensile and impact toughness tests have limited applicability, and elongation and absorbed energy values are not always available. Some of the mechanical properties of the different types of cast irons are shown in the tables below. The wide variation in mechanical properties within a particular class of cast iron, as shown below, can be attributed to a variation in microstructure.

Property	Class 25 (as-cast)	Class 30 (as-cast)	Class 30 (annealed)	Class 35 (as-cast)	Class 40 (as-cast)
Brinell Hardness	187	207	109	212	235
Tensile Strength	29.9 ksi (206 MPa)	33.7 ksi (232 MPa)	20.6 ksi (142 MPa)	34.8 ksi (240 MPa)	41.9 ksi (289 MPa)
Modulus of Elasticity	16.6 Msi (114 GPa)	17.0 Msi (117 GPa)	14.5 Msi (100 GPa)	18.0 Msi (124 GPa)	18.2 Msi (126 GPa)
Tensile Poisson's Ratio	0.29	0.19	0.21	0.22	0.24
Compression Poisson's Ratio	0.27	0.26	0.26	0.28	0.23
Compression-to-Tensile Strength Ratio	3.68	3.84	4.05	3.63	3.71

Gray Cast Iron Classifications & Properties (ASTM A48)

Grade	Heat Treatment	Tensile Strength	Yield Strength	% Elongation (min. 2 in.)	Brinell Hardness	Poisson's Ratio	Tensile Elastic Modulus
60-40-18	1	60,000 psi (413 MPa)	40,000 psi (276 MPa)	18	130-170	0.28	24.5 Msi (169 GPa)
65-45-12	2	65,000 psi (448 MPa)	45,000 psi (310 MPa)	12	150-220	0.28	24.5 Msi (169 GPa)
80-50-06	2	80,000 psi (551 MPa)	55,000 psi (379 MPa)	6	170-250	0.28	24.5 Msi (169 GPa)
100-70-03	3	100,000 psi (689 MPa)	70,000 psi (482 MPa)	3	241-300	0.28	25.5 Msi (176 GPa)
120-90-02	4	120,000 psi (827 MPa)	90,000 psi (620 MPa)	2	240-300	0.28	25.5 Msi (176 Gpa)

Ductile Cast Iron Classifications & Properties (ASTM A536)

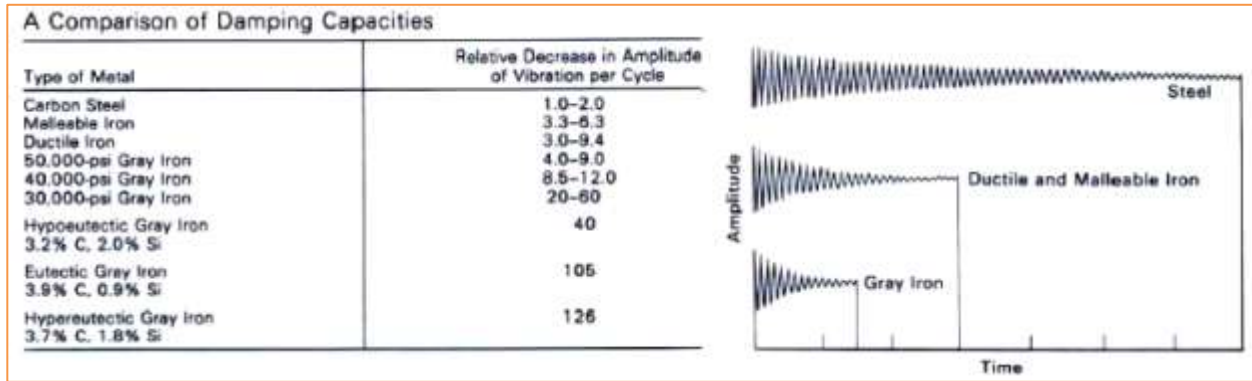| Grade	Min. Tensile Strength	Min. 0.2% Yield Strength	% Elongation (in 50 mm)	Brinell Hardness
250	36.2 ksi (250 MPa)	25.3 ksi (175 MPa)	3.0	179 max
300	43.5 ksi (300 MPa)	30.4 ksi (210 MPa)	1.5	143-207
350	50.7 ksi (350 MPa)	35.5 ksi (245 MPa)	1.0	163-229
400	58.0 ksi (400 MPa)	40.6 ksi (280 MPa)	1.0	197-255
450	65.2 ksi (450 MPa)	45.6 ksi (315 MPa)	1.0	207-269

Compacted Graphite Iron Classifications & Properties (ASTM A842)

Grade	Tensile Strength	Yield Strength	% Elongation	Brinell Hardness	Fracture Toughness (ksi-sq.in./MPa-sq. m)
1	140 ksi (966 MPa)	110 ksi (759 MPa)	11	302	100/ 109
2	165 ksi (1,139 MPa)	130 ksi (897 MPa)	10	340	78/ 85
3	190 ksi (1,311 MPa)	160 ksi (1,104 MPa)	7	387	55/ 60
4	220 ksi (1,518 MPa)	180 ksi (1,242 MPa)	5	418	48/ 52
5	240 ksi (1,656 MPa)	210 ksi (1,449 MPa)	3	460	40/ 44

Austempered Ductile Iron Classifications & Properties (ASTM A897)

The machinability of gray, malleable and ductile cast irons is superior to that of carbon steel, and these alloys even outperform free-cutting steel. The excellent machinability can be attributed to the lubricating effect of the graphite particles in the microstructure. Gray cast iron has a very high damping capacity (ability to quell vibrations) and is therefore well suited for bases and supports, as well as for moving parts. A comparison in damping capacity is given below. This characteristic is what makes gray cast iron a material of choice for brake

rotor applications.
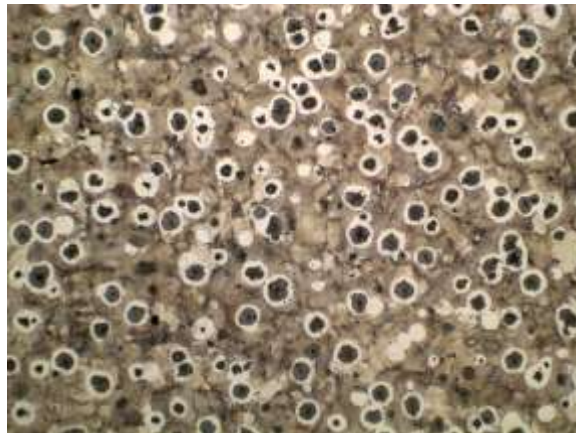
A Comparison of Damping Capacities		
Type of Metal	Relative Decrease in Amplitude of Vibration per Cycle	
Carbon Steel	1.0–2.0	
Malleable Iron	3.3–6.3	
Ductile Iron	3.0–9.4	
50,000-psi Gray Iron	4.0–9.0	
40,000-psi Gray Iron	8.5–12.0	
30,000-psi Gray Iron	20–60	
Hypoeutectic Gray Iron 3.2% C, 2.0% Si	40	
Eutectic Gray Iron 3.9% C, 0.9% Si	105	
Hypereutectic Gray Iron 3.7% C, 1.8% Si	126	

INOCULATION OF CAST IRON

Inoculation of cast iron involves providing nucleation sites for either the growth of graphite flakes or nodules, and by avoiding undercooling prevents formation of hard carbides (i.e. chill) in the structure.

A wide variety of inoculants are available, most of which are based on ferrosilicon and contain active agents such as Calcium, Aluminum, Barium, Strontium, Zirconium.

The benefits of inoculation can be illustrated as shown below. Uniformly distributed graphite nodules are found in a pearlitic ductile iron matrix instead of hard brittle iron carbides (cementite, Fe3C), and randomly oriented flakes have replaced a poor graphite structure in a gray iron.
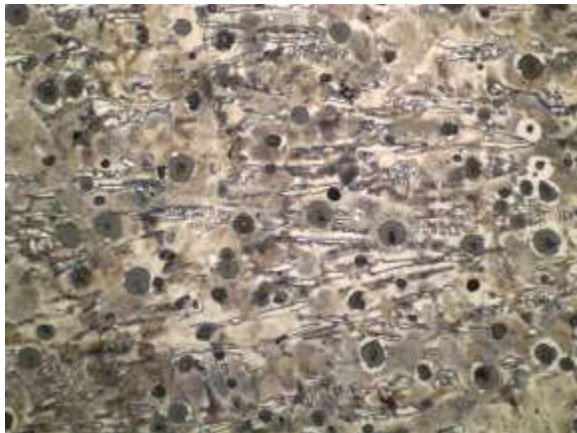
Uninoculated ductile iron structure   Inoculated ductile iron structure
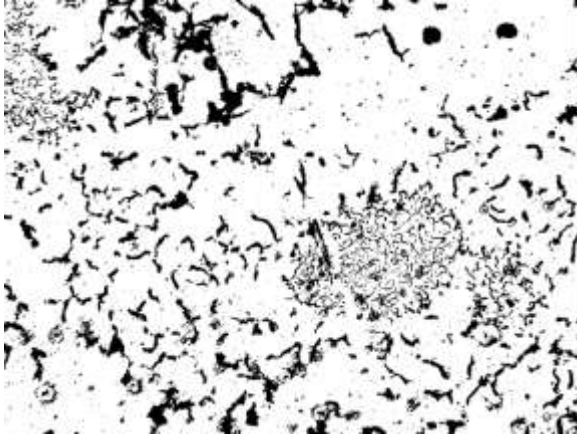
Uninoculated gray iron structure   Inoculated gray iron structure

Benefits of Inoculation:

In Gray Irons:
1.   Reduces chill effect and promotes graphite formation
2.   Reduces the formation of fine graphite
3.   Proper inoculation leads to the desired Graphite size
4.   Promotes uniform structures and properties in sections with various thicknesses
5.   Improves mechanical properties
6.   Improves machinability

In Ductile Irons:
1.   Reduces tendency for chill
2.   Increases the nodule count
3.   Promotes the formation of fully spheroidal graphite (increased nodularity)
4.   Improves mechanical properties
5.   Makes it possible to obtain as-cast ferrite structure in thin sections

Inoculation Practices

Inoculants are added to cast irons at either one of the following stages during the casting process;

-       Ladle inoculation (up to 1.0%; low end for gray higher end for ductile, typically 0.5-6 mm)
-       In stream inoculation (0.02-0.2%; low end for gray higher end for ductile, typically 0.2-0.7 mm)
-       In mold inoculation (0.05- 0.12%, typically with a pressed insert)

The time from filling the ladle with molten iron to pouring the last casting, commonly known as the fade time, and the metal temperature are the two main factors influencing the inoculation method.

COMMON DEFECTS AND MICROSTRUCTURAL ANOMALIES IN CAST IRONS AND THEIR CAUSES

Achieving the desired microstructure of ductile cast iron is dependent on employing appropriate casting practices, with most important ones being the nodularizing and inoculation processes. If the process fails, a number of other types of graphite may develop, causing structural imperfections.

The outstanding properties of ductile iron are due to a nodular or spheroidal form of precipitated graphite in the microstructure. This favorable graphite shape is obtained by treating with magnesium to retain residual Mg content within narrow control limits, then inoculating with ferrosilicon to nucleate that graphitization.

Introducing a *nodulizing agent,* such as magnesium, creates the condition for the graphite to precipitate and grow in a nodular shape. If insufficient Mg is added, or if the molten metal is held for an extended period after the Mg has been added, the graphite will not precipitate in a round shape.

The performance of the cast irons are strongly affected by the graphite elements morphological peculiarities (e.g., graphite elements nodularity, volume fraction, density, distribution, dimension). The most common metallurgical defects can be classified as follows:

Exploded graphite, mainly due to excess of rare earth additions.

Chunky graphite, due to excess of rare earth additions.

Compacted graphite, mainly due to low residual magnesium and/or rare earth (high temperatures or long holding time).

Spiky graphite, due to very small amounts of tramp elements such as lead, which have not been neutralized by rare earth additions.

Graphite floatation, which potential causes can be high carbon equivalent, excess of pouring temperature, slow cooling rate in thicker sections or an insufficient inoculation.

Flaky surface structure, due to a sulfur excess in molding sand.

Nodule alignment, due to the presence of large dendrites, with nodules aligned between arms of dendrites.

Carbides, due to different causes, with a key role played by the presence of carbide promoting elements such as Mn, Cr, V, Mo, and by a rapid cooling rate.

Irregular graphite, due to high holding and/or long holding temperature or to a poor inoculation.
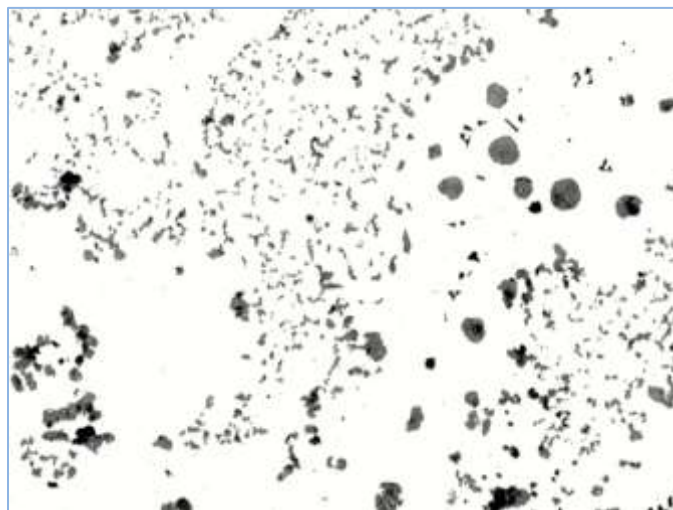
Slag inclusions, which can be due to different causes (e.g., inadequate slag control from pouring system).

Shrinkage, due to inadequate feed of available metal, excess of magnesium, under or over inoculation.
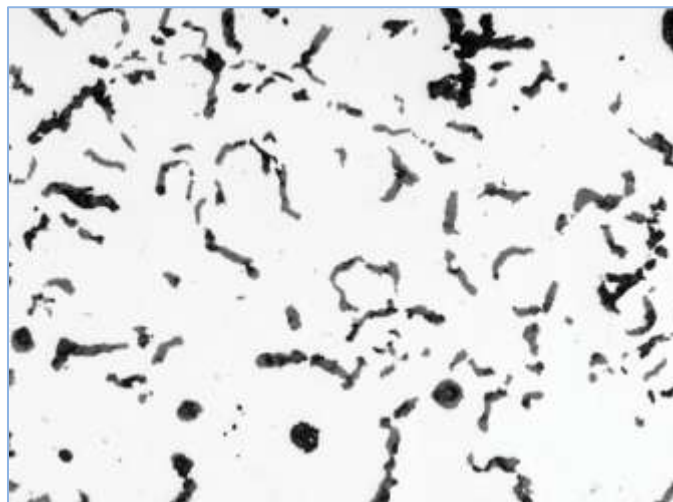
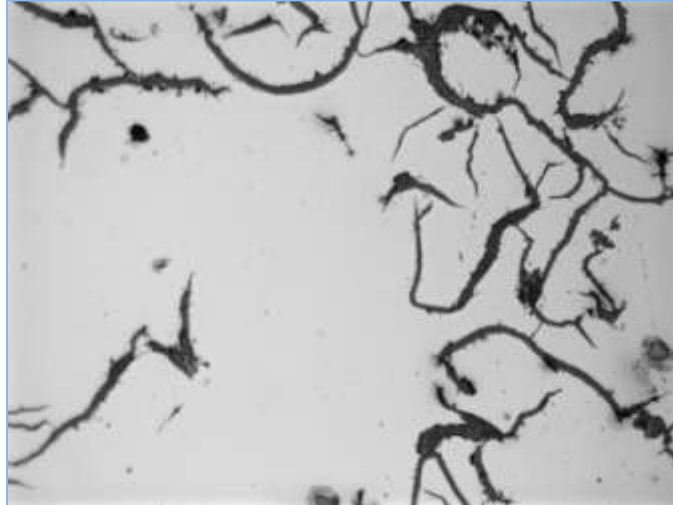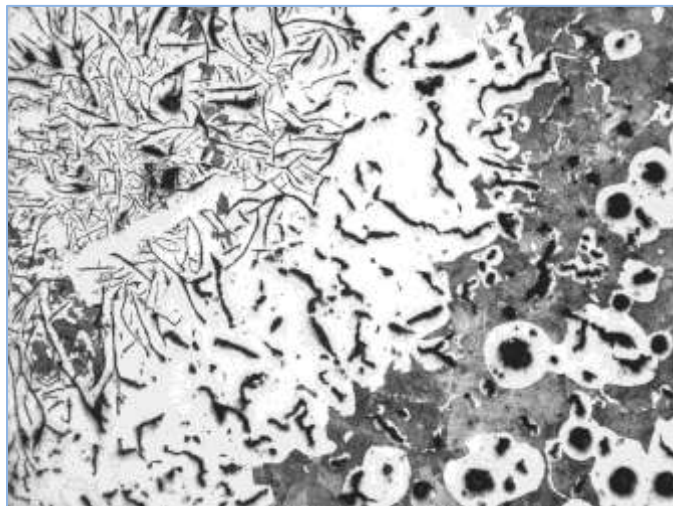Gas holes, which can be due to many causes (e.g., melting procedures).
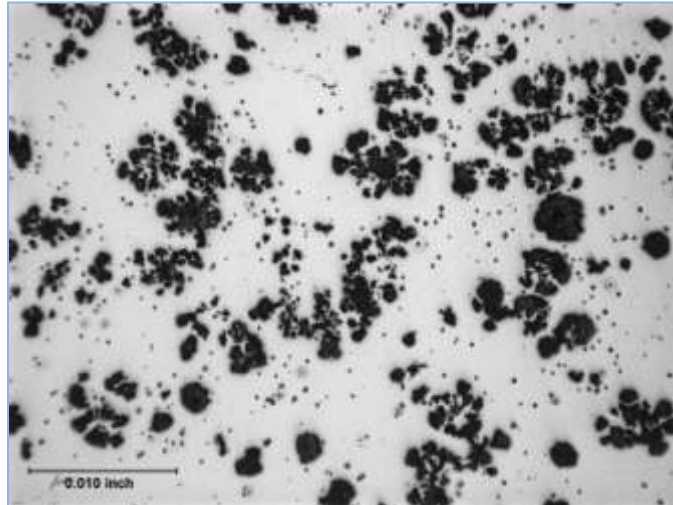
Exploded Graphite

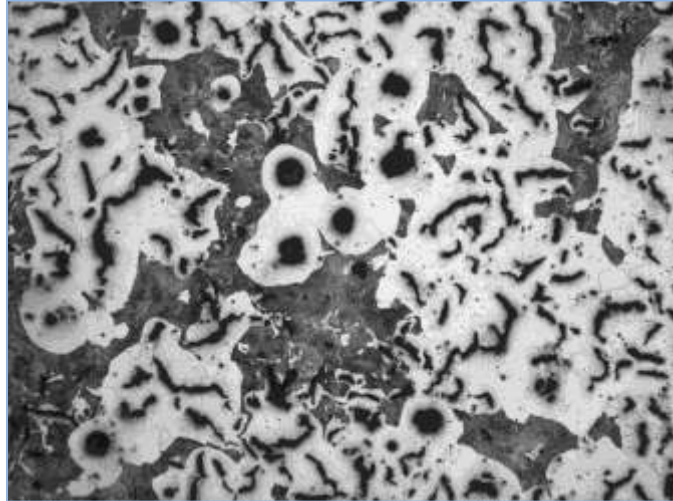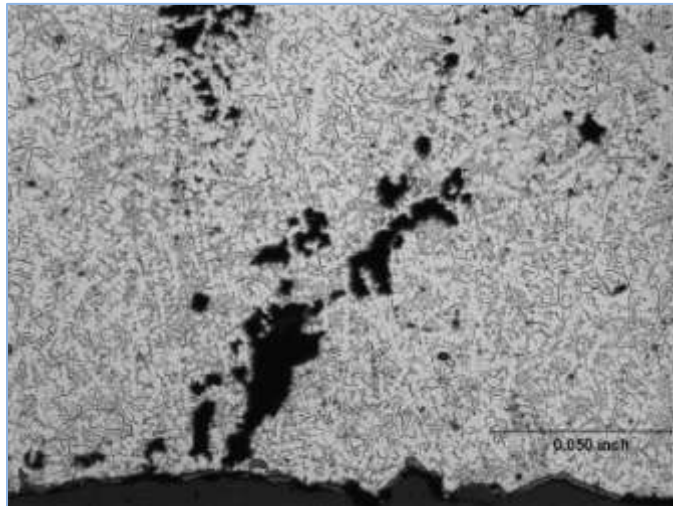Chunky Graphite

Compacted Graphite

Spiky Flakes

Flaky Graphite at the surface

Nodule Alignment

Irregular Graphite

Shrinkage Porosity

The Fading Effect

The main purpose of the inoculation process is to increase the graphite nucleation potential. Since from each graphite nuclei one graphite nodule is formed, nucleation potential can be determined by graphite nodule count. Experimental results indicate that the highest graphite nodule count and minimizing the risk of carbide formation are achieved while the inoculant is completely dissolved in the bath.

The effectiveness of the treatment depends not only on temperature but also on time. The fading time begins with the addition of the inoculant and ends when the eutectic solidification temperature is reached. A reduction in the number and a coarsening of the inoculation-effective inclusions results during this time due to re-oxidation, concentration compensation as well as the dissolution of nuclei. This also explains the influence of the solidification times on the inoculation result. While the moderate wall thickness areas of castings (e.g. 5 to 50 mm) solidify in a few minutes, thicker-walled, heavy castings (sections larger than 60 mm) can take hours, depending on the casting temperature. These differences in the solidification times involve a greater fading effect of the inoculation for heavier castings and hence a reduction in the number of nuclei able to grow, which leads in turn to a longer crystallization time. Both factors have the result that the eutectic grains or graphite nodules present in heavy section castings are generally fewer in number but larger in size.

Effects of Magnesium Fading:

When magnesium is added to ductile iron, the conditions required to cause the graphite to come out of solution in a round or nearly round shape are generated in the iron. Obtaining this spheroidal graphite shape is critical to the attainment of the desired properties in ductile iron. Consequently, any degradation of the graphite shape into compacted graphite causes the properties of the resulting iron to degrade as well. The final magnesium required to produce acceptable graphite nodularity in ductile iron is usually between 0.025% and 0.05%. Lower levels may be acceptable depending on the amount of other elements such as rare earth additions.

Minimizing Mg Fading:

Magnesium is a very reactive element and will readily oxidize (or sulfurize). Agitating the liquid metal, for example, increases exposure to the atmosphere at the metal surface and thereby increases the rate of magnesium loss due to oxidation. Covering the molten iron bath with a slag that is stable with respect to the magnesium content (forsterite for example) will reduce the rate of magnesium loss. Slag covering isn't always practical because magnesium will react with the oxygen in slags (and even with the oxygen in the refractory of the furnace linings). The high chemical activity of magnesium makes the decay of the magnesium content difficult to control and impossible to avoid.

Effects of Inoculant Fading:

Actually, the most well-known fade that occurs in the ductile iron process is the fade of the response to inoculation. Inoculation is the procedure used to increase nucleation of graphite nodules and to minimize the possibility of carbides forming during ductile iron solidification. The inoculation step is critical to the production of acceptable ductile iron since ductile iron is highly susceptible to the occurrence of carbides. The main reason for this high susceptibility is that the nodularizing agent, magnesium, is a carbide-stabilizing element.

Inoculation is accomplished with the addition of a ferrosilicon additive containing small quantities of aluminum and or calcium (>0.5%) or some other proprietary elemental additive. The effect of the inoculation fades asymptotically while the increased silicon composition (and other elemental addition) that accompanies the inoculation addition does not change. High holding temperatures and long holding times should be avoided to minimize fading.

The mechanical properties of ductile iron are tied directly to nodularity. Castings with poor nodularity will display lower tensile elongation and often do not meet minimum tensile strength and/or impact strength requirements. Degenerate graphite particles are stress risers and can also reduce the fatigue strength of ductile iron. Consequently, industrial specifications usually establish the minimum acceptable percent nodularity allowed in a part.

The amount of degradation that occurs with a given deviation from 100% nodularity can vary with the ductile iron grade. The high-strength grades are more susceptible to the presence of degenerate graphite than the low-strength, high-ductility grades. The powerful influence of nodularity on strength is due to the effects of increased stress concentration associated with non-nodular graphite particles. As the graphite structure becomes more degenerated, some dimensions of the graphite particles increase in size. The larger particles produce an increase in stress intensity around each particle and thus reduce the critical stress for crack propagation. The stress concentration increases in proportion to the square root of the major dimension of the particle. This change in the shape of the graphite particles also changes the elastic modulus and sonic properties of the material, thus, making it possible to evaluate change in structure by nondestructive (NDT) methods (ultrasonic techniques).
This technique has been used successfully in quality control screenings to sort gray and ductile iron castings.
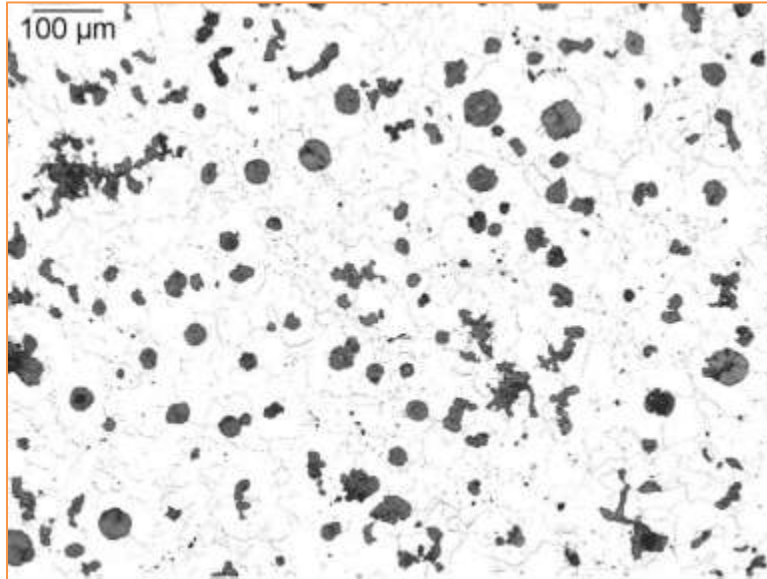
Ductile iron with poor nodularity

Primary Carbides in Ductile Cast Iron:

Ductile cast iron is particularly prone to the formation of primary carbides during solidification. One of the main reasons for this susceptibility is that the graphite forms into a spherical shape, which is the lowest surface area-to-volume ratio for the graphite. The limited surface area available for graphite precipitation, during solidification, increases the carbide-forming tendency. In addition, the principle element added for the nodulizing treatment is Mg, a known carbide stabilizer.

Another factor is that the S content in ductile iron is purposely lowered to less than 0.02%, to facilitate the formation of spherical graphite nodules. Therefore, inoculation is crucial to successfully cast ductile iron without carbides. Even after effective inoculation, fade can occur and result in the formation of primary carbides. Figure below shows primary carbides in a pearlitic ductile iron.
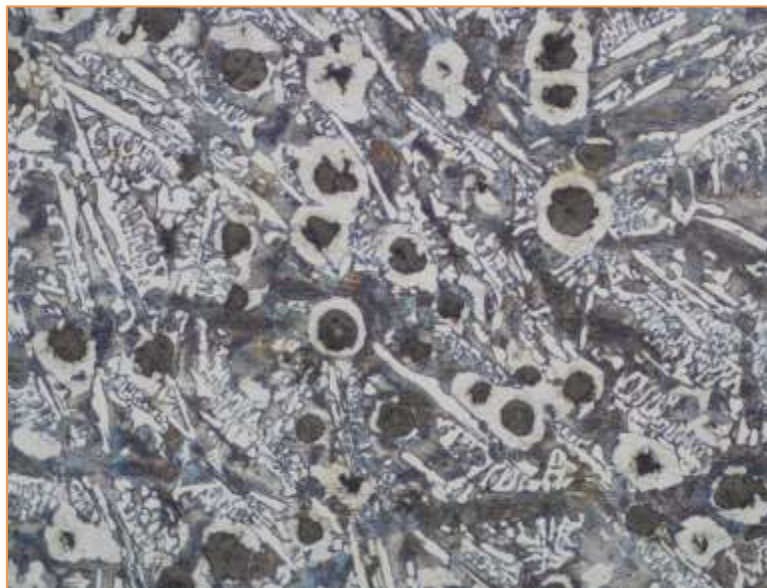
Primary carbides in ductile iron

These carbides have several names, including ledeburite, chill, primary carbide, Fe3C, iron carbide cementite, white iron and hard iron.

The principle step in controlling the occurrence of primary carbides in ductile iron calls for close attention to detail concerning inoculation and fade time. The effects of inoculation fade with time and, therefore, processing time within the foundry should be closely controlled. In many instances, modern-day foundries have utilized late-stream inoculation or mold inoculation to counteract effects of fade.

In addition to the inoculating effects and fade effects, some contaminants can cause primary carbides. In ductile iron, chromium is particularly noted for the formation of stable primary carbides that are not easily removed with heat treatment and are not easily removed with proper inoculation. Hydrogen is also noted for causing primary carbides. In this instance, however, the primary carbides can occur in the last iron to solidify because of H segregation to the liquid during solidification. When this occurs, a particular carbide form results, known as inverse chill.

Primary Carbides and Steadite in Gray Cast Iron

Two microstructure constituents in gray cast iron can cause hard spots, which aggravate machinists. These two constituents are iron carbides and iron phosphides (steadite). Figures below show typical examples of carbides, and iron phosphides.

Carbides in Gray Iron

Steadite in Gray Iron

Steadite, more commonly known as the phosphide eutectic, is really a precipitation of iron phosphides. Normally this is not regarded as a defect unless excess phosphorus enters the system and clusters are detected at the grain boundaries.

Phosphorus has the benefits in iron of increasing fluidity and wear resistance when present in the right amounts. Less than 0.04% may lead to metal penetration and finning, while levels of 0.1% and above can lead to the formation of a network of steadite at grain boundaries with subsequent problems of shrinkage and embrittlement. Some irons are deliberately produced with higher phosphorous levels where fluidity is a big issue, radiator castings, stove plates and some electrical casings for example.

The cure for excess steadite, apart from reducing the levels of phosphorous, is to disperse the phosphorous within the casting by improving inoculation or to increase the solidification rate. Care should be taken in the selection of scrap to avoid domestic heating castings and analysis should be made of the pig iron as some brands contain higher levels of phosphorus.

As indicated previously, iron carbide has several names. Iron phosphide is more commonly known as steadite. Both of these constituents are eutectic phases between iron and carbon, and iron and phosphorus, respectively. Because they are eutectic, they are the last to solidify. The solidification temperature for iron carbide is 2066°F (1130°C). For iron phosphide, the solidification temperature is 1920°F (1049°C).

When these two eutectics combine, a tertiary iron-carbon-phosphorus eutectic, with a still lower melting point, will occur in the microstructure. Although the melting point for this constituent is not published, it is believed to be lower than the melting points for the individual eutectics.

Since these eutectics are the last to solidify, they can be present in the cast iron structure as liquid surrounded by solid, and can be drawn from thin sections to feed thick sections. The consequence can be microscopic shrinkage voids in thin sections. These voids have a shape that is similar to the carbide and steadite constituents that would be found in the structure.

As with ductile iron, inoculation in gray cast iron is primarily used to control the occurrence of primary carbides. Ladle inoculation, mold inoculation, late stream inoculation or a combination of the various inoculation techniques have all proven effective. Control of tramp elements that are known carbide stabilizers, such as chromium, vanadium and molybdenum, and other less common elements in gray cast iron, such as antimony, tellurium and hydrogen, are also essential.

ANOMALIES RESULTING FROM PROCESSING AFTER SOLIDIFICATION

Widmanstätten Graphite

Widmanstätten graphite can occur in cast iron as the result of lead contamination. Other elements are also known to cause this problem. Lead levels as low as 0.005% have been known to create the Widmanstätten graphite. Widmanstätten graphite occurs after solidification with the precipitation of carbon atoms on crystallographic planes creating a spiky appearance to existing graphite flakes. If the condition becomes significant, the precipitation onto crystallographic planes can occur, aside from the primary graphite flakes, creating hatch marks in the structure.

Often, this graphite structure is associated with phosphorus- rich steadite regions. Research has shown that this graphite type can be controlled with the addition of rare earth elements, primarily cerium. As a consequence, the condition does not often occur in ductile cast iron because of the presence of rare earth elements in the treatment alloy. If the condition is occurring in gray cast iron, it can be controlled by eliminating the lead. However, inoculation with a cerium-bearing inoculant can also reduce the effect.

The presence of this graphite form greatly reduces the mechanical properties of the resulting iron. For example, a normal Class 30 gray iron, having a Pb concentration of 0.05% without the benefit of Ce or other rare earths, can actually have a tensile strength of less than 15,000 psi because of the presence of Widmanstätten graphite form. This graphite form is referred to as Type F.
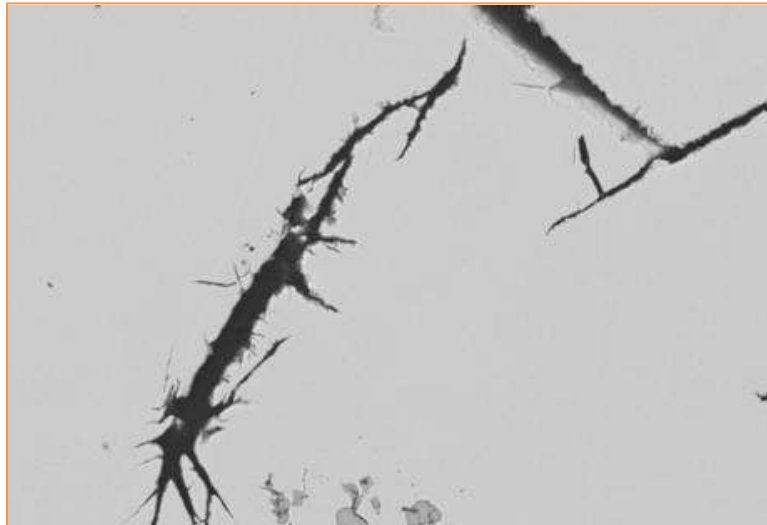

Widmanstätten Graphite

Retained Austenite in Gray and Ductile Iron

Cast irons that are quenched and tempered to form martensite can have unusual micro-constituents. In addition to the expected martensite, an unexpected white constituent in the structure can occur. This white constituent is *retained austenite.*

Carbon can stabilize austenite and, since cast irons are hypereutectoid, the austenitizing temperature can affect the amount of carbon dissolved in the austenite, prior to quenching. As the temperature increases above the eutectoid reaction, the amount of carbon dissolved in the austenite increases. When this iron is quenched, some of the high carbon austenite is retained, leaving a mixed structure of martensite and austenite. More specifically, this is a mixed structure of martensite and high carbon austenite.

To prevent retained austenite from occurring in quenched martensitic cast iron structures, the temperature from which the iron is quenched should be lowered to a temperature immediately above the eutectoid. The correct temperature may require trial and error to establish it for individual irons. The reason is that the eutectoid temperature varies significantly, as a function of Si, and no single temperature for gray iron or for ductile iron can be stated. Nickel also stabilizes austenite. As Ni content increases, so does the tendency for

retained austenite.
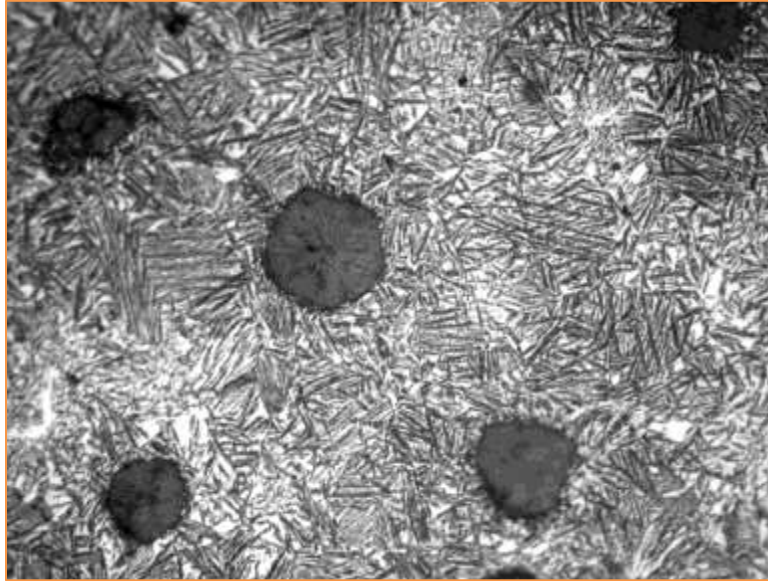
Retained Austenite (white phase) in DI

OTHER ANOMALIES

Microstructure Anomalies That Affect Ductile Iron Properties

The microstructure of ductile iron plays a vital role in affecting the mechanical properties of the final casting. Examples below illustrate the vital role the microstructure plays and the cause of the deficiencies in a desired ductile iron grade of 80-55-06 per ASTM 536. This grade is an as-cast pearlitic ductile iron with a minimum ultimate tensile strength of 80,000 psi, a minimum yield strength with 0.2% offset of 55,000 psi and a minimum 6% elongation.

Inconsistencies:

The following test results were obtained in different heats of the casting:

Heat 1: The castings failed to meet the elongation requirement, exhibiting only 3% maximum elongation.

Heat 2: The castings failed to meet the yield strength requirement, with only a 50,000 psi at 0.2% offset.

Heat 3: The castings failed to meet the yield strength and the elongation requirements.

Metallographic evaluation of the microstructures revealed the reasons for these inconsistencies.

In Heat 1, the microstructure at the tensile fractured surface had a required graphite nodularity (greater than 80%) and pearlite content (greater than 50%), but the structure had a high incidence of intercellular carbides. Analysis revealed these carbides were high in titanium, vanadium, molybdenum and niobium. These carbides significantly detracted from the ability of the casting to meet the elongation requirements.

In Heat 2, the microstructure had acceptable nodularity, but the ferrite content was excessive (approximately 70% of the matrix). For this grade, the matrix should be in excess of 50% pearlite. Excessively high ferrite content detracted from the yield strength.

In Heat 3, the microstructure exhibited an acceptable pearlite content, but the graphite nodularity was not acceptable. Poor nodularity negatively affected both the yield strength and elongation.

Correcting the Problem:

Correcting these problems required different approaches. For Heat 1 (failing to meet the elongation requirement), closer scrutiny of the charge material was required to minimize the influx of tramp elements.

For Heat 2 (failing to meet the yield strength requirement), either an increase in the amount of pearlite stabilizers was required or the foundry needed to shake out the castings at a temperature hot enough to force rapid cooling from "red heat."

For Heat 3 (failing to meet both yield strength and elongation requirements), the magnesium/cerium content was not adequate as the result of fade or ineffective treatment.

Hydrogen Pinholes

Hydrogen pinholes may be considered to be one of the most expensive defects as they are not normally revealed until after machining. They can be found both in gray and ductile irons and tend to appear as small spherical holes just beneath the casting surface. The inner surface of the hole will have a continuous graphite lining and hence appear to be black and shiny on examination.

Hydrogen pinholes can be caused by several factors, either alone or in combination. Most commonly, high levels of aluminum or titanium in the base iron causes a reaction with moisture from the greensand, damp tools or wet refractories. Other sources of moisture could be damp or oily charge materials (including rust), a build up of dead clay in the sand system, which will tend to retain moisture or the use of old cores, which have picked up moisture from humid atmospheres.

Pinholes may be prevented, or the occurrence reduced, by restricting the aluminum content of the base metal below 200ppm and minimizing the titanium content. Careful control of steel scrap, avoidance of CG iron returns (if made using Ti) and elimination of enameled scrap will help in this respect. Some pig irons can also contain titanium. Care should be taken to fully dry refractory patches and coated tools before use and sufficient new sand added to the molding system to prevent build up of dead clay. Moisture in the system should preferably be below 3%. Cores and water-based coatings should be fully cured and dry before the metal is poured into the mold. Increasing metal pouring temperatures and carbon equivalents have also been noted to reduce the incidence of this particular defect.

Nitrogen Blowholes

Nitrogen blowholes may be either a surface defect or a sub-surface occurrence. Subsurface blowholes are only revealed on machining, thus being detected at the most expensive post-foundry finishing operation. Blowholes appear more frequently in medium to heavy section thicknesses and are often adjacent to resin bonded core or mold materials. The holes, or fissures, are normally irregular in shape (as opposed to the more spherical hydrogen holes) and are perpendicular to the casting surface, protruding some millimeters into the casting. The inner surface of the hole has a continuous or discontinuous graphite lining coupled with the subsequent decarburization in the immediate surrounding matrix. On occasions, the graphite flakes are seen to have become shorter and thicker, this being a typical sign of high nitrogen.

Nitrogen fissures are caused simply by excess nitrogen in the system. In cupola melted gray irons, this comes from high proportions of steel scrap in the charge which require high levels of coke, whereas in induction melting, poor quality, high nitrogen containing carburizer is normally the cause. The use of some resins in the production of cores or molds can also lead to nitrogen pick up locally within the casting, particularly at a potential hot spot.

Restricting the dissolved nitrogen content to 80 ppm in medium to heavy sections and 120ppm in thin, uncored sections will normally not give nitrogen blowhole problems. In addition, careful selection of raw materials will also help reduce the potential for blowhole problems. Titanium and zirconium are known to neutralize the effects of nitrogen by producing carbonitrides, however care should be taken when using titanium as this can then promote hydrogen pinholes in the presence of aluminum and moisture as previously discussed. Increases in pouring temperature and carbon equivalent are also known to reduce the incidence of nitrogen defects.

Often, it is very difficult to distinguish between hydrogen and nitrogen gas defects. Analysis of a defect sample may show that the control parameters for both elements are within limits, yet a gas hole, characteristic of hydrogen or nitrogen, will appear. In such cases, it is likely that there is a synergistic effect where the elements have combined to form the hole. In such cases, a full examination of the causes for both gases needs to be undertaken with tighter controls put in place.

Carbon Monoxide Blowhole

The third of the common gas defects is the carbon monoxide blowhole, which can normally be seen as a

surface blow. The carbon monoxide blow can appear as a hole a few millimeters across, or in large castings the hole can be large enough to put a fist into. Normally seen in conjunction with slag and clouds of manganese sulfides, it is also possible to see dendrites protruding from the inner surfaces of the hole.

The most common cause of this problem is the failure to totally empty ladles between taps. This results in a lowering of the overall metal temperature and a build up of cold manganese sulfide/oxide rich slags. Eventually, the point is reached where a metal/slag reaction takes place as;

$MeO + C = Me = CO$
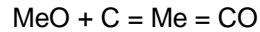
The defect may also be attributed to excess manganese and/or sulphur in the system. These should be balanced according to the equation:

$\%Mn = \%S + 0.3$

Carbon monoxide blowholes can normally be eliminated by ensuring a complete emptying of ladles between taps, operating with clean ladles and preventing slag build up on the refractory. Increasing metal temperature can also help.

Shrinkage

Shrinkage porosity in gray and ductile irons are typically present as internal cavities of varying size and shape from large isolated holes to more scattered and smaller porosity only visible in the microscope. Very often a characteristic dendritic sub-structure is revealed inside the porosities. The defect normally occurs due to contraction in the last liquid metal to solidify and is thus often associated with heavier sections, changes in section thickness or hot-spots in a complex casting geometry.

These same locations are also prone to release certain gas related porosity and thus it is often difficult to distinguish between gas and shrinkage related defect.

A typical shrinkage defect is shown in the below micrograph. Typically the shrinkage appears at the thermal center of the casting and the cause is attributed to poor metal flow design.

Possible causes:

- Soft molds or not properly cured binder
- Insufficient clamping or weighing
- Excessive pouring temperature
- Excessive inoculation giving pronounced   graphite expansion early in solidification and thus mold wall dilatation
- Insufficient or excessive (>3.8%) carbon content or inadequate carbon equivalent
- Hot spots resulting from poorly designed gates and risering systems
- Poor casting design causing unnecessary changes in casting section sizes.

Possible cures:

- Improve mold rigidity
- Clamp or weight the molds adequately
- Avoid unnecessarily high pouring temperatures   and over-inoculation
- Adjust carbon content or carbon equivalent
- Provide adequate feed metal by proper gating and risering. Use solidification simulation.
- Minimize hotspots by improving casting and gating design
- Use internal or external chills to avoid hot-spots
- Use inoculant designed to minimize shrinkage effects
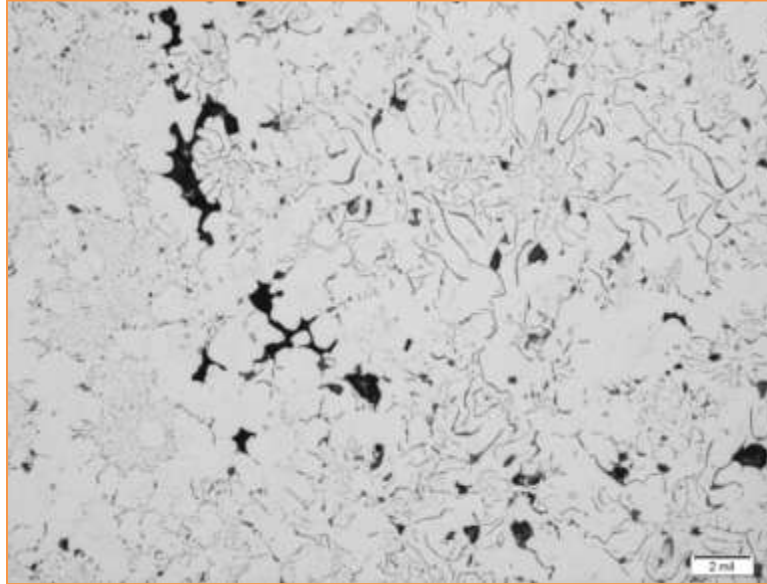
Shrinkage porosity in gray iron

- Thicker sections of a casting that are not properly fed or have inadequate runner/gate designs
- Low carbon or carbon equivalent irons are more prone to shrinkage due to a lack of low density graphite being precipitated and not providing an "expansion" effect to counter the natural solidification shrinkage
- Insufficient clamping or weighting of the mold can lead to lifting
- Under-inoculation or over-inoculation both increase the potential for shrinkage, the former due to the lack of precipitated graphite, the latter produces too many eutectic cells, which can result in porosity between the cells.
- High phosphorous contents, in excess of 0.1% tend to promote shrinkage, as does excessive pouring temperatures
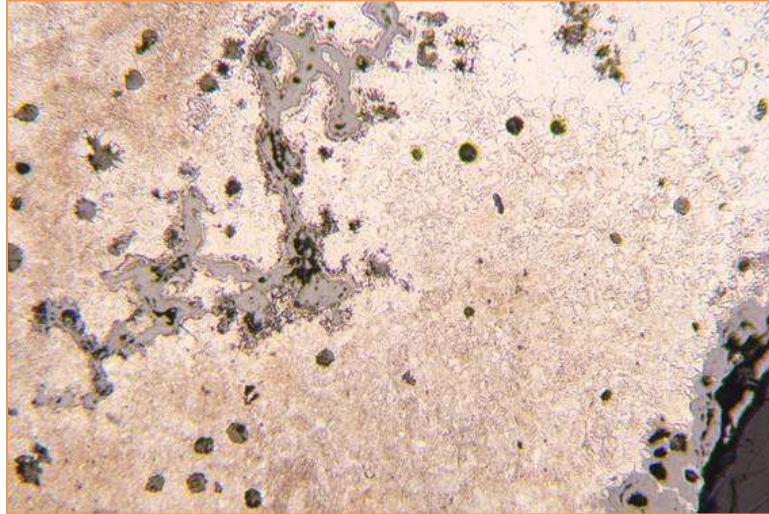
Slag

Slag inclusions may be found both at the surface of the casting, or as illustrated below within the body of the casting. They are recognizable as having no decarburization associated with them and the slag usually seems to have several different phases within the particle.

Slag defects are caused by inadequate slag removal during the melting and pouring phase or by a build up of slag in the pouring ladle or receiver. Slag traps or filters built into the running system often help with the removal of slag, but do not help with the root cause of slag build up and are no substitute for good metal cleaning practice. Slag may also be formed if there is excessive turbulence in the running system or metal is poured from some height. Examination of the runner design or time spent watching the ladle operator's practice is well spent.

Sand Inclusions

Another casting defect is entrapped sand. It can be distinguished from slag in that it has a single phase and the sand grains are relatively regular in shape. Sand is normally generated within the mold, loose sand around the downsprue or erosion of sand if the metal is dropping a large distance onto sand at the bottom of the sprue. Sharp corners are also a common cause of sand erosion. Care should be taken to blow loose sand from the mold during the assembly of the mold and frequent examination of pattern plates in horizontal molding machines should be made to ensure that nothing is sticking to the plate. As with slag inclusions, avoidance of excess turbulence when pouring will help to avoid subsequent problems.

Slag Inclusions in DI

WELDING OF CAST IRONS

Cast irons include a large family of ferrous alloys covering   a wide range of chemical compositions and metallurgical microstructures. Some of these materials are readily weldable, while others require great care to produce sound welds. Certain cast irons are considered unweldable.

A major factor contributing to the difficulty of welding cast iron is its lack of ductility. If cast irons are loaded beyond their yield points, they break rather than deform to any significant extent. Weld filler metal and part configuration should therefore be selected to minimize welding stresses.

Shielded Metal Arc Welding (SMAW), Flux cored arc, Metal Inert Gas (MIG), Tungsten Inert Gas (TIG) and gas welding processes are normally used with nickel-based welding consumables to produce high-quality welds, but cast iron and steel electrodes can also produce satisfactory welds in certain alloys.

Iron castings are generally welded to:

- Repair defects in order to salvage or upgrade a casting before service,
- Repair damaged or worn castings, and
- Fabricate castings into welded assemblies.

Repair of defects in new iron castings represents the largest single application of welding cast irons. Defects such as porosity, sand inclusions, cold shuts, washouts and shifts are commonly repaired. Fabrication errors, such as inaccurate machining and misaligned holes, can also be weld repaired.

Due to the widely differing weldability of the various classes of cast iron, welding procedures must be suited to the type of cast iron to be welded.

White Cast Iron

Because of its extreme hardness and brittleness, white cast iron is considered unweldable.

Malleable Cast Iron

During welding, the ductility of the heat affected zone (HAZ)   of malleable cast iron is severely reduced because graphite dissolves and precipitates as iron carbide. Although post weld annealing softens the hardened zone, minimal ductility is regained. Despite these limitations, malleable cast irons can be welded satisfactorily and economically if precautions are taken.

Because most malleable iron castings are small, preheating is seldom required. If desired, small welded parts

can be stress relieved at temperatures up to 550°C. For heavy sections and highly restrained joints, preheating at temperatures up to 200°C and a post weld malleabilising heat treatment are recommended. However, this costly practice is not always followed, especially when the design of the component is based on reduced strength properties of the welded joint.

Ferritic malleable grades display the best weldability of the malleable cast irons, even though impact strength is reduced by welding. Pearlitic malleable irons, because of their higher combined carbon content, have lower impact strength and higher crack susceptibility when welded. If a repaired area must be machined, welding should be performed with a nickel-based electrode.

SMAW welding cast iron, using low carbon steel and low hydrogen electrodes at low currents, produces satisfactory welds in malleable iron. If low carbon steel electrodes are used, the part should be annealed to reduce the hardness in the weld (due to carbon pick-up) and in the HAZ.

Gray Cast Iron

As gray cast iron contains graphite in flake form, carbon can readily be introduced into the weld pool, causing weld metal embrittlement. Consequently, techniques that minimize base metal dilution are recommended. Care must be taken to compensate for shrinkage stresses, and the use of low strength filler metals helps reduce cracking without sacrificing overall joint strength.

Gray cast iron welds are susceptible to the formation of porosity. This can be controlled by lowering the amount of dilution with the base metal, or by slowing the cooling rate so that gas has time to escape. Preheat helps reduce porosity and reduces the cracking tendency. A minimum preheat of 200°C is recommended, but 315°C is generally used.

The most common arc welding electrodes for gray cast iron are nickel and nickel-iron types. These electrodes have been used with or without preheating and/or post weld heat treatment. Cast iron and steel electrodes must be used with high preheats (550°C) to prevent cracking and the formation of hard deposits.

Ductile Cast Iron

Ductile cast irons are generally more weldable than gray cast irons, but require specialized welding procedures and filler materials. Pearlitic ductile iron produces a larger amount of martensite in the HAZ than ferritic ductile iron and is generally more susceptible to cracking.

SMAW, using nickel-iron electrodes, is the most common welding technique for welding ductile iron. Most castings do not require preheating, but preheats of up to 315°C are used on large components.

Practical Considerations for Base Metal Preparation

Proper preparation of a casting prior to welding is very important. All traces of the defect must be removed from the casting, usually by chipping, grinding, arc gouging or flame gouging. Dye-penetrant inspection is recommended to ensure complete removal of all defects. Thorough cleaning of the joint faces and adjacent material prior to welding is essential to ensure successful repair welding and to prevent porosity and wetting difficulties. Electrodes should be dried to minimize hydrogen damage and porosity. If machinability or optimum joint properties are desired, castings should be annealed immediately after welding.

Castings that have been in service are often saturated with oil or grease. Exposure to high temperatures during the weld thermal cycle can cause dissociation of these hydrocarbon compounds, resulting in the formation of porosity in the weld. For this reason, any surface oil or grease must be removed prior to welding, using solvents or steam cleaning. The surface skin of the casting, which may contain burned-in sand or other impurities from the mold, should also be removed. Castings that have been in service for extended periods of time may also require degassing by heating the casting uniformly to about 370°C for 30 minutes, or for a shorter time to almost red heat (approximately 540°C), using an oxy-fuel gas torch or circulating air furnace.

If localized degassing is preferred, the weld area can be heated by depositing a weld pass, which usually becomes very porous, and then removing it by grinding. This welding and grinding operation is repeated until the weld metal is sound. The weld may then be completed as specified in the welding procedure. Castings that have been impregnated with a plastic or glass sealer should not be repair welded, because the sealer may inhibit fusion or produce excessive porosity in the weld.

It is also important that the outer surface of the casting and any ground surfaces be wiped with mineral spirits, such as acetone, to remove residual surface graphite prior to welding. Residual graphite inhibits wetting and prevents complete joining and fusion. When wetting difficulties are encountered, the following cleaning methods can be used:

Electrochemical cleaning in a molten salt bath operating at a temperature of 455–510°C in a steel tank. By passing direct current through the bath, a surface essentially free of graphite, sand, silicon, oxides and other contaminants can be produced. Abrasive blasting with steel shot is suitable for preparing the surfaces of ductile and malleable cast iron, but should not be used for gray cast iron. Searing the surfaces to be welded with an oxidizing flame or heating the casting to about 900°C in a strongly decarburizing atmosphere, may be suitable in some applications.

Before any cleaning procedures are used in production, wetting tests should be conducted, using the proposed filler metal and welding procedure. The filler metal should be applied to a clean, flat surface and then examined visually. If the surface is not uniformly wetted, it has not been cleaned sufficiently.

**Special Welding Techniques for Cast Irons**

Improved weld performance can be achieved by application of several special techniques. These include:

- Joint design modifications
- Groove face grooving
- Studding
- Peening
- Special deposition sequences and electrode manipulation.

Joint Design Modification

Full penetration welds are better than partial penetration ones, since the crevice left unfused can act as a stress concentration, increasing the risk of cracking. It is therefore advisable, where possible, to modify joint design to allow full penetration weld to be made, as shown below. Welds at changes in thickness can suffer uneven expansion and contraction stresses during the welding cycle, and also are located at stress concentrations.

A change in design to move the weld to a region of constant thickness is therefore beneficial in some cases, since the weld is then removed from the 'danger area'. A backing fillet weld can also be used to support a weld in a region of stress concentration.
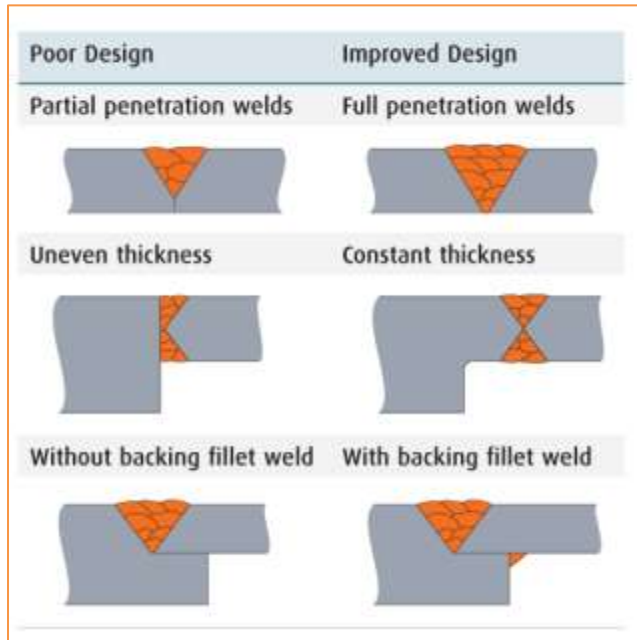
Modifications to joint design that would help minimize stress
concentrations and reduce the risk of cracking

Groove Face Grooving

Grinding or gouging grooves into the surface of the prepared weld groove, then filling the grooves with a weld bead, before filling the whole joint, as shown opposite, is sometimes recommended. This reduces the risk of cracking by deflecting the path of a crack. Also, as with conventional buttering, the beads that are in contact with the casting, and therefore most highly diluted, are deposited first, when the stresses on the fusion line and heat affected zone of the weld are lowest.
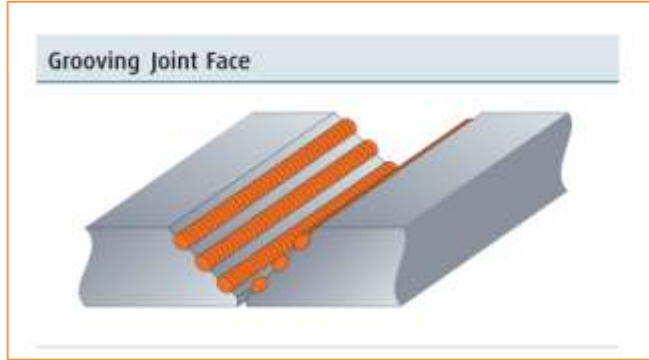
The technique of grooving the joint face before filling.
This interrupts the line of the heat affected zone.

Studding

Improved joint strength can be achieved by driving or threading studs into the joint face. These should be staggered as shown below, so that a stud does not face another directly opposite it across the joint. Provided the studs are of material compatible with the filler metal, this technique can help reduce underbead cracking in the HAZ or along the fusion line.
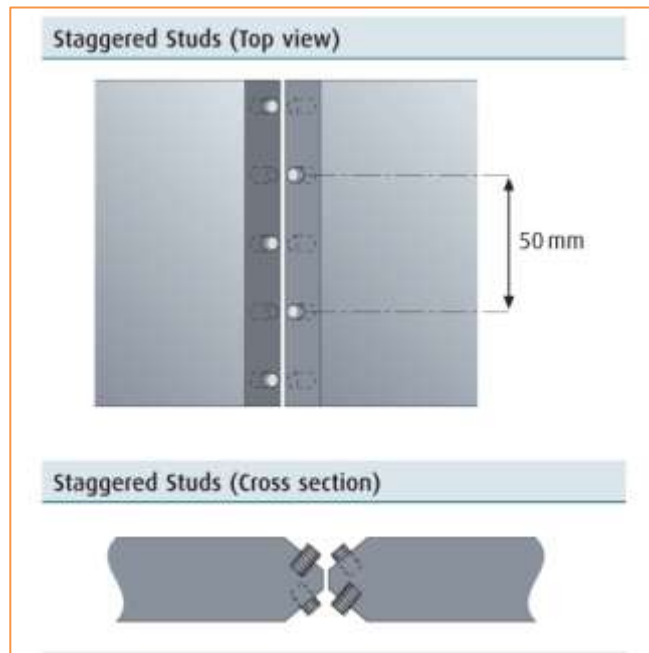
Screwing or Driving staggered studs into the joint face

before welding to improve joint strength.

Peening

By hammering (peening) a deformable weld bead, and thereby putting it into a state of compressive stress, the tensile stresses caused by thermal contraction can be opposed, thus reducing the risk of cracking in and around the weld. This requires a ductile weld metal. Nickel fillers are very suitable and, when welding brittle gray cast irons, this process is extremely useful. When stronger joints are required and iron-nickel consumables are used, then peening must be done at higher temperatures, while the metal is still sufficiently soft. Peening can be mechanized or done manually. For manual work, a 13–19 mm ballpeen hammer is used to strike moderate blows perpendicular to the weld surface. Mechanized hammers should operate at 620 kPa (90 psi) and at 750-1,000 mm/min. The hammer head should be no wider than the weld bead and should have a radius equal to half the width.

Deposition Techniques and Electrode Manipulation Arc Welding

Stringer or weave techniques can be used in depositing the weld bead, though weaving should be kept to within three times the electrode core diameter. Minimum dilution will result from using the stringer technique in the flat position, with the arc directed at the weld pool rather than the base metal. When re-striking the arc, this should be done on deposited metal, rather than base metal, though any slag must first be removed. This can be done with a cold chisel or chipping hammer.

In long welds, or welds on thick base material, depositing short, staggered beads will help minimize distortion, by balancing contraction stresses. Buttering of thick joint faces before filling in the rest of the joint is recommended. This is particularly effective if the buttering layers are of a composition more tolerant to dilution by the base metal.

To minimize penetration, short circuit dip-transfer modes should be used with MIG, and flux cored welding processes, and arc lengths in SMAW welding should be kept as short as possible while still maintaining good weld shape. In general, the welding current should be kept as low as possible within the range specified by the consumable manufacturer.

Oxy-Acetylene Welding

When depositing cast iron by the gas welding process, the torch flame should not be oxidizing, as the resulting loss of silicon promotes the formation of brittle white iron in the deposit. Similarly, the tip of the inner cone of the flame should be kept between 3 and 6 mm from the casting surface, and should not actually touch. The welding rod should be melted by immersion into the molten weld pool, and not melted directly by the torch flame.

Two types of sequence are recommended for depositing cast iron by gas welding. With the so-called 'block' sequence, filler metal can either be deposited in blocks of ~2,5 cm, before filling between the blocks. With the so-called 'cascade' sequence, thin layers are deposited, with each one being slightly longer than the preceding one.

Braze Welding

Since this process is particularly sensitive to the wetting of the base metal surface by the filler, cleanliness of the iron before welding is essential. This means that smeared graphite on the surface after grinding must be removed. The bronze welding rod is melted by contact with the base metal after preheating by the gas flame to 425-480°C. The slightly oxidizing inner cone of the flame should not be brought into contact with the consumable rod or the base metal. The rounded edges recommended for the joint faces in bronze welding increase the interface area between the casting and the deposited metal.

Cracking

All cast irons have a common problem affecting their weldability, namely their high carbon contents. Welding of cast iron is associated with rapid cooling of the weld pool and adjacent   base metal, compared with the slower cooling rates experienced during casting, and tends to produce undesirable microstructures, such as iron carbide and high-carbon martensite. Martensite and iron carbide are both very brittle and may cause cracking, either spontaneous or during service. The degree of embrittlement depends on the amount of iron carbide and martensite formed, which in turn depends on the cast iron composition and thermal treatment. The presence of

hard, brittle martensite in the HAZ also increases the risk of hydrogen-induced cracking.

Martensite in the HAZ may be tempered to a lower strength or a more ductile structure during post weld heat treatment, or it may be totally eliminated by ensuring very slow cooling rates after welding. Multiple-pass welding and minimum preheat and interpass temperatures are commonly specified to retard the cooling of cast iron welds and to prevent the transformation to martensite. Alternatively, welding procedures designed to reduce the size of the HAZ, and thus minimize cracking, can be used. Methods of accomplishing this include:

- Reduction of heat input
- Use of small-diameter electrodes
- Use of low melting point welding rods and wires
- Use of lower preheat temperatures.

Typical preheat levels for welding cast irons

Cast iron type	Preheat temperature, degrees C			
	SMAW	MIG	Gas (fusion)	Gas (powder)
Ferritic flake	300	300	600	300
Ferritic nodular	RT-150	RT-150	600	200
Ferritic malleable	RT*	RT*	600	200
Pearlitic flake	300-330	300-330	600	350
Pearlitic nodular	200-330	200-330	600	300
Pearlitic malleable	300-330	300-330	600	300
RT - room temperature * 200 degrees C if high C core involved.				

HEAT TREATMENT OF CAST IRONS

Cast iron has a wide variety of properties because of the possible combination of graphite and matrix structures. An even wider variety of properties can be achieved through heat treat. Heat treating of cast iron involves heating to a specified temperature, holding at that temperature for a specified time, then cooling at a specified rate. The conditions under which a part is subjected to each of these parameters will determine the final properties of the part.

Holding temperatures depend upon the type of heat treatment. Temperatures about 1550°F (845°C) are often required to be above the critical, meaning the matrix structure transforms to austenite which can be cooled to form martensite, pearlite or ferrite, depending on the cooling rate. Temperatures between 1300-1400°F (705-760°C) are considered to be below the critical and the matrix does not transform to martensite; instead the pearlite and carbides begin to dissolve to form ferrite and free carbon. Sub-critical temperatures are normally used to soften cast iron making it more machinable.
Temperatures between 800-1200°F (425-650°C) will not significantly change the matrix structure, and this range is most commonly used to stress relieve the material. In general, heat treat will not affect the size and shape of the graphite. The matrix structure can be altered dramatically, and it is this change that influences the resulting properties.

This section is divided into six subsections containing general information on each of the following heat treat processes:

A. Stress Relieving
B. Annealing
C. Hardening
D. Surface Treatments

E. Austempering
F. Hardness Measurements
G. Growth

A. Stress Relieving

Residual stresses may be present in either an as-cast or a machined part. The presence of these stresses can cause problems in machining, particularly in the ability of the machine to hold dimension. Differences in cooling rate will cause thermal stresses to develop in a cast part. Simple shapes will cool more uniformly than complex shapes, and residual stresses are minimized in simple shapes. Residual stresses can be thought of as a load on a part that exists internally. That load is not strong enough initially to cause distortion because there is enough machine stock to resist the distortion. During machining, material is removed and the amount of stress may now be sufficient to distort the work-piece. It is, in this case, where residual stresses will be a problem. Stresses can also be created during machining. As a cutting tool enters the work-piece, the grain structure is deformed slightly before the material is sheared off. Deformed areas will stress the work-piece and may cause distortion of the machined parts.

Stress relieving is used to eliminate residual stresses in a cast part prior to machining so that the deformation will not occur. It is a low temperature operation, and no change in the matrix structure or in the mechanical properties will occur. In most cases, parts made from continuous cast iron bar stock will not have to be stress relieved. Round bars will have the most uniform cooling and will contain minimal residual stresses in the as-cast state. Rectangles and squares will be subjected to some differences in cooling rate and may have to be stress relieved when   cut into plate. Large section parts, such as manifolds, will not normally require stress relieving because the mass of the part is sufficient to contain the residual stresses. Special shapes will be subjected to non-uniform cooling to a degree dependent on the complexity of the shape. The shape, amount of machining, and final section thickness should all be considered. Even under these conditions, stress relieving may not be necessary unless problems are occurring with warping during machining.
Proper stress relieving temperatures are a compromise between the degree of stress relieving and the resulting mechanical properties. Temperature has a stronger influence on stress relieving than the time at temperature. Stress relieving will start at relatively low temperatures but at least 800°F (425°C) is recommended.

A typical cycle is to hold the part at 1000°F (540°C) for one hour per inch of cross section. This will relieve approximately 90% of the residual stress, will prevent a change in the matrix structure, and should be sufficient for most applications. In order to ensure zero percent residual stress, the temperature would be too high to retain the original matrix. The cooling rate is also important and should be slow enough that the part does not develop high thermal gradients which can induce stresses. Furnace cooling at a rate less than 100°F-600°F (40°-315°C) per hour is recommended. Furnace cooling to 300°F (150°C) will be more costly but will ensure that the ultimate amount of stress relieving was accomplished.

B. Annealing

Annealing is a softening process that is achieved by first heating the work-piece to the desired temperature, then slow cooling the metal through the critical temperature range. Iron can be annealed so that only ferrite is present and optimal machinability will be achieved. Strength, hardness and wear characteristics will be significantly lower.

Several types of annealing are performed depending on the desired results. It is important to note that only the matrix structure is changed during the annealing process. The original graphite structure remains essentially unchanged. Alloy carbides that are present due to chrome additions will not be annealed and will still remain as a hard spot in the iron.

C. Hardening

Austenitizing, then quenching and tempering will produce maximum hardness on an iron part. This process will increase strength, and a wide range of both hardness and strength is possible by altering the tempering

temperature.

It is important to note the effect of nickel additions on the ductile iron. Hardenability and depth of hardness are dramatically improved, and a greater degree of through-hardening is possible. Steels alloyed with nickel and molybdenum are usually done so for this purpose.

A hardened part may not need to be fully martensitic depending on the application. The depth of hardness obtained after quench and tempering is usually sufficient to achieve desired results. It is also important to note that the depth is achieved on all outside surfaces. A part 1" x 1" x 1" will be through-hardened even if depth of hardness is only 0.500". It is always best to leave the specific cycle for heat treating to the heat treater. A suggested cycle is given below:

> Heat uniformly to 1650°F (900°C).
> Hold at temperature for one hour per 1" of cross section at the maximum thickness.
> Quench in agitated oil.
> Temper to desired hardness. Hold at tempering temperature for twice the length of time it takes to heat
the part to temperature.

Tempering temperatures will typically be between 400°F and 1000°F (205°C and 540°F). Maximum hardness will be achieved at a 400°F temperature. Temperatures above 1000°F are usually not recommended because the martensite can start to break down, significantly lowering the hardness of the quenched part. Tempering must immediately follow the quench. Thermal stresses will develop be- cause of the temperature gradients within the part while it is cooling. A quenched part can develop cracks if it is not tempered soon enough.

Any surface imperfection can cause stress risers to occur during the quenching operation. In order to minimize the chance of cracks occurring, all parts should be machined with the as-cast surface removed prior to hardening-if possible.

D. Surface Hardening

Surface hardening of cast irons will improve wear resistance on outside surfaces as needed. The two most common methods are induction hardening and flame hardening. Each method requires that the area to be hardened is heated, held at temperature and rapidly cooled.

E. Austempering

Austempering utilizes a high temperature salt quench tank that causes austenite to transform to acicular ferrite and high-carbon austenite. The process is commonly performed on ductile iron grades 65-45-12 and 80-55-06. Nickel additions may be required for austempering ductile iron parts greater than 2.0" thick. The resulting structure will give excellent wear characteristics, high impact strength and mechanical properties.

F. Hardness Measurements

The best method of evaluating heat treat results is by measuring the hardness of the finished part. Since the properties of the graphite and matrix varies significantly methods that use larger indenters, such as Brinell tests are preferred for cast iron, but Rockwell tests are acceptable if used and interpreted correctly. The average value of several Rockwell tests is preferred in order to avoid the negative effect of graphite on the results.

A typical hardness value for a gray iron part that is quenched and tempered is 45 HRC. The matrix structure is fully martensitic, which will have a hardness of 60-65 HRC, as determined by a micro-hardness test. The influence of graphite causes a lower apparent hardness on the finished part.
A more conclusive test for successful heat treat is to prepare a sample for microstructural evaluation and examine the etched structure.

G. Growth

Cast irons will increase in size when heat treated primarily because of the decomposition of carbides from the pearlitic structure. The amount of growth depends on the chemistry and microstructure of the material. It is also difficult to perform the exact same heat treatment on every part, and growth variations may be inherent in the process. To a certain extent, growth can be predicted to a range, which helps to determine initial machining tolerance.

Since growth occurs as a result of the decomposition of carbide, irons having a higher pearlite content will grow more when heat treated than ferritic grades. If the heat treat process is exactly the same every time, a fully pearlitic part or a fully ferritic part will show the most consistent growth. Expected growth will be between .05-.20% in ductile irons and .10-.50% in gray irons.

CORROSION OF CAST IRONS

Cast Iron has, for hundreds of years, been the preferred piping material throughout the world for drain, waste, and vent plumbing applications and water distribution. Gray iron can be cast in the form of pipe at low cost and has excellent strength properties. Unique corrosion resistance characteristics make cast iron soil pipe ideally suited for plumbing applications.

Cast iron and steel corrode; however, because of the free graphite content of cast iron (3% - 4% by weight or about 10% by volume), an insoluble graphitic layer of corrosion products is left behind in the process of corrosion. These corrosion products are very dense, adherent, have considerable strength, and form a barrier against further corrosion. Because of the absence of free graphite in steel, the corrosion products have little or no strength or adherence and flake off as they are formed, thus presenting fresh surfaces for further corrosion. In tests of severely corroded cast iron pipe, the graphitic corrosion products have withstood pressures of several hundred pounds per square inch although corrosion had actually penetrated the pipe wall.

The majority of soils throughout the world are non-corrosive to cast iron. More than 300 water and gas utilities in the United States have cast iron distribution mains with continuous service records of more than 100 years. Nine have mains more than 150 years old. Over 95 percent of all cast iron pipe that has ever been installed in underground service in the United States is still in use.

The corrosion of metals underground is an electrochemical phenomenon of two main types: galvanic and electrolytic.

Galvanic corrosion is self-generating and occurs on the surface of a metal exposed to an electrolyte (such as moist, salt-laden soil). The action is similar to that which occurs in a wet, or dry, cell battery. Differences in electrical potential between locations on the surface of the metal (pipe) in contact with such soil may occur for a variety of reasons, including the joining of different metals (iron and copper or brass for example). Potential differences also may be due to the characteristics of the soil in contact with the pipe surface, e.g., pH, soluble salt, oxygen and moisture content, soil resistivity, temperature and presence of certain bacteria. Any one or a combination of these factors may cause a small amount of electrical current to flow through the soil between areas on the pipe or metal surface. Where this current discharges into the soil from such an area, metal is removed from the pipe surface and corrosion occurs.

Graphitic corrosion is possible only in structures composed of cast irons containing graphite particles. Gray, nodular, and malleable cast irons, which contain graphite particles of different morphologies, are susceptible to graphitic corrosion. Although frequently considered immune to graphitic corrosion, nodular cast iron and malleable iron are often attacked. Gray cast iron, which contains flakes of graphite, is more widely used and has more dramatic and recognizable corrosion characteristics than other cast irons.

Although graphitic corrosion is often considered to be a form of dealloying or selective leaching, it actually has more in common with galvanic corrosion. Microscopic galvanic cells form between the metal matrix and graphite particles embedded in the casting when the same mildly aggressive water contacts both materials. The graphite is cathodic to the adjacent metal, causing the anodic metal portion of the casting to corrode.

Graphitic corrosion converts the casting to mechanically weak corrosion products containing graphite particles. Graphitic corrosion usually progresses slowly, taking many months or even years to produce significant attack. Corrosion is accelerated if waters are mildly acidic, soft, of high conductivity, and/or contain high concentrations of aggressive anions such as sulfate and chloride.

Feedwater pump impellers, water supply lines, valves, and other components made of graphitic cast irons may experience graphitic corrosion. Because cast irons are used mainly in pre-boiler regions, attack occurs primarily in water pretreatment and transport equipment. However, graphitic cast iron components in other parts of the boiler water and steam circuit, such as steam trap bodies, may also experience graphitic corrosion.

Graphitic corrosion requires a susceptible graphite-containing cast iron microstructure and a common electrolyte that contacts both the graphite and iron phases. Environmental factors that promote graphitic corrosion include soft waters, stagnant conditions, slightly acidic pH, high conductivity, and the presence of chlorides, sulfates, or low concentrations of hydrogen sulfide. Graphitic corrosion tends to occur in relatively mild environments. In more aggressive environments, corrosion may be more general, rather than graphitic in nature. Attack often occurs predominantly during idle periods under stagnant conditions. If turbulence is pronounced (e.g., in pumps), the mechanically weak corrosion products may be dislodged, accelerating wastage.

The flake morphology of the graphite in gray cast iron provides a larger cathode-to-anode surface area ratio compared to nodular graphite. Consequently, gray cast iron is more susceptible to attack than nodular and malleable cast irons. Cast iron is converted to a soft mixture of iron oxide corrosion products and graphite. Attack is often uniform, with all exposed surfaces corroded to roughly the same depth. Fractures that result from graphitic corrosion are thick-walled due to the brittleness of the corrosion products and the alloy. If localized deposits are present, especially those containing sulfate, chloride, or other acid-producing species, corrosion may be confined to distinct regions beneath such deposits. When attack is severe or prolonged, the entire component is converted to corrosion product. Surface contour and appearance are often preserved, although the graphitically corroded material may appear black, rather than the original metallic gray. Attack is usually not apparent until surfaces are probed or stressed. Craters can be dug in the soft, black corrosion products to reveal the depth of penetration. Corroded areas can be broken with bare hands or by gentle taps with a hard implement.

Metallographic examination will reveal graphite particles from the microstructure (flakes or nodules, depending on the type of cast iron) surrounded by corrosion products and embedded in corrosion product layers as shown below.

Graphitic Corrosion Attack in Gray Iron

Attack is reduced by alloy substitution, chemical treatment, and/or operational changes. Alloy substitution can entirely eliminate graphitic corrosion if the replacement alloy does not contain graphite. The substitute alloy choice is dictated by requirements unique to each environment. Alloys that may be suitable substitutes include austenitic cast iron; corrosion-resistant cast irons containing chromium, nickel, or silicon; and cast steels because they are essentially immune to graphitic corrosion. When changing alloys, care should be taken to avoid the formation of galvanic couples between components in electrical contact with each other.

Raising water pH to neutral or slightly alkaline levels decreases attack, especially if relatively high concentrations of aggressive anions such as chloride and sulfate are present. When water flow is slight, such as during prolonged shutdowns and lengthy idle periods, attack increases. Stagnant conditions promote graphitic corrosion and should be avoided. Only cast irons containing graphite can corrode graphitically. Due to microstructural differences in graphite particle size, morphology, and distribution, as well as other differences in alloy composition, attack is usually worst in gray cast irons.
Although pipes and other components may be severely corroded, they may not fail. The corrosion product has some mechanical strength, but is brittle. If corroded components are stressed, failure may occur catastrophically.

Graphitic corrosion should not be confused with graphitization, which is a microstructural change that can occur in carbon-containing irons and steels at temperatures from approximately 800 to 1025°F (427 to 552°C). In graphitization, iron carbide is converted to elemental iron and graphite.

Electrolytic corrosion occurs when direct current from outside sources enters and then leaves an underground metal surface to return to its source through the soil; metal is removed and in this process and corrosion occurs.

Over 95 percent of the soils in the United States are non-corrosive to cast iron. Those few soils that are somewhat corrosive to cast iron include natural soils containing high concentrations of decomposing organic matter (swamps, peat bogs, etc.) alkalis, or salt (tidal marshes). Man-made corrosive soils result from the discharge of various mining and other industrial and municipal wastes into refuse dumps or landfills.

Internal corrosion of cast iron soil pipe and fittings can be caused by strong acids or other aggressive reagents with a pH of 4.3 or lower if allowed to remain in contact cast iron pipe for an extended period of time without sufficient dilution to raise the pH above 4.3. If the run of piping into which the acidic waste is discharged has sufficient upstream flow of non-acidic waste, the resulting rinsing action tends to raise the pH of the combined waste to a level, which will not corrode cast iron. However, by avoiding low pH discharges altogether, one can limit or eliminate internal corrosion problems, assuring the building owner and occupants many years of trouble free service.