



## Cast Irons -- Properties and Applications

Semih Genculu, P.E.

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 tend to fracture with little prior deformation. Cast iron, however, has excellent compressive strength and is commonly used for structures that require this property. The composition of cast iron, the method of manufacture and heat treatments employed are critical in determining its final characteristics.

To achieve the best casting for a particular application consistent with the component's requirements, it is necessary to have an understanding of the various types of cast iron. The general designation of cast iron is meaningless, except when distinguishing the part from a steel casting. Therefore, a more specific designation should be made. Cast irons can be divided into five groups, based on composition and metallurgical structure:

- Gray cast iron,
- Ductile cast iron,
- White cast iron,
- Malleable cast iron,
- Compacted graphite iron and,
- Alloy cast iron.

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.

Because of their relatively high silicon content, cast irons inherently resist oxidation and corrosion by developing a tightly adhering oxide and subscale to minimize further attack. Iron castings are used in applications where this resistance provides relatively long service lives. 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, easily cast into complex shapes and readily machined, they are an important group of materials. Unfortunately most grades are not weldable and special precautions are normally required even with the so-called weldable grades.

One reason for the wide use of iron castings is the high ratio of performance to cost that they offer. 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. However, 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. 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.

Cast irons have 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 deteriorate during 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 rates. 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 tightly adhere to the unaffected metal substrate, providing a barrier and limiting the rate at which further corrosion attacks can occur.

### GRAY CAST IRON

Gray cast iron is one of the most widely used castings 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. 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 brittleness of gray iron is also assigned to all CIs.

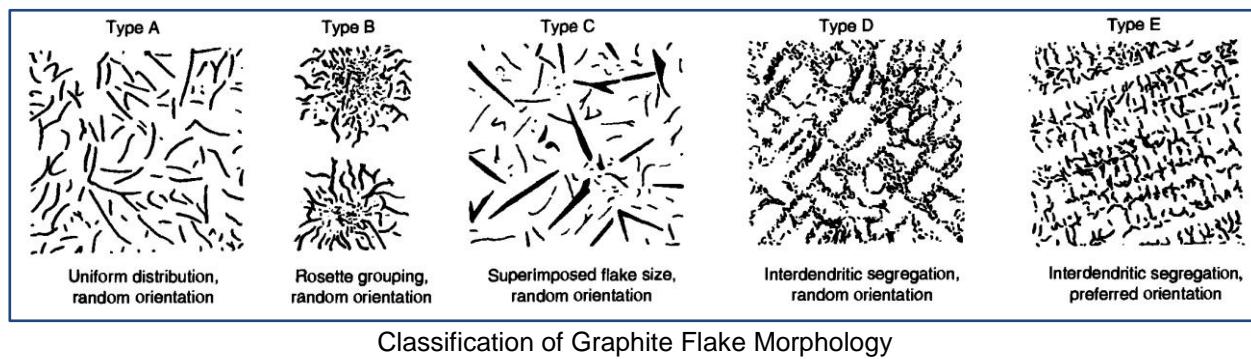
When a gray iron casting fractures, the crack path follows these graphite flakes and the fracture surface appears gray

because of the presence of exposed graphite. 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.

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, 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. Both major and minor elements have a direct influence on the morphology of flake graphite. The typical graphite shapes for flake graphite are shown in the figure below. Type A graphite is found in inoculated irons cooled with moderate rates. In general, it is associated with the best mechanical properties. Not only the shape but also the size of graphite is important, since it is directly related to strength with finer flake sizes resulting in higher strength in gray irons.

The strength of gray cast iron depends mainly 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. Ferritic gray cast iron is normally soft and weak. 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 gray cast iron).

Pipes with diameters from 1.5 to 5 in (38 to 127 mm) with wall thicknesses ranging from 0.138 to 0.25 in (3.5 to 6.4 mm) are readily produced by continuous casting, using tubular blanks as molds. Centrifugal casting is also used to produce pipes as this process permits good dimensional control. Other gray CI products are valve bodies, valve parts, machine tool housings, and brake drums.



Classification of Graphite Flake Morphology



Ferritic Gray Cast Iron Microstructure



Pearlitic Gray Iron Microstructure

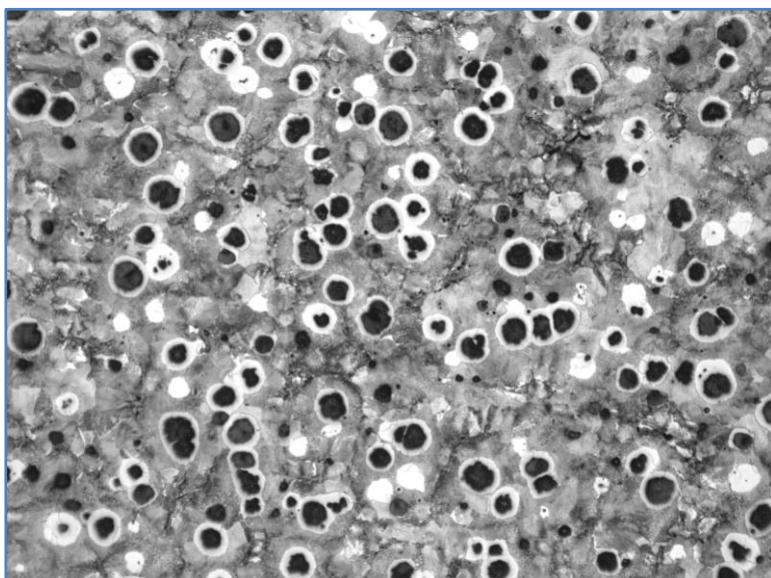
### SPHEROIDAL GRAPHITE (DUCTILE) CAST IRON

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 castings 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 or the molds just before pouring. The spherical graphite particles do not form a continuous crack-like network in the matrix like graphite flakes, resulting in higher strength and toughness compared with gray cast iron of similar composition.

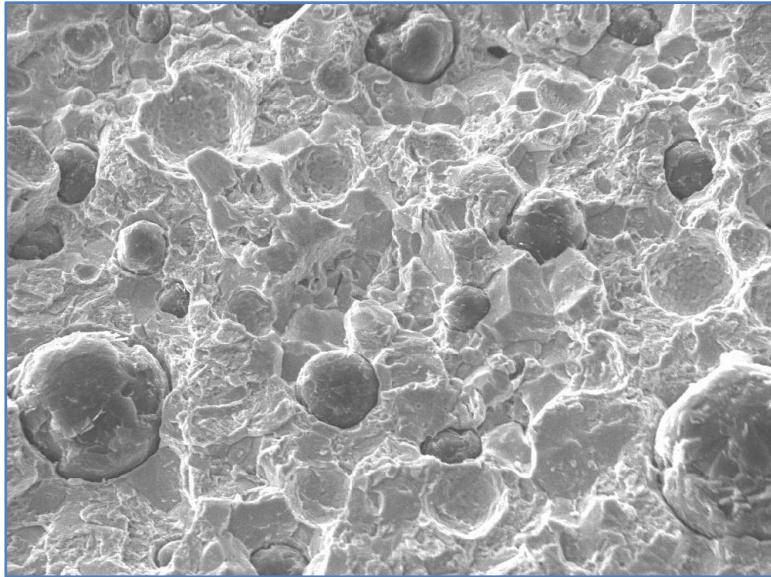
Magnesium is frequently added as an alloy with iron and silicon (Fe-Si-Mg) rather than as pure magnesium. Magnesium tends to encourage the precipitation of cementite, however, so silicon is also added as ferro-silicon inoculant to ensure the precipitation of carbon as graphite. Spheroidal graphite CI has excellent toughness and is widely used in crankshafts.

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 (i.e. grade 60-40-18).

Typical applications are water and sewer pipes, 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); and steel mill (work rolls, furnace doors, table rolls and bearings).



Ductile Iron, As-cast Bulls-eye Microstructure in a Pearlitic Matrix

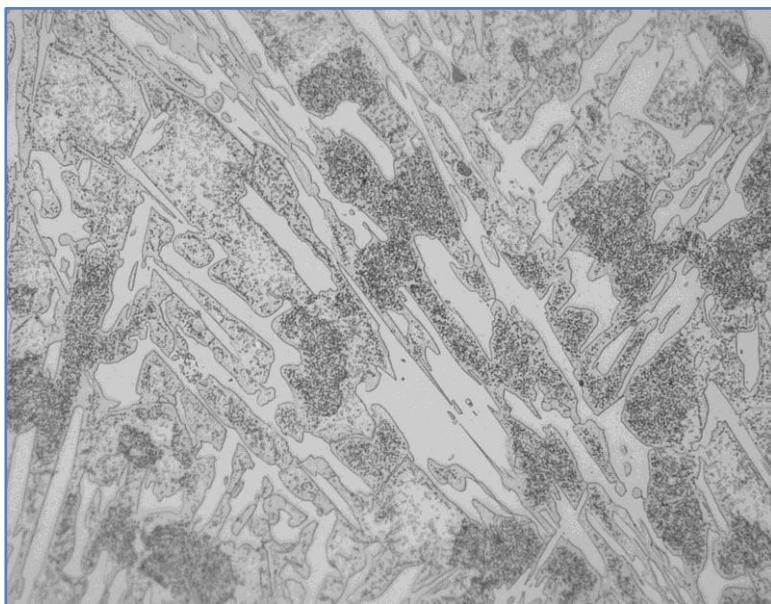


Scanning Electron Microscope Image Showing the Fracture Surface of a Ductile Iron-Note the Graphite Nodules

## 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 carbides. 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 also very brittle. The microstructure of white CI contains massive cementite (white) and pearlite. White cast iron derives its name from the white, crystalline crack surface observed when a casting fractures. Most white cast irons contain less than 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 Microstructure

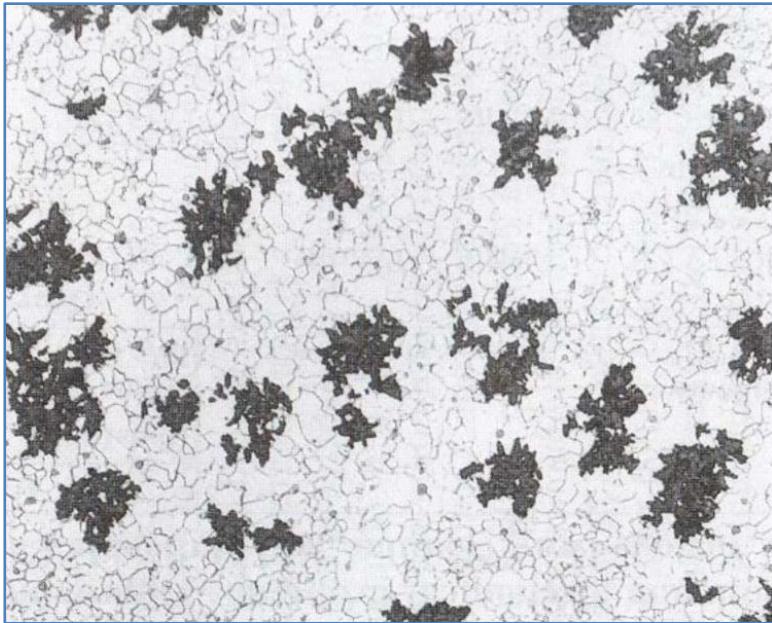
## MALLEABLE CAST IRON

Malleable irons are a class of cast irons with mechanical strength properties that are intermediate to those of gray and 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 at the surface due to the rapid cooling rates in thin sections). Another significant aspect is that the malleable properties can exist up to the surface of the casting (as opposed to in ductile irons where the cast surface can contain flake or distorted graphite), creating a stronger casting.

Malleable cast iron is produced by heat treating white cast iron. Iron carbide decomposes into iron and carbon under certain conditions. This decomposition 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<sup>[12]</sup> as ferritic malleable cast iron resulting in 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.

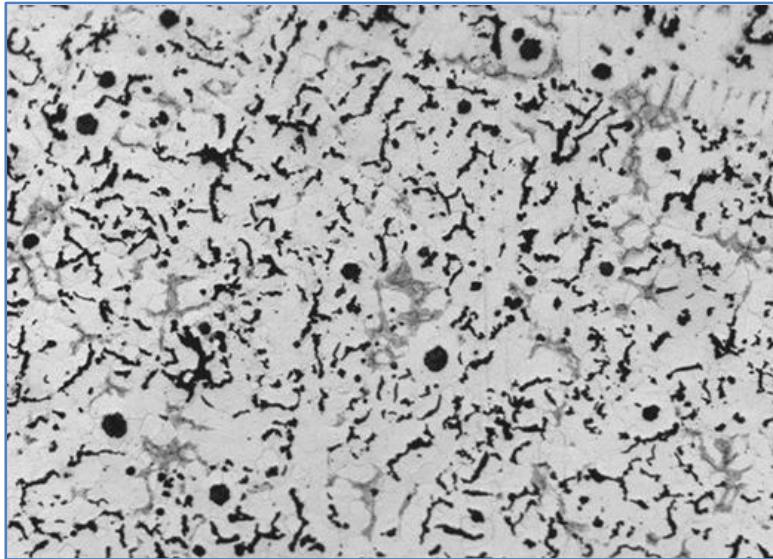


Ferritic Malleable Cast Iron Microstructure

## COMPACTED (VERMICULAR) GRAPHITE CAST IRON

Compacted graphite irons (CG irons) are a type of cast irons having properties between those of flake and nodular graphite cast irons. They are of interest because of their useful combination of strength, thermal conductivity and other properties. 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. Higher level of inoculant additions results in a fine distribution of compacted graphite throughout castings, and less sensitivity to carbide formation.

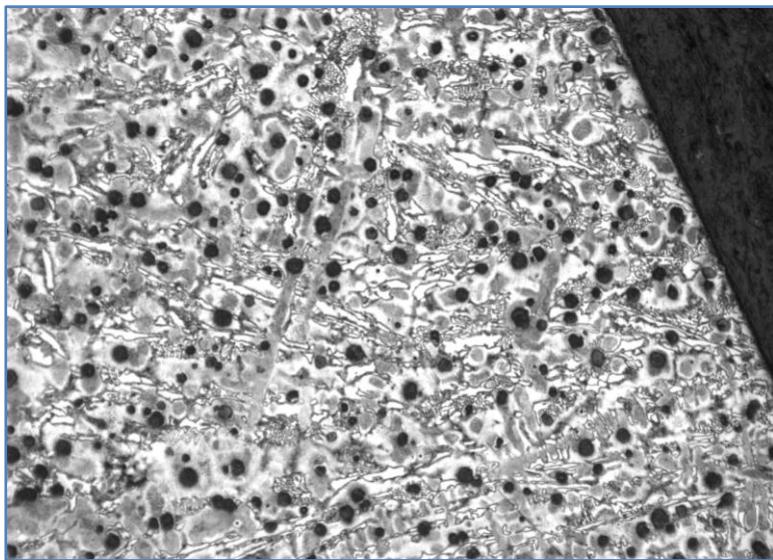
Although the graphite particles are elongated and randomly oriented as in gray iron, they are shorter and thicker, and have rounded edges. Furthermore, while the compacted graphite particle shape may appear worm-like when viewed on a cross section, the 'worms' are actually interconnected. This complex graphite morphology, together with the irregular bumpy surfaces, results in strong adhesion between the graphite and the iron matrix, and inhibits both crack initiation and propagation and is the source of the improved mechanical properties relative to gray cast iron.



CG Iron Microstructure

### CHILLED CAST IRON

When a localized area of a cast iron is cooled very rapidly from the melt, carbides are formed. This type of cast iron is called chilled iron. Adjusting the carbon composition of the white CI can produce a chilled iron casting, so that the normal cooling rate at the surface is just fast enough to produce carbides while the slower cooling rate below the surface will produce gray or ductile 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.



Micrograph Showing the Chilled Surface of a Ductile Iron Casting

### 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. It is reported to have excellent fatigue properties and its damping characteristics reduce engine noise.

ADI is a versatile material. By selecting precise heat treatment parameters a specific set of properties can be achieved. The lower hardness ADI 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.

## 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 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 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

Most common characteristics and typical applications for the various types of CIs are given below with their corresponding industry specifications.

	<b>Standard Specifications</b>	<b>Characteristics</b>	<b>Applications</b>
Gray Irons	ASTM A48: Gray Iron Castings ASTM A74: Cast Iron Soil & Pipe Fittings ASTM A126: Gray Iron Castings for Valves, Flanges & Pipe Fittings ASTM A159 & SAE J431: Automotive Gray Iron Castings ASTM A278: Gray Iron Castings for Pressure-Containing Parts for Temperatures Up to 650F ASTM A319: Gray Iron Castings for Elevated Temperatures for Non-Pressure Containing Parts ASTM A823: Statically Cast Permanent Mold Gray Iron 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, good machinability	Automobile engine blocks & heads, manifolds for internal combustion engines, gas burners, machine tool bases, cylinder liners, intake manifolds, soil pipes, counter weights, enclosures & housings
Ductile Irons	ASTM A395: Ferritic Ductile Iron Pressure-Retaining Castings for Use at Elevated Temperatures ASTM A439: Austenitic Ductile Iron Castings ASTM A476: Ductile Iron Castings for Paper Mill Dryer Rolls ASTM A536: Ductile Iron Castings ASTM A571: Austenitic Ductile Iron Castings for Pressure-Containing Parts Suitable for Low-Temperature Service ASTM A716: Ductile Iron Culvert Pipe ASTM A746: Ductile Iron Gravity Sewer Pipe 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	Steering knuckles, gears, automotive & truck suspension components, brake components, valves, pumps, linkages, hydraulic components, wind turbine housings
CGI	ASTM A842: Compacted Graphite Iron Castings	A compromise of properties between gray & ductile iron	Diesel engine blocks & frames, cylinder liners, brake discs for trains, exhaust manifolds, pump housings & brackets
White Irons	ASTM A532: Abrasion-Resistant Casting Irons	Extremely hard & wear resistant	Crushing & grinding applications, grinding balls

Malleable Irons	ASTM A47: 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 at Temperatures Up to 650F ASTM A602 & SAE J158; Automotive Malleable Iron Castings	Soft & extremely ductile	Chains, sprockets, hardware, connecting rods, drive train & axle components
Alloyed Irons	ASTM A436: Austenitic Gray Iron Castings ASTM A518: Corrosion-Resistant High-Silicon Iron Castings	Corrosion resistant, retains strength & dimensions during elevated temperature exposure, ability to withstand thermal cycling	Parts for chemical processing plants, petroleum refining, food handling, marine service, control of corrosive fluids, pressure valves

### Specifications, Characteristics and Typical Applications

## WELDING OF CAST IRONS

Cast irons include a large family of alloys covering a wide range of chemical compositions and metallurgical microstructures. Some of these materials are weldable, while others require great care to produce sound welds. Certain cast irons are considered not weldable. Major factors contributing to the difficulty of welding cast iron are its high carbon content and lack of ductility.

Shielded Metal Arc Welding (SMAW), Flux cored arc (FCAW), Metal Inert Gas (MIG), and Tungsten Inert Gas (TIG) 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. Because of its extreme hardness and brittleness, white cast iron is considered not weldable.

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. 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.