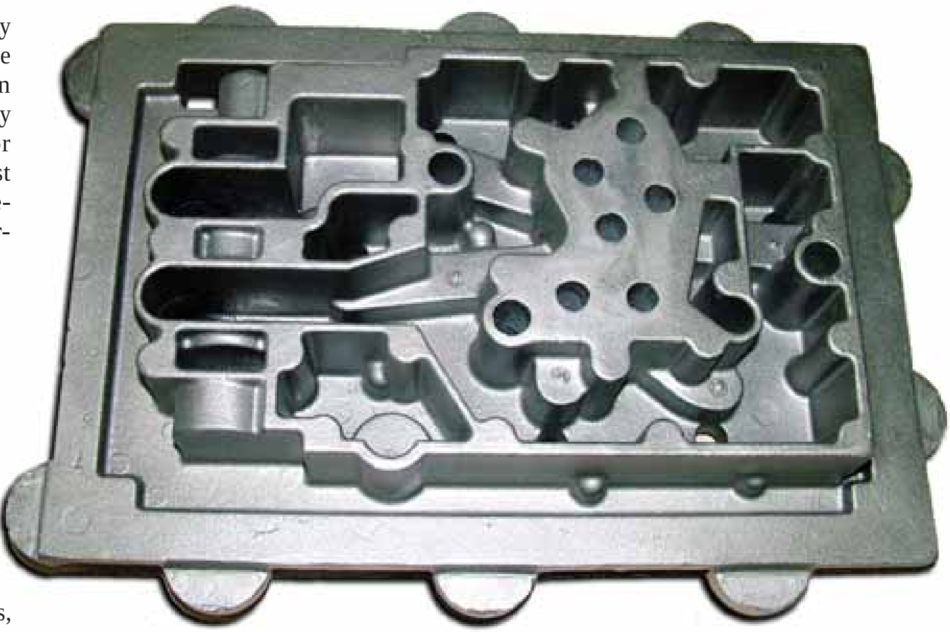
Iron Alloys

Joseph S. Santner, *American Foundry Society, Schaumburg, Illinois*
George M. Goodrich, *Professional Metallurgical Services, Buchanan, Michigan*

Iron castings are produced by a variety of molding methods and are available with a wide range of properties. Cast iron is a generic term that designates a family of metals. 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 six types of cast iron:

- gray iron;
- ductile iron;
- compacted graphite iron (CGI);
- malleable iron;
- white iron;
- alloyed iron.

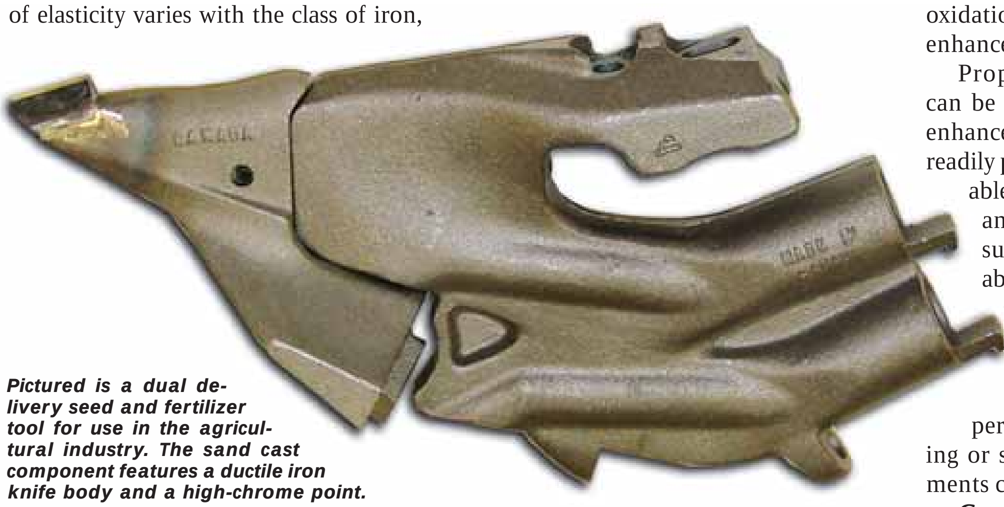
Table 1 lists the typical composition ranges for common elements in five of the six generic types of cast iron. The classification for alloyed irons has a wide range of base compositions with major additions of other elements, such as nickel, chromium, molybdenum or copper.



This gray iron manifold for wheel loaders was developed by the casting supplier and customer from concept-to-casting in less than one month. The new design cut the processing time of the component in half.

The basic strength and hardness of all iron alloys is provided by the metallic structures containing graphite. The properties of the iron matrix can range from those of soft, low-carbon steel (18 ksi/124 MPa) to those of hardened, high-carbon steel (230 ksi/1,586 MPa). The modulus of elasticity varies with the class of iron, shape (sphericity) and volume fraction of the graphite phase (percent free carbon).

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.



Pictured is a dual delivery seed and fertilizer tool for use in the agricultural industry. The sand cast component features a ductile iron knife body and a high-chrome point.

Table 1. Composition Range for Un-Alloyed Cast Irons

Iron Family	Carbon	Silicon	Manganese	Sulfur	Phosphorus
Gray	2.5-4.2	1.0-3.0	0.15-1.0	0.02-0.25	0.02-1.0
Ductile	3.0-4.0	1.8-3.0	0.1-1.0	0.01-0.03	0.01-0.1
CGI	2.5-4.0	1.5-3.0	0.10-1.0	0.01-0.03	0.01-0.1
Malleable	2.2-2.8	1.2-1.9	0.15-1.2	0.02-0.2	0.02-0.2
White	1.8-3.6	0.5-2.0	0.15-0.8	0.02-0.2	0.02-0.2

Properties of the cast iron family can be adjusted over a wide range and enhanced by heat treatment. Annealing readily produces a matrix of soft machinable ferrite. In limited situations, this annealing can be accomplished at sub-critical temperatures. Heating above this critical temperature takes the carbon from the graphite and places it in the matrix. This engineered material can be through-hardened and tempered using conventional heat treating or surface hardening. These adjustments create the cast iron family.

***Gray iron*—**Flake graphite provides gray iron with unique properties (such as excellent machinability) at hardness levels that produce superior wear-resistant characteristics, the ability to resist galling and excellent vibration damping.

***Ductile iron*—**An unusual combination of properties is obtained in ductile iron because the graphite occurs as spheroids rather than as flakes. The different

grades are produced by controlling the matrix structure around the graphite either as-cast or by heat treatment. Only minor compositional differences (to promote the desired matrix microstructure) exist among the regular grades. Alloy additions may be made to assist in controlling the matrix structure as-cast or to provide response to heat treatment.

The high-strength grades 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.

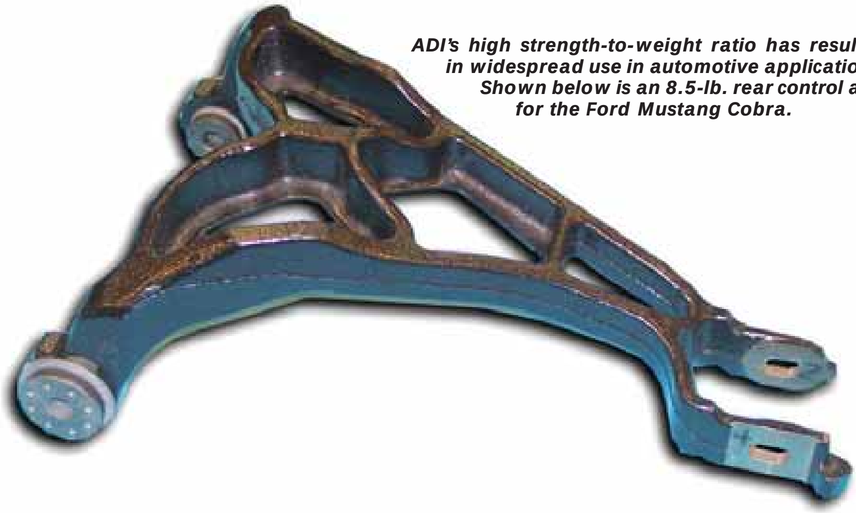
Compacted Graphite Iron (CGI)—In CGI, graphite locally occurs as interconnected blunt flakes. This graphite structure

Table 2. Iron Specifications, Characteristics & Applications

	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.

Table 3. Property Comparisons for Gray Iron Classes

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	0.28	0.26	0.28	0.23
Compression-to-Tensile Strength Ratio	3.68	3.84	4.05	3.63	3.71



ADI's high strength-to-weight ratio has resulted in widespread use in automotive applications. Shown below is an 8.5-lb. rear control arm for the Ford Mustang Cobra.

and the resulting properties are intermediate between gray and ductile irons. The compacted graphite shape also is called quasi-flake, aggregated flake, semi-nodular and vermicular graphite.

***White iron*—**White iron is hard and essentially free of graphite. The metal solidifies with a compound called cementite, which is a phase that dominates the microstructure and properties of white iron. The carbides are in a matrix that may be pearlitic, ferritic, austenitic, martensitic or any combination thereof.

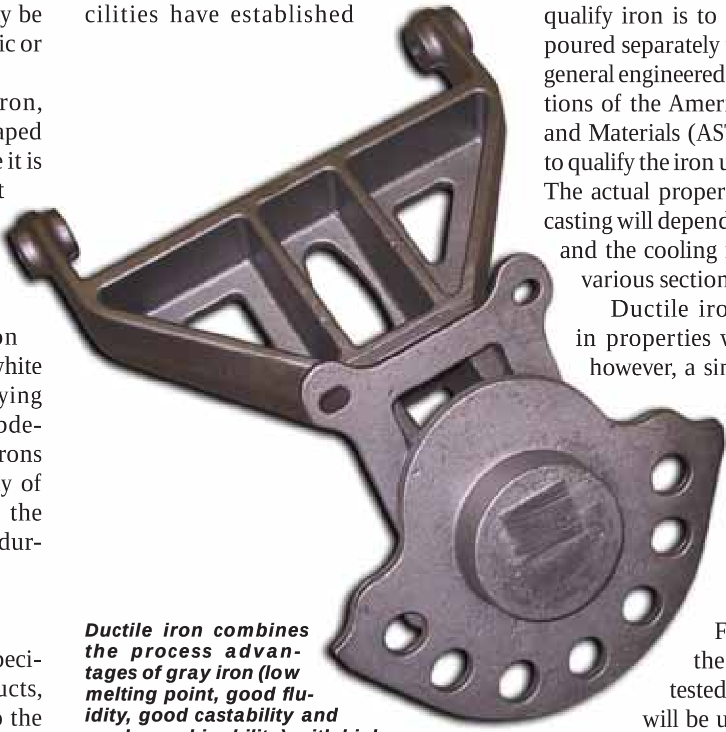
***Malleable iron*—**In malleable iron, the graphite occurs as irregularly shaped nodules called temper carbon because it is formed in the solid state during heat treatment. The iron is cast as a white iron of a suitable chemical composition to respond to the malleabilizing heat treatment.

***Alloyed iron*—**This classification includes gray irons, ductile irons and white irons that have more than 3% alloying elements (nickel, chromium, molybdenum, silicon or copper). Malleable irons are not heavily alloyed because many of the alloying elements interfere with the graphite-forming process that occurs during heat treatment.

Specification Sources

There are a number of standard specifications for several cast iron products, such as pipes and fittings. But due to the important influence of the individual design on the characteristics of a casting, requirements (actual strength, dimensional tolerances and surface finish) cannot be stated in a general specification.

Table 2 gives iron specifications, characteristics and applications. There are no generally accepted standards for the surface finish, machining allowances or dimensional tolerances. Although some production metalcasting facilities have established guidelines for their own capability in dimensional control, these controls are typically established through concurrent engineering based on the requirements of the application.



Ductile iron combines the process advantages of gray iron (low melting point, good fluidity, good castability and ready machinability) with high ductility. Shown above is a 40-lb. rear chute pivot for concrete mixer trucks.

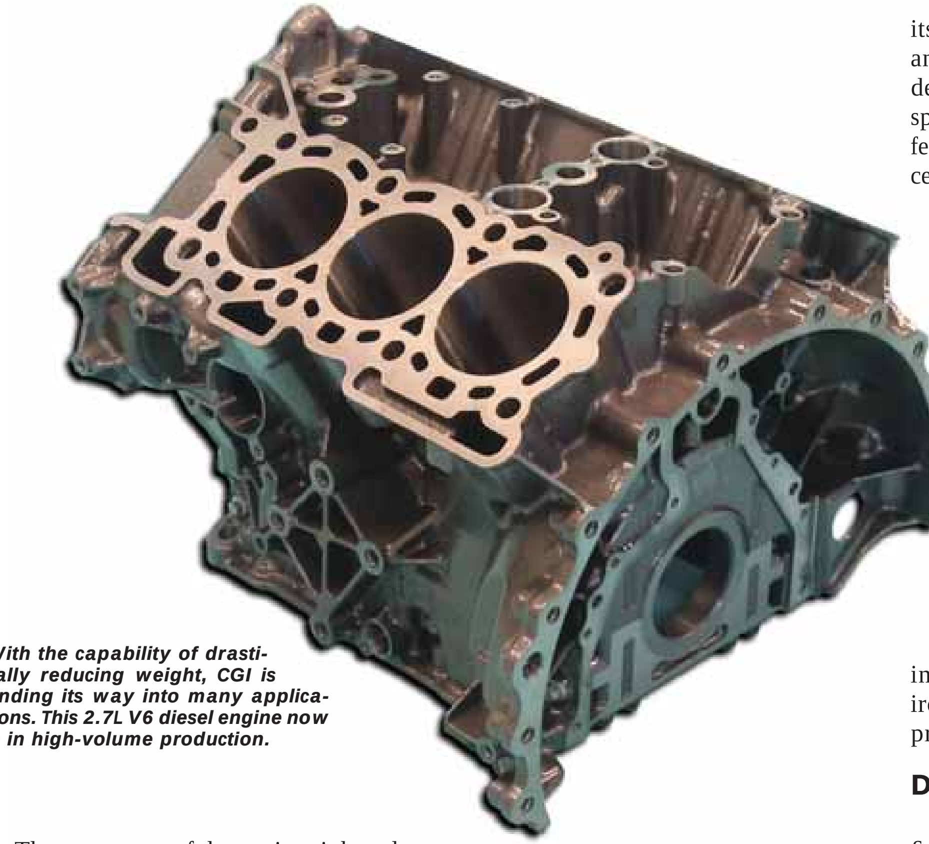
Material Properties vs. Casting Processes

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. Therefore, a series of standard test bars of increasing size has been established specifically for gray iron. One of these bars should be selected to determine the cooling rate in the critical sections of the casting.

Types of Specifications

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.

Ductile iron has some variation in properties when not heat treated; however, a single size test bar generally is satisfactory (except for large castings). Malleable iron is not poured into heavy sections, and because all malleable iron castings are heat treated, a single size test bar will work. For some applications, the finished component is tested in a manner in which it will be used. For example, pressure-containing parts can be 100% hydraulically proof tested.



With the capability of drastically reducing weight, CGI is finding its way into many applications. This 2.7L V6 diesel engine now is in high-volume production.

The acceptance of the castings is based on characteristics that a metalcasting facility can evaluate and control during production. Some specifications limit the amount of certain elements because they can affect properties or characteristics of the iron that are not readily apparent or measured. For example, the alloy content of iron can influence its corrosion resistance or its properties at elevated temperatures. With the exceptions of castings that have special performance applications, such as use at elevated temperatures, the most economical approach is to let the metalcasting facility recommend an iron composition that provides the desired properties.

Gray Iron Properties

Gray iron's high damping capacity, combined with its excellent machinability and high hardness, is unique to this material and makes it ideally suited for machine bases and supports, engine cylinder blocks and brake components. Excessive vibration causes inaccuracies in precision machinery and excessive wear on gear teeth and bearings. The damping capacity of gray iron is considerably greater than that of steel and other iron types. For example, if gray iron, CGI and ductile iron have a similar composition, the relative damping capacity of gray iron is 1.0, CGI is 0.35 and ductile iron is 0.14. The damping capacity of gray iron is about 20-25 times higher than steel. For comparison, aluminum's damping capacity is one-tenth that of steel.

The graphite flakes in gray iron have less influence on its compression properties than on tension properties. A comparison of compression and tension properties is shown in Table 3.

Gray iron's compressive strength is typically three to four times more than its tensile strength. The lack of graphite-associated volume changes allows for a similar Poisson's ratio to other engineering metals but different tension properties. Poisson's ratio remains constant at 0.25 over a large compressive stress range and increases at higher stress levels.

To classify gray iron in accordance to its tensile strength, ASTM Standard A48 and SAE Standard J431 provide the best details to accomplish this task. The two specifications approach the task from different standpoints but essentially the concept remains the same. For example, the number in a Class 30 gray iron refers to the minimum tensile strength in ksi. In ASTM A48, a standard size test bar is added to the class. Class 30A indicates that the iron must have a minimum 30 ksi (207 MPa) tensile strength in an "A" bar (0.875-in. as-cast diameter).

In SAE Standard J431, tensile strength is not required, but hardness and a minimum tensile strength to hardness ratio are required. The class then is identified as a grade. A Class 30B iron for ASTM A48 would be comparable to a grade G3000 in SAE Standard J431. The other gray iron specifications build off of these two primary specifications.

Ductile Iron Properties

Five grades of ductile iron are classified by their tensile properties in ASTM Standard A536 (Table 4). SAE Standard J434c (for automotive castings and similar applications) identifies these five grades of ductile iron only by Brinell hardness. However, the appropriate microstructure for the indicated hardness also is a requirement. Specifications for specialty applications not only define tensile properties, but also have composition limits. In the ASTM specification, the focus is more on tensile properties than chemical composition.

The development and commercialization of ADI provides design engineers with a new group of cast ferrous materials. Austempering at higher temperatures produces ADI with lower strength and hardness as well as higher ductility and toughness.

In regards to heat treatment, it has been found that quenching certain troublesome parts in hot media (more than 450F/230C) resulted in tougher parts with less distortion than those conventionally quenched and tempered. These materials offer mechanical properties that are stronger and

Table 4. Property Comparisons for Ductile Iron Grades (ASTM A536)

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)

Table 5. Property Comparisons for ADI Grades (ASTM A897)

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

tougher than conventionally heat treated, as-cast or as-formed ferrous materials. The property combinations available for ADI list five standard grades in ASTM A897. These specifications give the minimum tensile and impact levels along with typical Brinell hardness values (Table 5).

Compared to the best forged steel, ASTM 897 Grade 5 ADI Charpy V-notch impact toughness is low, but the fracture toughness is approximately equal. Ausferrite microstructures respond to shot peening, fillet rolling and grinding and leads to an increase in bending fatigue strength with favorable compressive residual stresses impacted on the surfaces.

CGI

CGI is an alternative to both gray iron and light metals in heavily loaded applications. It combines much of the strength and stiffness of ductile iron with the thermal conductivity and castability of gray cast iron. The microstructure definition of CGI is formally specified by ASTM Standard A842 as a cast iron containing a minimum of 80% of the graphite particles in compacted form. This means that at least 80% of the graphite particles must be individual vermicular or "worm shaped" on a metallographic plane of polish with fewer than 20% of the particles in spheroidal form. Contrarily, flake graphite—even in small amounts—reduces the elastic modulus of CGI by as much as 20%.

The grades of CGI are 250, 300, 350, 400 and 450, based on their tensile strength, shown in Table 6. The lowest strength is ferritic, and the highest strength is pearlitic. Although considerable range exists, relative damping capacities among gray iron, CGI and ductile iron are 1.0, 0.35 and 0.14. The damping capacity is independent of carbon content and pearlite content for all practical CGI compositions. The damping capacity can be increased 5–10% by increasing the coarseness of graphite; however, this will decrease the modulus.

White Iron & Alloyed Iron Properties

High-chromium white irons are used for elevated-temperature service while both high-chromium white irons and nickel-chromium white irons (Ni-hard) are used for abrasion-resistant service. Other alloyed irons are used for corrosion resistance or elevated-temperature service.

Nickel alloyed austenitic irons are a well-established group of the high-alloy austenitic irons (commonly known as Ni-Resist) that are produced for corrosion-resistant applications. These versatile irons have excellent corrosion resistance due to the presence of nickel (12–37%), chromium (0.5–6%) and copper (5.5–7.5%). Most of the Ni-Resist compositions can be produced as either gray or ductile iron.

This silicon-molybdenum ductile iron automotive exhaust manifold was converted from a stainless steel welded fabrication.

The chromium-bearing ductile irons D-2 and D-5B, and the high-silicon Type D-5S, provide good oxidation resistance and useful mechanical properties at temperatures up to 1,400F (760C). At higher temperatures, D-2B, D-3, D-4 and D-5S have useful properties, and D-5S has good oxidation resistance up to 1,700F (925C). The high-nickel austenitic irons are metallurgically stable over their useful temperature range, experience no phase changes and are resistant to warping, distortion, cracking and growth during thermal cycling.

Malleable Iron Properties

Malleable iron can be specified either by its tensile properties or by hardness of the casting. Unless the relationship between the test bar properties and the specific casting hardness is established, both strength and hardness should not be specified together. ASTM Specification A220 defines eight grades of pearlitic malleable iron with increasing strength and decreasing ductility. Specification A47 is for ferritic malleable iron, which has the lowest strength and highest ductility. The tensile properties of malleable iron are determined with a 0.625-in. (16-mm) diameter cast-to-size test bar. Machining these test bars before testing has only a slight effect on the properties.

Machining Cast Iron

To efficiently machine cast irons, the appropriate tool material of the correct grade and shape must be selected. Coated carbides, particularly those with aluminum oxide exteriors, are effective in production machining applications. New tool materials for economical machining of iron castings are in a continual state of improvement and development.

Coating & Surface Engineering

The proper selection of a coating often is difficult because it depends on knowing what coatings are available, what coatings are suitable, what limitations are imposed by the casting design and how well the coating will adhere to the casting. Coating technologies that have been used on cast iron components include electroplating, hot-dipping, thermal spraying, diffusion coating, conversion coating, porcelain enameling, liquid organic coating and dry powder organic coating.

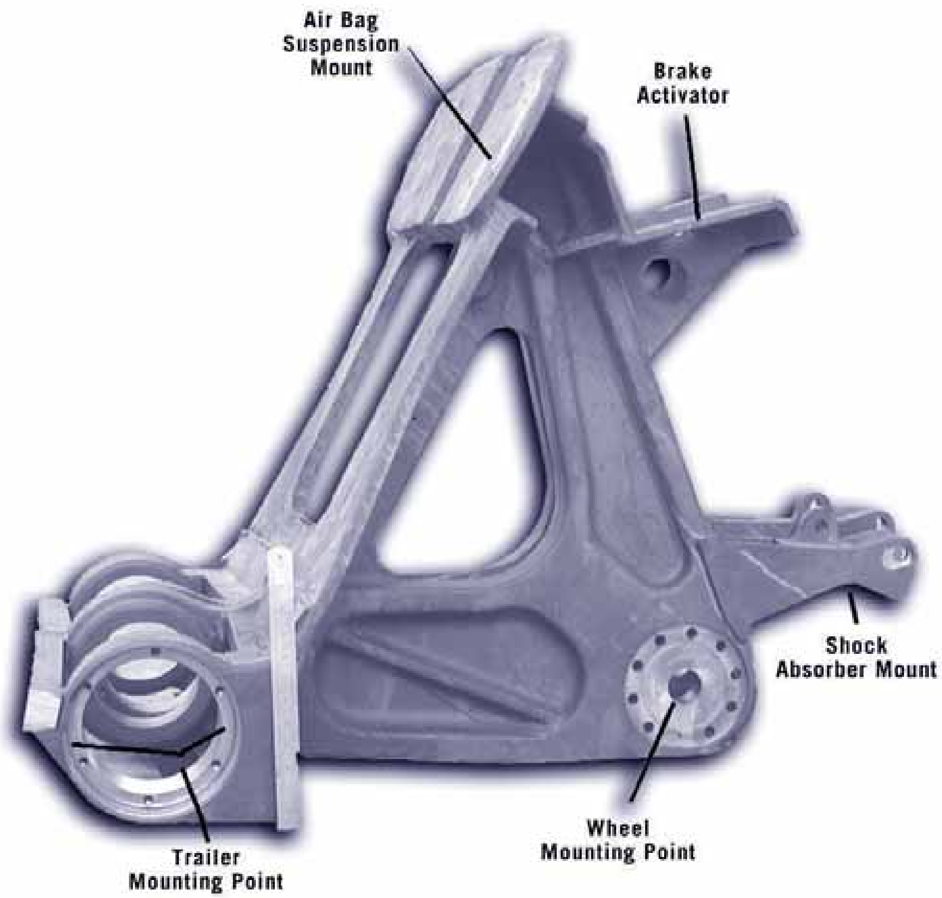
Design Range of Properties

Gray iron—Strength and hardness

Table 6. Property Comparisons for CGI Grades (ASTM A842)

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

are sensitive to section thickness. In thin sections, the material can be hard and difficult to machine. In heavy sections, its strength is reduced significantly. Because the modulus of elasticity for gray iron is higher in compression than it is in tension, the use of standard structural formulas results in a conservative design.



Shown here is a cast ADI independent truck trailer suspension bracket (top). Also shown is the bracket installed on a truck trailer (below).

Ductile iron—Ductile iron has the ability to be used as-cast and without heat treatments or other further refining. It has a tensile strength comparable to many steel alloys and a modulus of elasticity between that of gray iron and steel. As its name implies, it has a high degree of ductility. It can be cast in a wide range of casting sizes and section thickness; however, thinner sections may require annealing to obtain a high ductility. Alloy additions may be needed to obtain the higher-strength grades in heavy sections.

CGI—CGI has benefits in tensile strength, stiffness, fatigue behavior and strength-to-weight ratios for moderately thin and medium section castings compared to other irons.

White iron—This iron is unique in that it is the only member of the cast iron family in which carbon is present only as a carbide. The presence of different carbides, depending on the alloy content, makes white iron hard and abrasion-resistant but also very brittle.

Malleable iron—Malleable iron is ideal for thin-sectioned components that require ductility. Ferritic malleable iron is produced to a lower strength range than pearlitic malleable iron but with higher ductility. It is the most machinable of cast irons, and it can be die-strengthened or coined to bring key dimensions to close tolerance limits. However, ductile iron is replacing malleable iron in many different applications because the engineering properties of ductile iron are almost identical to that of malleable iron, and ductile iron does not require extensive heat treatment to precipitate graphite.

Alloyed irons—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 1,100F (600C). 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. *ECS*