

Types of Metal Alloys

11.2 FERROUS ALLOYS

Ferrous alloys—those in which iron is the prime constituent—are produced in larger quantities than any other metal type. They are especially important as engineering construction materials. Their widespread use is accounted for by three factors:

- (1) Iron containing compounds exist in abundant quantities within the Earth's crust;
- (2) Metallic iron and steel alloys may be produced using relatively economical extraction, refining, alloying, and fabrication techniques;
- (3) Ferrous alloys are extremely versatile, in that they may be tailored to have a wide range of mechanical and physical properties.

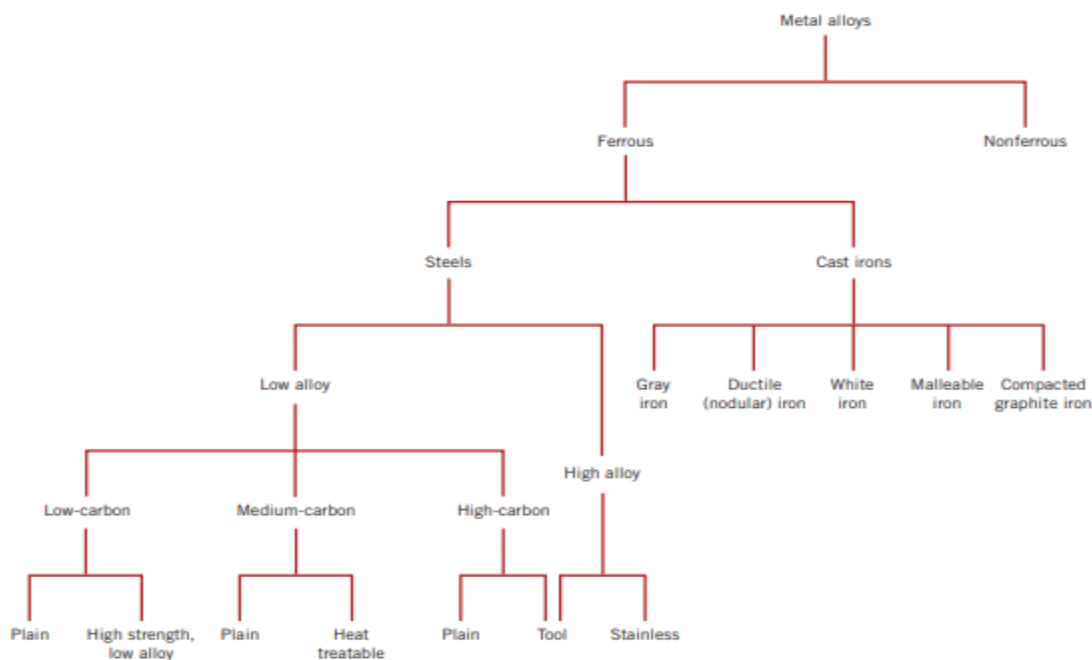


Figure 11.1 Classification scheme for the various ferrous alloys.

Steels are iron–carbon alloys that may contain appreciable concentrations of other alloying elements; there are thousands of alloys that have different compositions and/or heat treatments. The mechanical properties are sensitive to the content of carbon, which is normally less than 1.0 wt.%. Some of the more common steels are classified according to carbon concentration into low-, medium-, and high-carbon types. Subclasses also exist within each group according to the concentration of other alloying elements.

Plain carbon steels contain only residual concentrations of impurities other than carbon and a little manganese. For alloy steels, more alloying elements are intentionally added in specific concentrations.

Low-Carbon Steels

Of the different steels, those produced in the greatest quantities fall within the low-carbon classification. These generally contain less than about 0.25 wt% C and are unresponsive to heat treatments intended to form martensite; strengthening is accomplished by cold work. Microstructures consist of ferrite and pearlite constituents. As a consequence, these alloys are relatively soft and weak but have outstanding ductility and toughness; in addition, they are machinable, weldable, and, of all steels, are the least expensive to produce. Typical applications include automobile body components, structural shapes (e.g., I-beams, channel and angle iron), and sheets that are used in pipelines, buildings, bridges, and tin cans.

Medium-Carbon Steels

The medium-carbon steels have carbon concentrations between about 0.25 and 0.60 wt. %. These alloys may be heat-treated by austenitizing, quenching, and then tempering to improve their mechanical properties. They are most often utilized in the tempered condition, having microstructures of tempered martensite. The plain medium-carbon steels have low hardenabilities and can be successfully heat-treated only in very thin sections and with very rapid quenching rates. Additions of chromium, nickel, and molybdenum improve the capacity of these alloys to be heat-treated, giving rise to a variety of strength–ductility combinations. These heat-treated alloys are stronger than the low-carbon steels, but at a sacrifice of ductility and toughness. Applications include railway wheels and tracks, gears, crankshafts, and other machine parts and high-strength structural components calling for a combination of high strength, wear resistance, and toughness.

High-Carbon Steels

The high-carbon steels, normally having carbon contents between 0.60 and 1.4 wt%, are the hardest, strongest, and yet least ductile of the carbon steels. They are almost always used in a hardened and tempered condition and, as such, are especially wear resistant and capable of holding a sharp cutting edge. The tool and die steels are high-carbon alloys, usually containing

chromium, vanadium, tungsten, and molybdenum. These alloying elements combine with carbon to form very hard and wear-resistant carbide compounds (e.g., Cr_2C_6 , V_4C_3 , and WC). These steels are used as cutting tools and dies for forming and shaping materials, as well as in knives, razors, hacksaw blades, springs, and high-strength wire. **Stainless Steels** The stainless steels are highly resistant to corrosion (rusting) in a variety of environments, especially the ambient atmosphere. is unusually strong and corrosion resistant. Strengthening is accomplished by precipitation-hardening heat treatments (Section 11.10).

Cast Irons

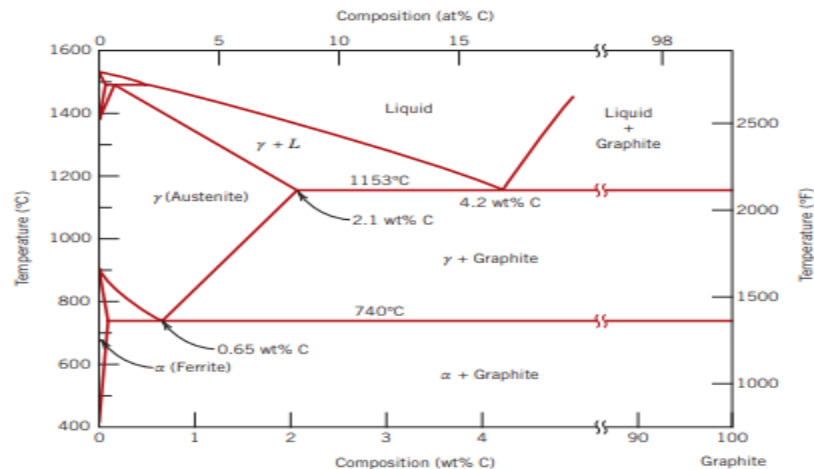
Generically, cast irons are a class of ferrous alloys with carbon contents above 2.14 wt%; in practice, however, most cast irons contain between 3.0 and 4.5 wt% C and, in addition, other alloying elements. A reexamination of the iron–iron carbide phase diagram (Figure 9.24) reveals that alloys within this composition range become completely liquid at temperatures between approximately 1150°C and 1300°C (2100°F and 2350°F), which is considerably lower than for steels. Thus, they are easily melted and amenable to casting. Furthermore, some cast irons are very brittle, and casting is the most convenient fabrication technique. Cementite (Fe_3C) is a metastable compound, and under some circumstances it can be made to dissociate or decompose to form α -ferrite and graphite, according to the reaction

Gray Iron

The carbon and silicon contents of gray cast irons vary between 2.5 and 4.0 wt% and 1.0 and 3.0 wt%, respectively. For most of these cast irons, the graphite exists in the form of flakes (similar to corn flakes), which are normally surrounded by an α -ferrite or pearlite matrix; the microstructure of a typical gray iron is shown in Figure 11.3a. Because of these graphite flakes, a fractured surface takes on a gray appearance—hence its name. Mechanically, gray iron is comparatively weak and brittle in tension as a consequence of its microstructure; the tips of the graphite flakes are sharp and pointed and may serve as points of stress concentration when an external tensile stress is applied. Strength and ductility are much higher under compressive loads. Typical mechanical properties and compositions of several common gray cast irons are listed in Table 11.5. Gray irons have some desirable characteristics and are used extensively. They are very effective in damping vibrational energy; this is represented in Figure 11.4, which compares the relative damping capacities of steel and gray iron. Base structures for machines and heavy equipment that are exposed to vibrations are frequently constructed of this material. In addition, gray irons exhibit a high resistance to wear. Furthermore, in the molten state they have a high fluidity at casting temperature,

which permits casting pieces that have intricate shapes; also, casting shrinkage is low. Finally, and perhaps most important, gray cast irons are among the least expensive of all metallic materials. Gray irons having microstructures different from that shown in Figure 11.3a may be generated by adjusting composition and/or using an appropriate treatment. For example, lowering the silicon content or increasing the cooling rate may prevent the complete dissociation of cementite to form graphite (Equation 11.1). Under these circumstances the microstructure consists of graphite flakes embedded in a pearlite matrix. Figure 11.5 compares schematically the several cast iron microstructures obtained by varying the composition and heat treatment.

Figure 11.2 The true equilibrium iron–carbon phase diagram with graphite instead of cementite as a stable phase. [Adapted from *Binary Alloy Phase Diagrams*, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.]



about 1 wt%. Also, slower cooling rates during solidification favor graphitization (the formation of graphite). For most cast irons, the carbon exists as graphite, and both microstructure and mechanical behavior depend on composition and heat treatment. The most common cast iron types are gray, nodular, white, malleable, and compacted graphite.

Ductile (or Nodular) Iron

Adding a small amount of magnesium and/or cerium to the gray iron before casting produces a distinctly different microstructure and set of mechanical properties. Graphite still forms, but as nodules or spherulike particles instead of flakes. The resulting alloy is called ductile or nodular iron, and a typical microstructure is shown in Figure 11.3b. The matrix phase surrounding these particles is either pearlite or ferrite, depending on heat treatment (Figure 11.5); it is normally pearlite for an as-cast piece. However, a heat treatment for several hours at about 700°C (1300°F) yields a ferrite matrix, as in this photomicrograph. Castings are stronger and much more ductile than gray iron, as a comparison of their mechanical properties in Table 11.5 shows. In fact, ductile iron has mechanical characteristics approaching those of steel. For example, ferritic ductile irons have tensile strengths between 380 and 480 MPa (55,000 and 70,000 psi) and ductilities (as percent elongation) from 10% to 20%. Typical applications for this

materials include valves, pump bodies, crankshafts, gears, and other automotive and machine components.

phase/microconstituent. An increase in degree of nodularity of the graphite particles leads to enhancements of both strength and ductility. Furthermore, CGIs with ferritic matrices have lower strengths and higher ductilities than those with pearlitic matrices. Tensile and yield strengths for compacted graphite irons are comparable to values for ductile and malleable irons, yet are greater than those observed for the higher-strength gray irons (Table 11.5). In addition, ductilities for CGIs are intermediate between values for gray and ductile irons; moduli of elasticity range between 140 and 165 GPa (20×10^6 and 24×10^6 psi). Compared to the other cast iron types, desirable characteristics of CGIs include the following:

- Higher thermal conductivity
- Better resistance to thermal shock (i.e., fracture resulting from rapid temperature changes)
- Lower oxidation at elevated temperatures

Compacted graphite irons are now being used in a number of important applications, including diesel engine blocks, exhaust manifolds, gearbox housings, brake discs for high-speed trains, and flywheels.