4.2 Structure of Alloys

When describing the basic crystal structure of metals in Chapter 1, it was noted that the atoms are all of the *same* type, except for the presence of rare impurity atoms; these metals are known as **pure metals**, even though they may not be completely pure. *Commercially pure* metals are used for various purposes, such as aluminum for foil, copper for electrical conductors, nickel or chromium for plating, and gold for electrical contacts. Pure metals have somewhat limited properties but they can be enhanced and modified by **alloying**. An **alloy** consists of two or more chemical elements, at least one of which is a metal; the majority of metals used in engineering applications are some form of alloy. Alloying consists of two basic forms: *solid solutions* and *intermetallic compounds*.

4.2.1 Solid Solutions

Two terms are essential in describing alloys: **solute** and **solvent**. The solute is the *minor* element (such as salt or sugar) that is added to the solvent, which is the *major* element (such as water). In terms of the elements in a crystal structure, the solute (composed of *solute atoms*) is the element that is added to the solvent (composed of *host atoms*). When the particular crystal structure of the solvent is maintained during alloying, the alloy is called a *solid solution*.

Substitutional Solid Solutions. If the size of the solute atom is similar to that of the solvent atom, the solute atoms can replace solvent atoms and form a *substitutional solid solution* (see Fig. 1.8). An example is brass, which is an alloy of zinc and copper in which zinc (the solute atom) is introduced into the lattice of copper (solvent atoms). The properties of brass can thus be altered by controlling the amount of zinc in copper.

Interstitial Solid Solutions. If the size of the solute atom is much smaller than that of the solvent atom, each solute atom can occupy an *interstitial* position; such a process forms an *interstitial solid solution.*

An important family of interstitial solid solutions is **steel** (Chapter 5), an alloy of iron and carbon in which the carbon atoms are present in interstitial positions between iron atoms. The atomic radius of carbon is 0.071 nm, which is very small compared to the 0.124-nm radius of the iron atom. The properties of carbon steels can be varied over a wide range by adjusting the ratio of carbon to iron. The ability to control this ratio is a major reason why steel is such a versatile and useful material, with a very wide variety of properties and applications.

4.2.2 Intermetallic Compounds

Intermetallic compounds are complex structures consisting of two metals in which solute atoms are present among solvent atoms in certain proportions. Typical examples are the aluminides of titanium (Ti_3Al), nickel (Ni_3Al), and iron (Fe_3Al). Some intermetallic compounds have solid solubility, and the type of atomic bond may range from metallic to ionic. Intermetallic compounds are strong, hard, and brittle. Because of their high melting points, strength at elevated temperatures, good oxidation resistance, and relatively low density, they are candidate materials for such applications as advanced gas-turbine engines.

4.2.3 Two-phase Systems

Recall that a solid solution is one in which two or more elements form a single homogeneous solid phase, in which the elements are uniformly distributed throughout the solid mass. Such a system has a maximum concentration of solute atoms in the solvent-atom lattice, just as there is a solubility limit for sugar in water. Most alloys consist of two or more solid phases and may be regarded as mechanical mixtures; such a system with two solid phases is known as a *two-phase system.*

A **phase** is defined as a physically distinct and homogeneous portion in a material. Each phase is a homogeneous part of the total mass, and has its own characteristics and properties. Consider a mixture of sand and water as an example of a two-phase system. These two different components have their own distinct structures, characteristics, and properties; there is a clear boundary in this mixture between the water (one phase) and the sand particles (the second phase). Another example is ice in water: the two phases are the same chemical compound of exactly the same chemical elements (hydrogen and oxygen), even though their properties are very different. Note that it is not necessary that one phase be a liquid; for example, sand suspended in ice is also a two-phase system.

A typical example of a two-phase system in metals occurs when lead is added to copper in the molten state. After the mixture solidifies, the structure consists of two phases: one having a small amount of lead in solid solution in copper, the other having lead particles (roughly spherical in shape) *dispersed* throughout the structure (Fig. 4.3a). The lead particles are analogous to the sand particles in water, described above. This copper–lead alloy has properties that are different from those of either copper or lead alone.

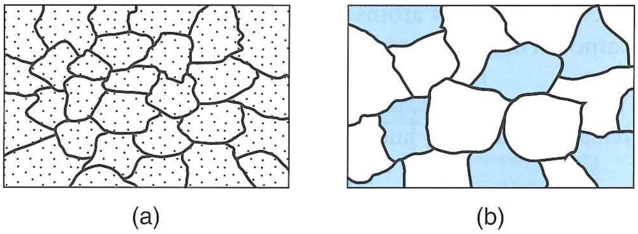
(a) (b)

FIGURE 4.3 (a) Schematic illustration of grains, grain boundaries, and particles dispersed throughout the structure of a two-phase system, such as a lead–copper alloy. The grains represent lead in solid solution in copper, and the particles are lead as a second phase. (b) Schematic illustration of a two-phase system consisting of two sets of grains: dark and light. The colored and white grains have different compositions and properties.

Alloying with finely dispersed particles (**second-phase particles**) is an important method of strengthening metal alloys and controlling their properties. In two-phase alloys, the second-phase particles become obstacles to dislocation movement and thus increase the strength of the alloy. Another example of a two-phase alloy is the aggregate structure shown in Fig. 4.3b, where there are two sets of grains, each with its own composition and properties. The darker grains in the figure may have a different structure from the lighter grains; they may, for example, be brittle, while the lighter grains are ductile.

Defects may develop during metalworking operations such as forging or extrusion (as described in Chapters 14 and 15, respectively). Such flaws may be due to the lack of ductility of one of the phases in the alloy. In general, two-phase alloys are stronger and less ductile than solid solutions.