COLD WORK

Cold work means to mechanically deform a metal at relatively low temperatures. This concept was introduced in Section 6.3 in relating dislocation motion to mechanical deformation. The amount of cold work is defined relative to the reduction in cross-sectional area of the alloy by processes such as rolling or drawing (Figure 10.29). The percent cold work is given by

$$\%\ \mathrm{CW} = \frac{A_0 - A_f}{A_0} \times 100\%, \tag{10.2}$$

where A_0 is the original cross-sectional area and A_f is the final cross-sectional area after cold working. The hardness and strength of alloys are increased with increasing % CW, a process termed *strain hardening*. The relationship of mechanical properties to % CW of brass is illustrated in Figure 11.7, relative to a discussion of design specifications. The mechanism for this hardening is the resistance to plastic deformation caused by the high density of dislocations produced in the cold working. (Recall the discussion in Section 6.3.) The density of dislocations can be expressed as the length of dislocation lines per unit volume (e.g., m/m^3 or net units of m^{-2}). An annealed alloy can have a dislocation density as low as $10^{10}\ m^{-2}$, with a correspondingly low hardness. A heavily cold-worked alloy can have a dislocation density as high as $10^{16}\ m^{-2}$, with a significantly higher hardness (and strength).

A cold-worked microstructure is shown in Figure 10.30a. The severely distorted grains are quite unstable. By taking the microstructure to higher temperatures where sufficient atom mobility is available, the material can be softened and a new microstructure can emerge.

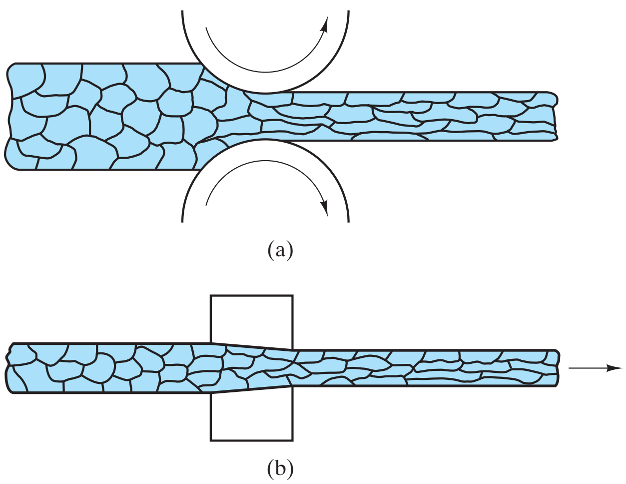
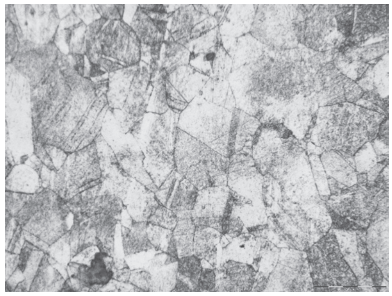


FIGURE 10.29 *Examples of cold-working operations: (a) cold-rolling a bar or sheet and (b) cold-drawing a wire. Note in these schematic illustrations that the reduction in area caused by the cold-working operation is associated with a preferred orientation of the grain structure.*



(a)

(b)

FIGURE 10.30 *Annealing can involve the complete recrystallization of a cold-worked microstructure. (a) A cold-worked* 70/30 *brass. (b) After 1 hour at* 450°C, *complete recrystallization has occurred. Both micrographs have a magnification of* 40×. *(Courtesy of T. G. Edwards, University of California, Davis.)*

RECOVERY

The most subtle stage of annealing is **recovery**. No gross microstructural change occurs. However, atomic mobility is sufficient to diminish the concentration of point defects within grains and, in some cases, to allow dislocations to move to lower-energy positions. This process yields a modest decrease in hardness and can occur at temperatures just below those needed to produce significant microstructural change. Although the structural effect of recovery (primarily a reduced number of point defects) produces a modest effect on mechanical behavior, electrical conductivity does increase significantly. (The relationship between conductivity and structural regularity is explored further in Section 13.3.)

RECRYSTALLIZATION

In Section 6.3, we stated an important concept: "The temperature at which atomic mobility is sufficient to affect mechanical properties is approximately one-third to one-half times the absolute melting point, T_m." A microstructural result of exposure to such temperatures is termed **recrystallization** and is illustrated dramatically in Figures 10.30(a) and (b). Between these two extremes, new equi-axed, stress-free grains nucleate at high-stress regions in the cold-worked microstructure followed by these grains growing together until they constitute the entire microstructure [Figure 10.30(b)]. As the nucleation step occurs in order to stabilize the system, it is not surprising that the concentration of new grain nuclei increases with the degree of cold work. As a result, the grain size of the recrystallized microstructure decreases with the degree of cold work. The decrease in hardness due to annealing is substantial, as indicated by Figure 10.31. Finally, the rule of thumb quoted at the beginning of this discussion of recrystallization effectively defines the **recrystallization temperature** (Figure 10.32). For a given alloy composition, the precise recrystallization temperature will depend slightly on the percentage of cold work. Higher values of % CW correspond to higher degrees of strain hardening and a correspondingly lower recrystallization temperature; that is, less thermal energy input is required to initiate the reformation of the microstructure (Figure 10.33).

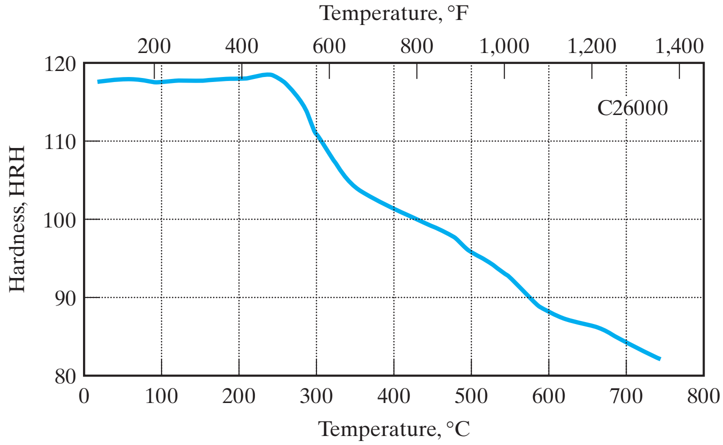


FIGURE 10.31 *The sharp drop in hardness identifies the recrystallization temperature as ~290°C for the alloy C26000, "cartridge brass." (From* Metals Handbook, *9th ed., Vol. 4, American Society for Metals, Metals Park, OH, 1981.)*

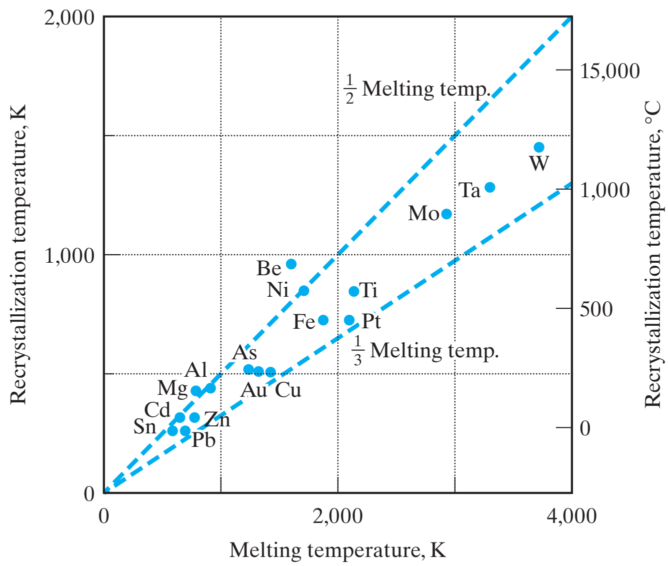


FIGURE 10.32 *Recrystallization temperature versus melting points for various metals. This plot is a graphic demonstration of the rule of thumb that atomic mobility is sufficient to affect mechanical properties above approximately $\frac{1}{3}$ to $\frac{1}{2}$ T_m on an absolute temperature scale. (From L. H. Van Vlack,* Elements of Materials Science and Engineering, *3rd ed., Addison-Wesley Publishing Co., Inc., Reading, MA, 1975.)*

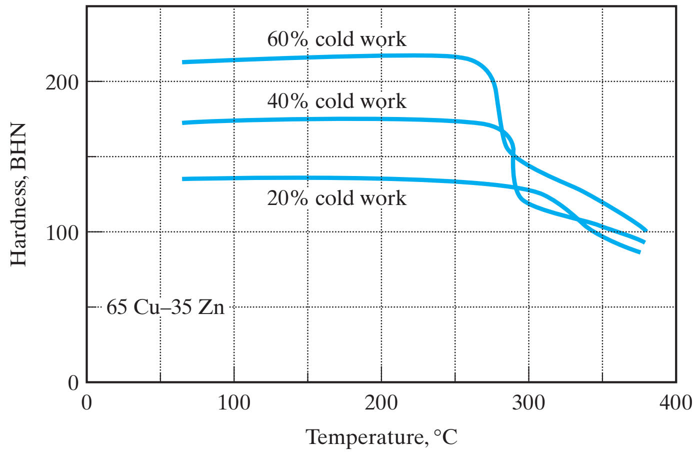


FIGURE 10.33 *For this cold-worked brass alloy, the recrystallization temperature drops slightly with increasing degrees of cold work. (From L. H. Van Vlack,* Elements of Materials Science and Engineering, *4th ed., Addison-Wesley Publishing Co., Inc., Reading, MA, 1980.)*

GRAIN GROWTH

The microstructure developed during recrystallization (Figure 10.30b) occurred spontaneously. It is stable compared with the original cold-worked structure (Figure 10.30a). However, the recrystallized microstructure contains a large concentration of grain boundaries. We have noted frequently since Chapter 4 that the reduction of these high-energy interfaces is a method of stabilizing a system further. The stability of coarse pearlite (Figure 10.10) was such an example. The coarsening of annealed microstructures by grain growth is another. **Grain growth**, which is not dissimilar to the coalescence of soap bubbles, is a process similarly driven by the reduction of surface area. Figure 10.34 shows that this grain-growth stage produces little additional softening of the alloy. That effect is associated predominantly with recrystallization.

EXAMPLE 10.9

Cartridge brass has the approximate composition of 70 wt % Cu and 30 wt % Zn. How does this alloy compare with the trend shown in Figure 10.32?

SOLUTION

The recrystallization temperature is indicated by Figure 10.31 as ~290°C. The melting point for this composition is indicated by the Cu–Zn phase diagram (Figure 9.28) as ~920°C (the solidus temperature). The ratio of recrystallization temperature to melting point is then

$$\frac{T_R}{T_m} = \frac{(290 + 273)\text{ K}}{(920 + 273)\text{ K}} = 0.47,$$

which is within the range of one-third to one-half indicated by Figure 10.32.

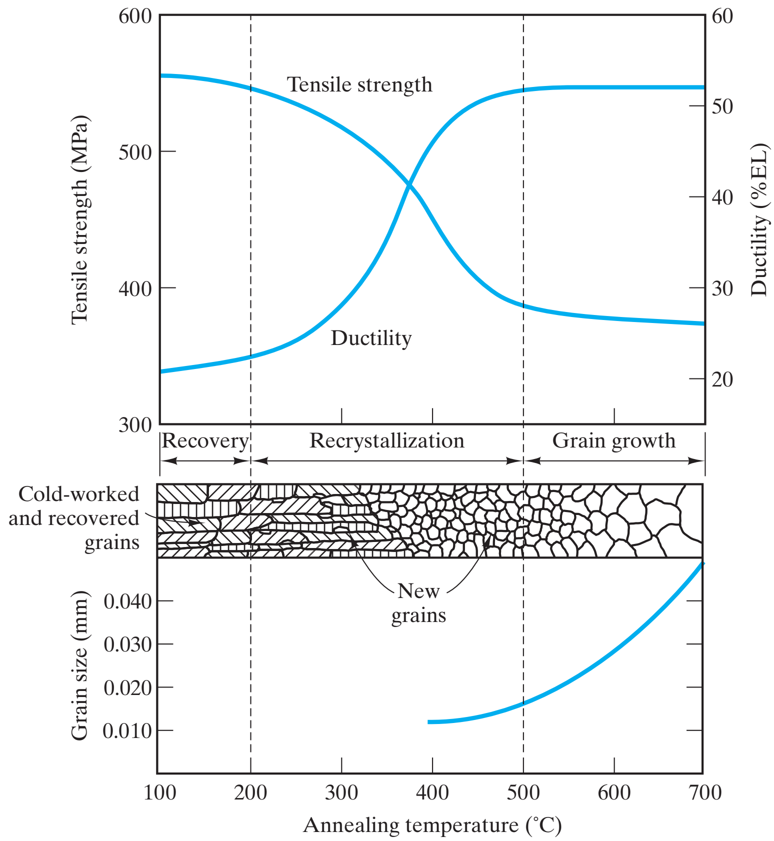


FIGURE 10.34 *Schematic illustration of the effect of annealing temperature on the strength and ductility of a brass alloy shows that most of the softening of the alloy occurs during the recrystallization stage. (After G. Sachs and K. R. Van Horn,* Practical Metallurgy: Applied Physical Metallurgy and the Industrial Processing of Ferrous and Nonferrous Metals and Alloys, *American Society for Metals, Cleveland, OH, 1940.)*

PRACTICE PROBLEM 10.9

Noting the result of Example 10.9, plot the estimated temperature range for recrystallization of Cu–Zn alloys as a function of composition over the entire range from pure Cu to pure Zn.