

## Introduction

The principles which govern heat treatment of metals and alloys are applicable to both ferrous and nonferrous alloys. However, in practice there are sufficient differences to make it convenient to emphasize as separate topics the peculiarities of the alloys of each class in their response to heat treatment. For example, in nonferrous alloys, eutectoid transformations, which play such a prominent role in steels, are seldom encountered, so there is less concern with principles associated with time-temperature-transformation diagrams and with martensite formation. On the other hand, the principles associated with chemical homogenization of cast structures are applicable to many alloys in both classes.

The diffusion process is involved in nearly all heat treatments for nonferrous alloys.

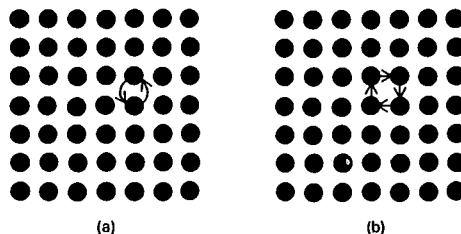
Common treatments include:

- Annealing after cold working
- Homogenization of castings
- Precipitation hardening treatments
- Development of two-phase structures

## Diffusion Process

In the heat treatment of metals and alloys, the rate of structural change usually is controlled by the rate at which atoms in the lattice change positions. For example, when cold-worked copper is annealed and softens, or an aluminum-base alloy is aged, it is important to know how the atoms move relative to each other so as to bring about the observed changes in properties. This movement of atoms is called diffusion. Two different diffusion mechanisms are shown in Fig. 1.

**Fig. 1 Schematic representation of two possible diffusion mechanisms. (a) Two atoms move simultaneously to exchange positions. (b) Four atoms move cooperatively to rotate simultaneously to move to new positions**



## Annealing Cold-Worked Metals

Cold working increases hardness, yield strength, and tensile strength, and lowers ductility. Also, electrical resistivity is improved because increasing density of dislocations scatters the electrons. The effects of cold working on several properties are shown in Fig. 2.

**Role of Annealing.** In shaping metals by cold working, there is a limit to the amount of plastic deformation possible without fracture. Annealing restores the metal to a structural condition similar to that prior to deformation, making further cold working possible.

Changes in strength that take place during annealing are indicated by the hardness data in Fig. 3(a). In this instance, data are for a fixed temperature. A similar result is obtained by annealing for a fixed time at increasing temperatures (Fig. 3b).

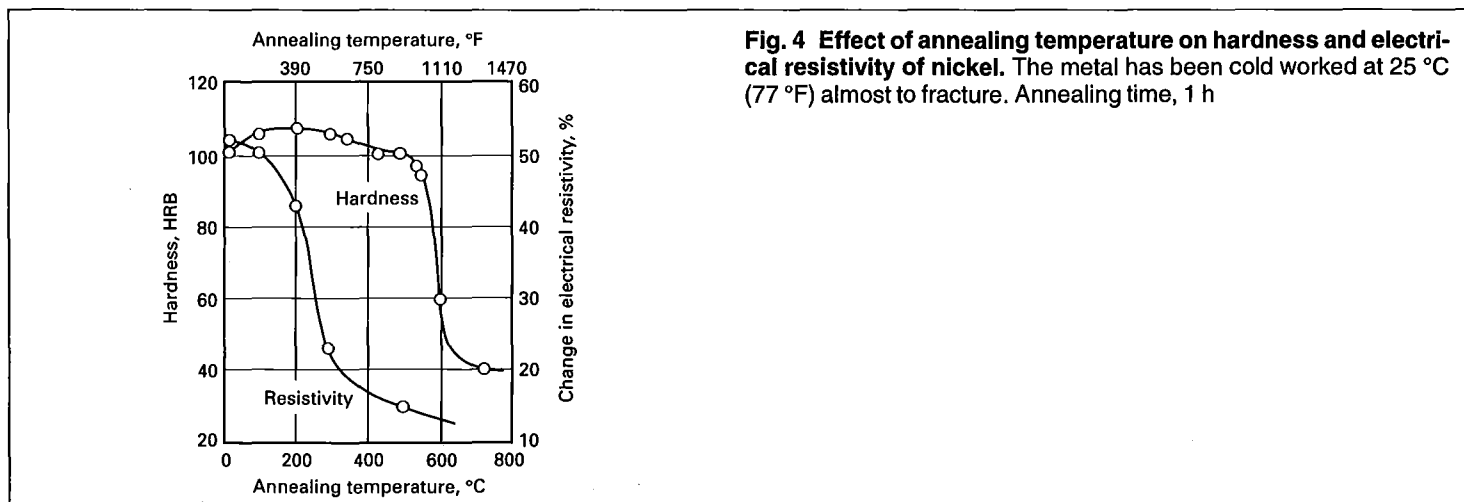
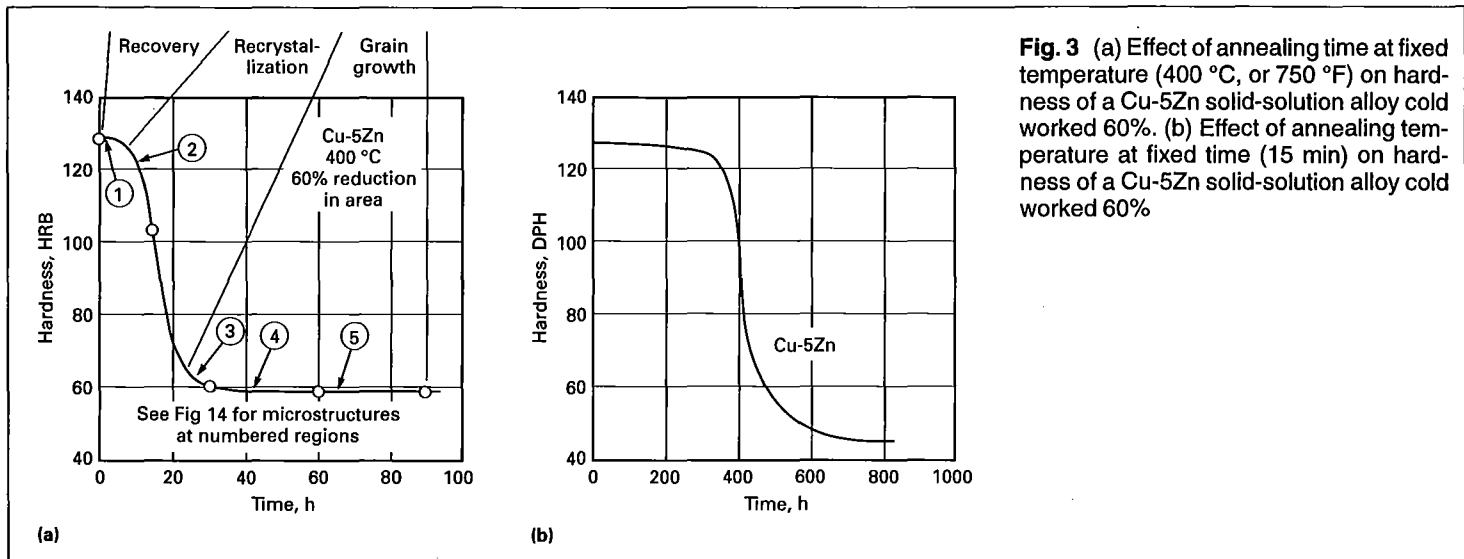
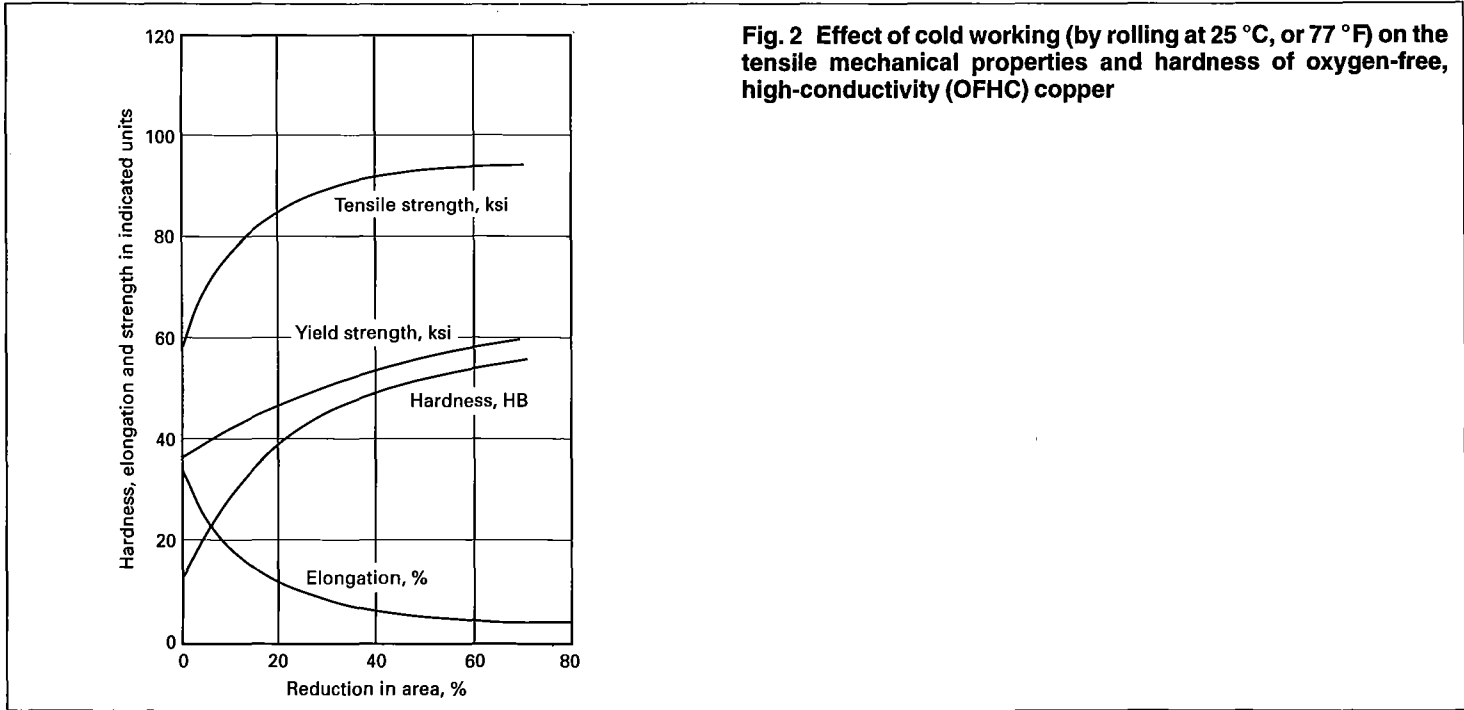
**Recovery, recrystallization, and grain growth are stages in annealing.** The stage for short times at low temperatures in which hardness remains constant, or increases slightly, is called the recovery region. Dislocations undergo movement by thermal activation, being rearranged into arrays somewhat more stable and more difficult to move than in the cold worked, unannealed condition. A slight increase in hardness results. Some properties regain values they had prior to cold working. Hence the

term recovery. Electrical conductivity is one of the properties involved (see Fig. 4).

**Recrystallization.** With longer times or at higher temperatures, the structure undergoes a more radical change. Small crystals appear which contain a low dislocation density (of a magnitude similar to that prior to cold working) and are relatively soft. Crystals nucleate in regions of high dislocation density, and in the microstructure appear at or near deformation bands. With time, the nuclei grow, and more nuclei form in the remaining cold-worked matrix. Eventually, grains contact each other (at that time the original cold-worked material has disappeared). The formation of grains is referred to as recrystallization. At this time, strength drops drastically (see Fig. 3 and 4).

**Growth in grain size.** Microstructural changes that occur during annealing are illustrated in Fig. 5. During recovery, the density of deformation bands drops, but the change is not marked. When crystallization commences, small, equiaxed grains begin to appear (see micrograph 2 in Fig. 5, and a recrystallized nucleus shown in Fig. 6). Grains continue to form and to grow until the cold-worked matrix is consumed, which marks the end of the recrystallization period and the beginning of grain growth.

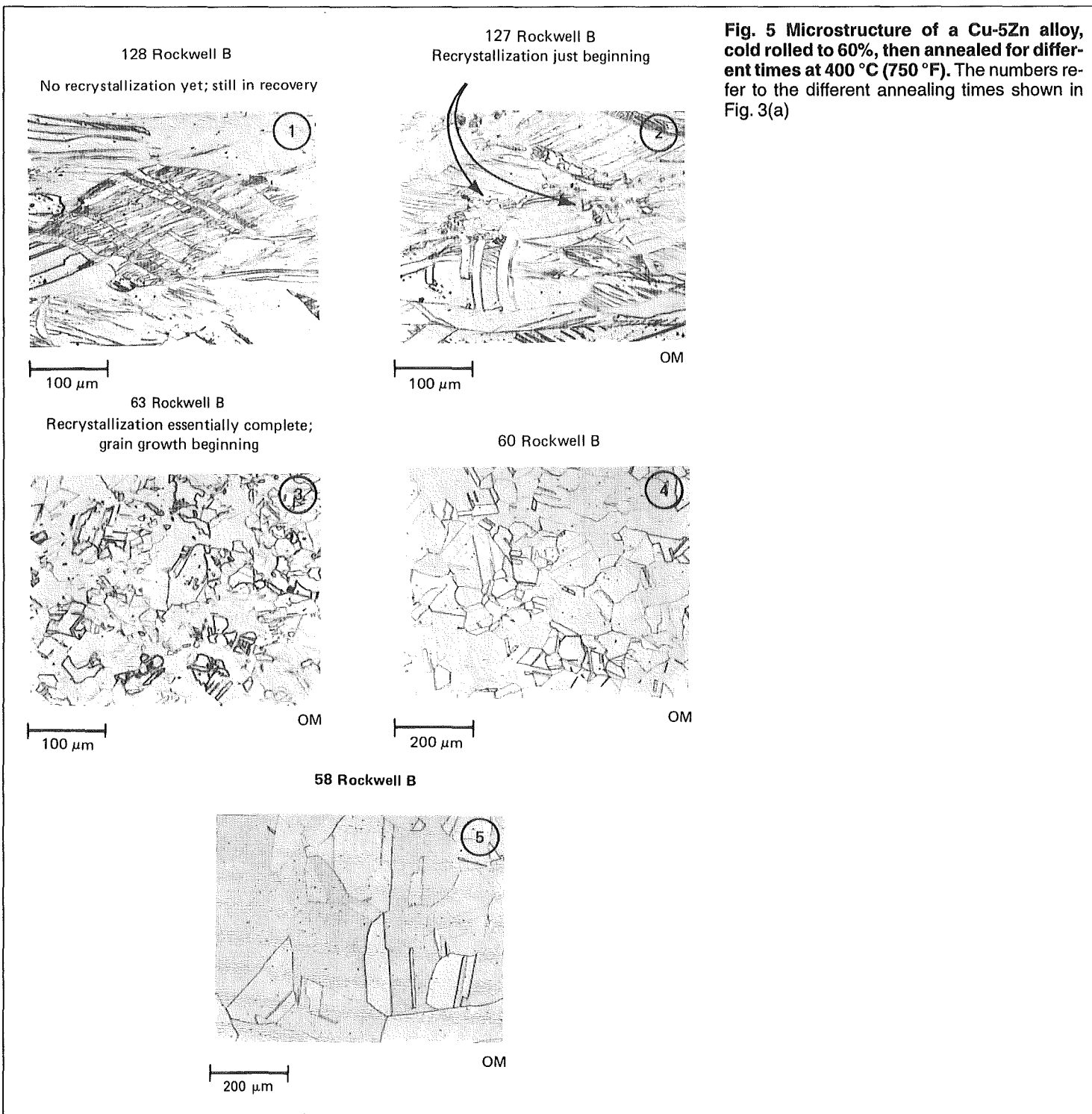
2 / Heat Treater's Guide: Nonferrous Alloys



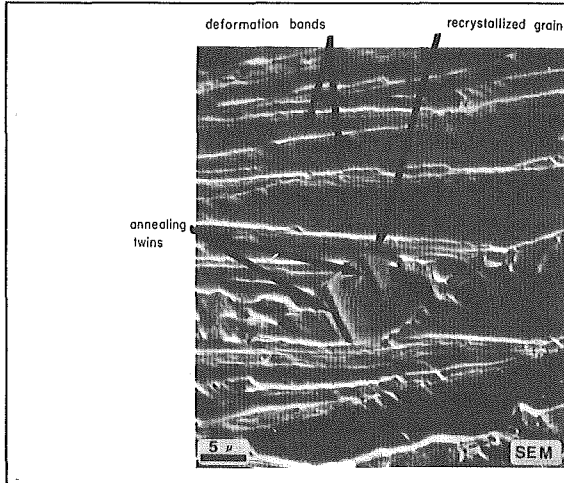
With further annealing, grain size continues to grow (see micrographs 3, 4, and 5 in Fig. 5).

Because annealing of cold-worked metals usually is carried out to soften the material, the temperature and time needed to complete recrystallization must be known to determine the proper heat treatment. The recrystallization temperature is commonly referred to as an indicator of the temperature at which metal must be annealed for softening.

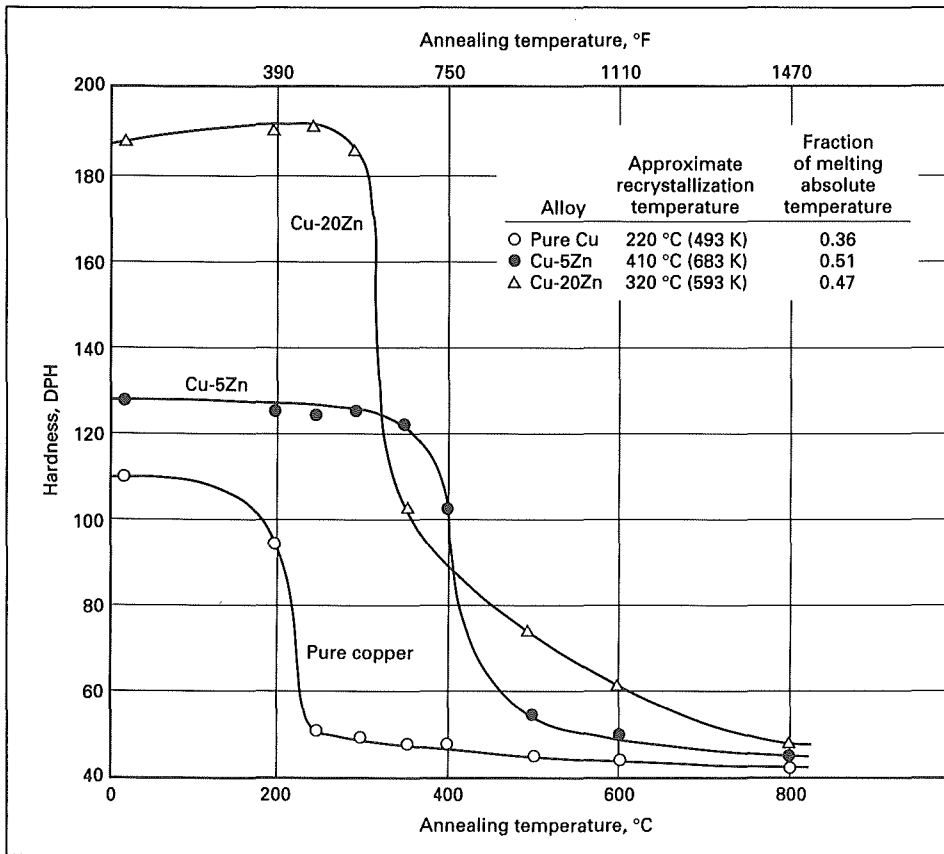
As a rule of thumb, the recrystallization temperature is approximately 0.3 to 0.6 of the absolute melting point. In the case of Cu-Zn solid solution alloys, the addition of zinc to copper lowers the melting point, and the recrystallization temperature will decrease for high zinc contents (20 to 30%, for example), see Fig. 7.



#### 4 / Heat Treater's Guide: Nonferrous Alloys



**Fig. 6 High-magnification scanning electron micrograph showing a small recrystallized nucleus. Cu-5Zn alloy, cold worked by rolling 20 °C (68 °F) to a reduction in thickness of 60%; annealed 60 min at 350 °C (660 °F)**



**Fig. 7 Illustration of effect of zinc content of Cu-Zn solid-solution alloys on the annealing process. The alloys were originally cold rolled at 25 °C (77 °F) to 60% reduction in thickness. The recrystallization temperatures listed are based on the inflection point of each curve**

## Homogenization of Castings

This treatment is applied prior to the mechanical processing of cast ingot and is often used even when an object is cast essentially to its final shape. Temperatures and times used in this process depend on the diffusion rate and the starting structure.

In chemical homogenization annealing, chemical gradients in a dendritically cored structure can be reduced at a sufficiently high temperature

for a sufficient time. The rate of diffusion is given by an appropriate solution to Fick's law. As a conservative approximation, the required time is  $x^2 \approx Dt$ , where  $x$  is the distance between regions of low and of high concentration in the dendrite cell, which is one-half of cell size.

## Precipitation Hardening Treatments

In designing alloys for strength, an approach often taken is to develop an alloy in which the structure consists of particles which impede dislocation motion dispersed in a ductile matrix. The finer the dispersion, for the same amount of particles, the stronger the material.

Such a dispersion can be obtained by choosing an alloy that, at elevated temperature, is single phase, but that on cooling will precipitate another phase in the matrix. A heat treatment is then developed to give the desired distribution of the precipitate in the matrix. If hardening occurs from this structure, then the process is called precipitation hardening or age hardening. However, not all alloys in which such a dispersion can be developed will harden.

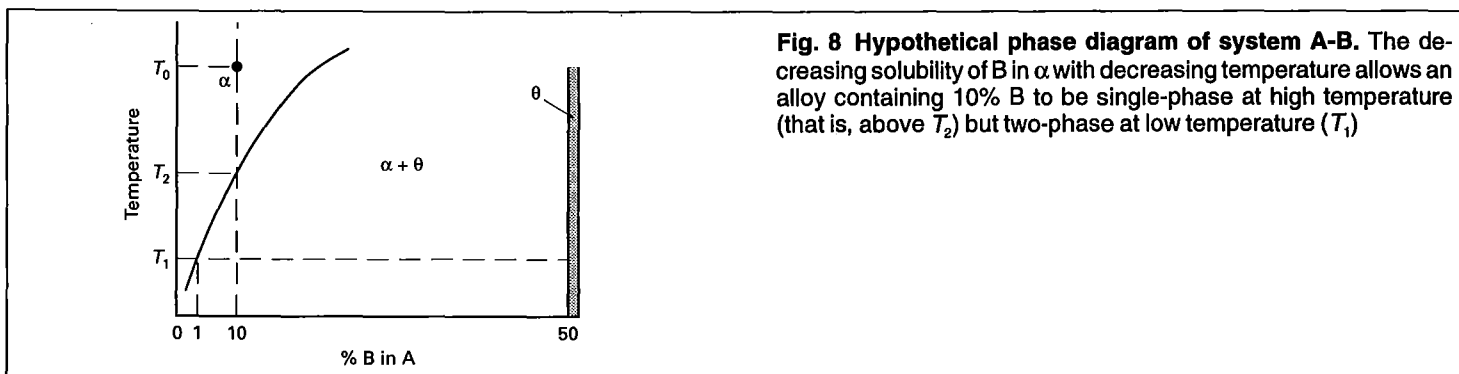
**Solution Heat Treatment.** A prerequisite to precipitation hardening is the ability to heat the alloy to a temperature range wherein all of the solute is dissolved, so that a single-phase structure is attained. This is shown schematically in Fig. 8 for a 10% B alloy in a hypothetical system A-B. Heating above the solvus temperature  $T_2$  for this alloy and holding in the  $\alpha$  range for sufficient time will form the single phase  $\alpha$ . This is the required solution heat treatment.

**The Process of Precipitation.** After quenching from the  $\alpha$  region (Fig. 8), precipitation is achieved by reheating the alloy below the solvus ( $T_2$  in Fig. 8) at a suitable temperature for a suitable time.

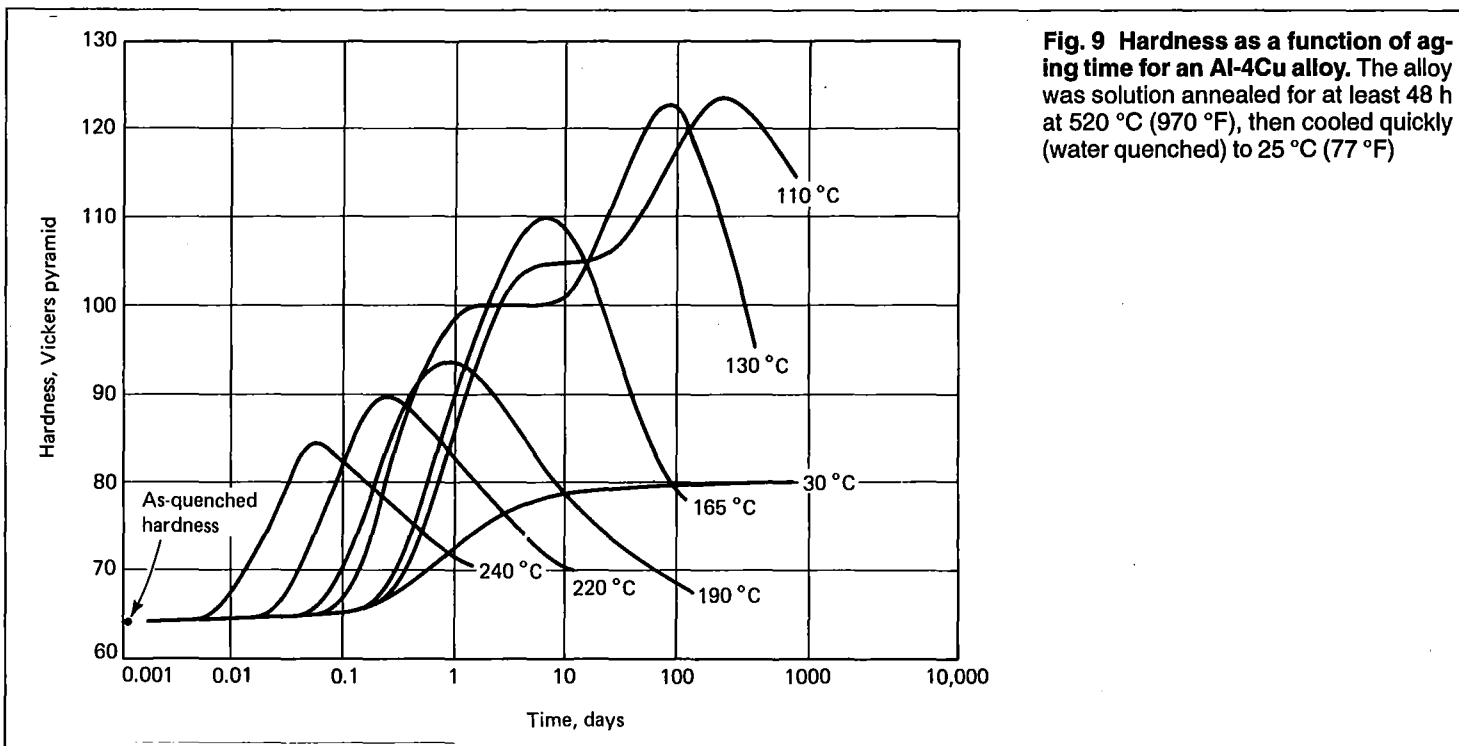
**Precipitation Hardening.** The high strength is produced by the finely dispersed precipitates that form during precipitation treatments (which may include either natural room-temperature aging, or artificial aging at elevated temperatures).

The effect of temperature and time on aging is illustrated by the data in Fig. 9. As pointed out previously, the higher the precipitation temperature, the lower the maximum hardness, because less precipitate forms as the solvus temperature is approached. However, the higher the temperature, the higher the rate of precipitation, and hence the maximum hardness is attained in less time.

In most commercial precipitation-hardenable alloys, the rate of precipitation is low at ambient temperature, although sufficiently rapid to bring about measurable hardness changes in a reasonable time, as shown in Fig. 9 for aging at 30 °C (85 °F). If hardening occurs at or near ambient temperature, it is termed *age hardening*; aging at other temperatures is called *precipitation hardening*.



**Fig. 8 Hypothetical phase diagram of system A-B.** The decreasing solubility of B in  $\alpha$  with decreasing temperature allows an alloy containing 10% B to be single-phase at high temperature (that is, above  $T_2$ ) but two-phase at low temperature ( $T_1$ )



**Fig. 9 Hardness as a function of aging time for an Al-4Cu alloy.** The alloy was solution annealed for at least 48 h at 520 °C (970 °F), then cooled quickly (water quenched) to 25 °C (77 °F)

## 6 / Heat Treater's Guide: Nonferrous Alloys

# Developing Two-Phase Structures

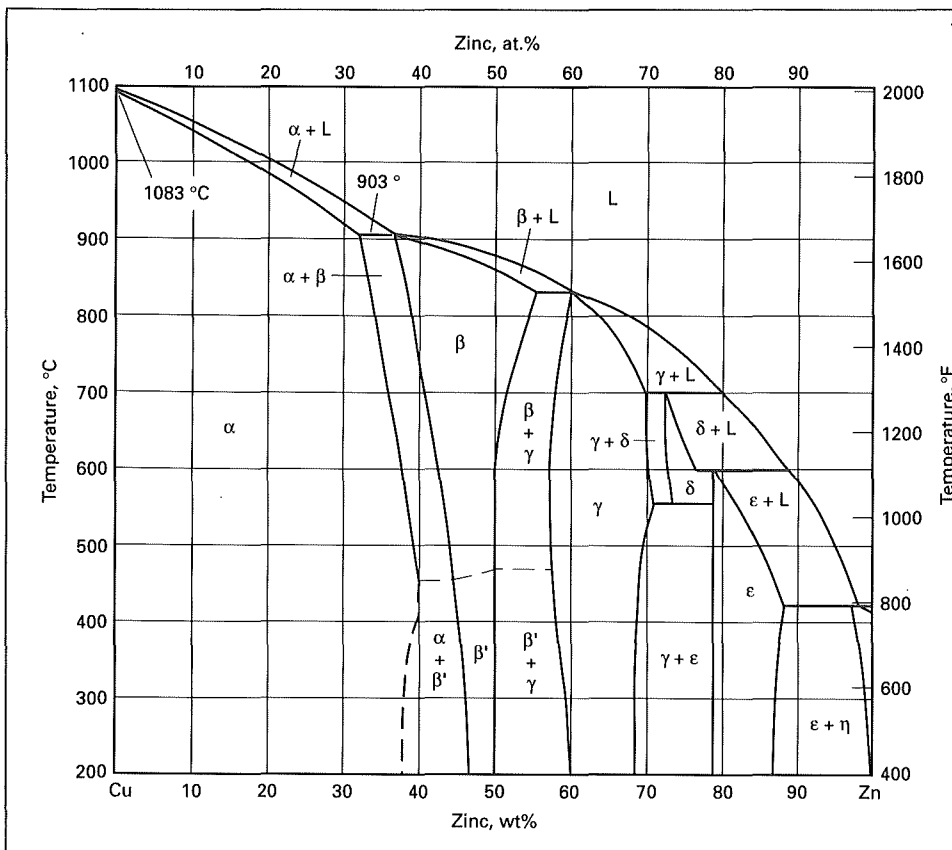
In some nonferrous alloys (for example, titanium-base alloys and high-zinc Cu-Zn alloys), the desired structure consists of a mixture of two phases of comparable quantity (unlike the two-phase structures developed in precipitation hardening, where the precipitate is in the minority). The morphology and amount of each are varied by control of the high temperature used and the cooling rate from that temperature. The preferred microstructure can be quite complex, and the required treatment differs considerably for different systems, so that a systematic treatment of the principles involved is difficult.

In the Cu-Zn system, alloys containing about 40% Zn serve as the basis for some commercial alloys (for example, Muntz metal and naval brass). The Cu-Zn phase diagram (Fig. 10) shows that the alloys of interest are in

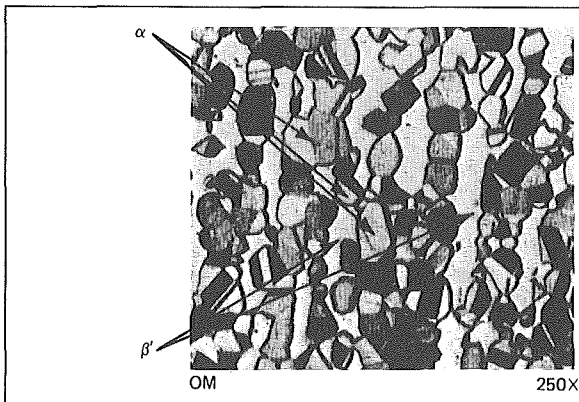
the region of  $\alpha$  and  $\beta$  phase stability. The  $\beta$  phase is a body-centered cubic, with the copper and zinc atoms located at random on the lattice sites.

On cooling to temperatures below the dashed line (about 450 °C, or 840 °F), the copper and zinc atoms take specific relative position on the sites, forming an *ordered structure*, or a *superlattice*. This phase is denoted  $\beta'$  in Fig. 10. If the composition is exactly 50 at.% Zn, then the ordered structure is based on a body-centered cubic cell with zinc atoms at the center and copper atoms on the corners (or vice versa).

See Fig. 11 for typical microstructure of Muntz metal (Cu-40Zn), Fig. 12 for microstructure of Cu-42Zn quenched from beta region, then reheated to develop an alpha precipitate structure.

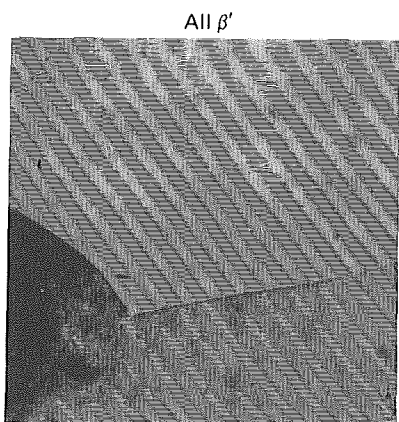


**Fig. 10 The Cu-Zn diagram.** The  $\beta$  phase is body-centered cubic; the  $\beta'$  phase is an ordered structure based on this arrangement



**Fig. 11 Typical microstructure of annealed Muntz metal (Cu-40Zn).** The clear, white regions are the  $\beta'$ , and the dark and gray regions showing annealing twins are  $\alpha$ . Optical micrograph. 250x

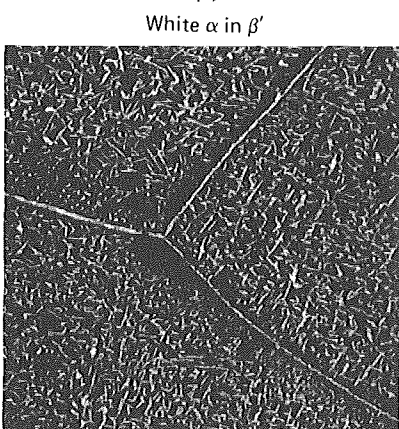
**Fig. 12 Microstructures of Cu-42Zn alloy quenched from the  $\beta$  region, then reheated to develop an  $\alpha$  precipitate structure. The higher reheating temperature gives a coarser structure and thus a softer material**



OM 100X

Quenched from 800 °C

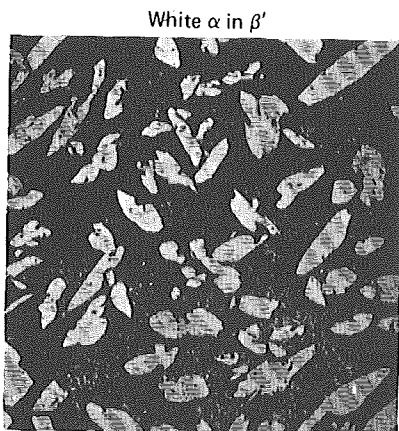
(a)



OM 100X

Quenched from 800 °C,  
reheated for 30 min  
at 400 °C

(b)



OM 100X

Quenched from 800 °C,  
reheated for 30 min  
at 600 °C

(c)