

## Chapter 9 – Precipitation Hardening: Lecture Outline

### Precipitation Hardening --- Background :

Generally associated with aluminum-based systems:

- e.g., 2024 Al, 6061 Al, 7075 Al, 7475 Al alloys

Observed in many materials systems:

- Fe alloys: Fe-C steels, low alloy steels, alloy steels, maraging steels
- Ni alloys: superalloys (intermetallic phases)
- Cu alloys: Cu-Be alloys
- Ti alloys: Ti-6Al-4Al, Ti-6Al-2Sn-4Zr-6Mo

Historical measures:

- hardness vs. aging time curves
- strength vs. aging time curves

### Process Procedures/Requirements :

Steps in a precipitation hardening (age hardening) heat treatment:

1. solution treatment
2. quench
3. age

Purposes of each step:

1. solution treatment – dissolve solute atoms into solid solution with solvent atoms, single phase (ideally no second phase present)
2. quench – maintain a single phase (supersaturated with solute atoms and excess vacancies)
3. age – thermal activation to allow solute atoms to segregate (diffuse) to form a finely dispersed 2nd phase particles, which inhibit dislocation motion

Phase diagram interpretation of process:

1. solution treatment – ideally must be able to obtain a single phase solid on heating (from a two phase solid field at room temperature)
2. quench – rapid cooling to a two phase solid field must yield a supersaturated single phase state
3. age – age in two phase solid field to yield a dispersion of submicron sized particles in a matrix
  - equilibrium interpretations helpful for steps (1) and (3), but step (2) means non-equilibrium conditions apply → non-equilibrium phases probable
  - single phase (high temperature) solid field must have decreasing solubility limit with temperature
  - liquid phase must never be formed at any step in the process

### **Control of hardness and strength via precipitation :**

1. Distance between precipitate particles – hardness/strength  $\uparrow$  as  $d \downarrow$
2. Size of precipitate particles – a submicron intermediate size is most effective; within this size range hardness/strength  $\uparrow$  as size  $\downarrow$
3. Shape of precipitate particles – plate/disk shapes more effective than rod shapes which are more effective for hardening/strengthening than spherical shapes
4. Volume fraction of precipitates – as  $V_f \uparrow$  hardness/strength  $\uparrow$
5. Type of precipitate/matrix interface – semi-coherent interfaces are more effective for hardening/strengthening
6. Distribution of precipitate particles – best balance of properties achieved with a uniform distribution

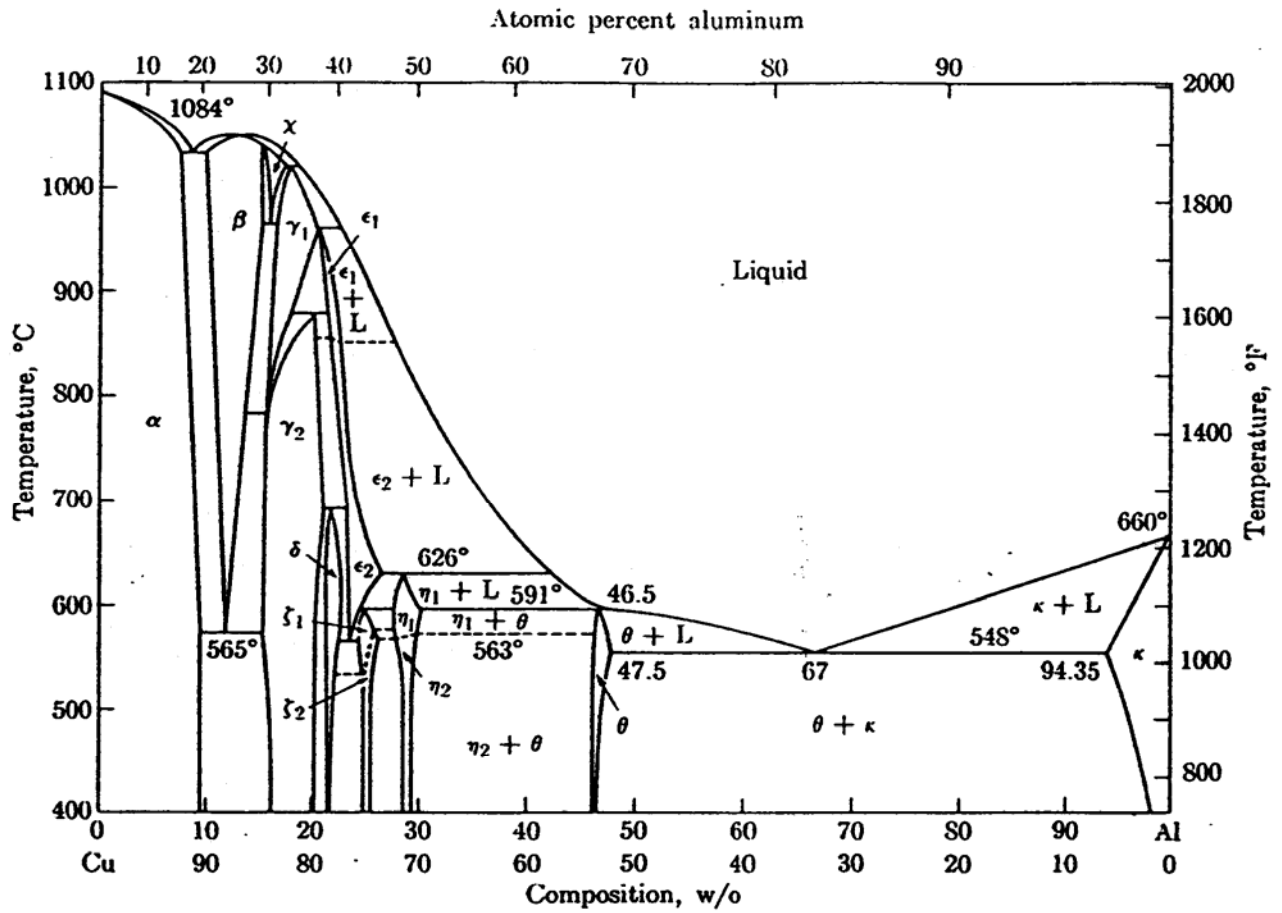


Fig. 9-5.3 Al-Cu diagram. (Adapted from *Metals Handbook*, American Society for Metals.)

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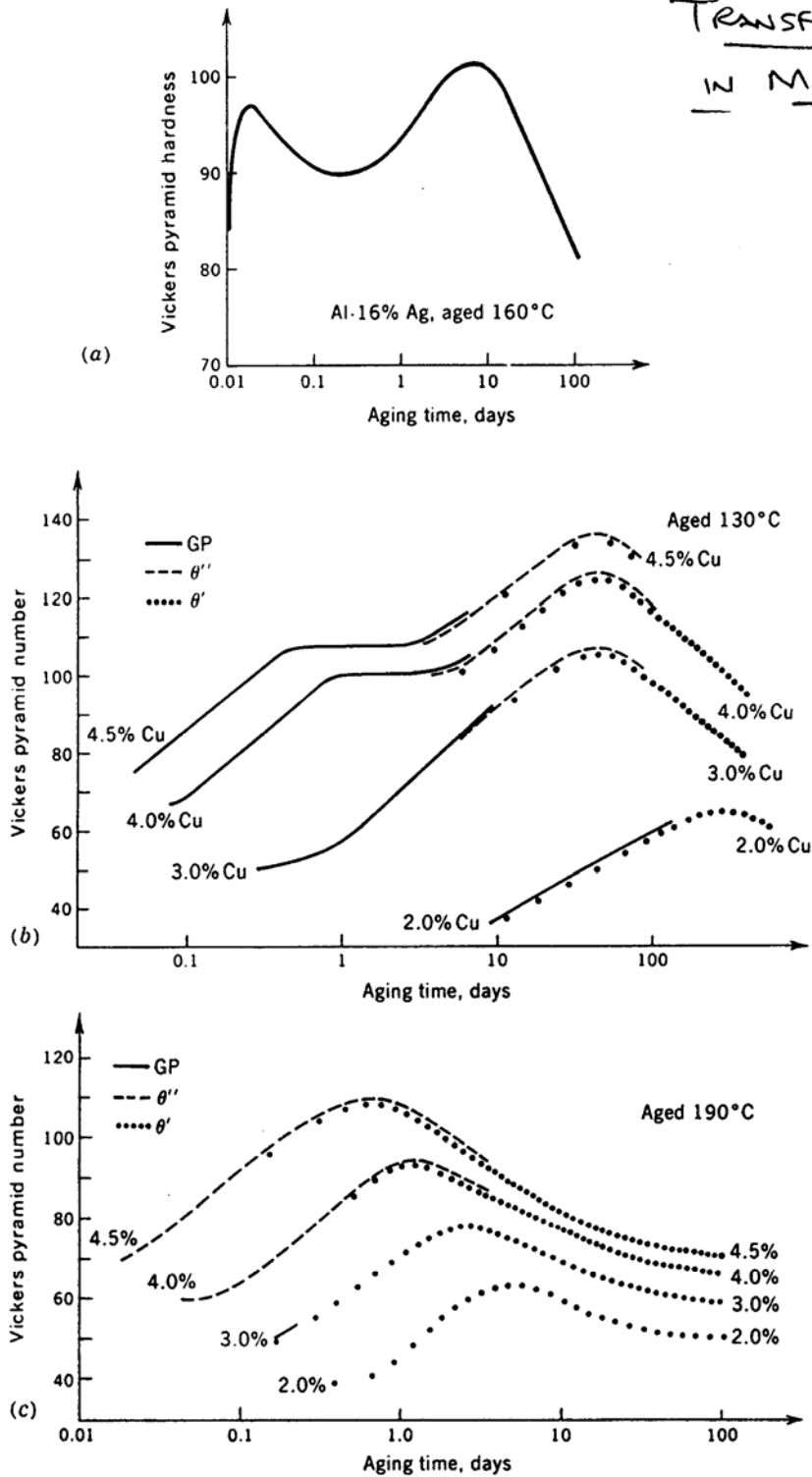
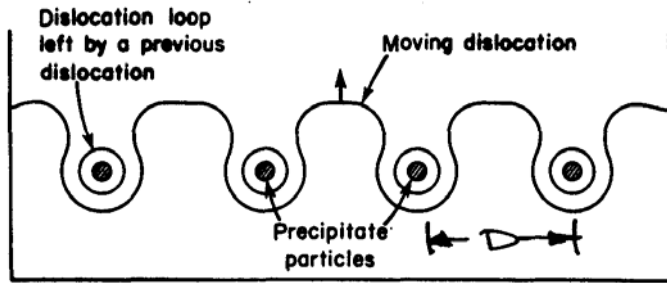


figure 7-14. Shown are figures of hardness vs. aging time at various temperatures in two aluminum alloy systems. Note the double peaks on all but the 190°C Al-Cu curves. The texture of the lines in (b) and (c) represent the type of precipitate present in the alloy at that time. [(a) From R. Nicholson and J. Nulling, *Acta Met.*, 9:332 (1961). (b) and (c) After Silcock, T. Heal, and H. Hardy, *J. Inst. Metals*, 82:239 (1953-1954).]



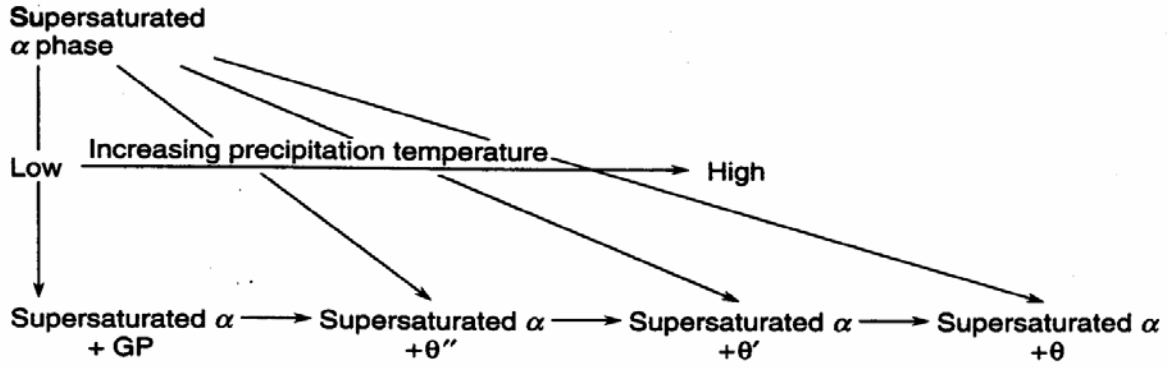
**Fig. 16.17** Orowan's mechanism for the movement of dislocations through a crystal containing precipitate particles.

$$\tau \propto \frac{Gb}{\Delta}$$

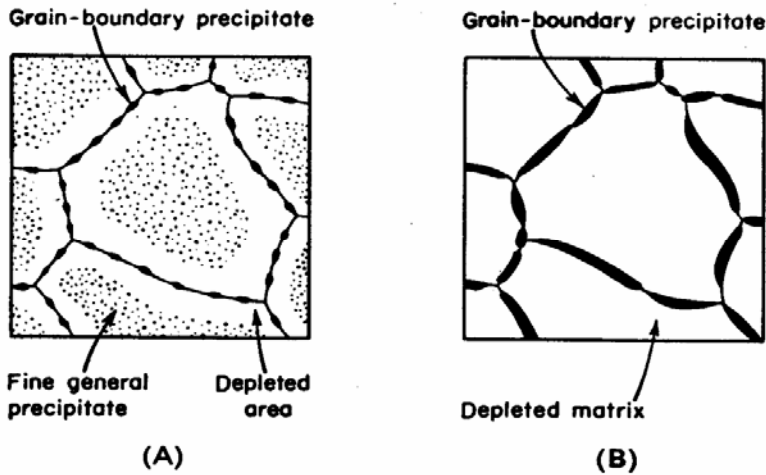
**16.7** The Orowan mechanism, which explains the hardening effect of precipitate particles when the precipitates have grown to a size where they are no longer coherent with the matrix, is shown in Fig. 16.17. The strengthening arises from the fact that the dislocations must bow out between two neighboring precipitate particles. This bowing out is opposed by the line tension of the dislocations. Ashby has deduced an equation giving the stress needed to move dislocations under conditions conforming to the Orowan model. An equation giving this stress, which assumes that the precipitate particles are spherical and that the system involves iron containing carbon, may be found in Leslie, W. C., *The Physical Metallurgy of Steels*, McGraw Hill Book Company, New York, 1980, p. 198. It is:

$$\sigma(\text{MPa}) = \left[ 5.9f^{1/2}/X \right] \cdot \ln(X/b)$$

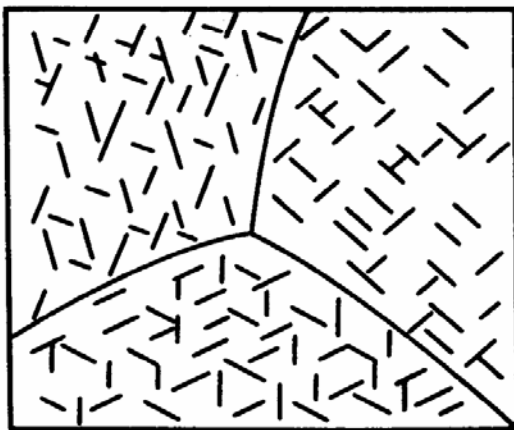
where  $\sigma(\text{MPa})$  is the stress,  $f$  is the volume fraction of the precipitate,  $X$  is the mean linear intercept diameter of the precipitate particles and  $b$  is the Burgers vector. In the case of iron,  $b = 2.5 \times 10^{-4} \mu\text{m}$ . In this equation  $X$  is expressed in  $\mu\text{m}$  units. Plot a curve showing the dependence of the stress on the particle diameter,  $X$ , for the case of a constant volume fraction of precipitate,  $f = 0.001$ . Let  $X$  vary from 0.001 to 0.100  $\mu\text{m}$ .



**Fig. 16.11** Precipitation sequence in Al-Cu alloys.



**Fig. 16.19** Heterogeneous nucleation at grain boundaries. (A) Moderate rate of cooling may result in both heterogeneous nucleation at grain boundaries and homogeneous nucleation in the centers of the grains. (B) Very slow cooling may result in the precipitate occurring only at grain boundaries.



**Fig. 16.20** Schematic representation of a Widmanstätten structure. Short, dark lines represent plate-shaped precipitate particles that are aligned on specific crystallographic planes of the crystals of the matrix.