

재료의 기계적 거동 (Mechanical Behavior of Materials)

Strengthening of Crystalline Materials

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What makes crystals strong?

Strengthening in crystals results from **the restriction of dislocation motion.**

- Dislocation- dislocation interactions
 - Work hardening

- *Grain boundaries*
 - Hall-Petch relationship

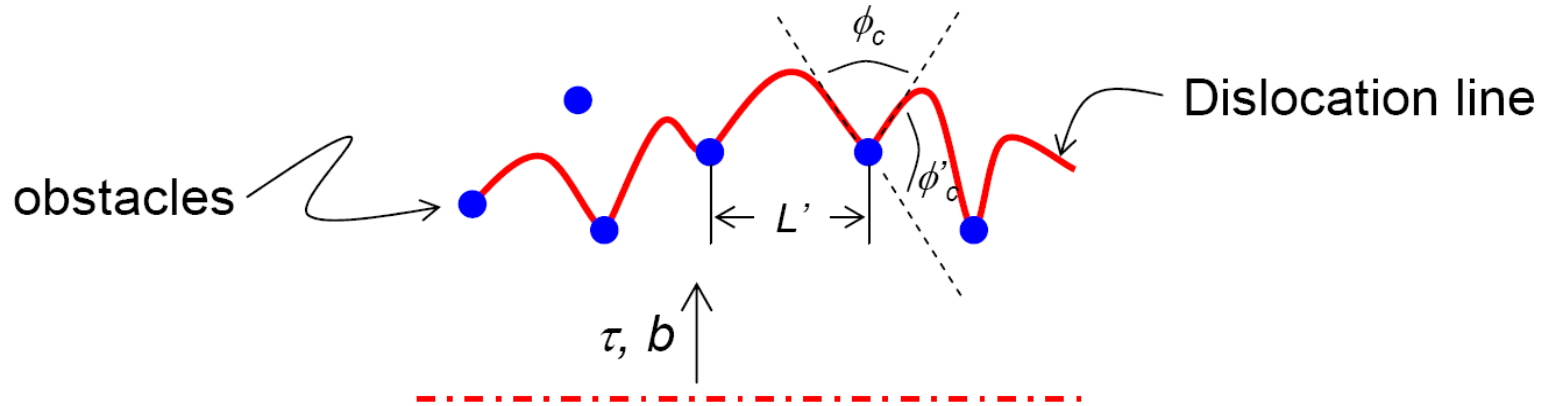
- *Solute atoms*
 - Solid solution hardening

- Precipitates or dispersed particles
 - Precipitation hardening or dispersion hardening

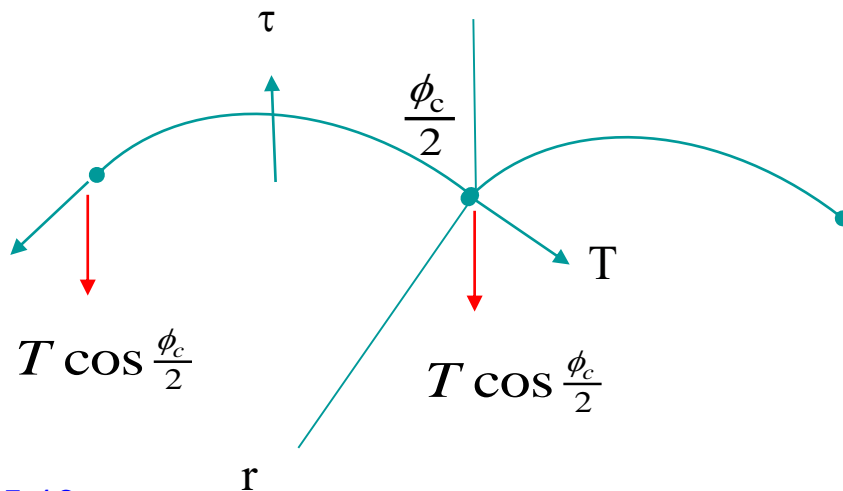
- *Phase changes*
 - Transformation hardening or toughening.

General model for strengthening

Consider a slip plane that contains a random array of obstacles.



L' = Effective particle spacing



$$\tau \cong \frac{Gb}{L'} \cos \frac{\phi_c}{2}$$

Work/Strain Hardening

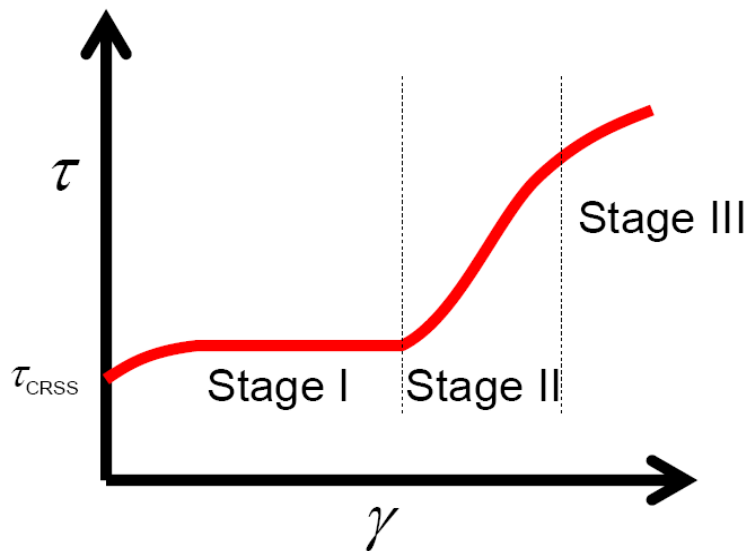
During plastic deformation, there is an increase in dislocation density. It is this increase in dislocation density that ultimately leads to work hardening.

Dislocations interact with each other and assume configurations that restrict the movement of other dislocations.

The dislocations can be either “strong” or “weak” obstacles depending upon the types of interactions that occurs between moving dislocations.

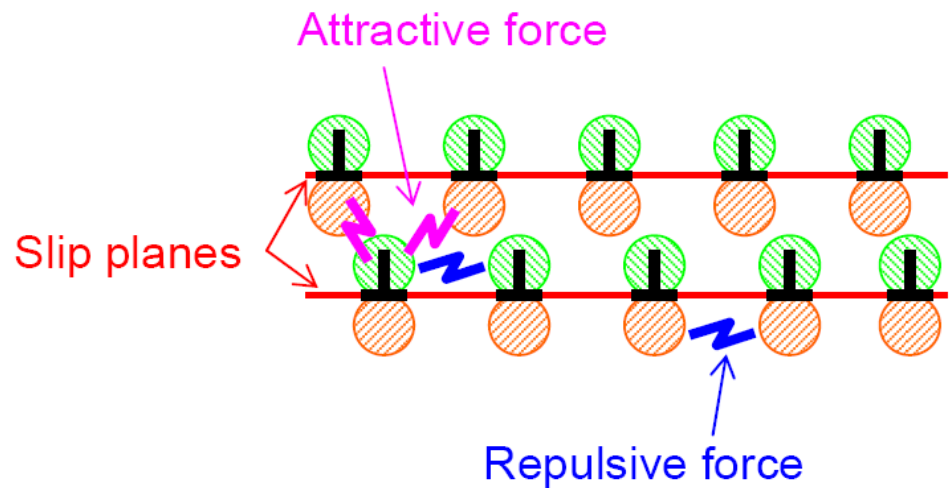


Work/Strain Hardening



Single crystal deformation

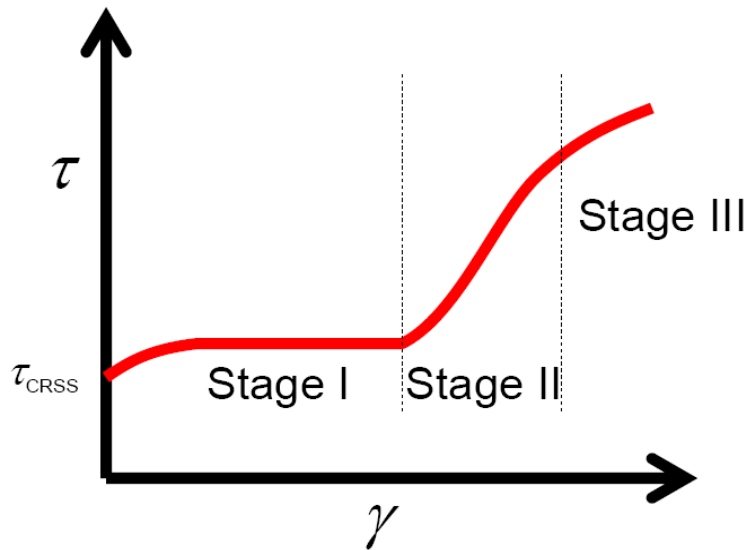
Stage I: Easy glide



These stress fields interact during the early stages of deformation resulting in “weak” drag effects.

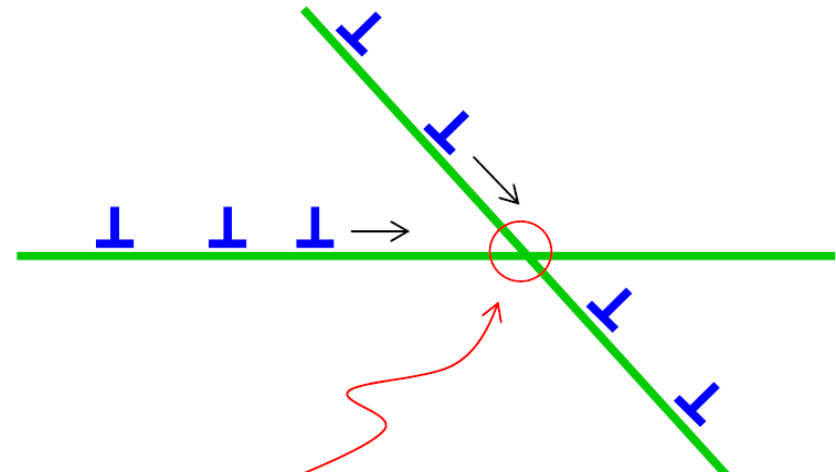
In stage I, dislocations are “weak” obstacles.

Work/Strain Hardening



Single crystal deformation

Stage II: LINEAR HARDENING



Interactions produce immobile dislocation configurations like jogs.

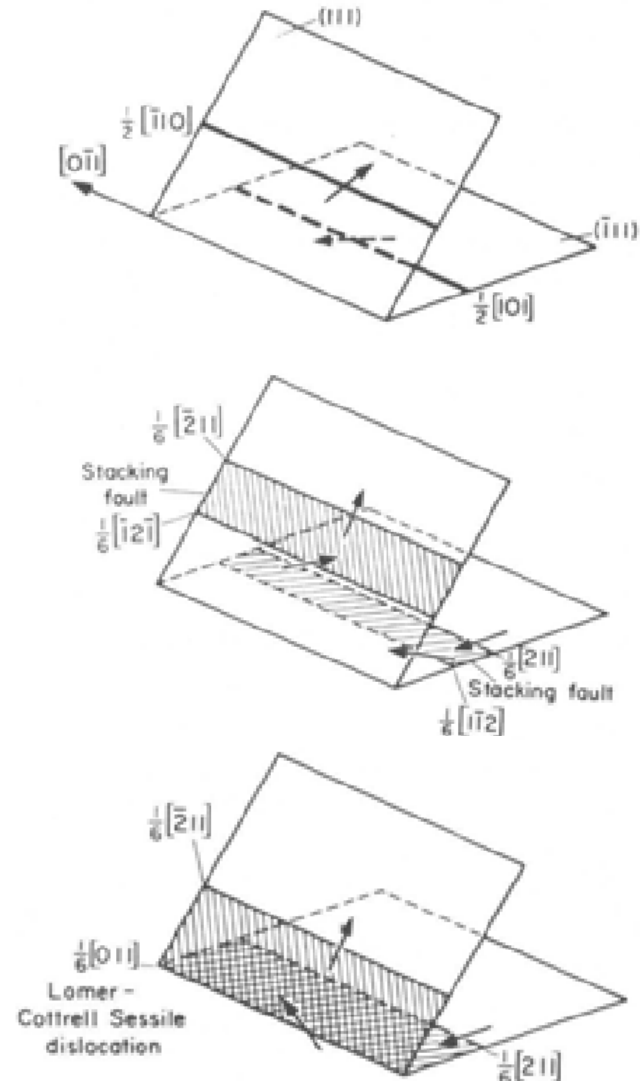
Work hardening depends strongly on dislocation density.

Work/Strain Hardening

Stage II: LINEAR HARDENING

Lomer-Cottrell locks are an example of sessile dislocation configurations that can form in FCC materials when dislocations intersect to produce a new dislocation between the two with a different Burgers vector

$$\frac{1}{6}[-12-1] + \frac{1}{6}[1-12] = \frac{1}{6}[011]$$



Work/Strain Hardening



Work/Strain Hardening

$$\tau_{\max} = \frac{Gb}{L} \quad \leftarrow \quad \bar{L} = \frac{\text{constant}}{\sqrt{\rho_{\perp}}} \cong \frac{\alpha}{\sqrt{\rho_{\perp}}}$$



$$\tau = \tau_o + \alpha Gb\sqrt{\rho_{\perp}}$$

where:

τ_o = intrinsic flow strength for \perp free material

α = constant (0.2 for FCC, 0.4 for BCC)



Work/Strain Hardening

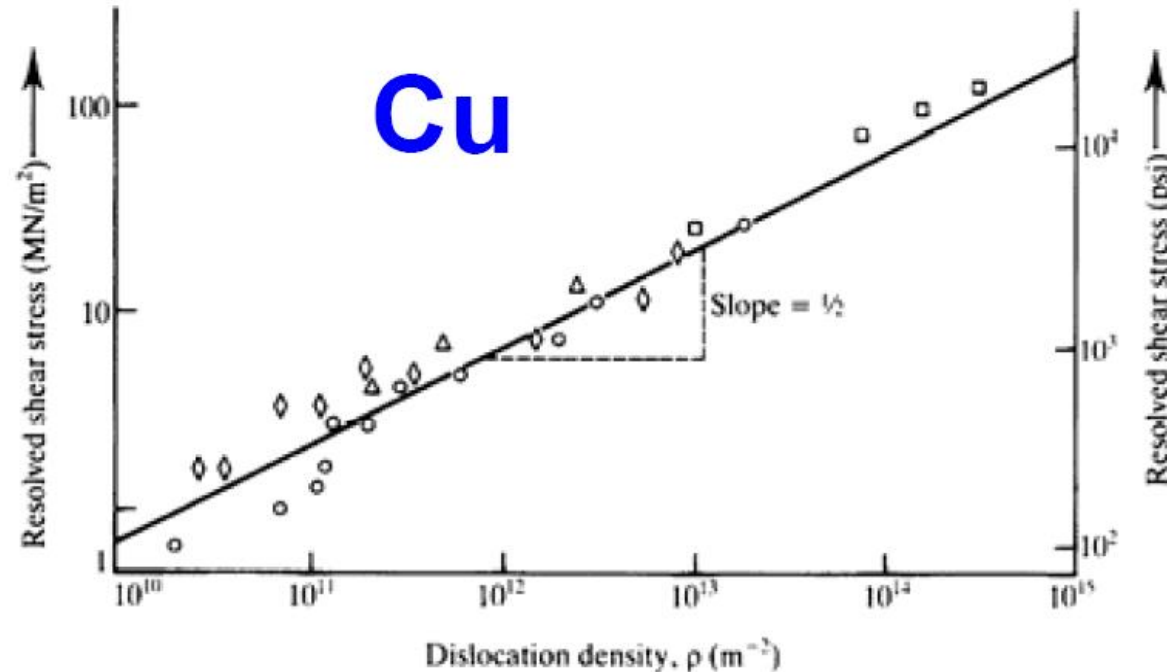


Figure 5.4

Critical resolved shear stress as a function of dislocation density for Cu single crystals and polycrystals. The observed slope of $\frac{1}{2}$ on the logarithmic coordinates verifies that Eq. (5.5) describes the flow strength of work-hardened materials as it relates to dislocation density. \square , polycrystalline Cu; \circ , single-crystal Cu-one slip system; \diamond , single-crystal Cu-two slip systems; \triangle , single-crystal Cu-six slip systems. (After H. Weidert, *J. Metals*, **16**, 425, 1964.)

Grain-Boundary Strengthening

- Grain boundaries impede dislocation motion. Thus, they contribute to strengthening.
- The magnitude of the observed strengthening depends upon **the structure of the grain boundaries and the degree of misorientation between grains**.
- Many models have been developed to describe grain boundary strengthening. Interestingly, nearly all of them can be reduced to the **Hall-Petch relationship** as originally proposed by Hall (1951) and Petch (1953).
 - E.O. Hall, Proceedings of the Physical Society B, 64 (1951) p. 747
 - N.J. Petch, “The cleavage strength of polycrystals,” J. Iron Steel Inst., 174 (1953), p. 25.



Hall - Petch Relation

Hall-Petch equation

$$\sigma_y = \sigma_0 + k_y d^{-1/2}$$



Tensile yield
strength



Material
constant



Grain size

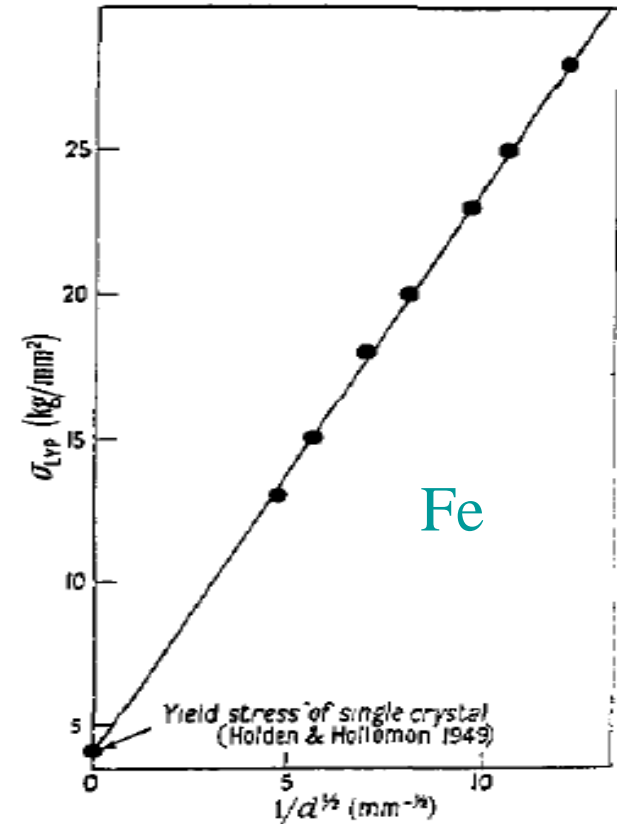


Figure 2.

E.O. Hall, Proc. Phys. Soc. B, (1951)



Yield Strength vs. (Grain size)^{1/2}

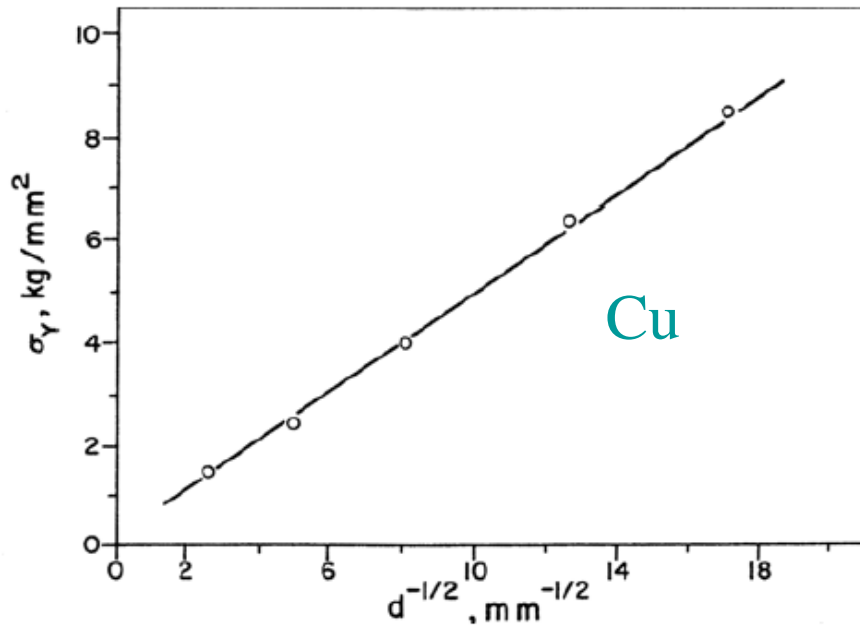


Fig. 4—Yield stress as a function of grain size. Yield stress was defined as the stress at 0.002 plastic strain.

A. W. Thomson, et. Al., Metall. Trans., (1971)

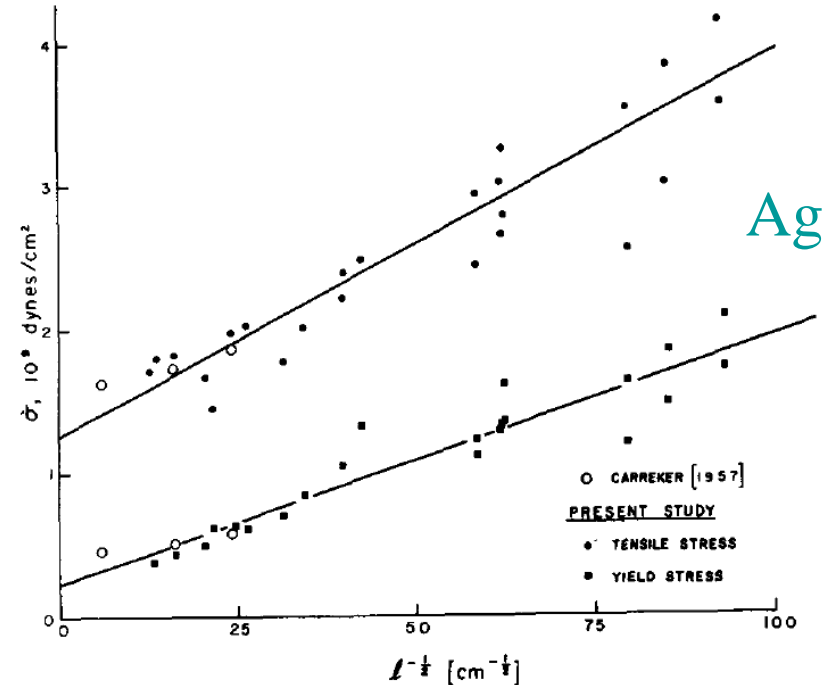


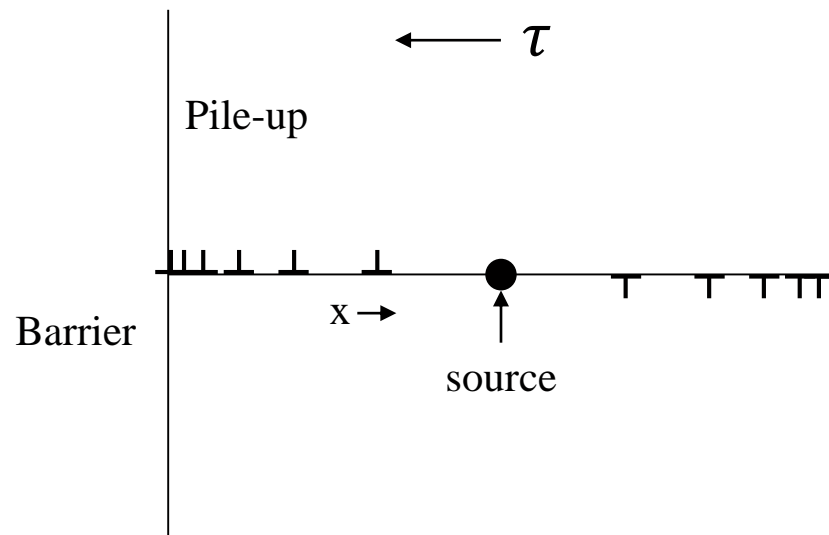
Fig. 2—The yield stresses and tensile fracture stresses of commercial purity silver as a function of the inverse square root of their grain size. 22°C

J.W. Aldrich and R.W. Armstrong, Metall. Trans., (1970)



Dislocation Pile-ups

A dislocation source emits a series of dislocations in the same slip plane. If a leading dislocation meets a barrier such as grain boundary or sessile dislocation, the dislocation pile-up behind the leading dislocation.



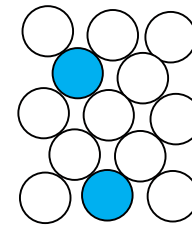
Theories of Hall-Petch Relation

- Pile-Up Theory
- Cottrell's Theory
- Work Hardening Theory
- Grain Boundary Source Theory



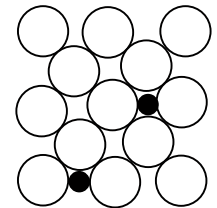
Solid-solute Strengthening

1. When two or more elements are combined such that single phase microstructures are maintained, **an elastic interaction occurs** between the solute atoms and the dislocations.
2. These interactions ultimately produce **an alloy that is usually stronger than the pure metal.**
3. Solute atoms of roughly similar sizes (i.e., within $\pm 15\%$ of the radii of the parent atoms) can occupy points in the crystal lattice of solvent atoms. We call this a **substitutional solid solution.**
4. When solute atoms are considerably smaller than the solvent atoms, they occupy interstitial sites in the solvent lattice. We call this type of solid solution an **interstitial solid solution.**



● - Solute atoms
(zinc)

○ - Solvent atoms
(copper)

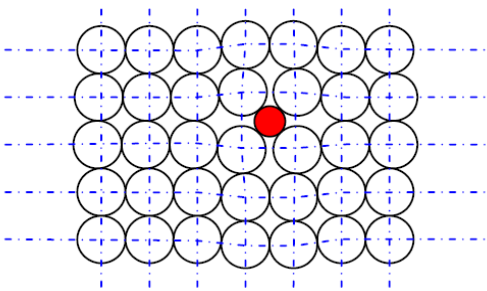


● - Solute atoms
(carbon)

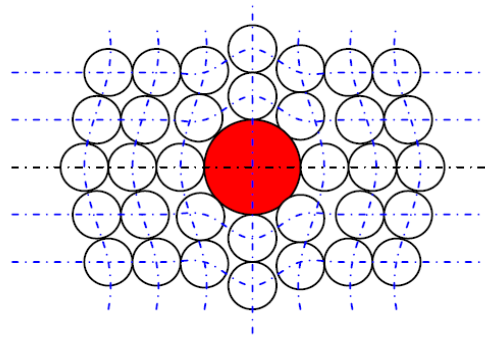
○ - Solvent atoms
(iron)

Solid-solute Strengthening

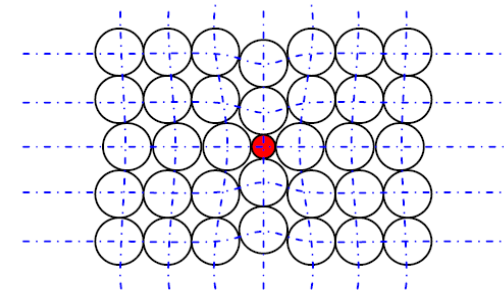
The size effect



Interstitial solute



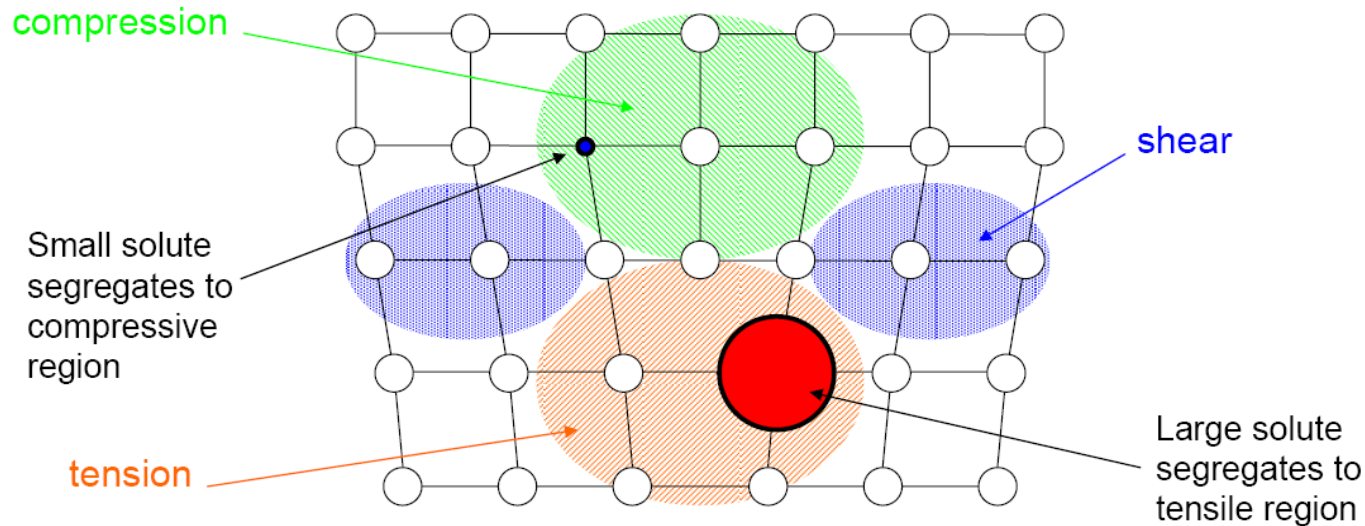
Big substitutional solute



Small substitutional solute

- 1. Foreign atoms “stretch” (i.e., dilate) the lattice.**
- 2. This increases the resistance to dislocation motion.**

Solid-solute Strengthening



There is an interaction between the strain fields around solute atoms and the strain fields around dislocations. This interaction is based on reducing the strain energy.

Using an edge dislocation in this example, solute atoms with dilatational strain fields will interact with these regions to cancel out strain and thus reduce the elastic strain energy.

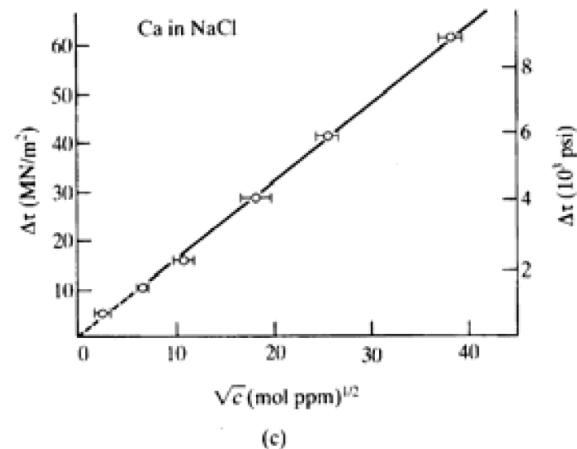
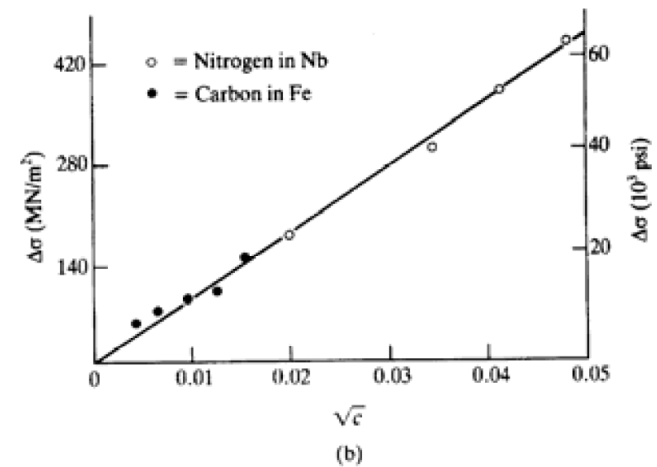
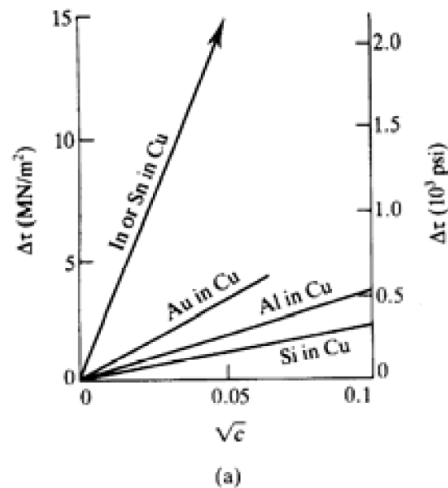
Both attractive and repulsive forces between solutes and dislocations will inhibit the motion of dislocations, thus increasing strength.

Solid-solute Strengthening

The general strengthening equation for “conventional” substitutional solid solution strengthening has been estimated by Fleischer.

$$\tau_y = \frac{G\varepsilon_s^{3/2}\sqrt{c}}{700}$$

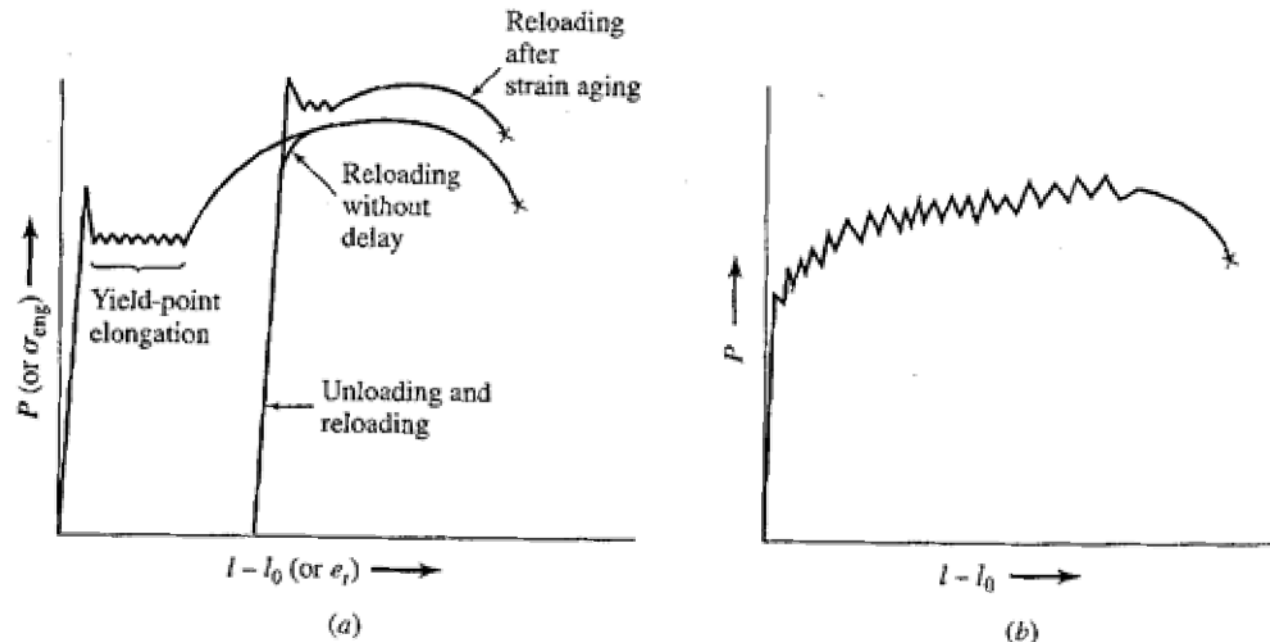
Verification of the $c^{1/2}$ dependence of solid solution hardening



Solute Atmospheres (Yield Point Phenomena)

Dense atmosphere of solute atoms around dislocations is induced and called as *Cottrell atmosphere*.

The stress should be required to dissociate the locked dislocation from the solute atmosphere.



Schematic illustrations of (a) upper yield point formation characteristic of static strain aging and (b) serrated yielding characteristic of dynamic strain aging.

Precipitation and Dispersion Hardening

How can dispersed particles influence strength?

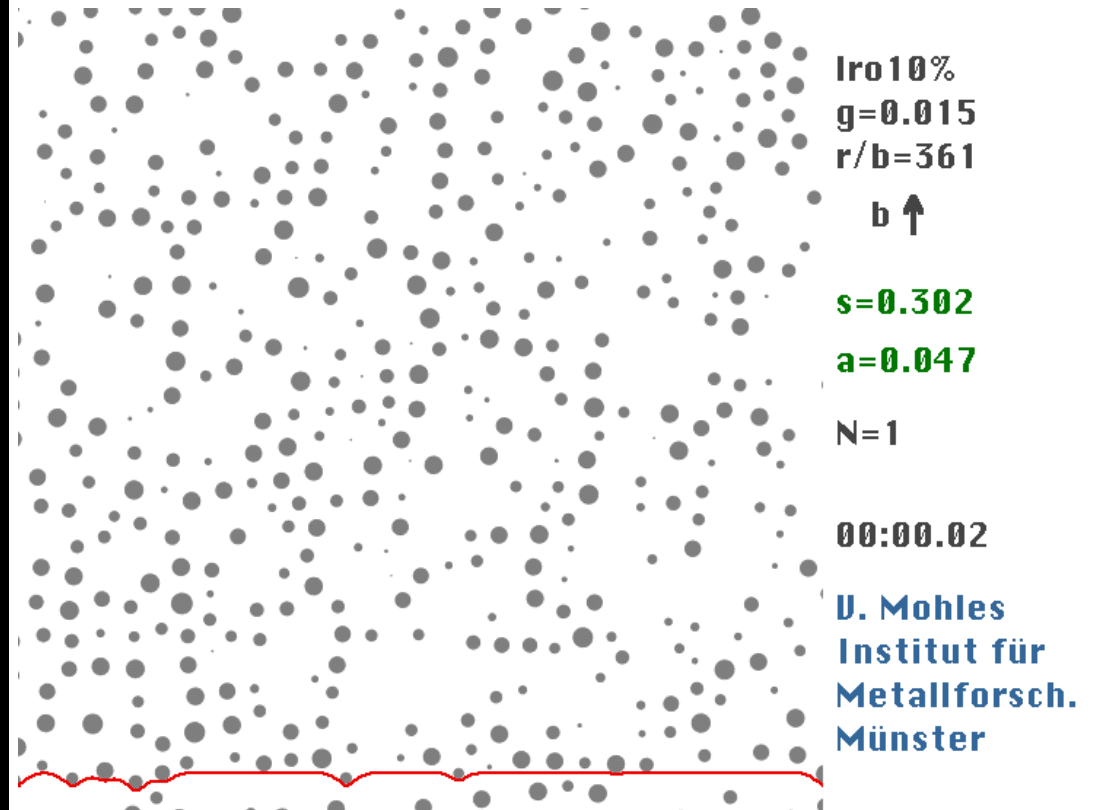
- Dispersed particles can also increase the strength of a solid by impeding dislocation motion.
- The particles can be precipitates, which are natural. They can also be things like dispersed oxide or carbide particles which are not natural.
- **Particle hardening is generally a more potent way to strengthen a material than solid solution hardening.** Precipitates and dispersed phases are usually more effective barriers to dislocation penetration than single solutes.

Strengthening is determined by the interaction of dislocations with the particles. Dislocations will either :

1. **Cut through particles**
2. **Extrude between (loop around) particles.**

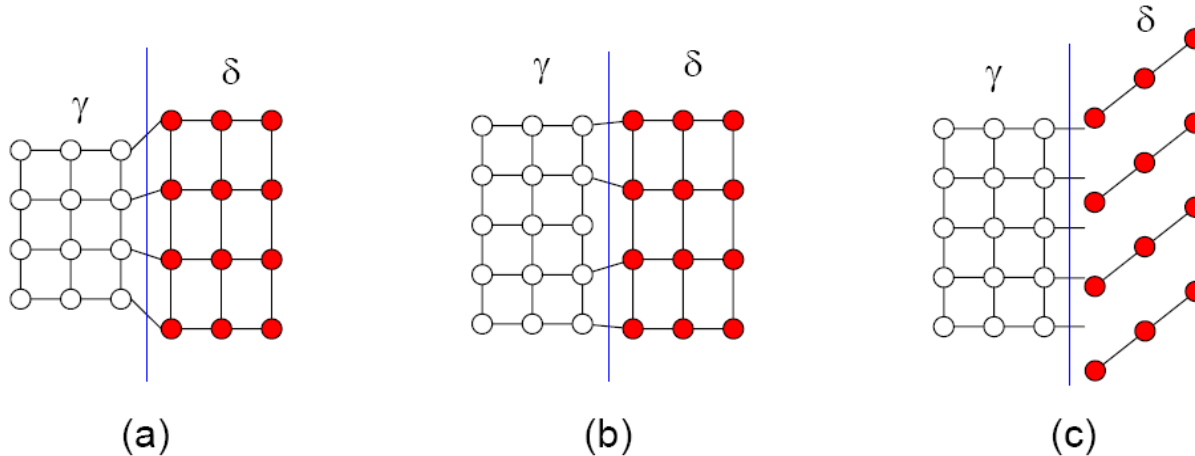


Precipitation and Dispersion Hardening



Precipitation and Dispersion Hardening

Coherency of interface



- a) **Coherent interface** – Two crystals/phases match perfectly at the interface plane so that the two lattices are continuous across the interface. **Strengthening arises from lattice parameter mismatch between phases.**
- b) **Semi-coherent interface** – Matching is imperfect between two crystals/phases. Mismatch strains are reduced by formation of dislocations at inter-phase boundaries.
- c) **Incoherent interface** – There is no matching between phases at the interface plane. Atomic planes do not line up. No coherency strain.

Precipitation and Dispersion Hardening

Precipitation

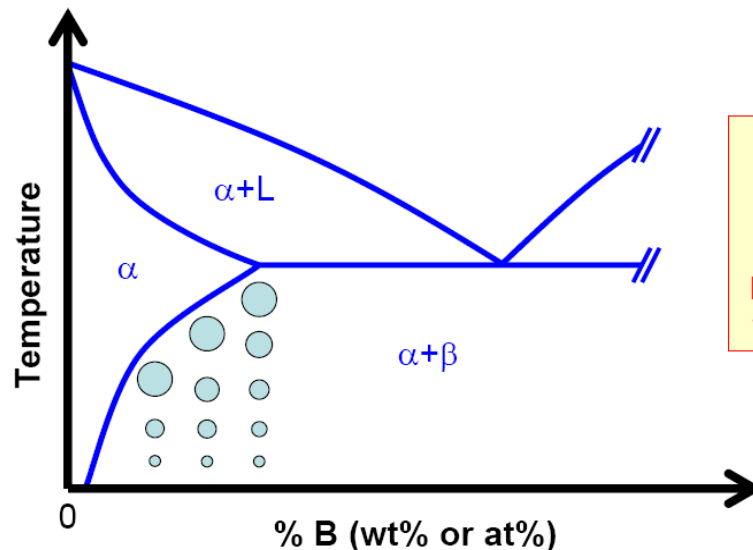
- Precipitates are generally very small in the early stages of precipitation. They coarsen with time at temperature.

1. Small particles are generally coherent

2. Intermediate particles are often partially coherent

3. Large particles are generally incoherent

- Properties will scale with precipitate size and spacing for a constant precipitate volume fraction.



Precipitate size scales with time and temperature.
THUS
Properties change with time at temp.

Precipitation and Dispersion Hardening

Coherency Strain

Dislocations interact with the strain fields that surround coherent particles in the same way that they interact with the strain fields surrounding solid solution atoms.

The increase in resolved shear stress is:

$$\tau_{coh} \cong 7 |\varepsilon_{coh}|^{3/2} G \sqrt{\frac{rf}{b}}$$

where

$$\varepsilon_{coh} = \frac{a_{ppt} - a_{matrix}}{a_{matrix}}$$

In this equation, the rf/b term \propto to solute concentration in that f is the precipitate volume fraction and r is the precipitate radius (i.e., “precipitate concentration”).



Precipitation and Dispersion Hardening

Modulus hardening

When a precipitate has a shear modulus that is different from that of the matrix, the line tension on a dislocation that enters a precipitate is altered.

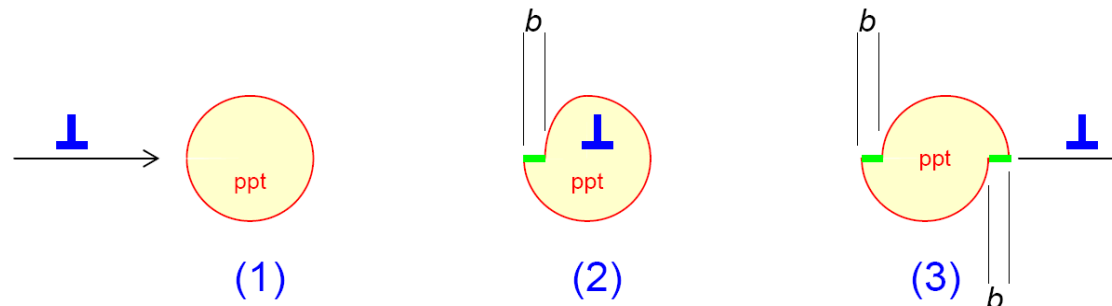
$$\tau_{Gppt} = 0.01G\varepsilon_{Gppt}^{3/2} \sqrt{\frac{fr}{b}}$$

where

$$\varepsilon_{Gppt} = \frac{(G_{ppt} - G_{matrix})}{G_{matrix}}$$

Chemical strengthening

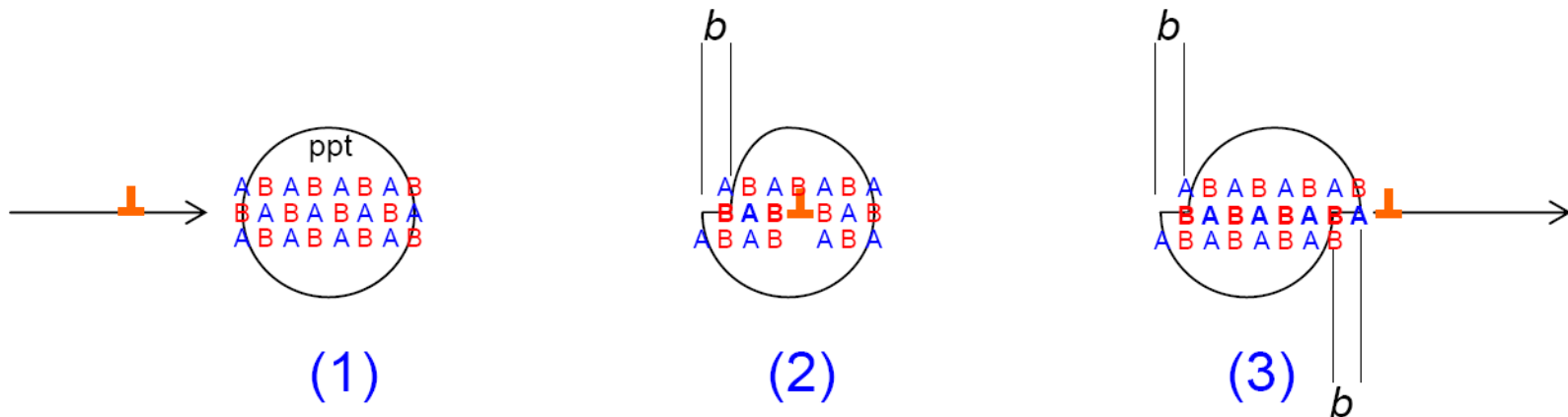
When a dislocation passes through a particle, a new region of particle-matrix interface is produced. There is a surface energy associated with this new interface.



Precipitation and Dispersion Hardening

Other factors to consider when particles are coherent

When a particle has an ordered structure, like bonds (i.e., A-A, B-B, etc.) will form when a single dislocation passes through the precipitate. These are called **anti-phase boundaries (APBs)**. This represents a higher energy state than the desired A-B type bonding. The energy increase is the APB energy.

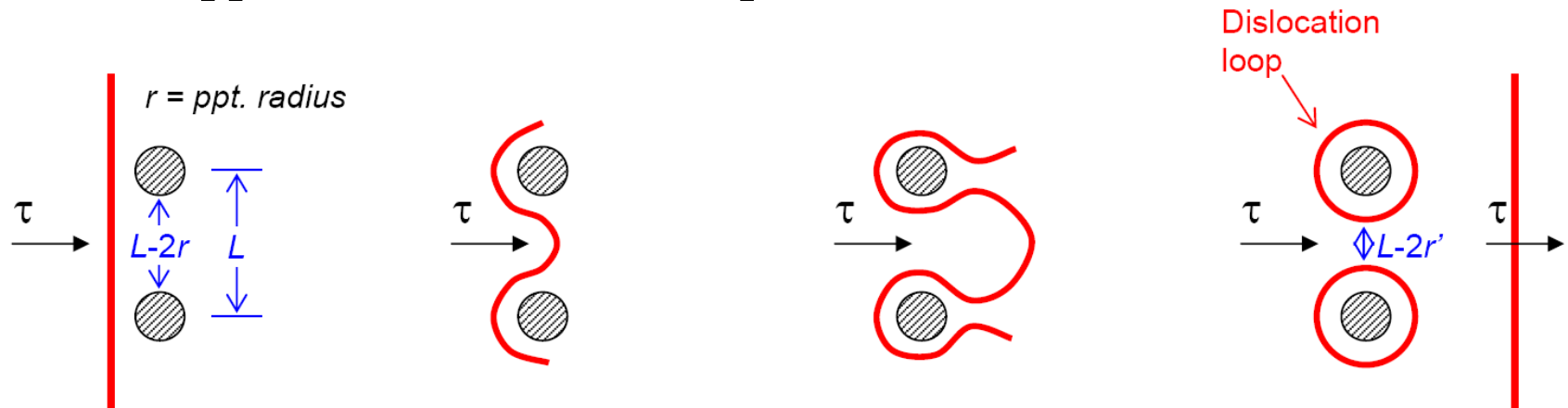


$$\tau_{order} = \frac{\pi\gamma_{APB}f}{2b}$$

Precipitation and Dispersion Hardening

Bypass mechanisms

Particles can bypass incoherent precipitates by looping around them. This also applies to non-deformable particles.



Dislocation bowing will occur when the volume of particle phase increases above some critical value or when the interface boundary is incoherent.

The shear stress required to cause bowing is given by:

$$\tau_{\text{bowing}} = \frac{Gb}{(L-2r)} = \frac{Gb}{L'}$$

Precipitation and Dispersion Hardening

Orowan looping

Orowan loops as they appear in
an electron microscope

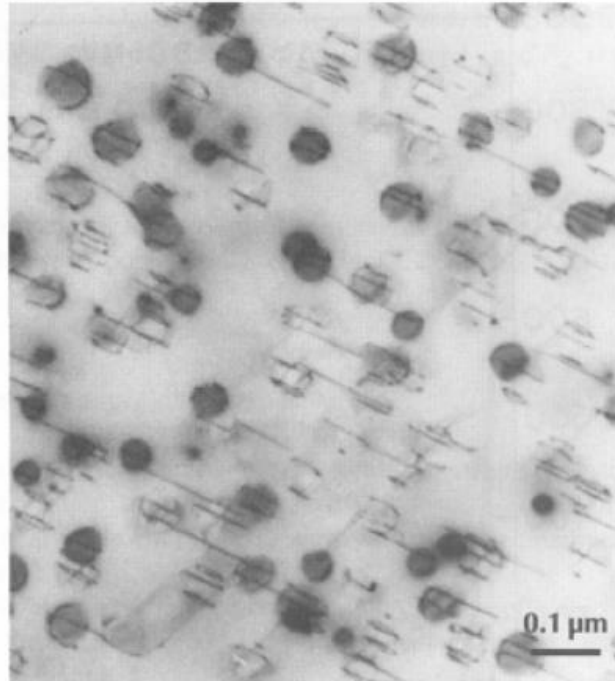


Fig. 2.16 TEM image of Orowan loops surrounding γ' particles in a precipitation-hardened austenitic steel deformed 1% at 650°C.

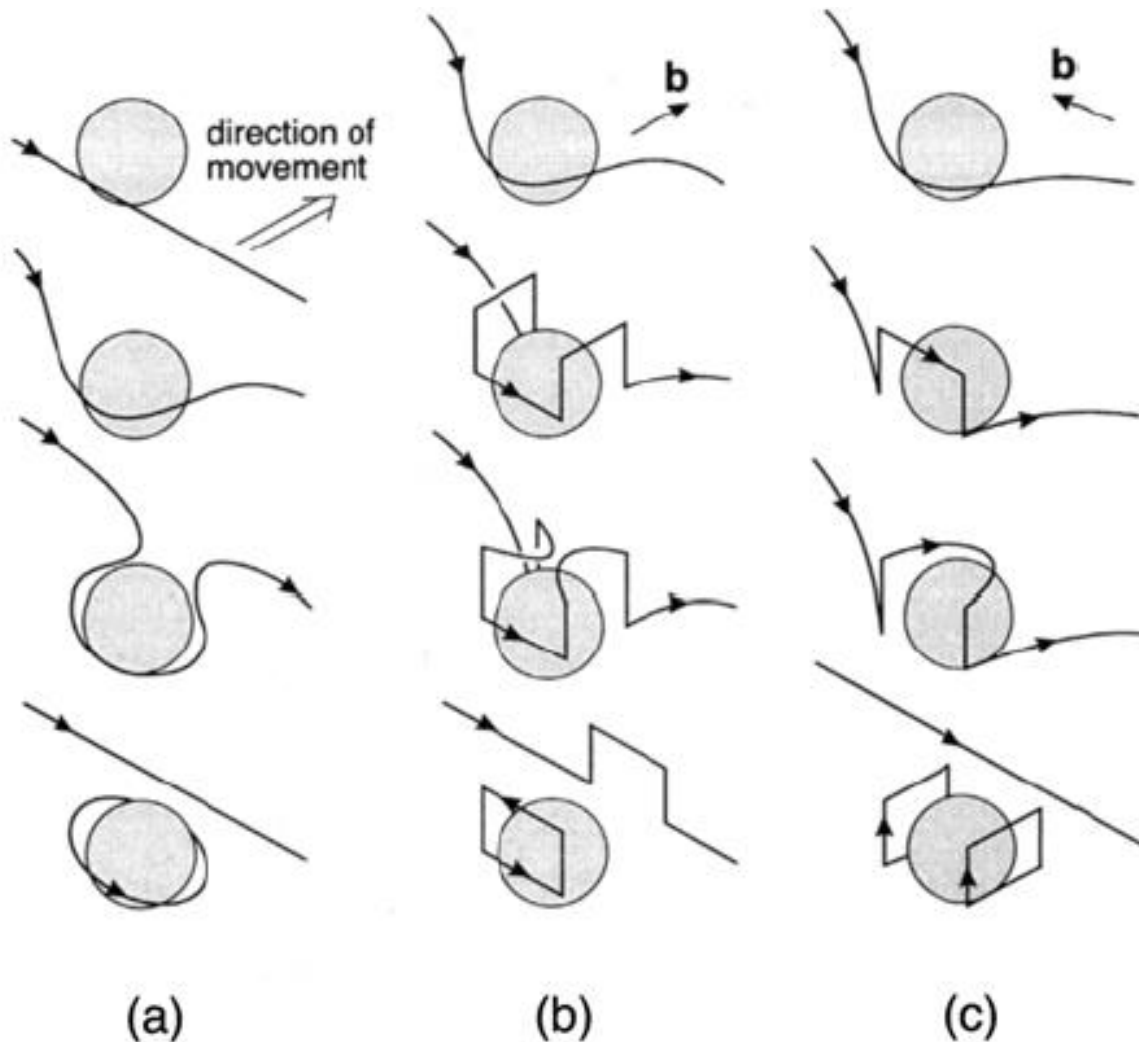
Precipitation and Dispersion Hardening

Transition from cutting to bowing

1. As particle size increases, it becomes more difficult for cutting to occur.
2. In general, particles that are smaller than some critical size are **“sheared.”** This means that dislocations cut through them. When particles are larger than the critical size, they are **“bypassed”** by **“bowing.”**



Precipitation and Dispersion Hardening



Precipitation-Hardened Al Alloy (Al-Cu)

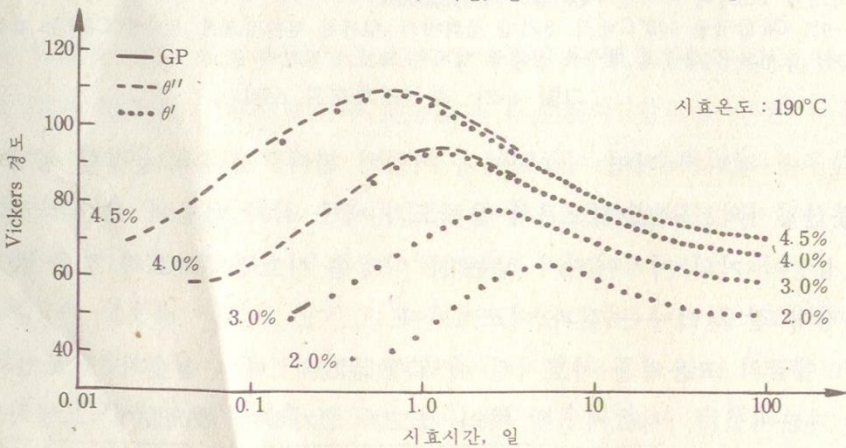
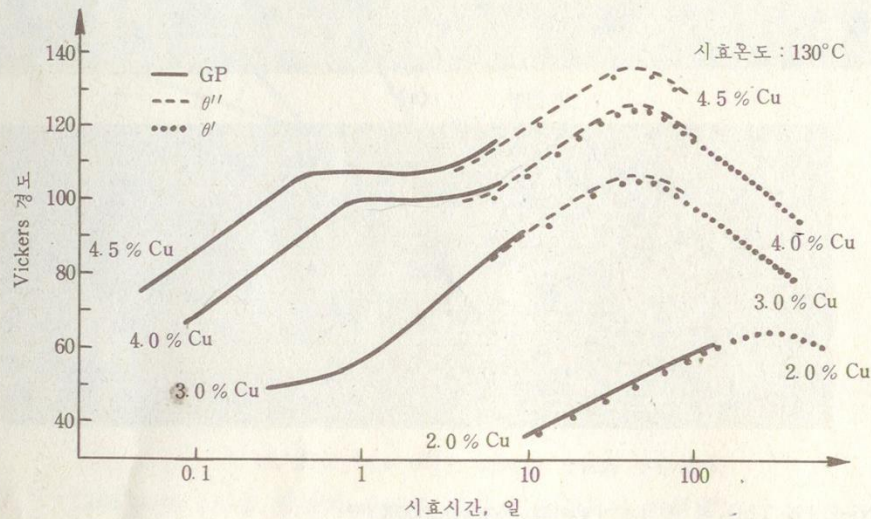


그림 4-23 Al-Cu 합금의 시효곡선⁽⁵⁵⁾

1. GP I or GP

- Plate (about 25 atoms-diameter)
- Guinier and Preston observed.
- Sheared by dislocation (Coherent)

2. GP II or θ''

- Plate (about 75 atoms-diameter)
- Sheared by dislocation (Coherent)

3. θ'

- CuAl_2
- Bowing (Coherent or Semi-coherent)
- Peak of hardness

4. θ

- Bowing (Incoherent)
- Decrease of hardness

(Space between the particles increase.)

GP I or GP \rightarrow GP II or $\theta'' \rightarrow \theta' \rightarrow \theta$



Martensite Transformation

The name martensite is after the German scientist Martens. It was used originally to describe the hard microconstituent found in **quenched steels**.

Many materials other than steel are now known to exhibit the same type of **solid-state phase transformation**, known as a martensitic transformation, frequently also called **a shear or displacive transformation**. Martensite occurs in, for example, nonferrous alloys, pure metals, ceramics, minerals, inorganic compounds, solidified gases and polymers.

Composition	M_S / K	Hardness HV
ZrO ₂	1200	1000
Fe-31Ni-0.23C wt%	83	300
Fe-34Ni-0.22C wt%	< 4	250
Fe-3Mn-2Si-0.4C wt%	493	600
Cu-15Al	253	200
Ar-40N ₂	30	



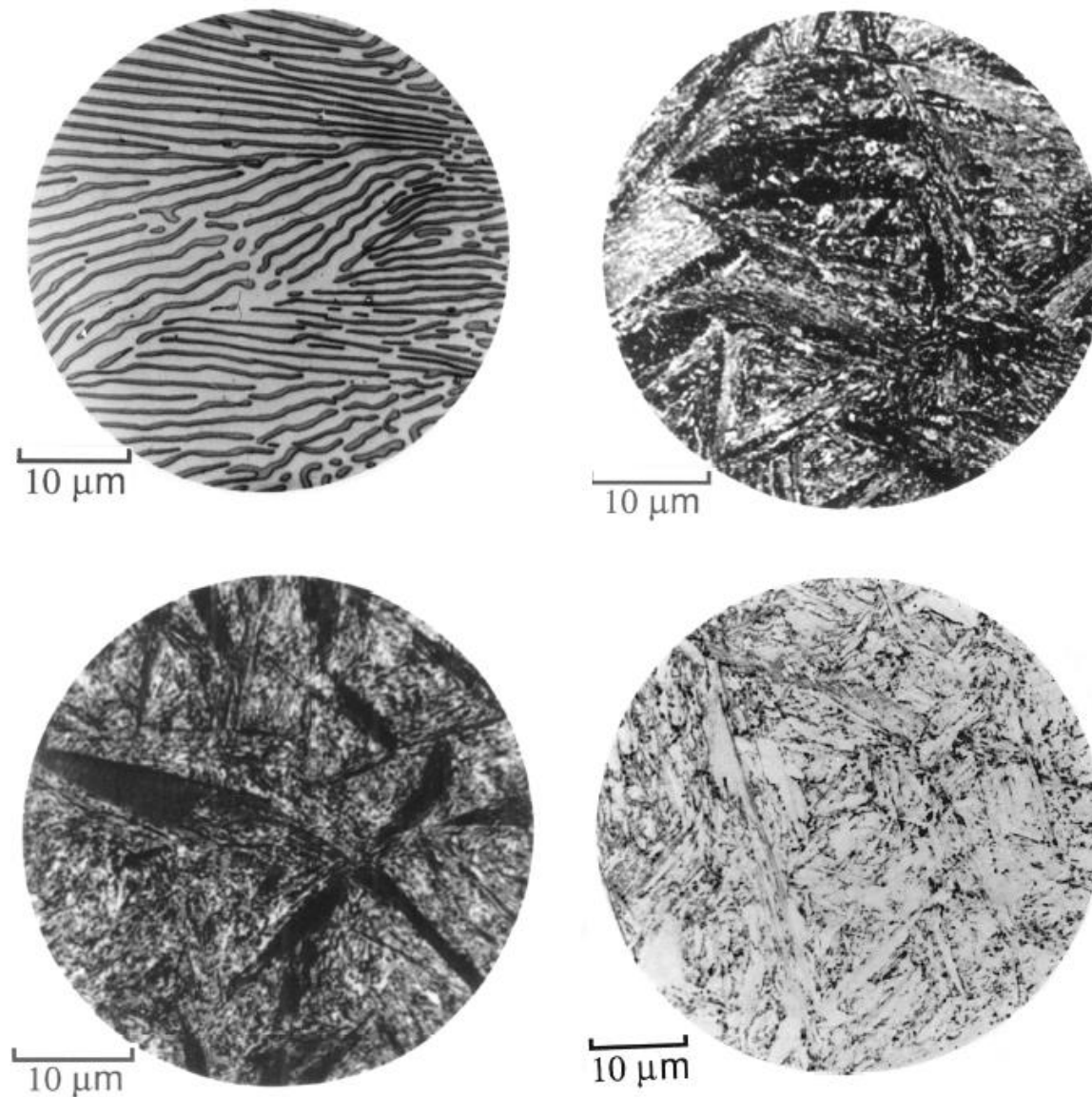
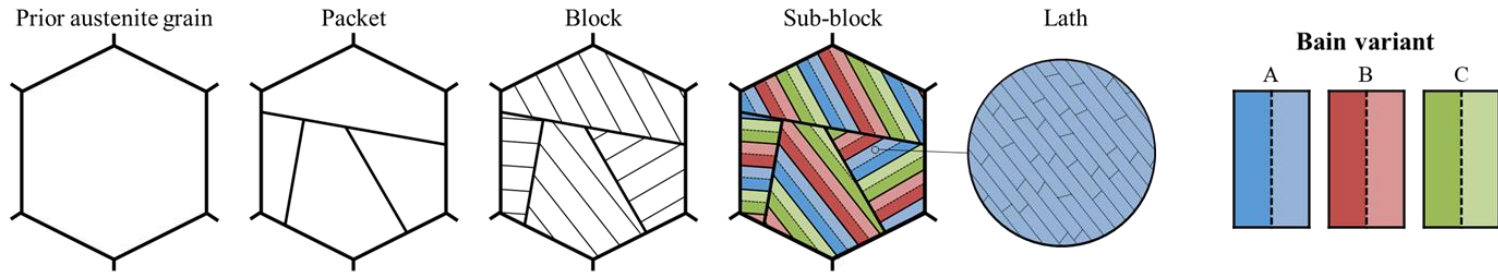


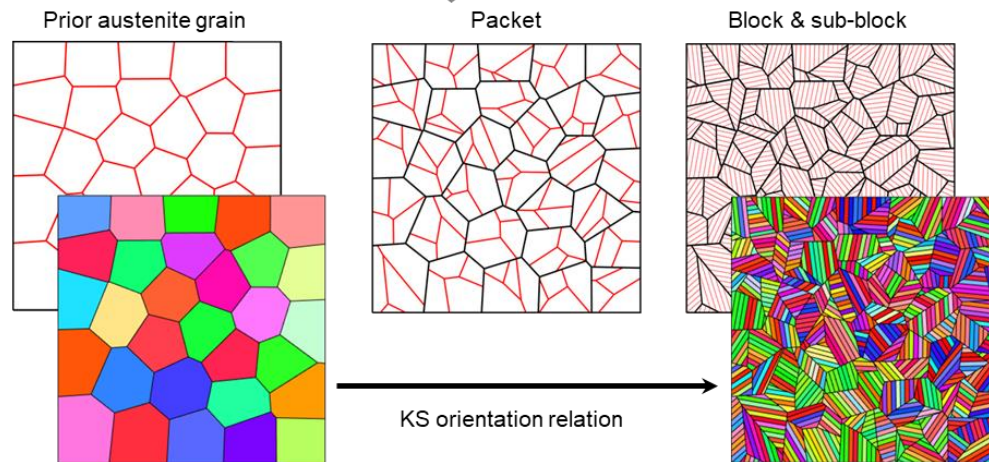
Fig. 1.1 Microstructures in a eutectoid steel: (a) Pearlite formed at 720 °C; (b) bainite obtained by isothermal transformation at 290 °C; (c) bainite obtained by isothermal transformation at 180 °C; (d) martensite. The micrographs were taken by Vilella and were published in the book *The Alloying Elements in Steel* (Bain, 1939). Notice how the bainite etches much darker than martensite, because its microstructure contains many fine carbides.

Theoretical lath martensite with hierarchical structure based on KS orientation relationship $\{111\}_\gamma // \{110\}_\alpha$
 $\langle 110 \rangle_\gamma // \langle 111 \rangle_\alpha$



Virtual microstructure

Voronoi-based hierarchical martensitic microstructure



Assumption

Sub-block is homogeneous.

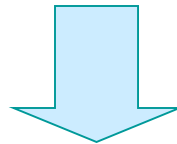
※ Most of the lath boundaries have misorientation angles $< 5^\circ$ [1]



Strengthening by Martensitic Transformations

Martensite can **form at very low temperatures**, where diffusion, even of interstitial atoms, is not conceivable over the time period of the experiment. A low transformation temperature is not sufficient evidence for **diffusionless** transformation.

Martensite plates can **grow at speeds which approach that of sound in the metal**. In steel, this can be as high as 1100m/s, which compares with the fastest recorded solidification front velocity of about 80m/s in pure nickel. Such large speeds are inconsistent with diffusion during transformation.

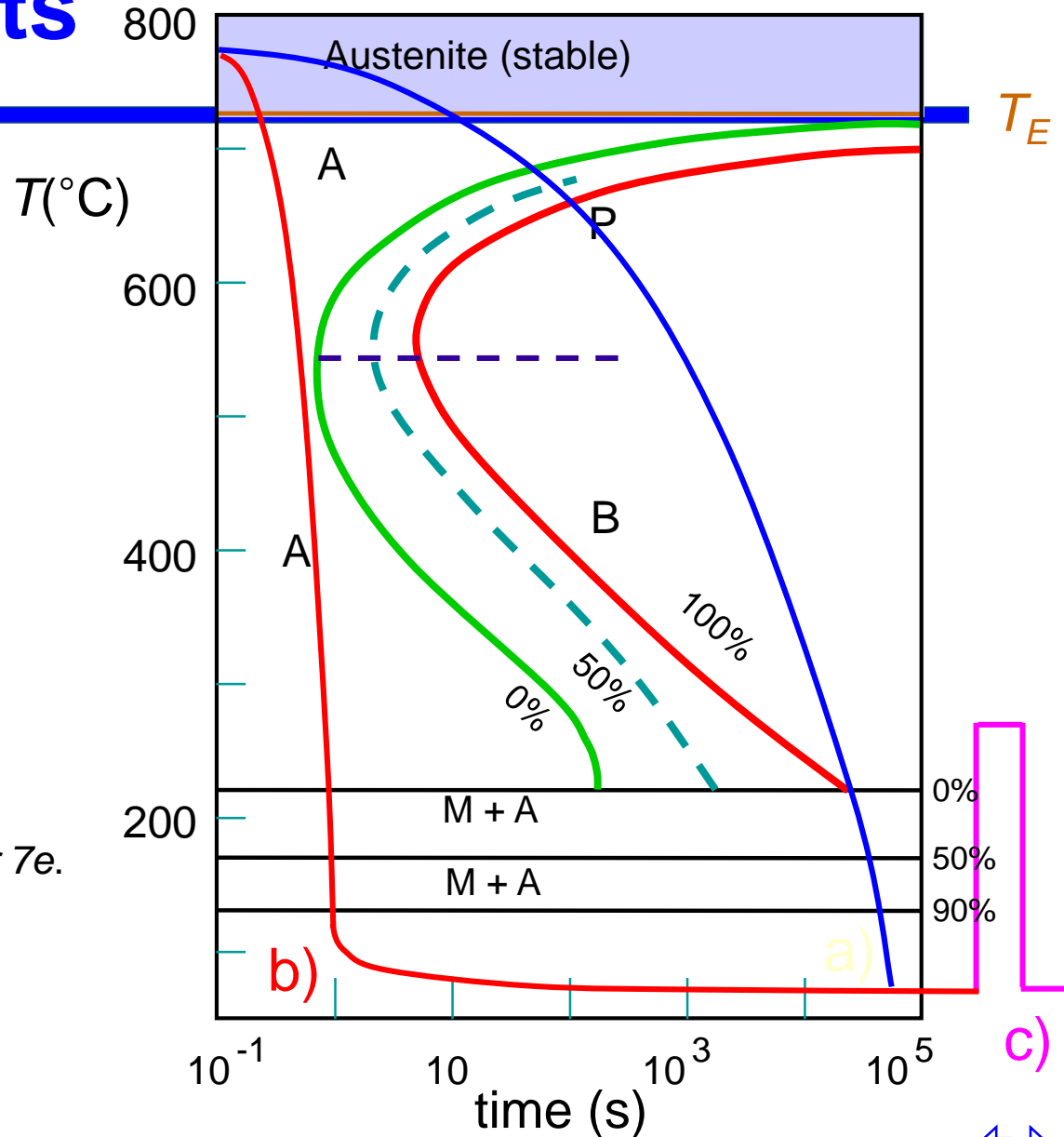


1. **High Dislocation Density.**
2. **High Content of Solute Atoms (mainly carbon)**

Heat Treatments

- a) Slow cooling
- b) Quenching
- c) Tempered Martensite

Adapted from Fig. 10.22, *Callister 7e*.



HOW DO WE “ENGINEER” AN ALLOY FOR OPTIMAL STRENGTH?

- **Use work-hardening to improve strength**
 - Reduces toughness. Work hardening capacity is reduced.
 - Can be annealed out at intermediate temperatures.
 - Limited effectiveness in high strength materials as YS is near UTS.
- **Use grain-size (GS) strengthening**
 - Reduction in GS can improve strength and toughness. Strength increase is limited.
 - Fine grains are bad at high temperature.
 - Alloys susceptible to creep.
 - Grain boundaries are rapid diffusion pathways.
 - Grains will grow.
- **Use solid solution strengthening**
 - Substitutional solutes can give moderate increase in strength. Effectiveness is limited by solubility. Solute with big lattice misfits often have low solubility.
 - Interstitial solutes can provide a low increase in strength for BCC metals (~70 MPa). You can quench in excess interstitial solutes such as C, or N into steels which will yield large strength increase (~1 GPa). However, this results in a large decrease in ductility.
- **Use precipitation hardening**
 - Need very fine dispersion of hard precipitates to get large strength increase (~1 GPa).
 - Dispersion of weak precipitates is not as effective.

