Introduction to

Materials Science and Engineering

Chapter 7

Dislocations and Strengthening

- Why are dislocations observed primarily in metals and alloys?
- How are the strength and dislocation motion related?
- How do we increase the strength?
- How can heating change the strength and other properties?

Contents

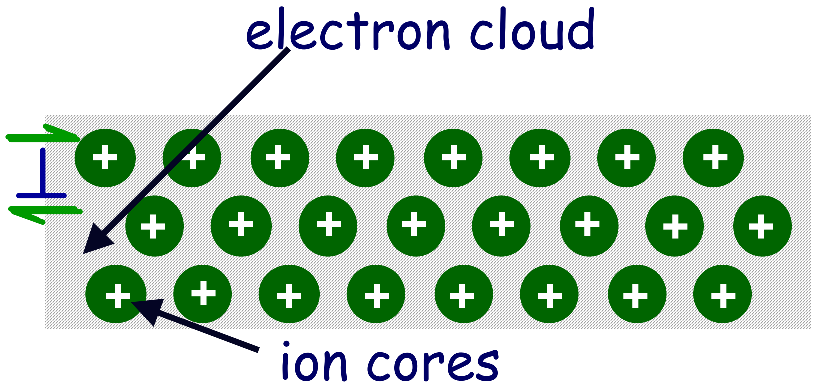
Dislocations & Materials Classes

- Metals:

  Dislocation motion easy

  √ Non-directional bonding

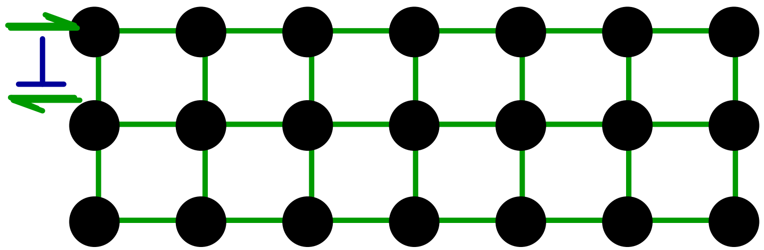
  √ Close-packed directions for slip



- Covalent Ceramics (Si, SiC, diamond):

  Motion hard

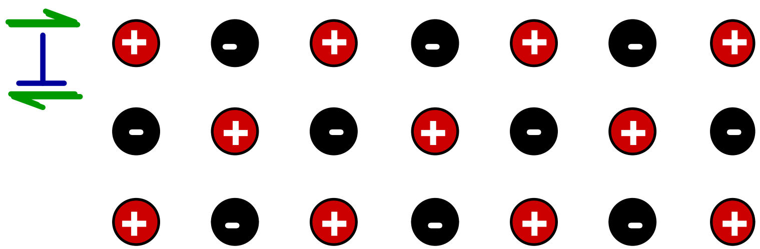
  √ Directional (angular) bonding



- Ionic Ceramics (NaCl):

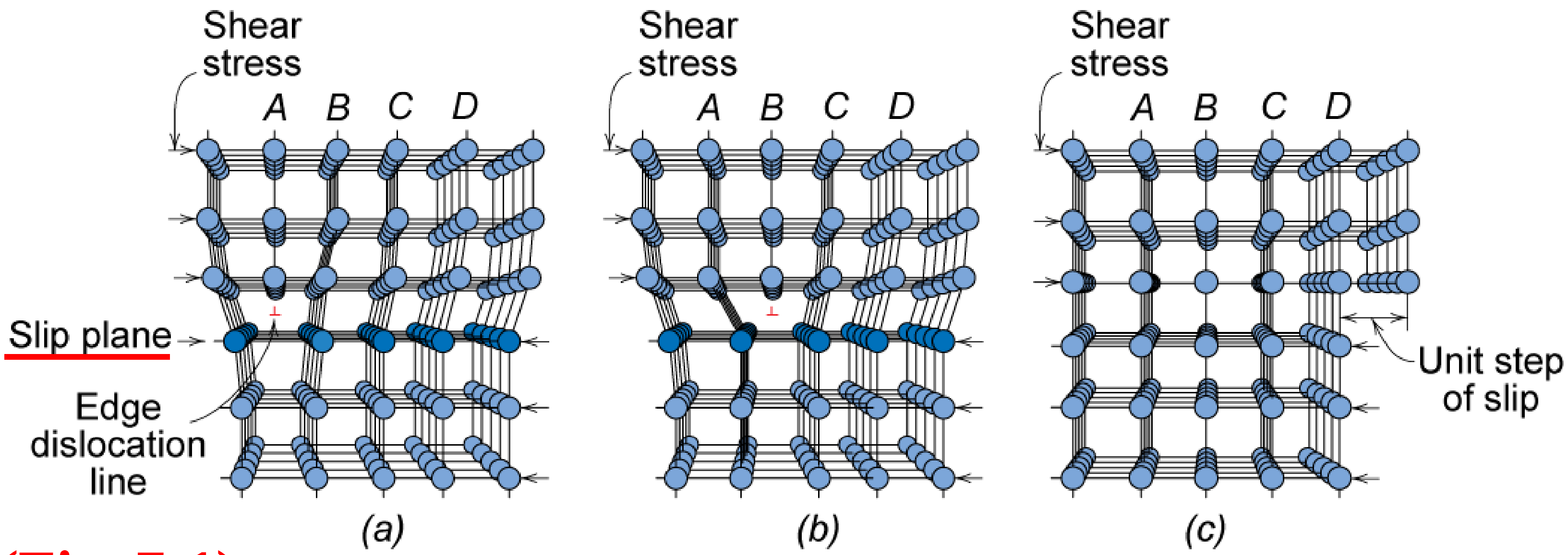
  Motion hard

  √ Need to avoid + and − neighbors

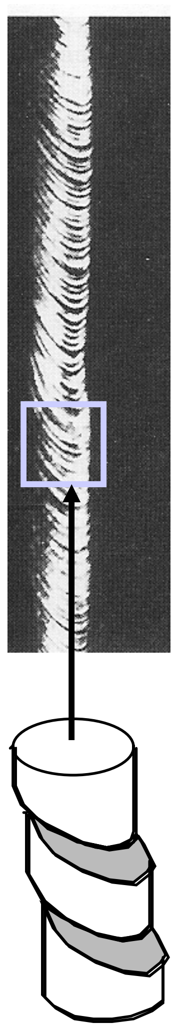


Dislocation Motion

- Produces plastic deformation.
- Depends on incrementally breaking bonds.
- Metals - plastic deformation by **plastic shear or slip** where one plane of atoms slides over adjacent plane by defect (dislocation) motion.



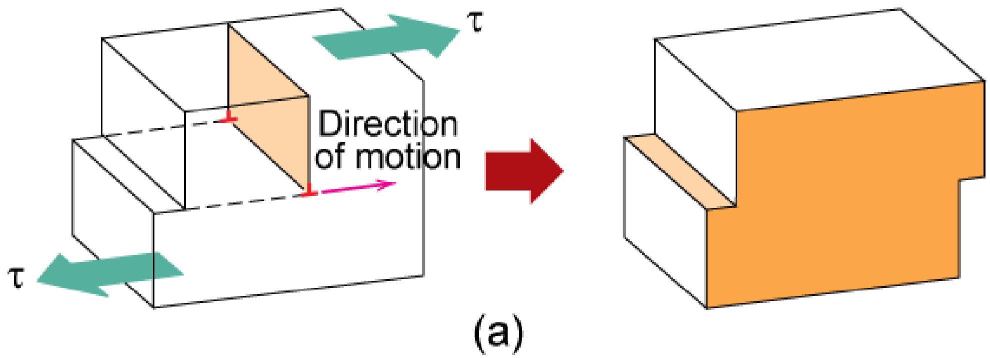
(Fig. 7-1)



If dislocation can not move, deformation doesn't occur.

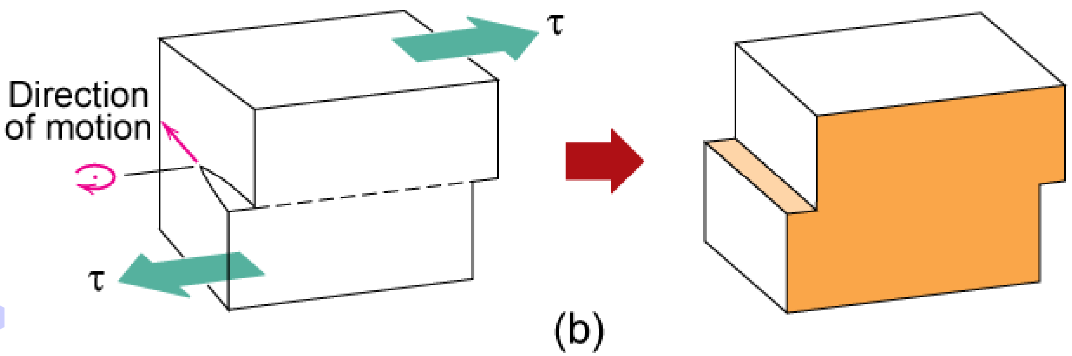
Dislocation Motion

- Edge:
  Dislocation line moves in the slip direction.
- Screw:
  Dislocation line moves perpendicular to the slip direction.
- Slip direction: the same direction as Burgers vector.



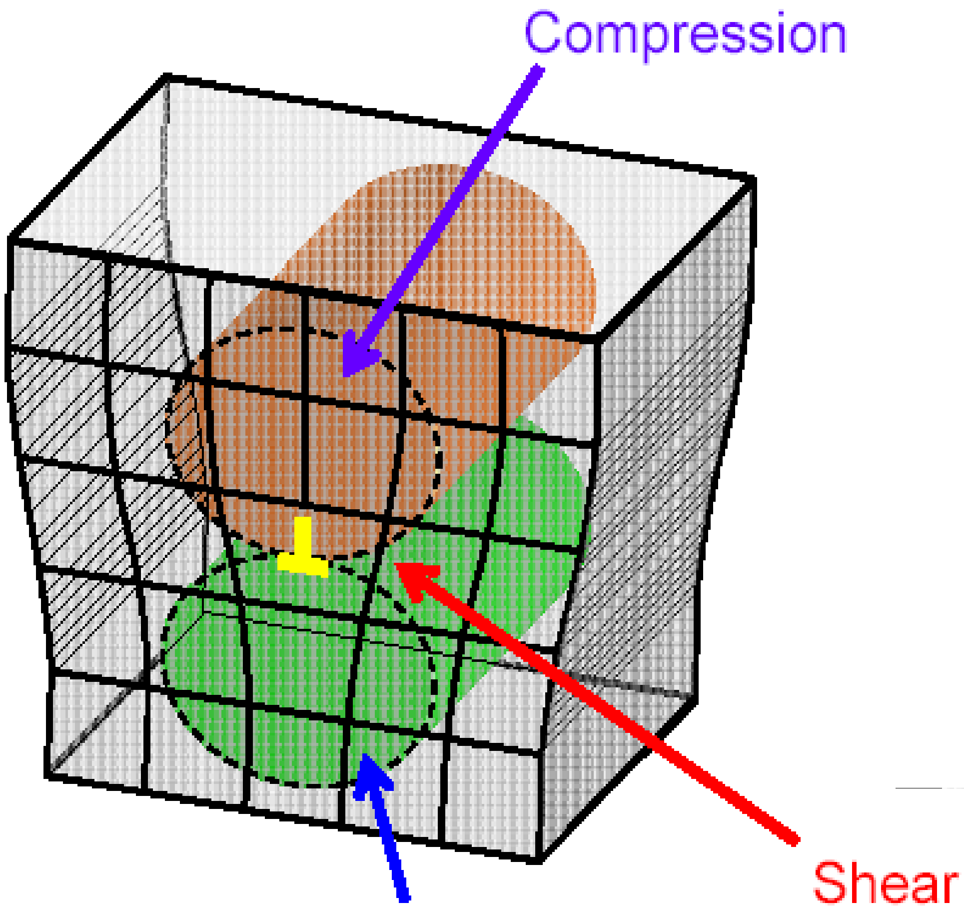
Edge dislocation

(Fig. 7-2)



Screw dislocation

Stress Field of Edge Dislocation



(Fig. 7-4)

$$\sigma_{rr} = \sigma_{\theta\theta} = -\frac{Gb}{2\pi(1-\nu)}\frac{\sin\theta}{r}$$

$$\sigma_{zz} = \nu(\sigma_{rr} + \sigma_{\theta\theta}) = -\frac{Gb\nu}{\pi(1-\nu)}\frac{\sin\theta}{r}$$

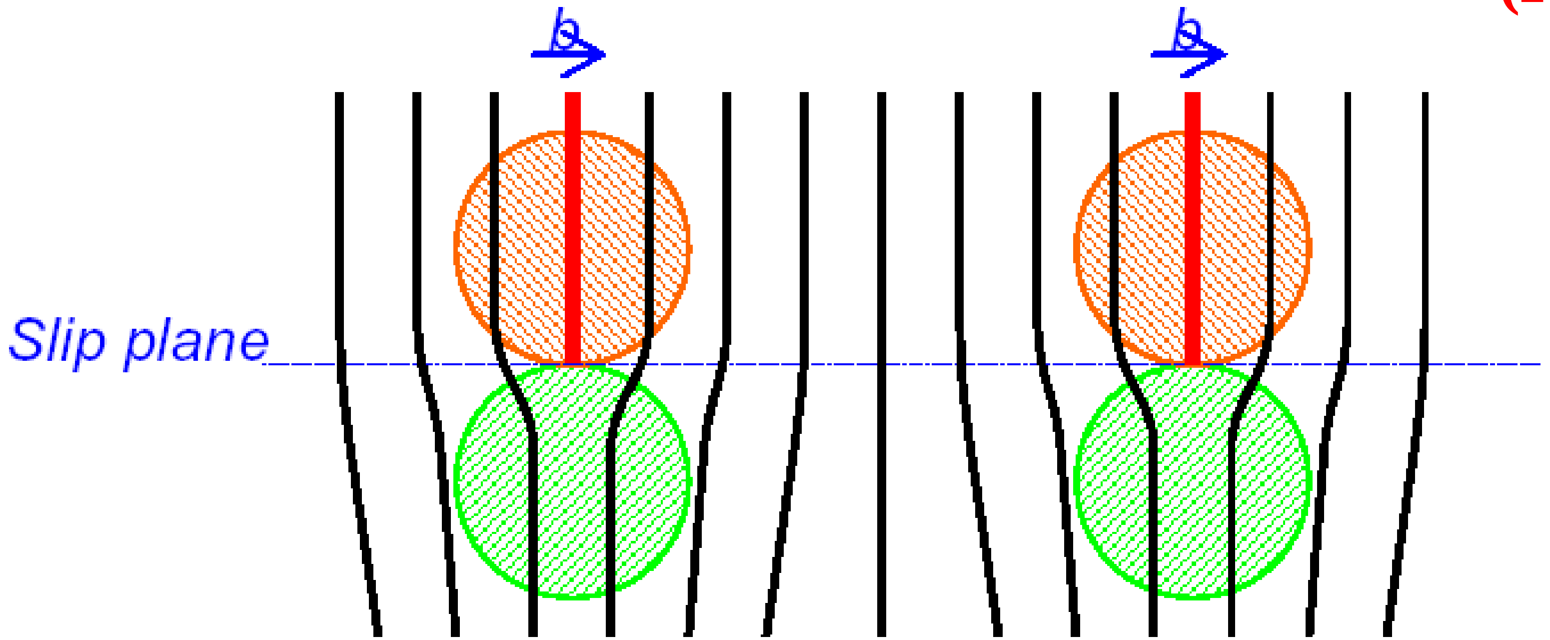
$$\sigma_{r\theta} = \frac{Gb}{2\pi(1-\nu)}\frac{\cos\theta}{r}$$

$$\sigma_{zr} = \sigma_{\theta z} = 0$$

(skip this box)

Forces between Dislocations

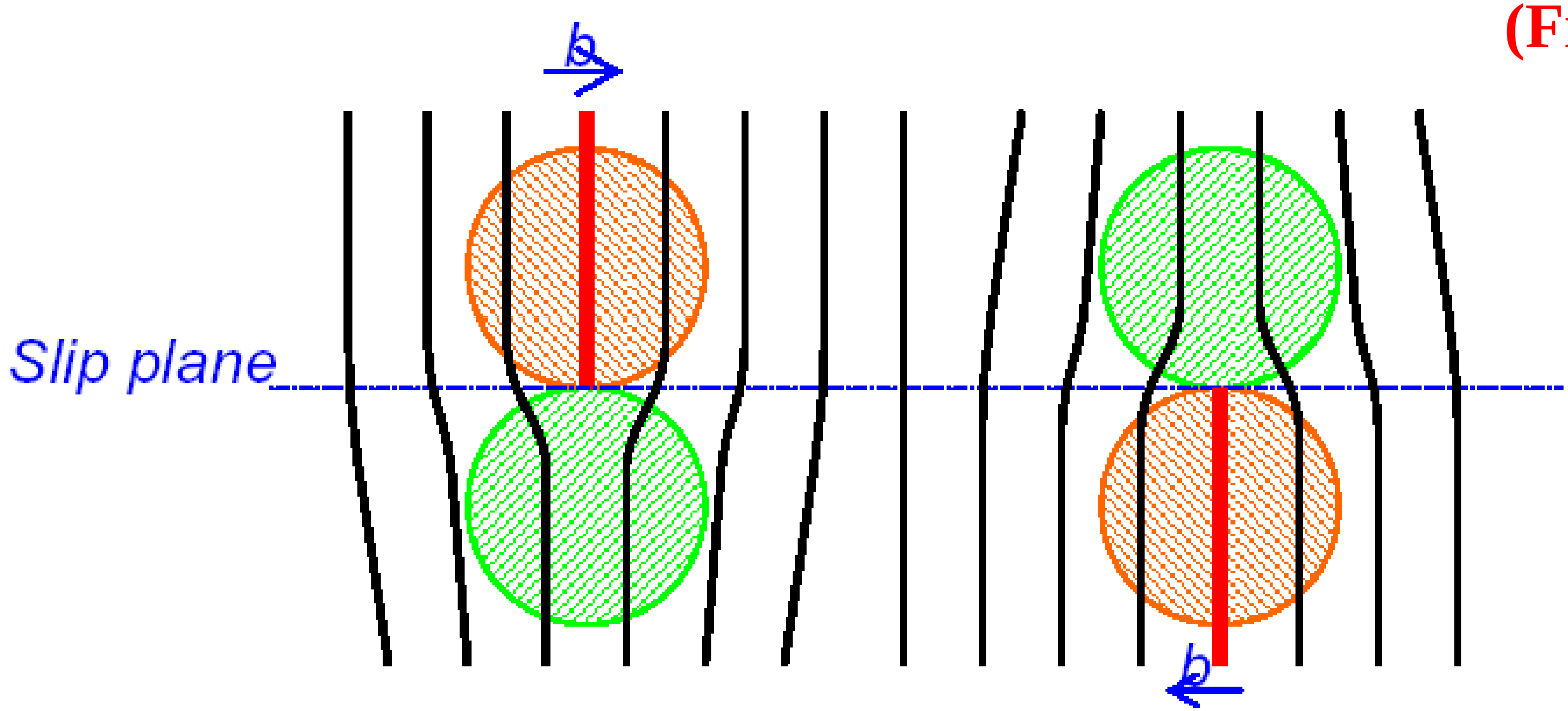
(Fig. 7-5)



Two like-edge dislocations (i.e., both have parallel Burgers vectors) lying on the same slip plane will repel each other.

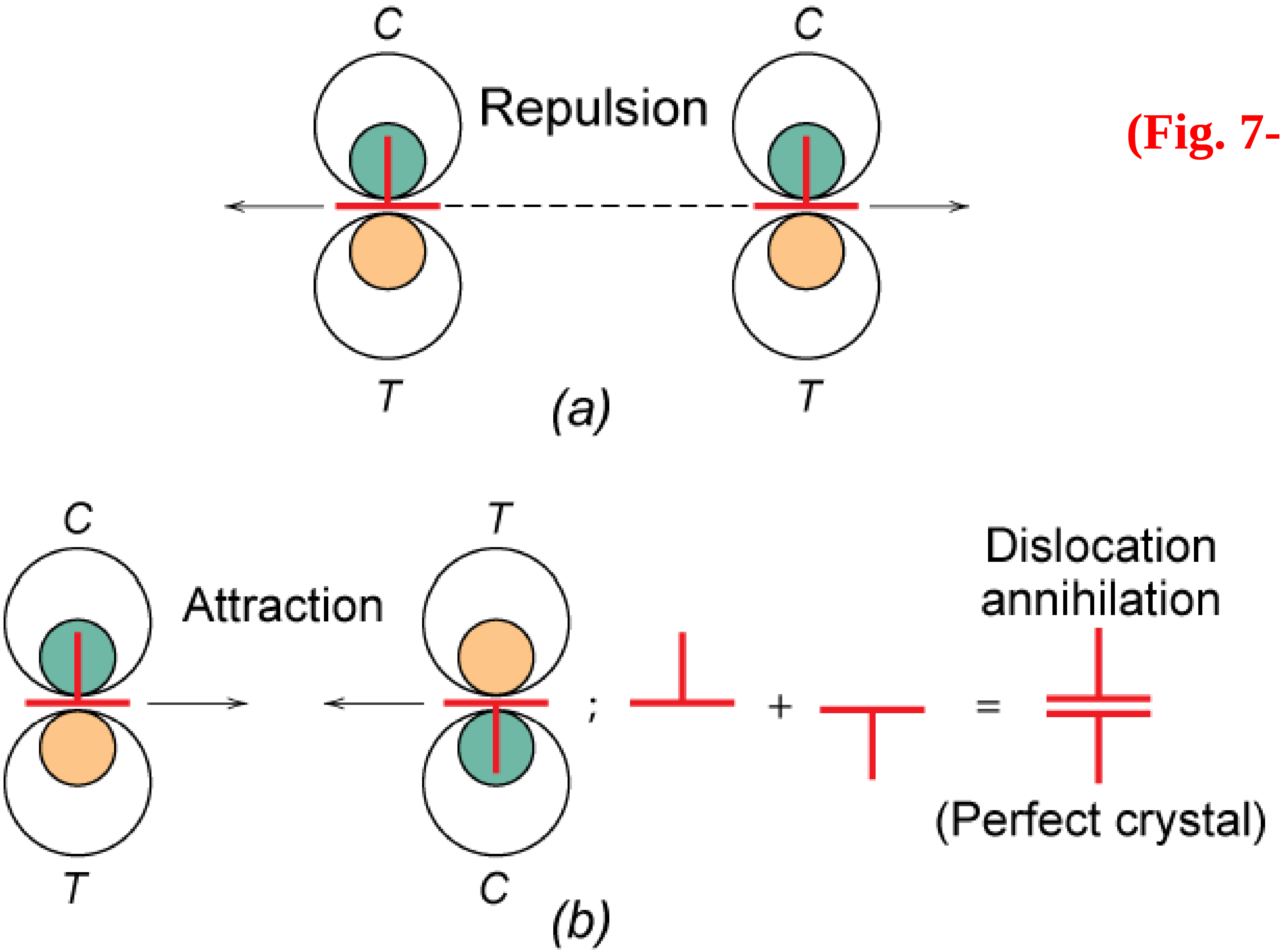
Forces between Dislocations

(Fig. 7-5)



Two unlike-edge dislocations (i.e., both have opposite Burgers vectors) lying on the same slip plane will attract each other, and annihilate out.

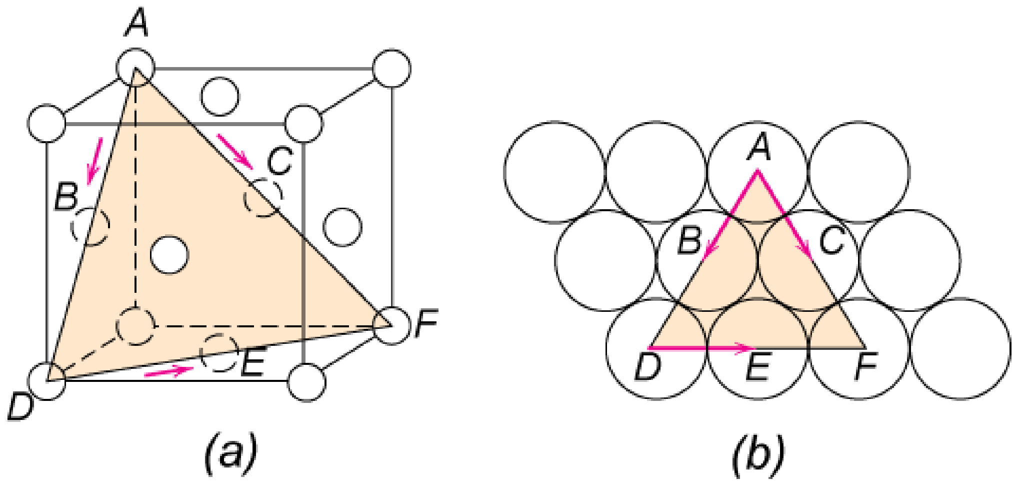
Effects of Stress at Dislocations



(Fig. 7-5)

➢ Slip System

- Slip plane - plane allowing easiest slip
  - Wide interplanar spacing - highest planar density
- Slip direction - direction of movement - highest linear density



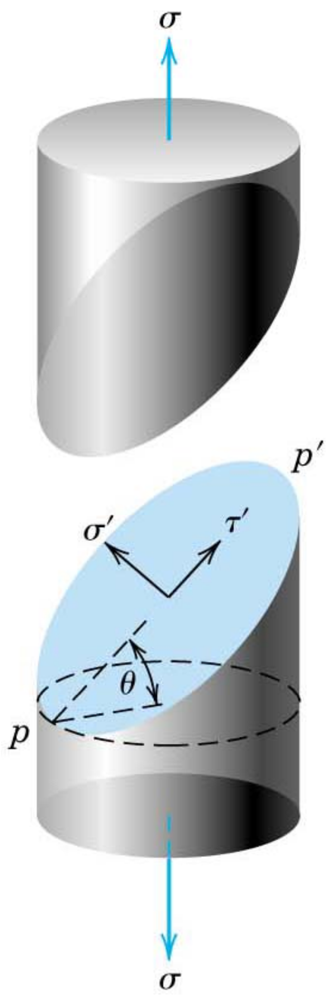
(Fig. 7-6)

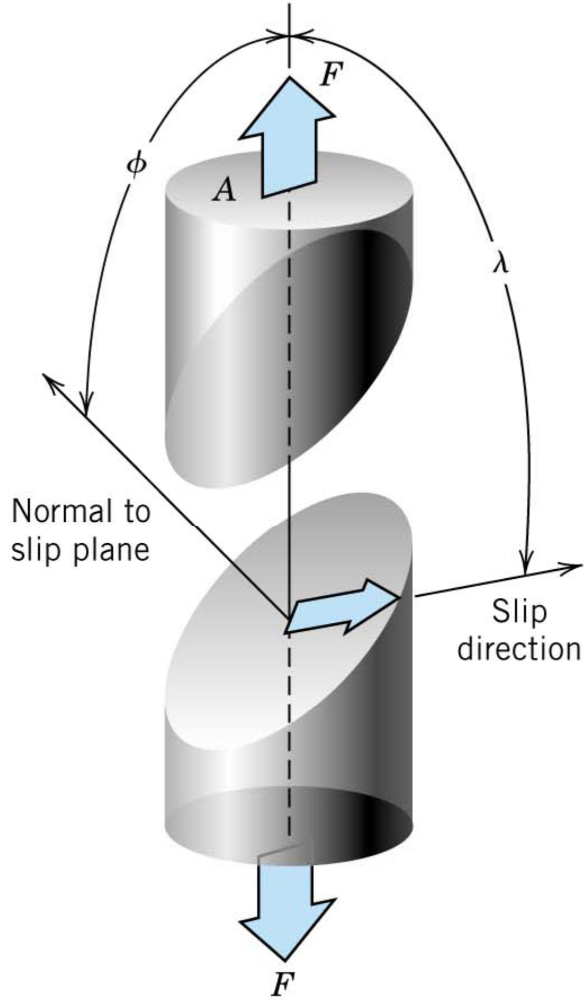
- **FCC** slip occurs on **{111}** planes (close-packed in 2-D)

  in **<110>** directions (close-packed in 1-D)

Stress and Dislocation Motion

- Crystals slip due to a resolved shear stress, τ_R
- Applied tension can produce such a stress.



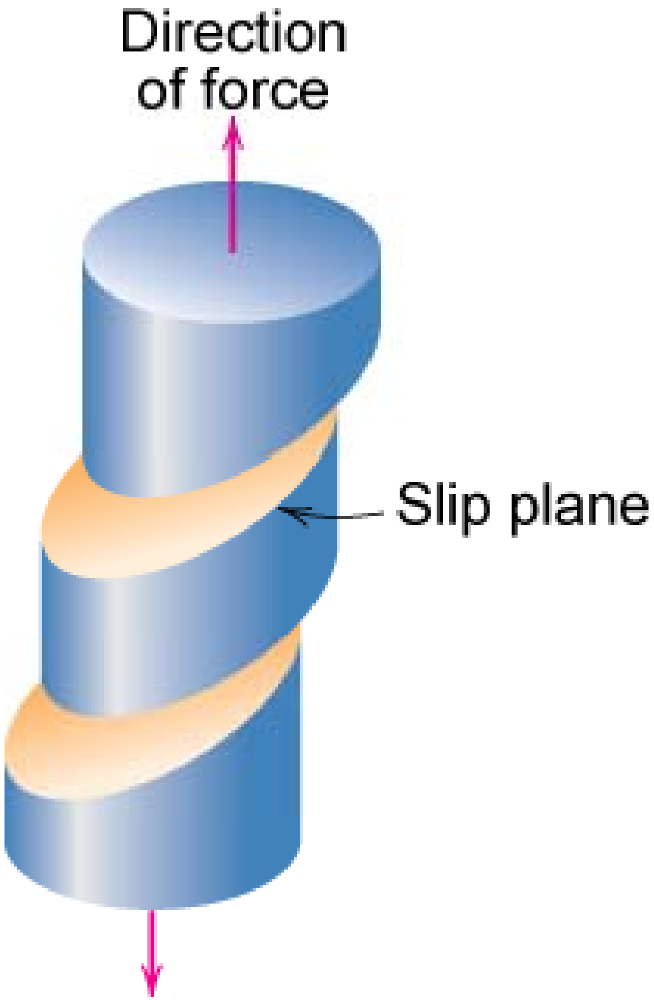


(Fig. 7-7)

(skip equations)

Single Crystal Slip

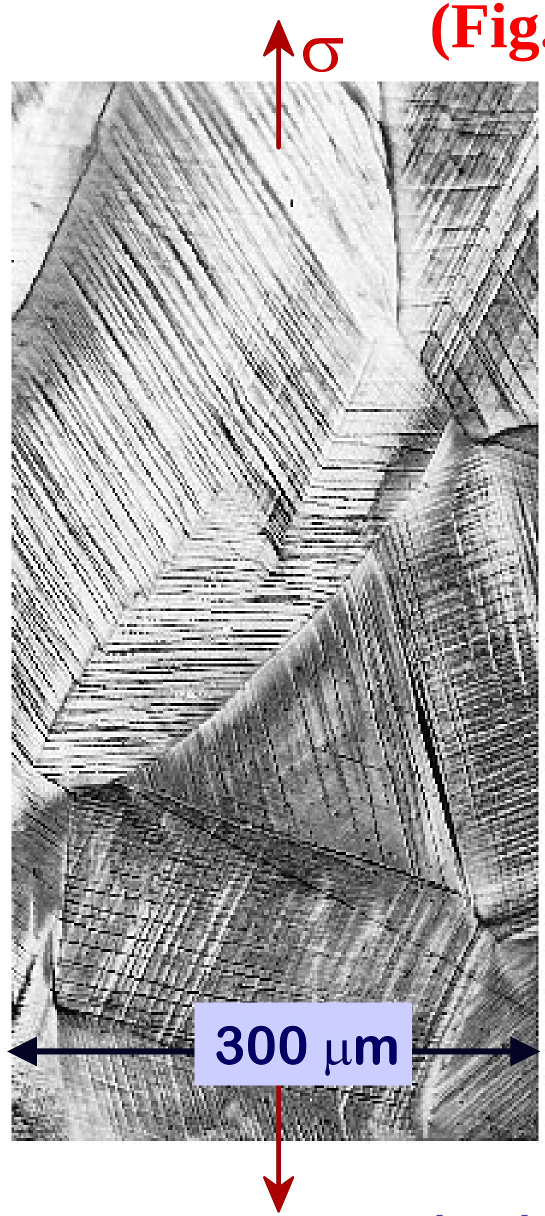
(Fig. 7-8)



(Fig. 7-9)

Dislocation Motion in Polycrystals

(Fig. 7-10)



- Slip planes & directions change from one grain (crystal) to another grain.

- Less-favorably-oriented crystals yield later.

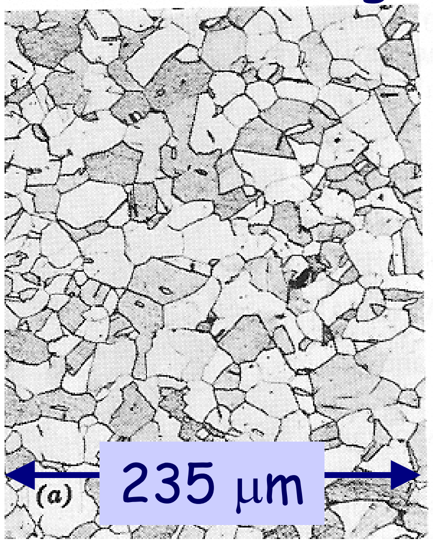
- Polycrystalline metals are stronger than their single-crystal equivalents (in general).

Anisotropy in σ_{yield}

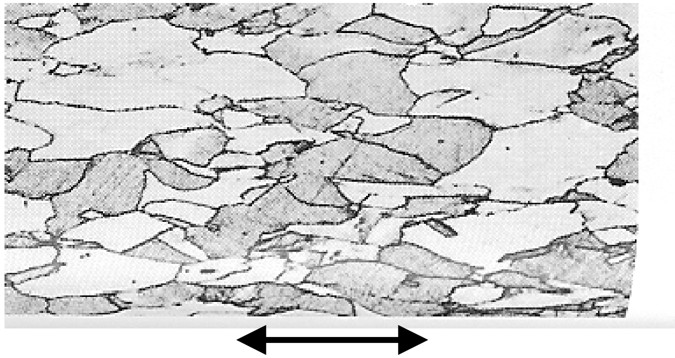
- Can be induced by rolling a polycrystalline metal.

(Fig. 7-11)

- before rolling



- after rolling



- Isotropic

Grains are approximately spherical & randomly oriented.

- Anisotropic

Rolling affects the grain orientation and shape.

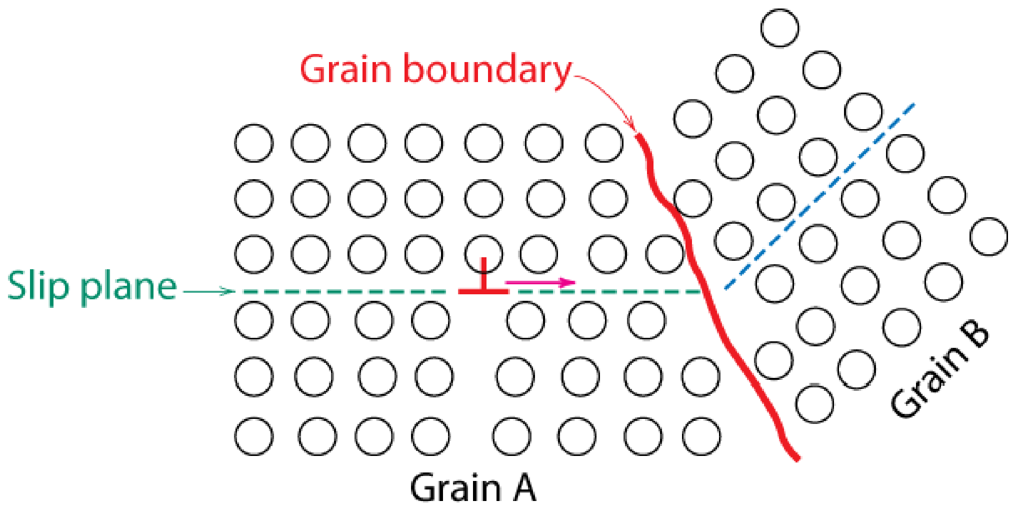
Contents

Four Strategies for Strengthening

- 1st: Grain Size Reduction
- 2nd: Solid-Solution Strengthening
- 3rd: Precipitate Strengthening
- 4th: Cold Work (= Strain Hardening)
  (= Work Hardening)

Four Strategies For Strengthening
1st: Grain Size Reduction

- Grain boundaries are barriers to slip.
- Smaller grain size: more barriers to slip.

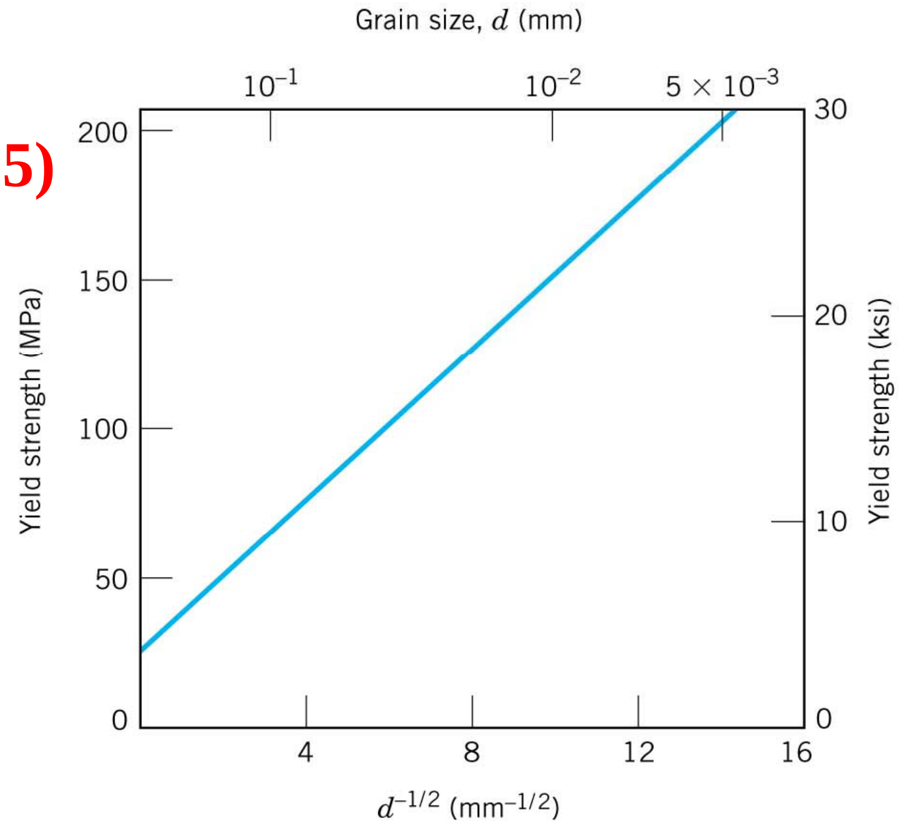


(Fig. 7-14)

- Hall-Petch Equation: $\sigma_{yield} = \sigma_o + k_y d^{-1/2}$

Grain Size Reduction

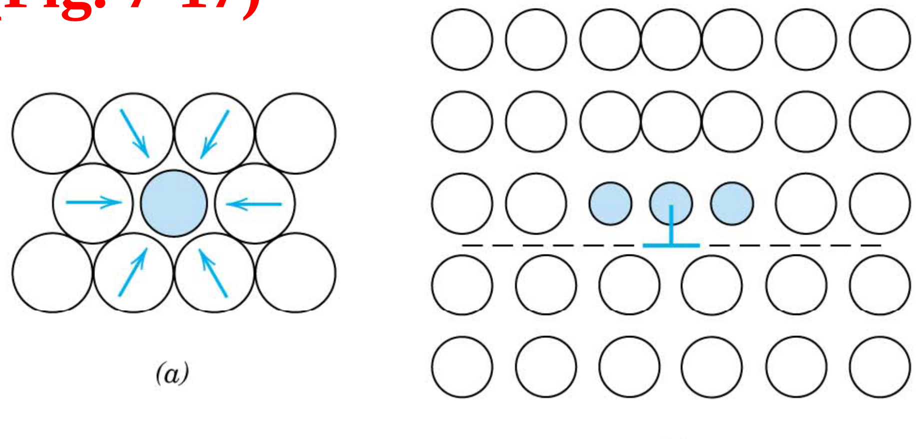
(Fig. 7-15)



0.75 mm

Four Strengthening Strategy
2nd: Solid Solutions

(Fig. 7-17)

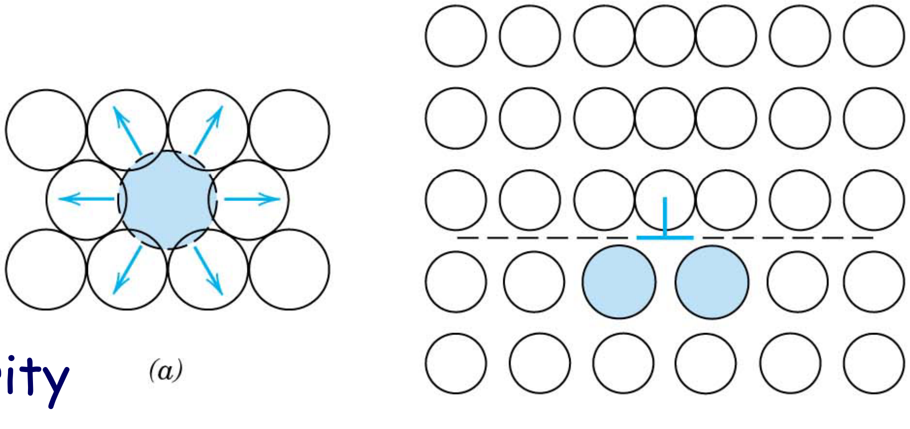


(a) (b)

Smaller substitutional impurities
→ Tensile lattice strain

(Fig. 7-18)

- Reduce mobility of dislocation
  → increase strength

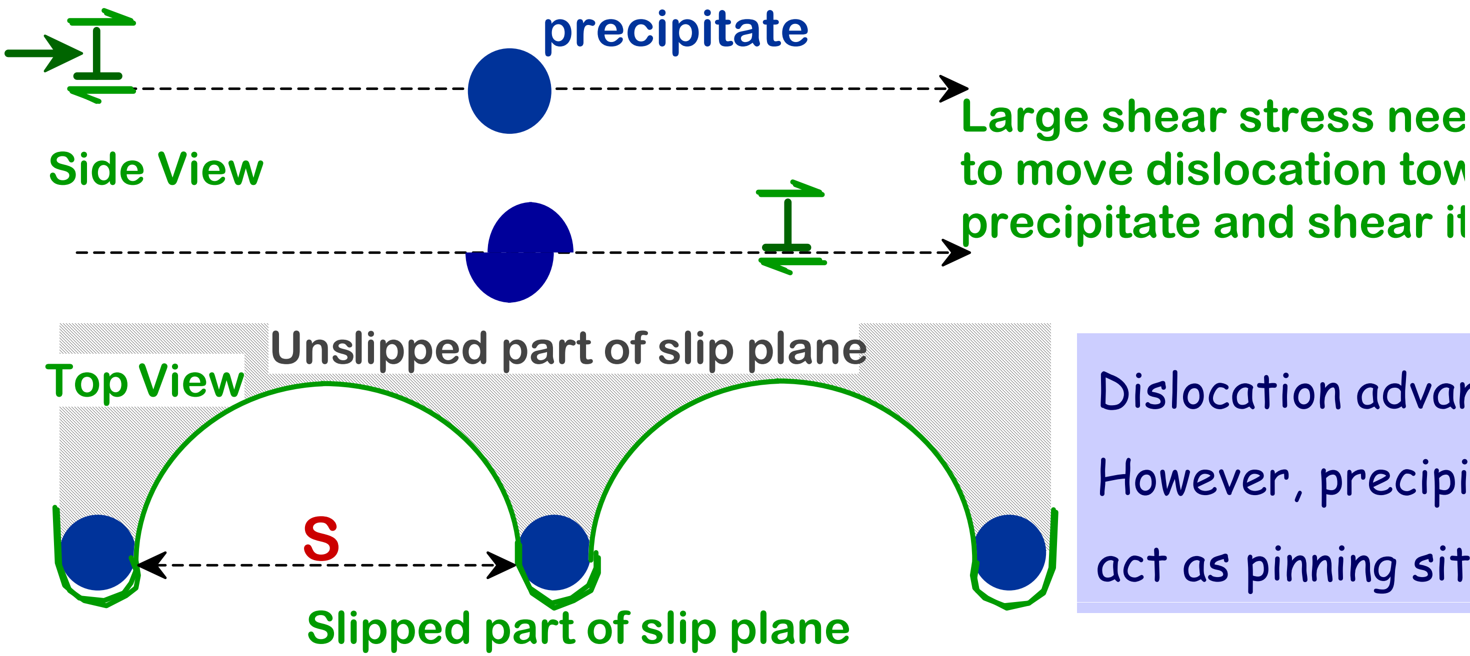


(a) (b)

Larger substitutional impurity
→ Compressive lattice strain

Four Strengthening Strategy
3rd: Precipitate Strengthening

Hard precipitates are difficult to shear.



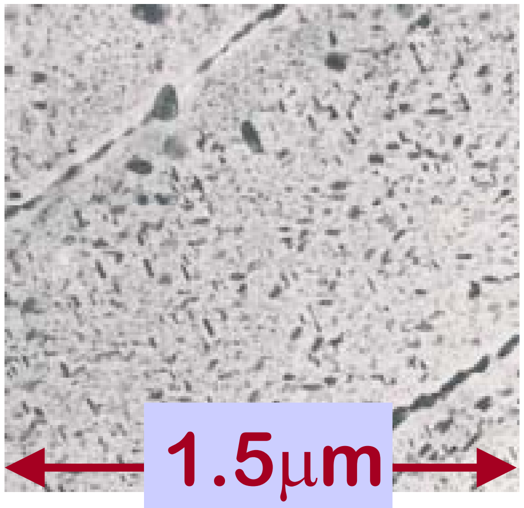
Dislocation advances.

However, precipitates act as pinning sites.

Precipitate Strengthening: Applications

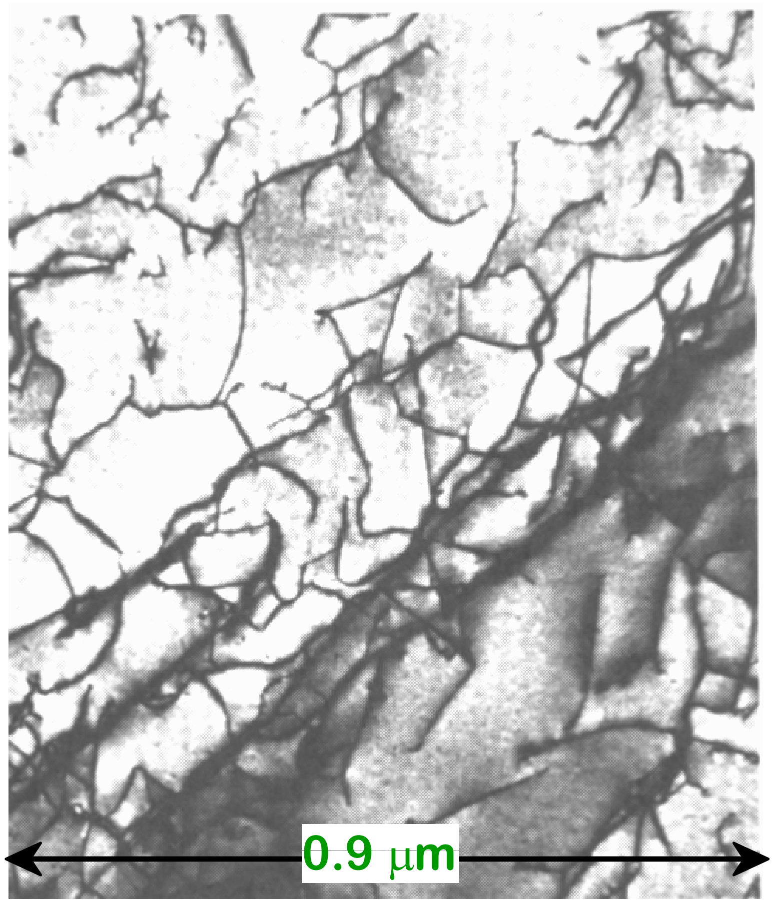
Internal wing structure on Boeing 767

Aluminum is strengthened with precipitates formed by alloying.



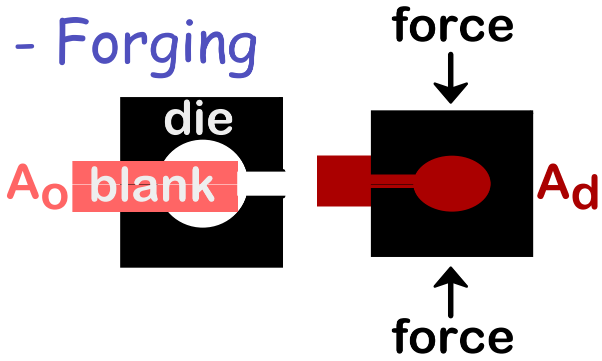
4th: Cold Work (Strain Hardening = Work Hardening)

- Room temperature deformation.



Ti alloy after cold working

- Forging



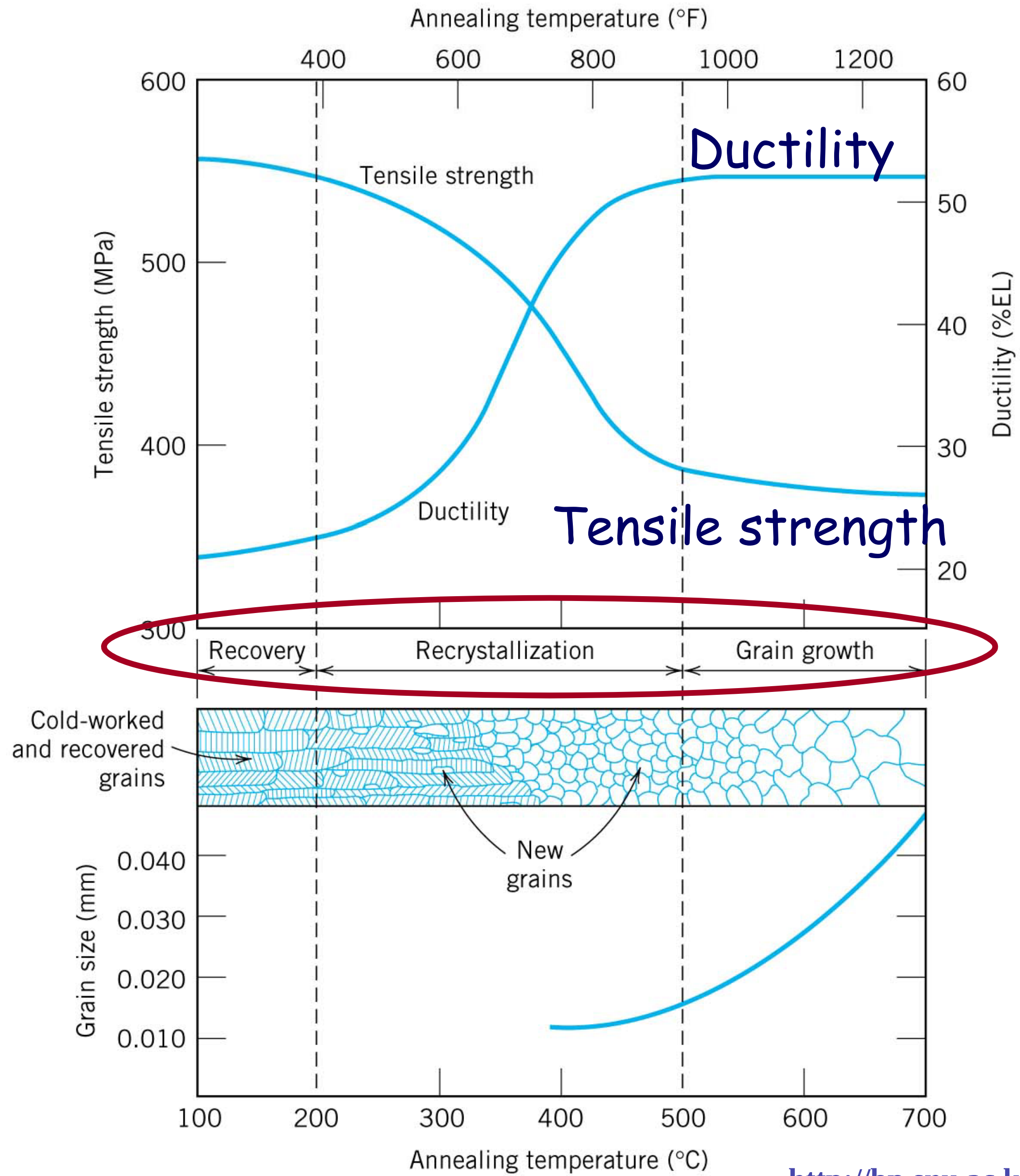
- **Dislocations entangle with one another during cold work.**
- **Dislocation motion becomes more difficult.**

Contents

Effect of Heating after Cold Work

- Heat treatment decreases the tensile strength and increases the ductility.
- Effects of cold work are reversed.

Three stages:



(Fig. 7-22)

1. Recovery

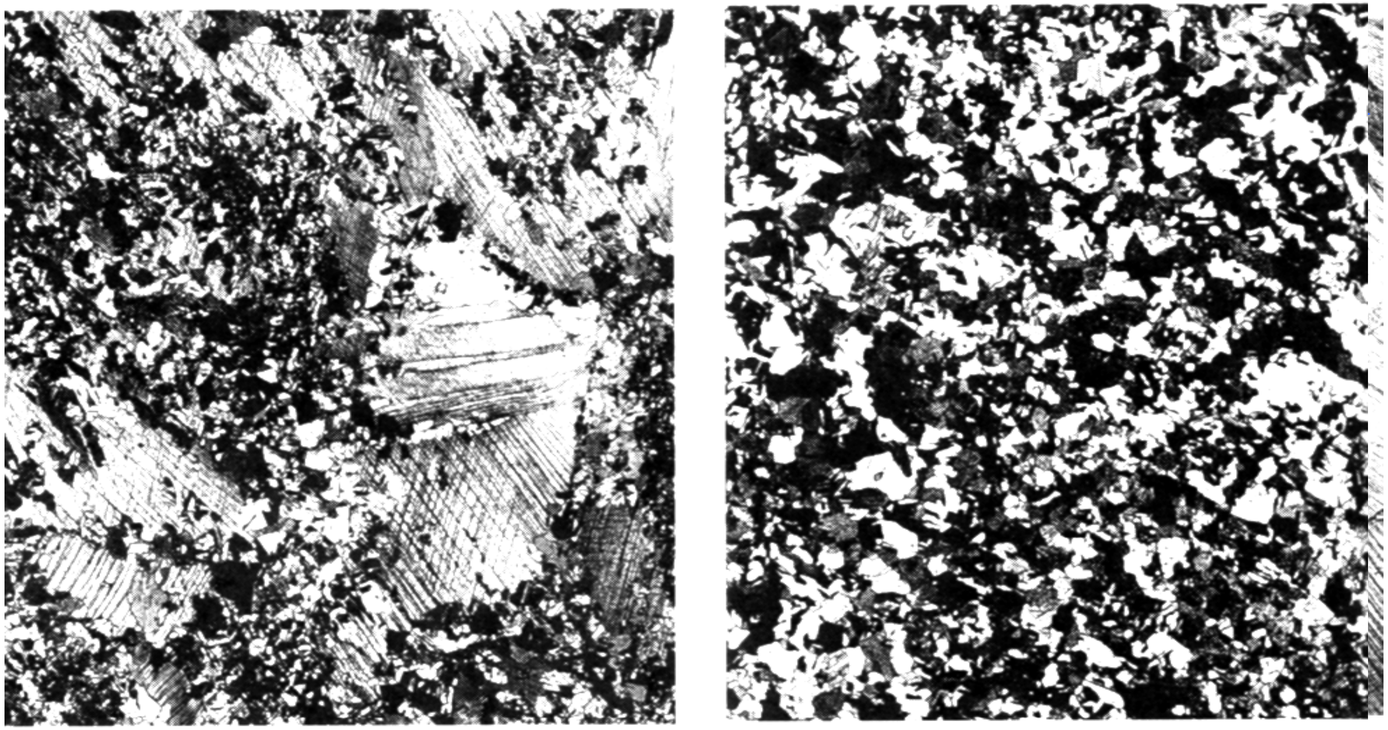
Thermal energy reduces the dislocation density by annihilation.

2. Recrystallization

➢ New grains (by thermal energy) are formed that:

- √ Have a smaller dislocation density.
- √ Are small.
- √ Consume cold-worked crystals.

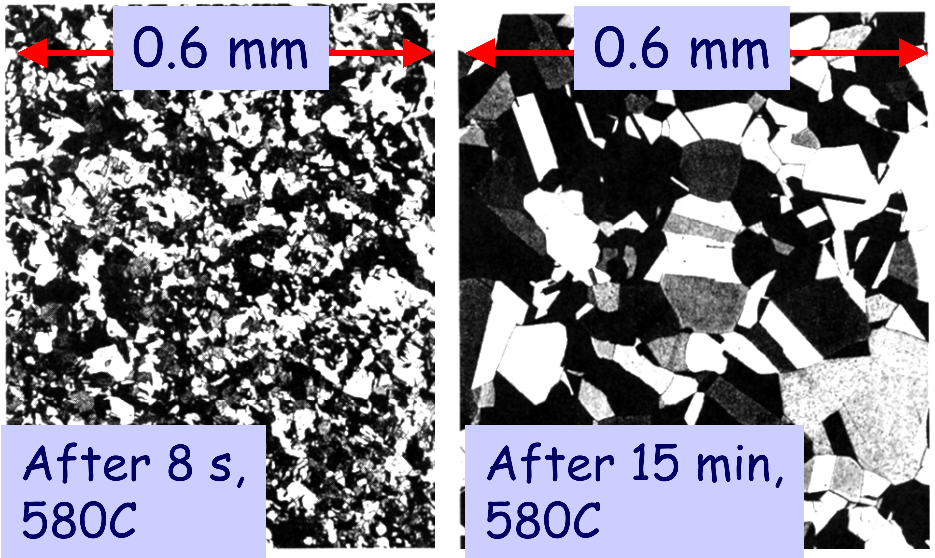
(Fig. 7-21)



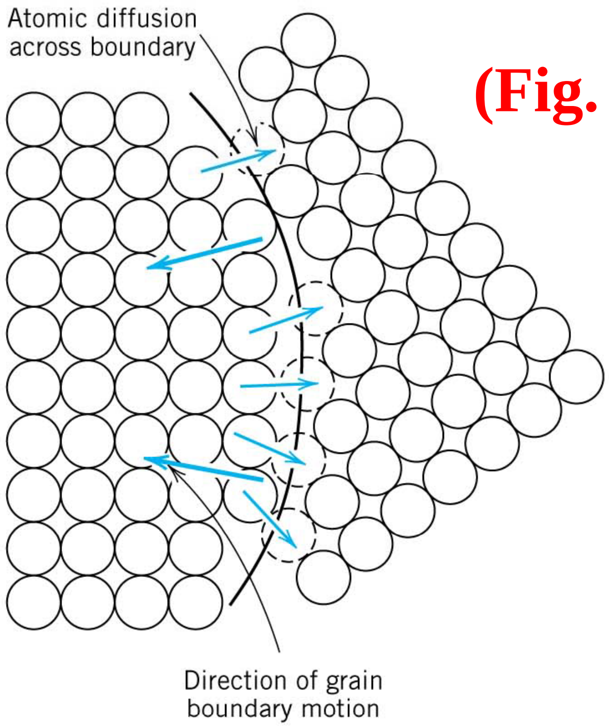
New crystals nucleate (신대륙 개척).

3. Grain Growth

- At longer times, larger grains consume smaller ones.
- Why? Grain-boundary area (and therefore energy) is reduced (the driving force).



(Fig. 7-21)



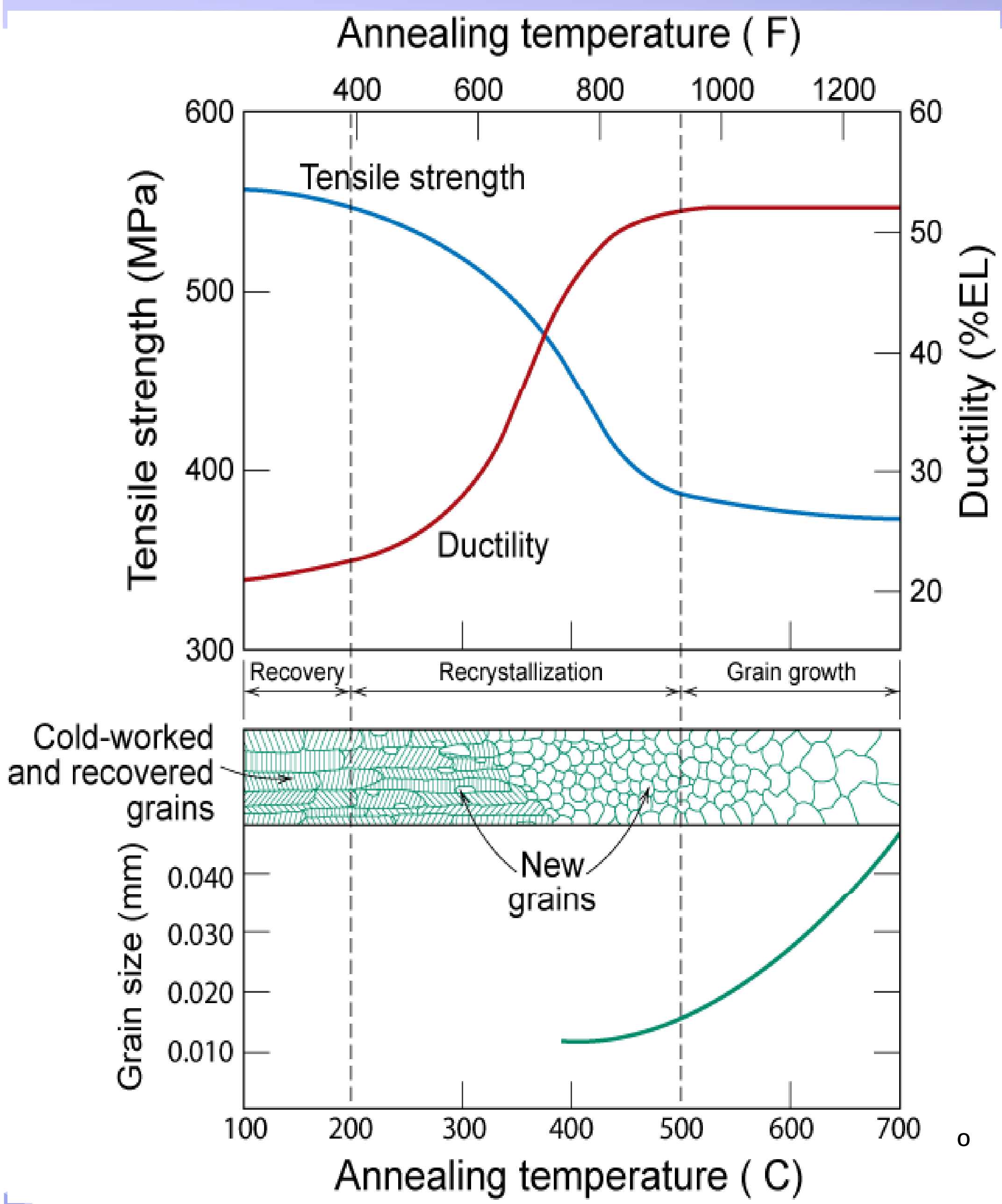
(Fig. 7-24)

$$d^n - d_o^n = Kt$$

- exponent typ. ~ 2
- grain diam. at time t: d
- coefficient dependent on material and T: K
- elapsed time: t

(Eq. 7-9)

Process



(Fig. 7-22)

Summary

- Dislocations are observed primarily in metals and alloys.
- Strength is increased by making the dislocation motion difficult.
- Particular ways to increase the strength are:
  - √ To decrease the grain size
  - √ Solid solution strengthening
  - √ Precipitate strengthening
  - √ Cold work
- Heating (annealing) can reduce the dislocation density and increase grain size. This decreases the strength.

- Problems from Chap. 7 http://bp.snu.ac.kr

  Prob. 7-1 (Please answer in cm, cm^{-2}, or cm^3 for your solutions.)

  Prob. 7-2 Prob. 7-4 Prob. 7-20 Prob. 7-22 Prob. 7-33 Prob. 7-36