Chemical Engineering 378

Science of Materials Engineering

Lecture 14

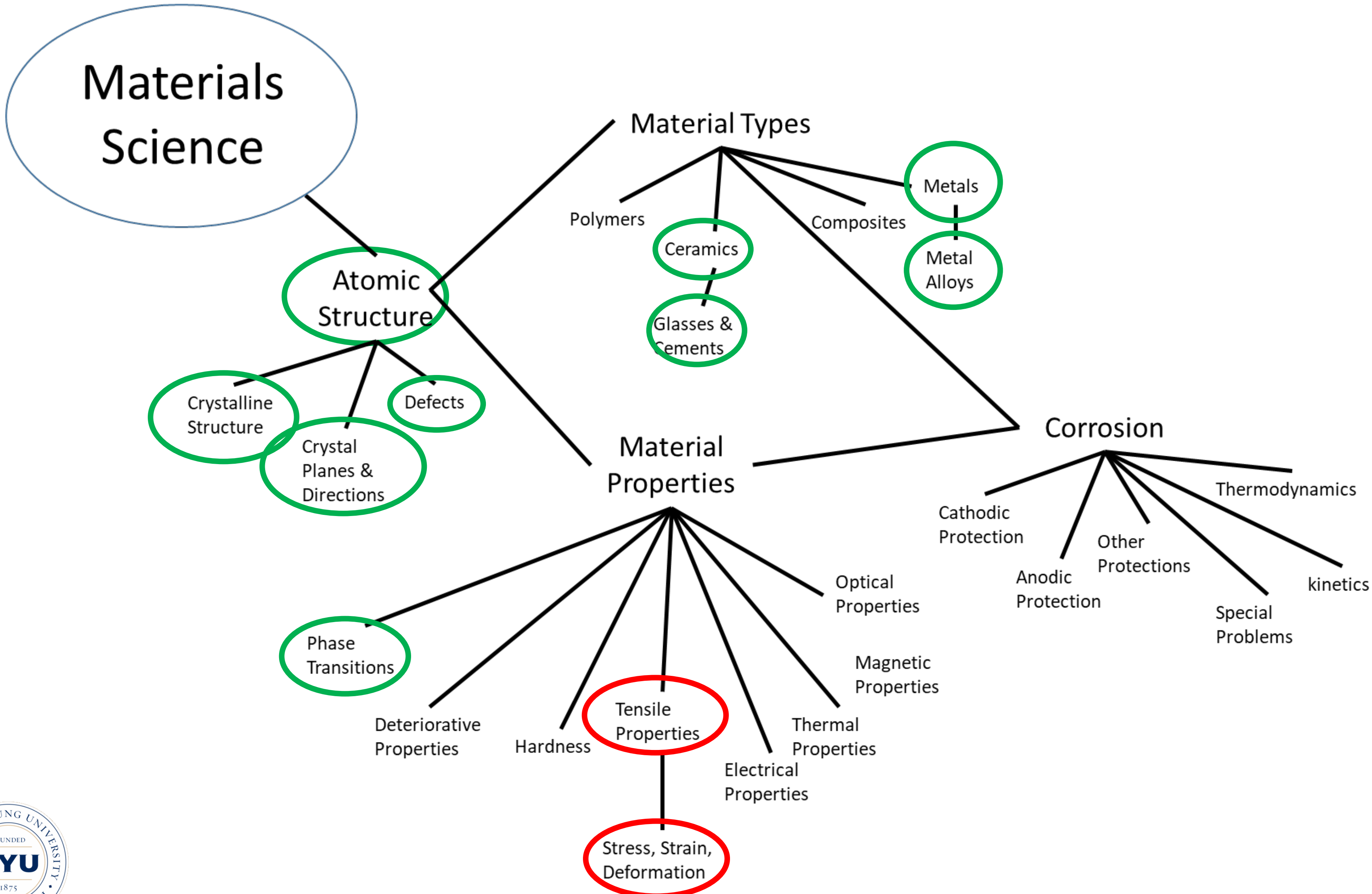
Dislocations, Strengthening

Spiritual Thought

"We don't always know the details of our future. We do not know what lies ahead. We live in a time of uncertainty. We are surrounded by challenges on all sides. Occasionally discouragement may sneak into our day; frustration may invite itself into our thinking; doubt might enter about the value of our work. In these dark moments Satan whispers in our ears that we will never be able to succeed, that the price isn't worth the effort, and that our small part will never make a difference. He, the father of all lies, will try to prevent us from seeing the end from the beginning…We know that God keeps His promises. We need to fulfill our part to receive His blessings. The Lord wants you, my young friends, to desire with all your heart to keep these standards and live by the gospel truths found in the scriptures. As you do this, you will see beyond the moment, and you will see your bright and wonderful future with great opportunities and responsibilities… God will bless you and open the eyes of your understanding so you can see the end from the beginning."

-Elder Dieter F. Uchtdorf

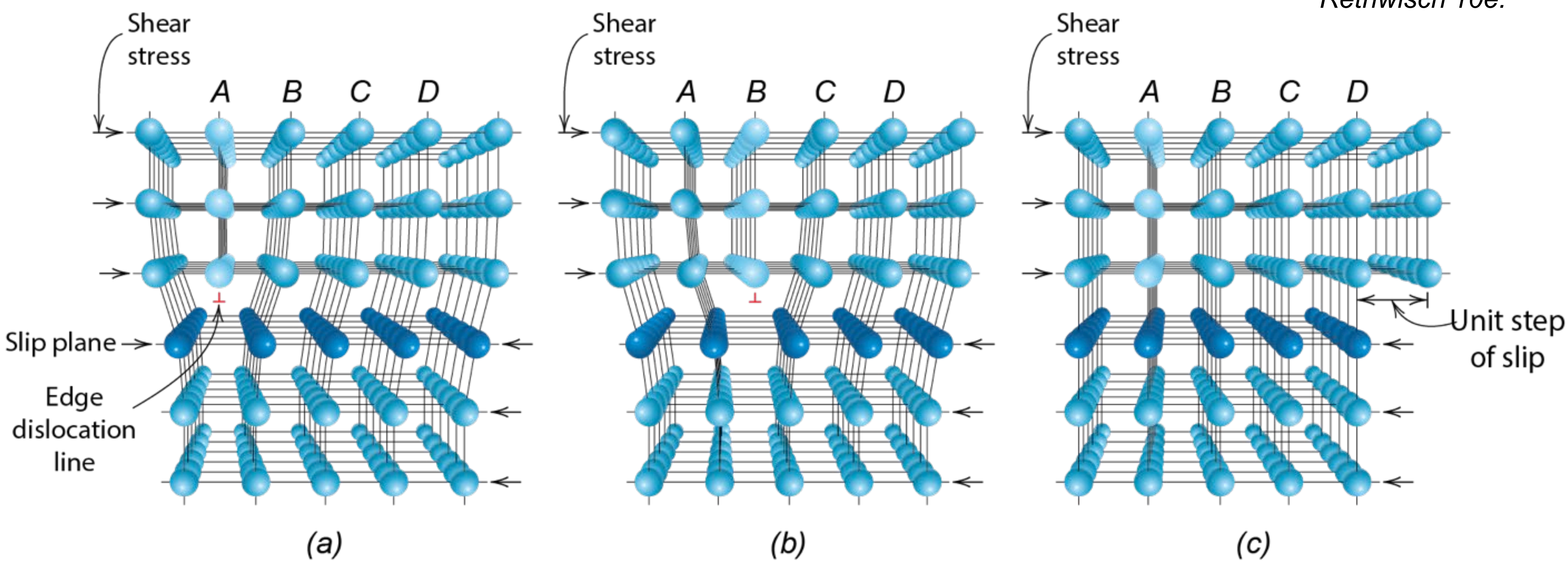
Materials Roadmap



Plastic Deformation by Dislocation Motion

- Plastic deformation occurs by motion of dislocations (edge, screw, mixed) – process called slip
- Applied shear stress can cause extra half-plane of atoms [and edge dislocation line (⊥)] to move as follows:

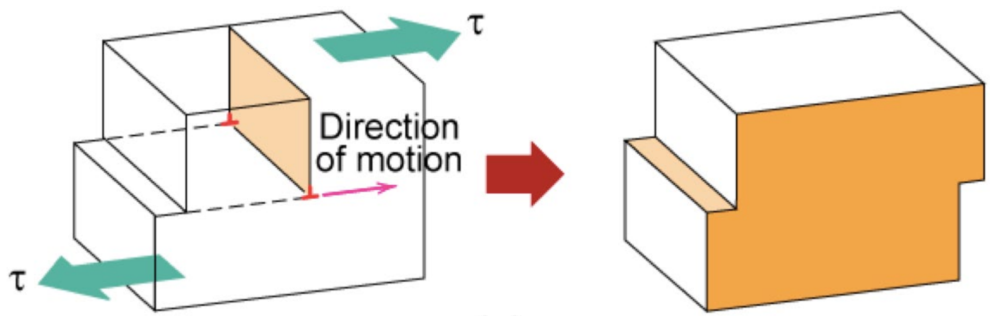
Fig. 7.1, *Callister & Rethwisch 10e.*



- Atomic bonds broken and reformed along slip plane as dislocation (extra half plane) moves.

Motion of Edge and Screw Dislocations

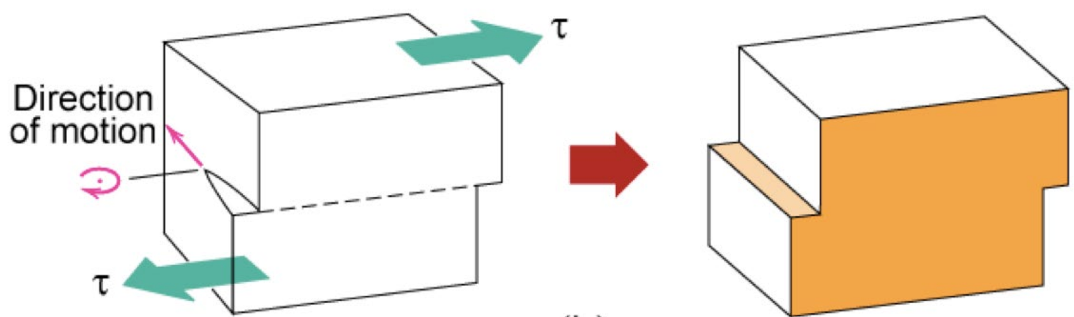
- Direction of edge disl. line ($\perp$) motion—in direction of applied shear stress τ.



(a)

Edge dislocation

- Direction of screw disl. line ( ) motion—perpendicular to direction of applied shear stress.

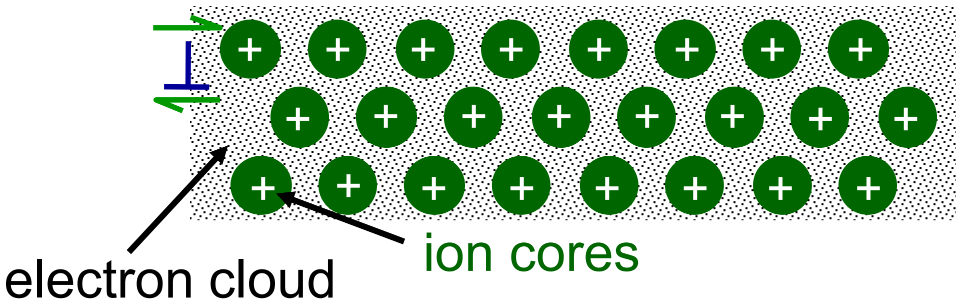


(b)

Screw dislocation

Fig. 7.2, *Callister & Rethwisch 10e.*

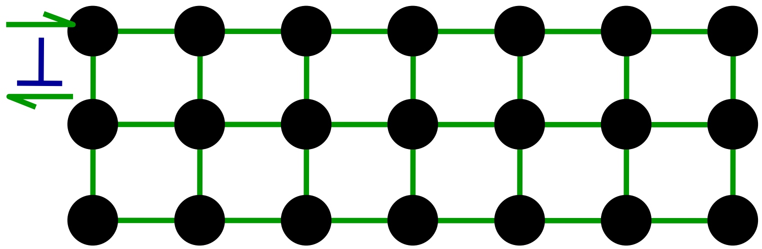
Dislocation Characteristics
Metals



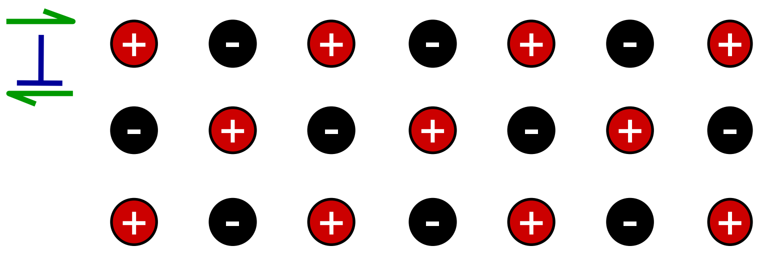
- Metals:
  - Examples: copper, aluminum, iron
  - Dislocation motion—relatively easy
  - Metallic bonding—non-directional
  - Close-packed planes and directions for slip

Dislocation Characteristics
Ceramics

- Ceramics—Covalently Bonded
  - Examples: silicon, diamond
  - Dislocation motion—relatively difficult
  - Covalent bonding—directional



- Ceramics—Ionically Bonded
  - Examples: NaCl, MgO
  - Dislocation motion—relatively difficult
  - Few slip systems
    - motion of nearby ions of like charge (+ and -) restricted by electrostatic repulsive forces



Slip Systems

Slip System—Combination of slip plane and slip direction

- Slip Plane
  - Crystallographic plane on which slip occurs most easily
  - Plane with high planar density
- Slip Direction
  - Crystallographic direction along which slip occurs most easily
  - Direction with high linear density

Slip Systems (cont.)

- For FCC crystal structure – slip system is $\{111\}\langle 110\rangle$
  - Dislocation motion on $\{111\}$ planes
  - Dislocation motion in $\langle 110\rangle$ directions
  - A total of 12 independent slip systems for FCC

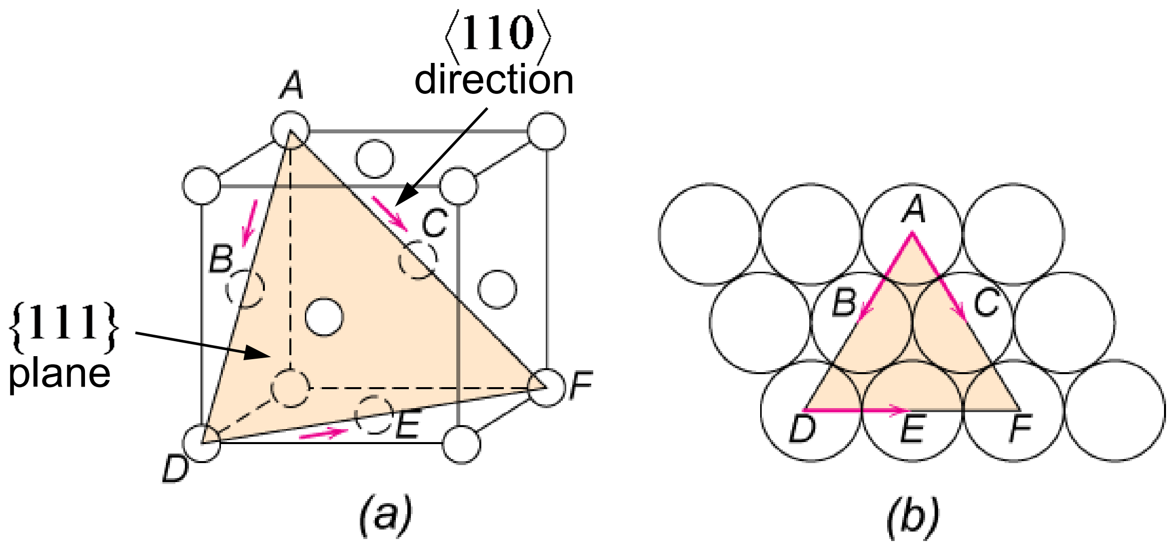


Fig. 7.6, *Callister & Rethwisch 10e.*

- For BCC and HCP— other slip systems

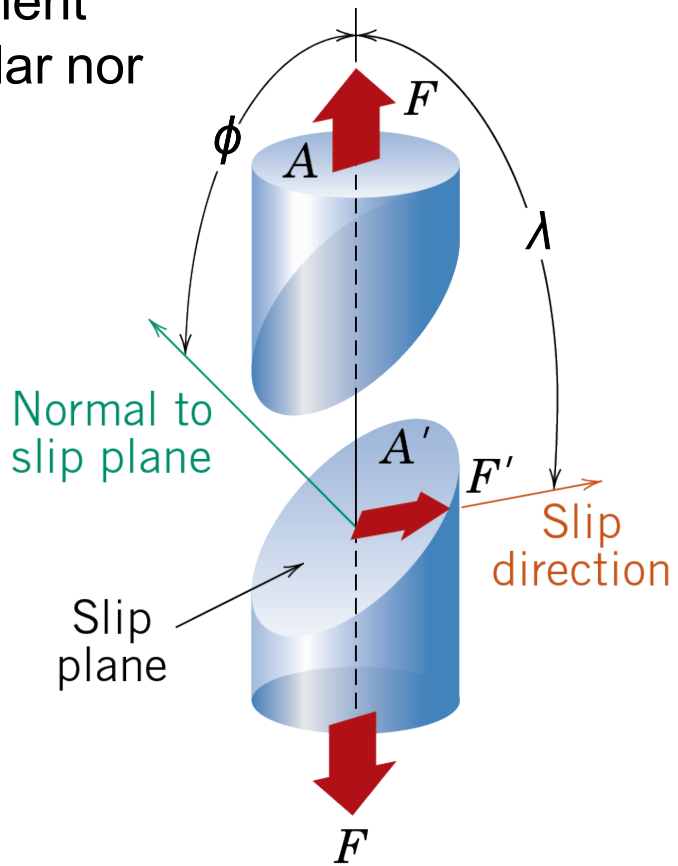
Slip in Single Crystals
Resolved Shear Stress

- Applied tensile stress—shear stress component when slip plane oriented neither perpendicular nor parallel to stress direction
  - -- From figure, resolved shear stress, τ_R

$$\tau_R = \frac{F'}{A'}$$

- τ_R depends on orientation of normal to slip plane and slip direction with direction of tensile force F:

$$F' = F\cos\lambda \qquad A' = \frac{A}{\cos\phi}$$

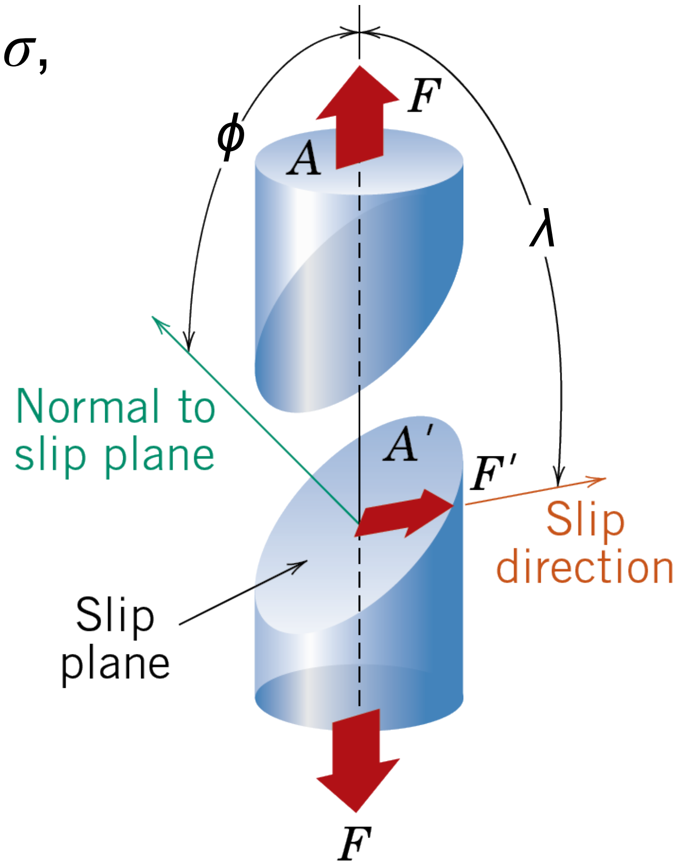


Slip in Single Crystals
Resolved Shear Stress (cont.)

- Relationship between tensile stress, σ, and τ_R:

$$\tau_R = \frac{F'}{A'} = \frac{F\cos\lambda}{\dfrac{A}{\cos\phi}} = \frac{F}{A}\cos\lambda\cos\phi$$

$$= \sigma\cos\lambda\cos\phi$$



Slip in Single Crystals: Critical Resolved Shear Stress

- Dislocation motion—on specific slip system—when τ_R reaches critical value:
  - -- "Critical resolved shear stress", τ_{CRSS}
  - -- Slip occurs when $\tau_R > \tau_{\text{CRSS}}$
  - -- Typically 0.1 MPa < τ_{CRSS} < 10 MPa
- In a single crystal there are
  - -- multiple slip systems
  - -- a variety of orientations
- One slip system for which σ_R is highest: τ_R(max) -> $(\cos\lambda \cos\phi)_{\max}$
  - -- Most favorably oriented slip system
- Yield strength of single crystal, σ_y, when

$$\sigma_y = \frac{\tau_{\text{CRSS}}}{(\cos\lambda \cos\phi)_{\max}}$$

Single Crystals
Slip—Macroscopic Scale

- Parallel slip steps form on surface of single crystal
- Steps result from motion of large numbers of dislocations on same slip plane
- Sometimes on single crystals appear as "slip lines" (see photograph)

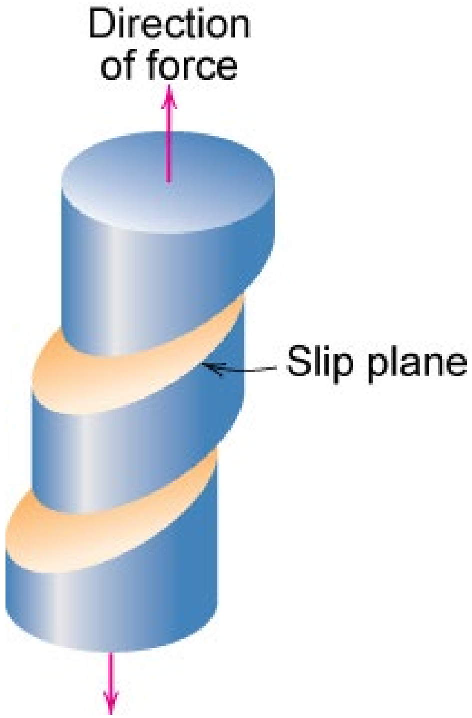


Fig. 7.8, *Callister & Rethwisch 10e.*

Deformation of Single Crystals Example Problem

A single crystal of some metal has a τ_{crss} of 20.7 MPa and is exposed to a tensile stress of 45 MPa.

(a) Will yielding occur when $\phi = 60°$ and $\lambda = 35°$?

(b) If not, what stress is necessary?

Solution:

(a) First calculate τ_R

$$\tau_R = \sigma \cos\lambda \cos\phi$$

$$\tau_R = (45 \text{ MPa})\left[\cos(35°)\cos(60°)\right]$$

$$= 18.4 \text{ MPa}$$

Since $\tau_R (18.4 \text{ MPa}) < \tau_{crss} (20.7 \text{ MPa})$ -- no yielding

Deformation of Single Crystals Example Problem (cont.)

(b) To calculate the required tensile stress to cause yielding use the equation:

$$\sigma_y = \frac{\tau_{\text{CRSS}}}{\cos\lambda \cos\phi}$$

With specified values

$$\sigma_y = \frac{20.7 \text{ MPa}}{\cos(35°)\cos(60°)}$$

$$= 50.5 \text{ MPa}$$

Therefore, to cause yielding, $\boxed{\sigma \geq 50.5 \text{ MPa}}$

Slip in Polycrystalline Materials

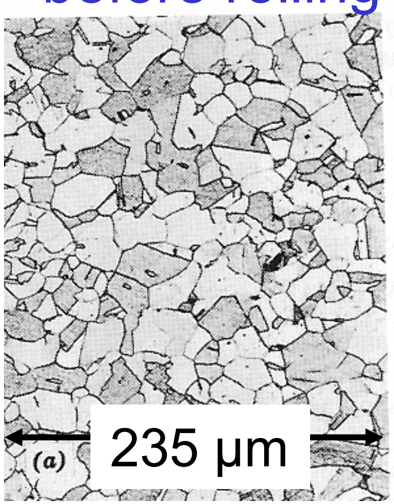
- Polycrystalline materials—many grains, often random crystallographic orientations
- Orientation of slip planes, slip directions (ϕ, λ)—vary from grain to grain.
- On application of stress—slip in each grain on most favorable slip system.
  - with largest τ_R
  - when $\tau_R > \tau_{crss}$
- In photomicrograph—note slip lines in grains have different orientations.

Adapted from Fig. 7.10, *Callister & Rethwisch 10e.* (Photomicrograph courtesy of C. Brady, National Bureau of Standards [now the National Institute of Standards and Technology, Gaithersburg, MD].)

Slip in Polycrystalline Materials (cont.)

- Grains change shape (become distorted)—during plastic deformation—due to slip
- Manner of grain distortion similar to gross plastic deformation
  - Grain structures before and after deformation (from rolling)
  - Before rolling—grains equiaxed & randomly oriented
    - Properties isotropic
  - After rolling (deformation)—grains elongated in rolling direction
    - Also preferred crystallographic orientation of grains
    - Properties become somewhat anisotropic

\- before rolling



\- after rolling

rolling direction

Adapted from Fig. 7.11, *Callister & Rethwisch 10e.* (from W.G. Moffatt, G.W. Pearsall, and J. Wulff, *The Structure and Properties of Materials*, Vol. I, *Structure*, p. 140, John Wiley and Sons, New York, 1964.)

Strengthening Mechanisms for Metals

- For a metal to plastically deform—dislocations must move
- Strength and hardness—related to mobility of dislocations
  -- Reduce disl. mobility—metal strengthens/hardens
  -- Greater forces necessary to cause disl. motion
  -- Increase disl. mobility—metal becomes weaker/softer
- Mechanisms for strengthening/hardening metals—decrease disl. mobility
- 3 mechanisms discussed
  -- Grain size reduction
  -- Solid solution strengthening
  -- Strain hardening (cold working)

Strengthening Mechanisms for Metals Mechanism I – Reduce Grain Size

- Grain boundaries act as barriers to dislocation motion
- At boundary
  - — Slip planes change directions (note in illustration)
  - — Discontinuity of slip planes

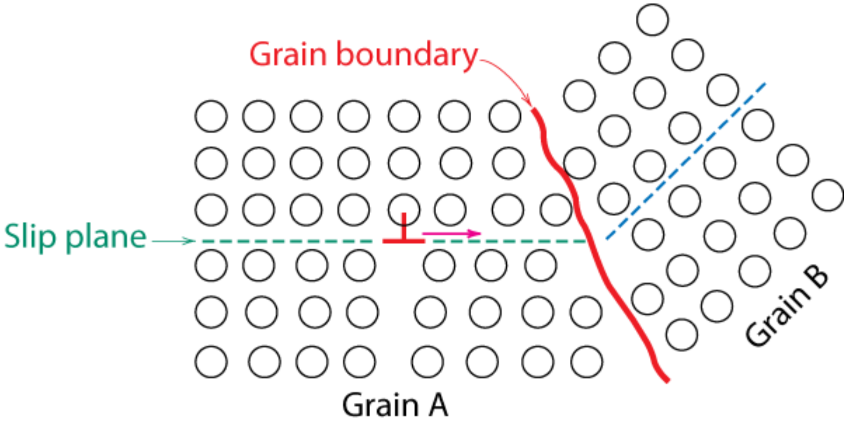


Fig. 7.14, *Callister & Rethwisch 10e.*
(From L. H. Van Vlack, *A Textbook of Materials Technology*, Addison-Wesley Publishing Co., 1973. Reproduced with the permission of the Estate of Lawrence H. Van Vlack.)

- Reduce grain size
  - — increase grain boundary area
  - — more barriers to dislocation motion
  - — increase yield strength, tensile strength & hardness
- Dependence of σ_y on average grain diameter, *d:*

$$\sigma_{yield} = \sigma_0 + k_y d^{-1/2}$$ Hall-Patch Eqn.

—σ_0, k_y = material constants

Strengthening Mechanisms for Metals
Mechanism II – Solid-Solution Strengthening

- Lattice strains around dislocations
  - Illustration notes locations of tensile, compressive strains around an edge dislocation

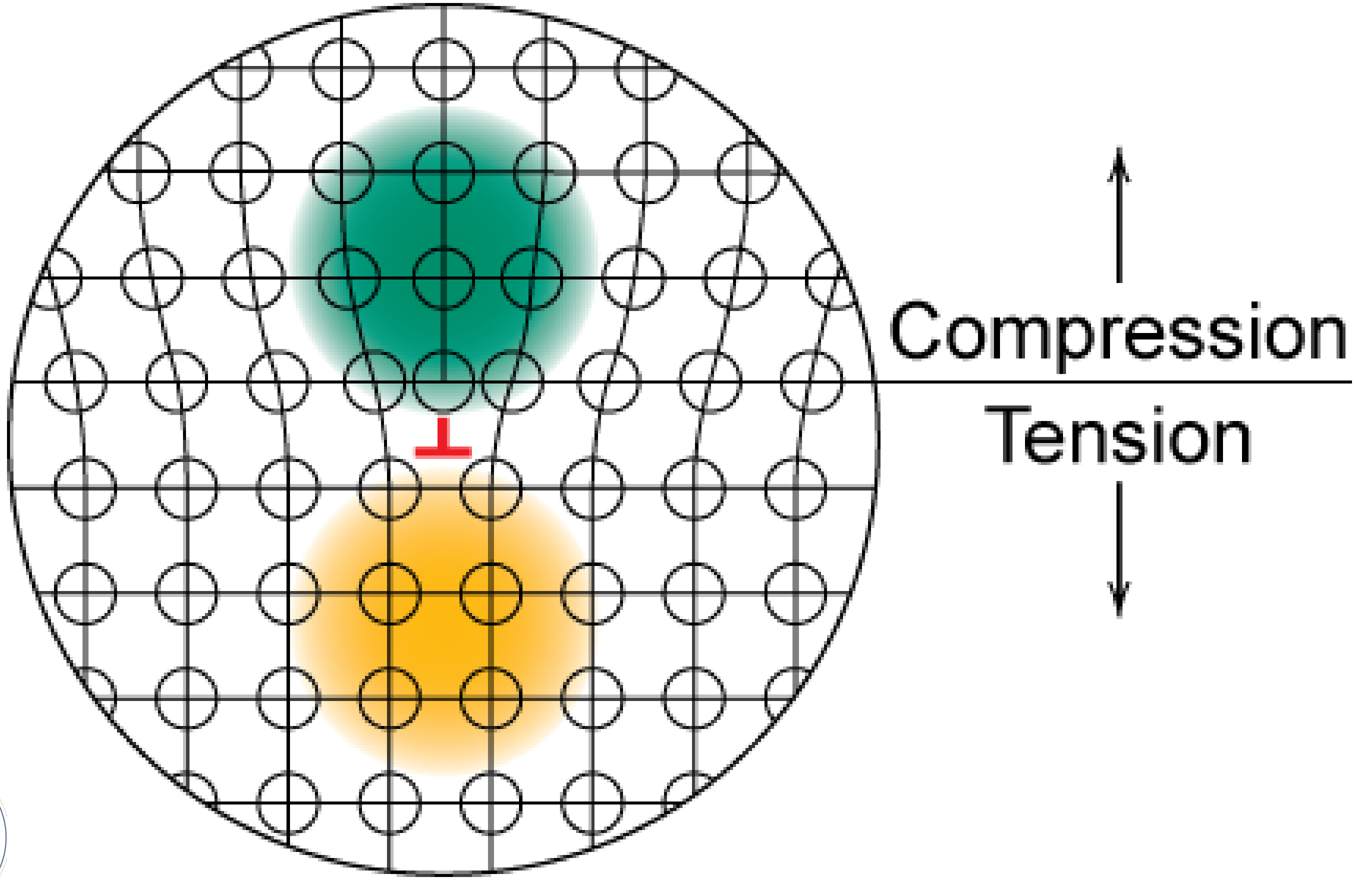


Fig. 7.4, *Callister & Rethwisch 10e.* (Adapted from W.G. Moffatt, G.W. Pearsall, and J. Wulff, *The Structure and Properties of Materials*, Vol. I, *Structure*, p. 140, John Wiley and Sons, New York, 1964.)

Solid Solution Strengthening (cont.)

- Lattice strain interactions with strains introduced by impurity atoms
- Small substitutional impurities introduce tensile strains
- When located above slip line for edge dislocation as shown:
  - partial cancellation of impurity (tensile) and disl. (compressive) strains
  - higher shear stress required to cause disl. motion

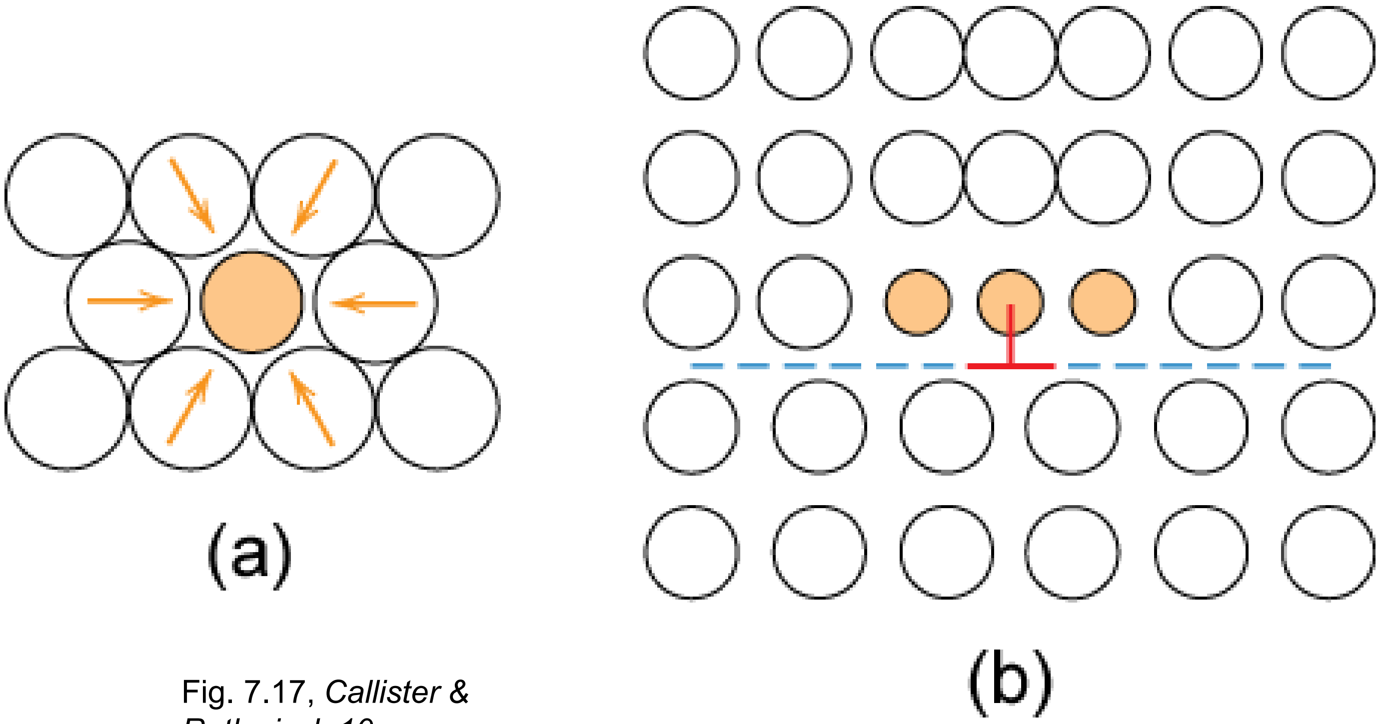


Fig. 7.17, *Callister & Rethwisch 10e.*

Solid Solution Strengthening (cont.)

- Large substitutional impurities introduce compressive strains
- When located below slip line for edge dislocation as shown:
  - partial cancellation of impurity (compressive) and disl. (tensile) strains
  - higher shear stress required to cause disl. motion

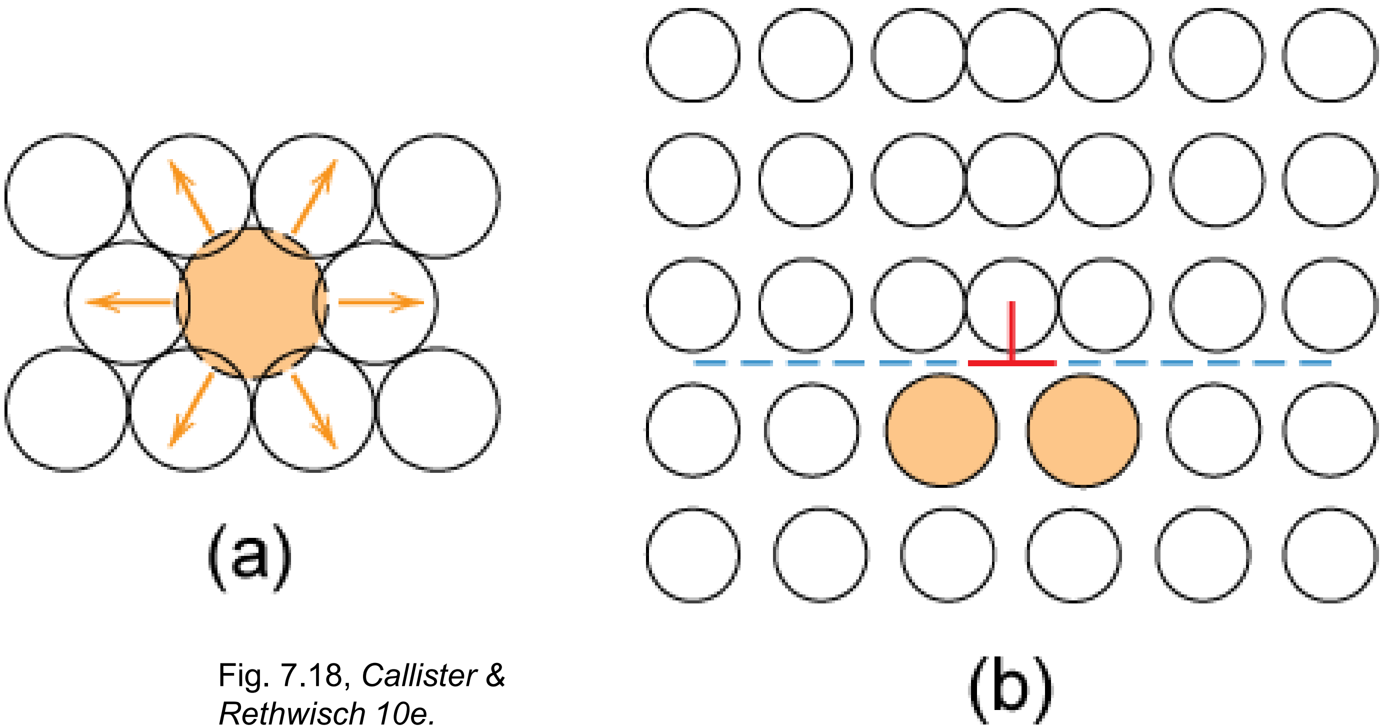
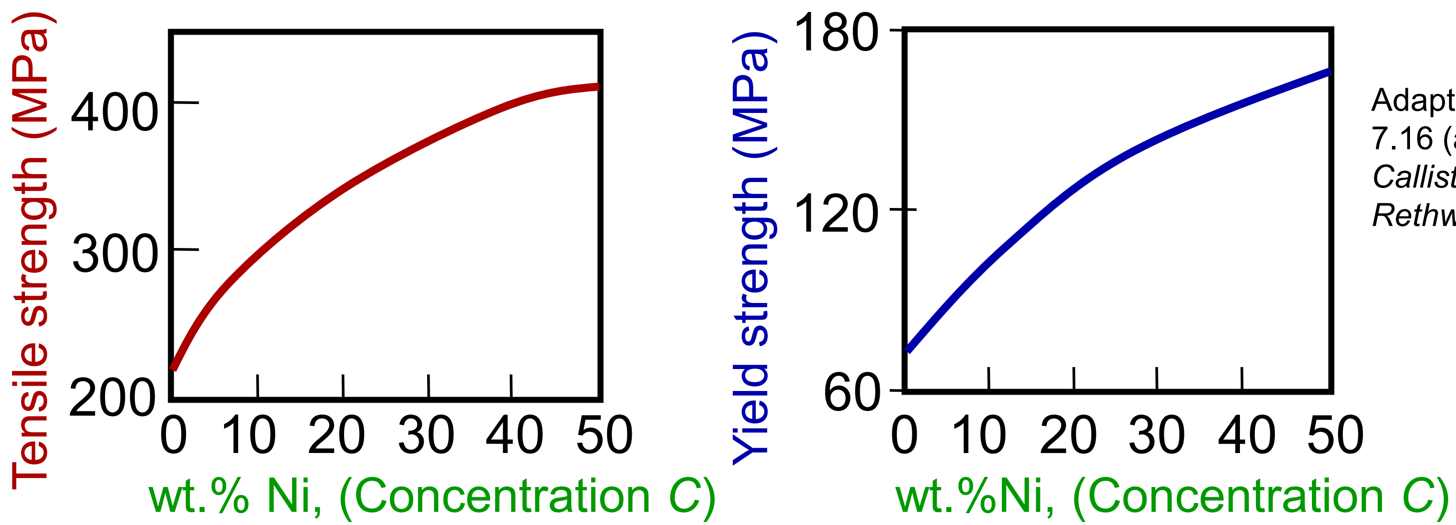


Fig. 7.18, *Callister & Rethwisch 10e.*

Solid Solution Strengthening (cont.)

- Alloying Cu with Ni increases σ_y and *TS*.
- Tensile strength & yield strength increase with wt% Ni.



Adapted from Fig. 7.16 (a) and (b), *Callister & Rethwisch 10e.*

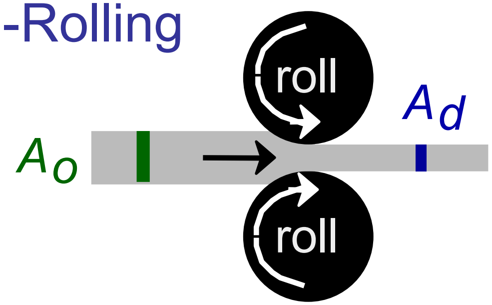
- Empirically,

$$\sigma_y \propto C^{1/2}$$

Strengthening Mechanisms for Metals
Mechanism III – Strain Hardening

- Plastically deforming most metals at room temp. makes them harder and stronger
- Phenomenon called "Strain hardening (or cold working)"
- Deformation—often reduction in cross-sectional area.

-Rolling



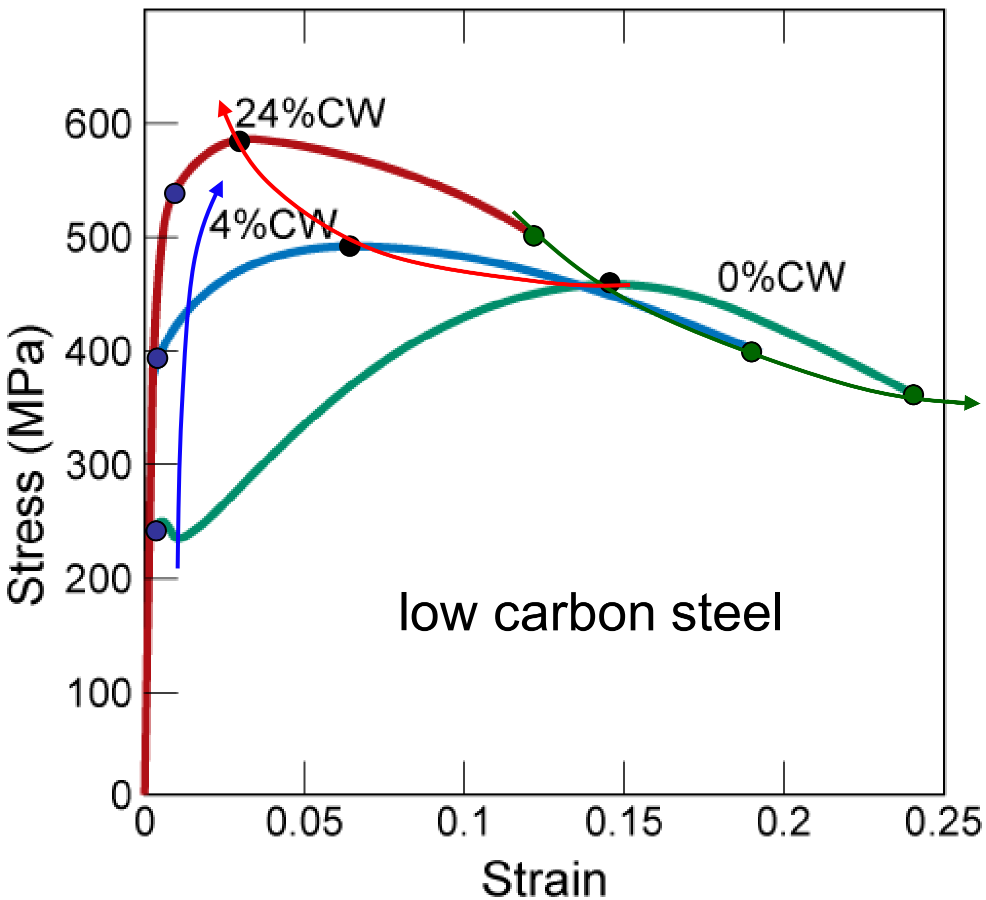
- Deformation amt. = percent coldwork (%CW)

$$\%CW = \frac{A_o - A_d}{A_o} \text{ x } 100$$

Strain Hardening (cont.)

As %CW increases

- Yield strength (σ_y) increases.
- Tensile strength (*TS*) increases.
- Ductility (%*EL* or %*AR*) decreases.



Adapted from Fig. 7.20, *Callister & Rethwisch 10e.*

Strain Hardening (cont.)

Lattice strain interactions between dislocations

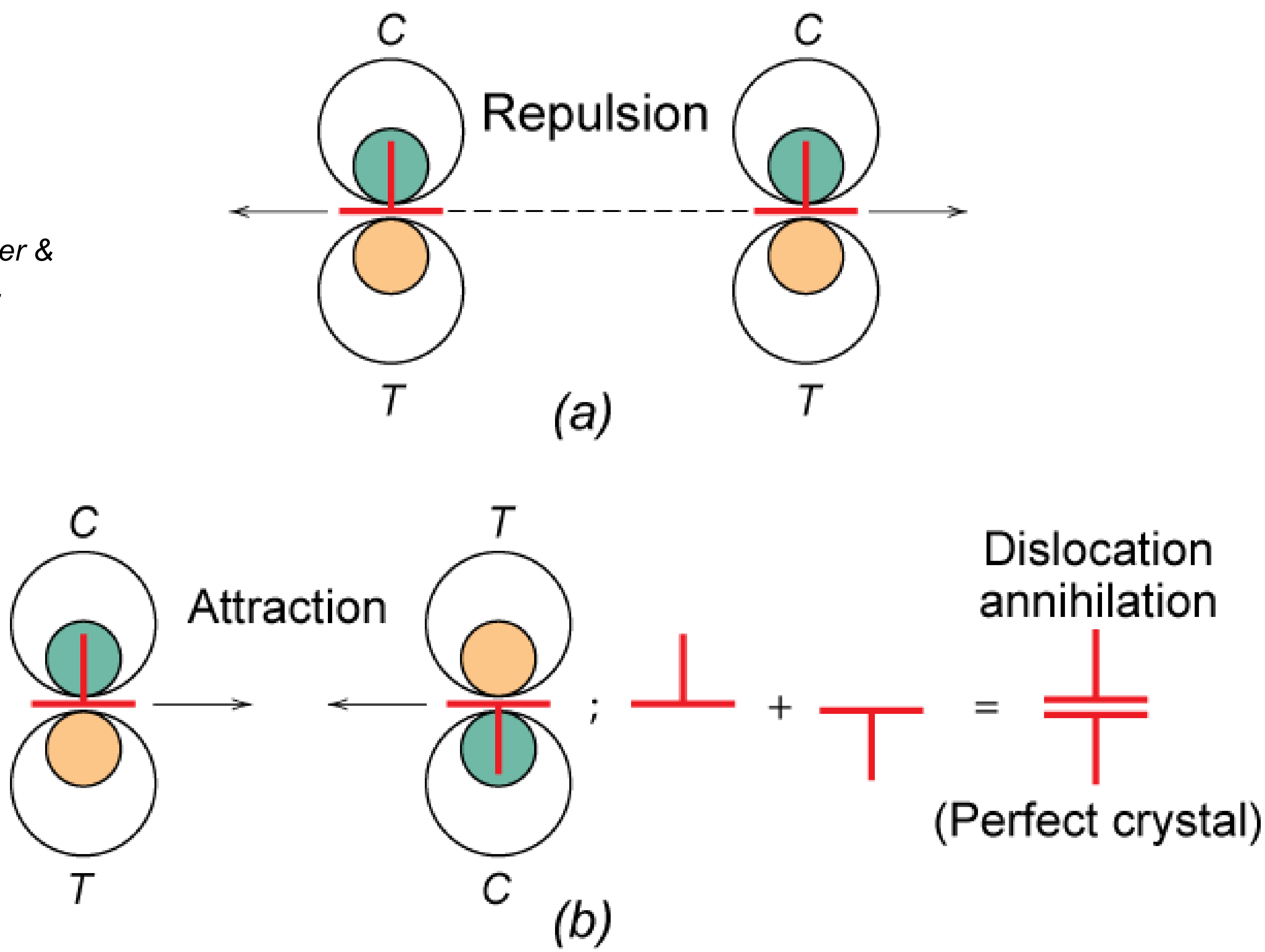


Fig. 7.5, *Callister & Rethwisch 10e.*