Chapter 7:

Deformation & Strengthening Mechanisms

ISSUES TO ADDRESS...

- Why are the number of dislocations present greatest in metals?
- How are strength and dislocation motion related?
- Why does heating alter strength and other properties?

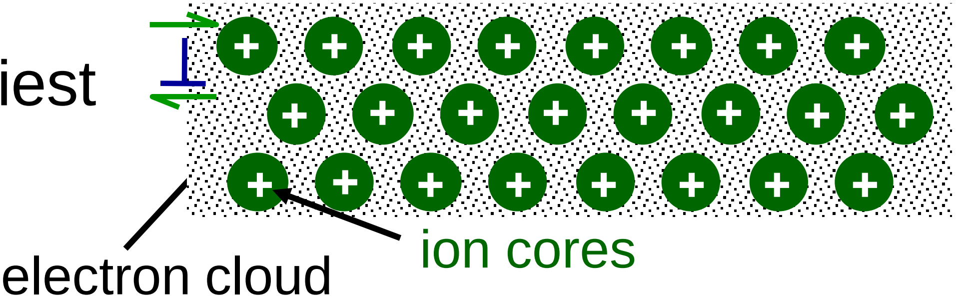
Dislocations & Materials Classes

- Metals (Cu, Al):

  Dislocation motion easiest

  - non-directional bonding

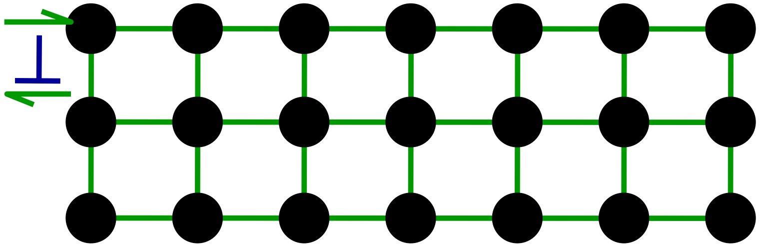
  - close-packed directions for slip



- Covalent Ceramics

  (Si, diamond): Motion difficult

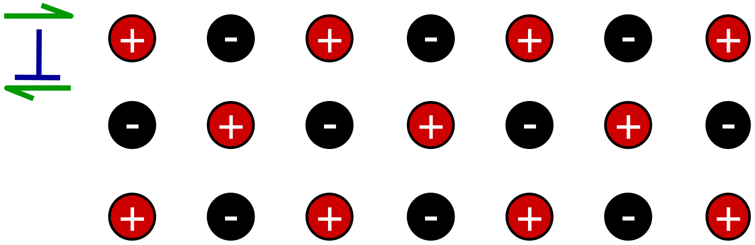
  - directional (angular) bonding



- Ionic Ceramics (NaCl):

  Motion difficult

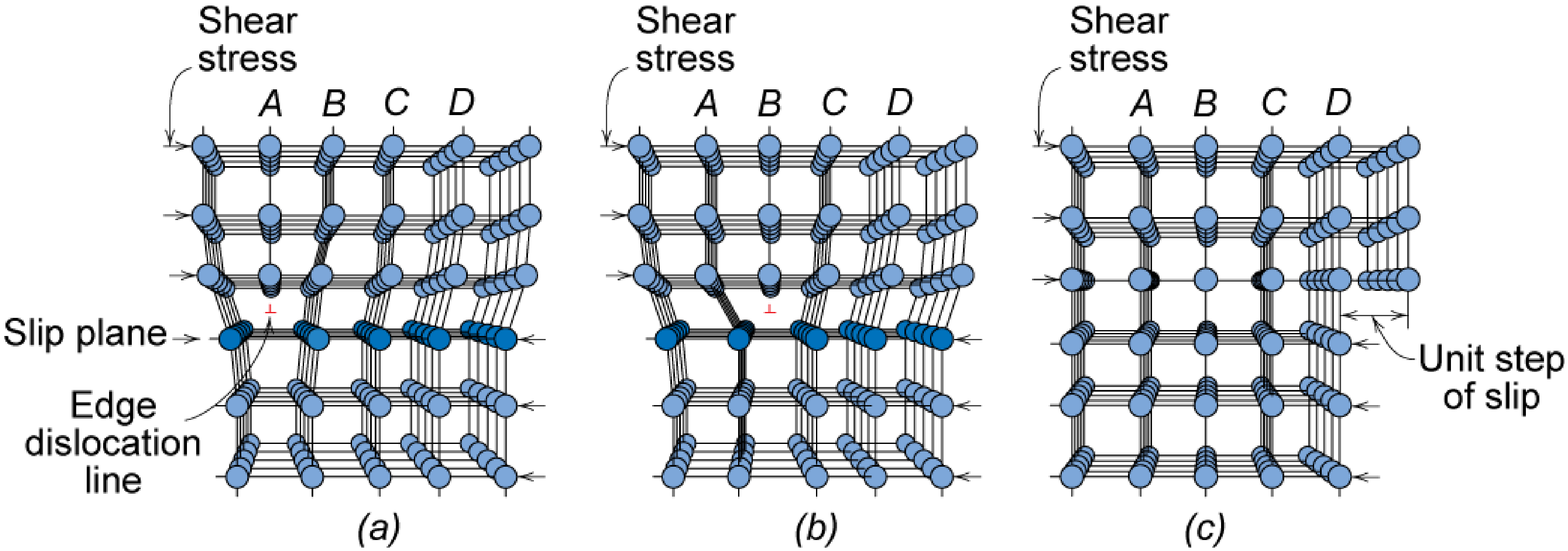
  - need to avoid nearest neighbors of like sign (- and +)



Dislocation Motion

Dislocation motion & plastic deformation

- Metals - plastic deformation occurs by slip – an edge dislocation (extra half-plane of atoms) slides over adjacent plane half-planes of atoms.

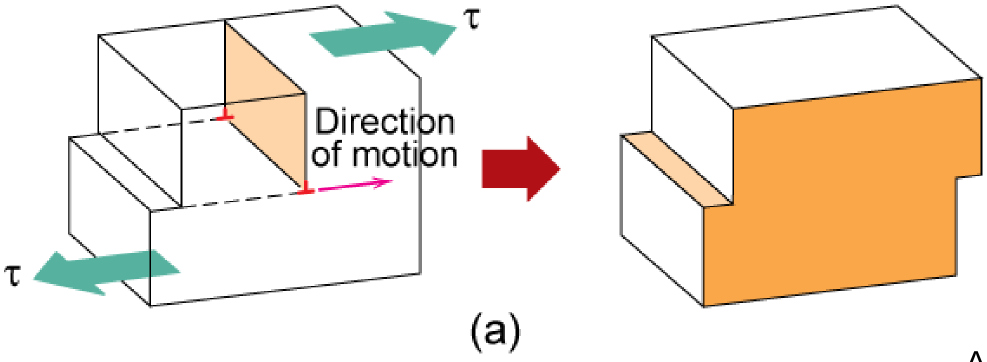


- If dislocations can't move,
  plastic deformation doesn't occur!

Adapted from Fig. 7.1,
Callister & Rethwisch 8e.

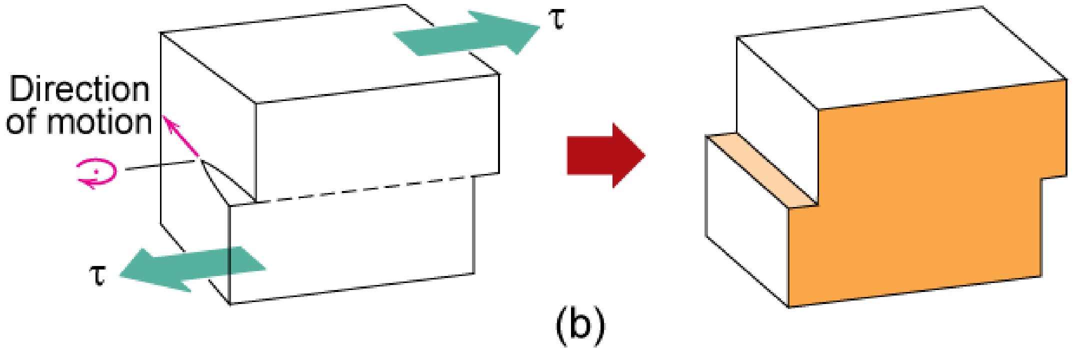
Dislocation Motion

- A dislocation moves along a slip plane in a slip direction perpendicular to the dislocation line
- The slip direction is the same as the Burgers vector direction



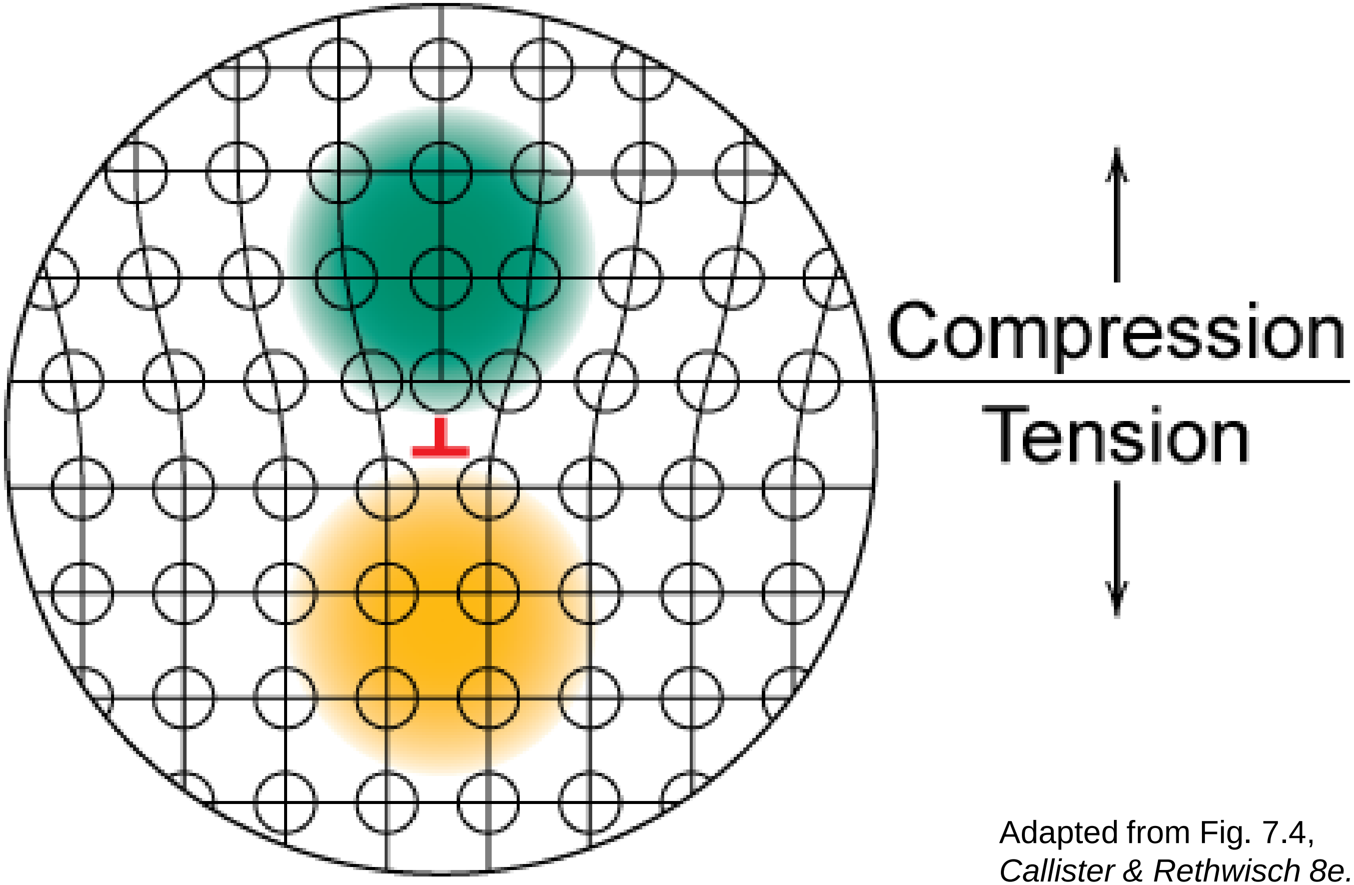
Edge dislocation

Adapted from Fig. 7.2, *Callister & Rethwisch 8e.*



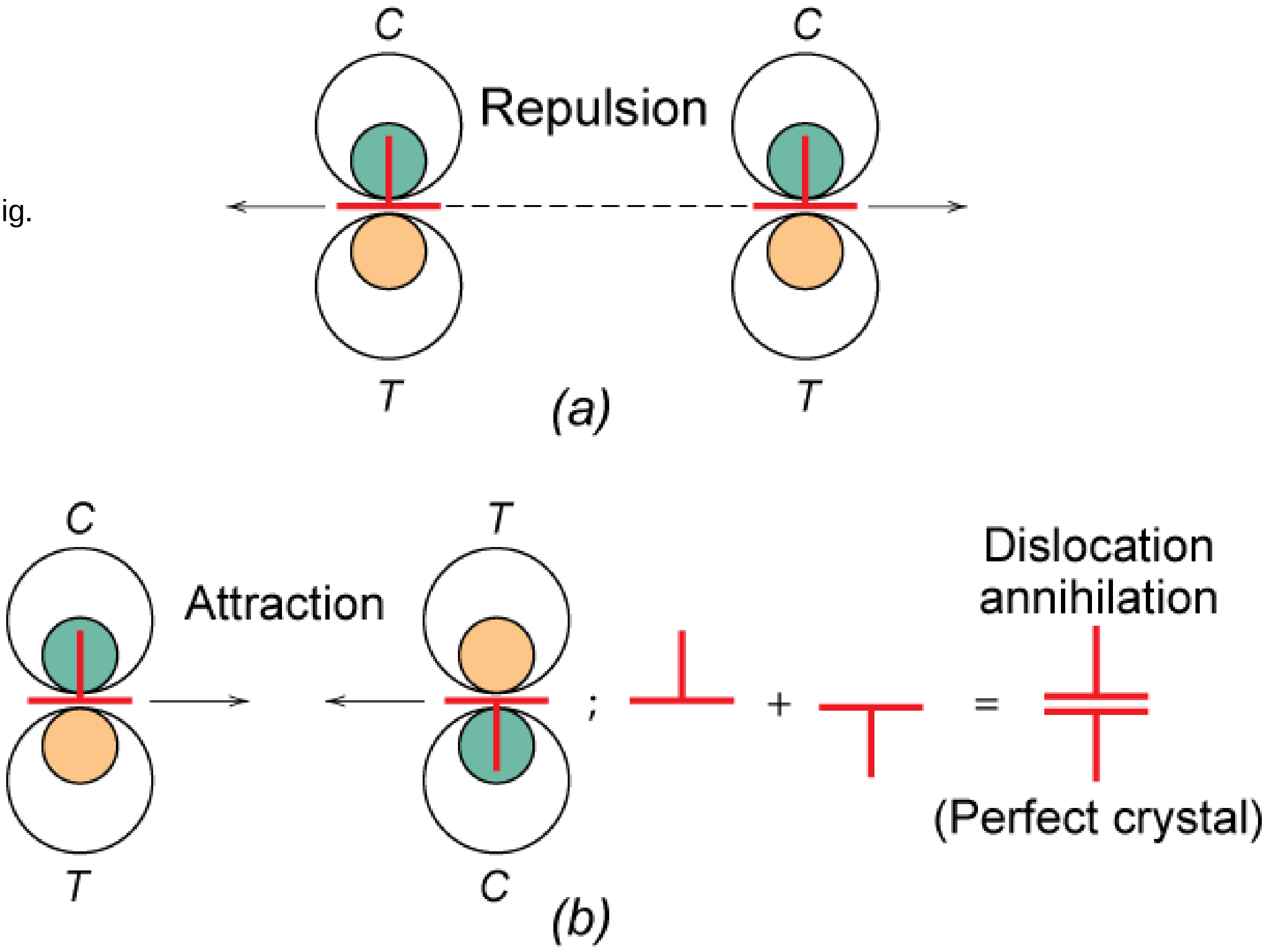
Screw dislocation

Lattice Strains Around Dislocations



Adapted from Fig. 7.4,
Callister & Rethwisch 8e.

Lattice Strain Interactions Between Dislocations

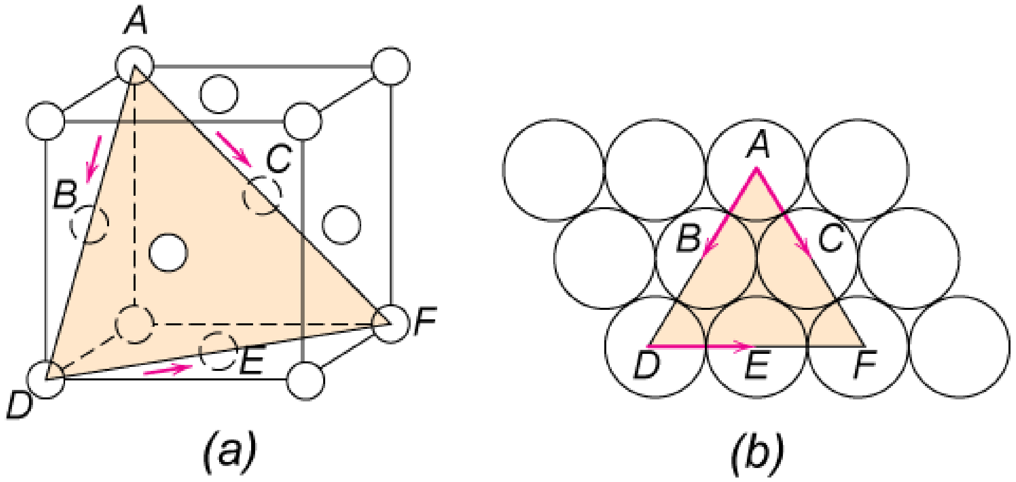


Adapted from Fig. 7.5, *Callister & Rethwisch 8e.*

Deformation Mechanisms

Slip System

- Slip plane - plane on which easiest slippage occurs
  - Highest planar densities (and large interplanar spacings)
- Slip directions - directions of movement
  - Highest linear densities



Adapted from Fig. 7.6, *Callister & Rethwisch 8e.*

- FCC Slip occurs on {111} planes (close-packed) in <110> directions (close-packed)

  => total of 12 slip systems in FCC
- For BCC & HCP there are other slip systems.

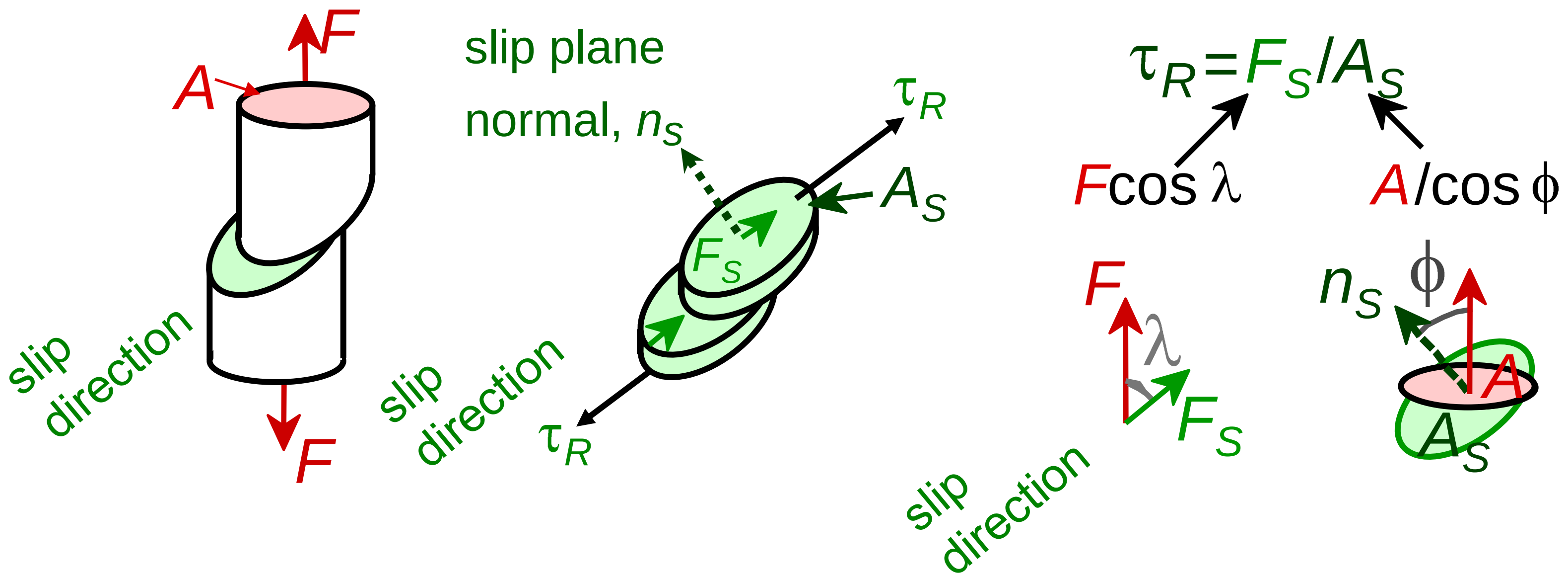
Stress and Dislocation Motion

- Resolved shear stress, τ_R
  - – results from applied tensile stresses

Applied tensile stress: $\sigma = F/A$

Resolved shear stress: $\tau_R = F_S/A_S$

Relation between σ and τ_R



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

Critical Resolved Shear Stress

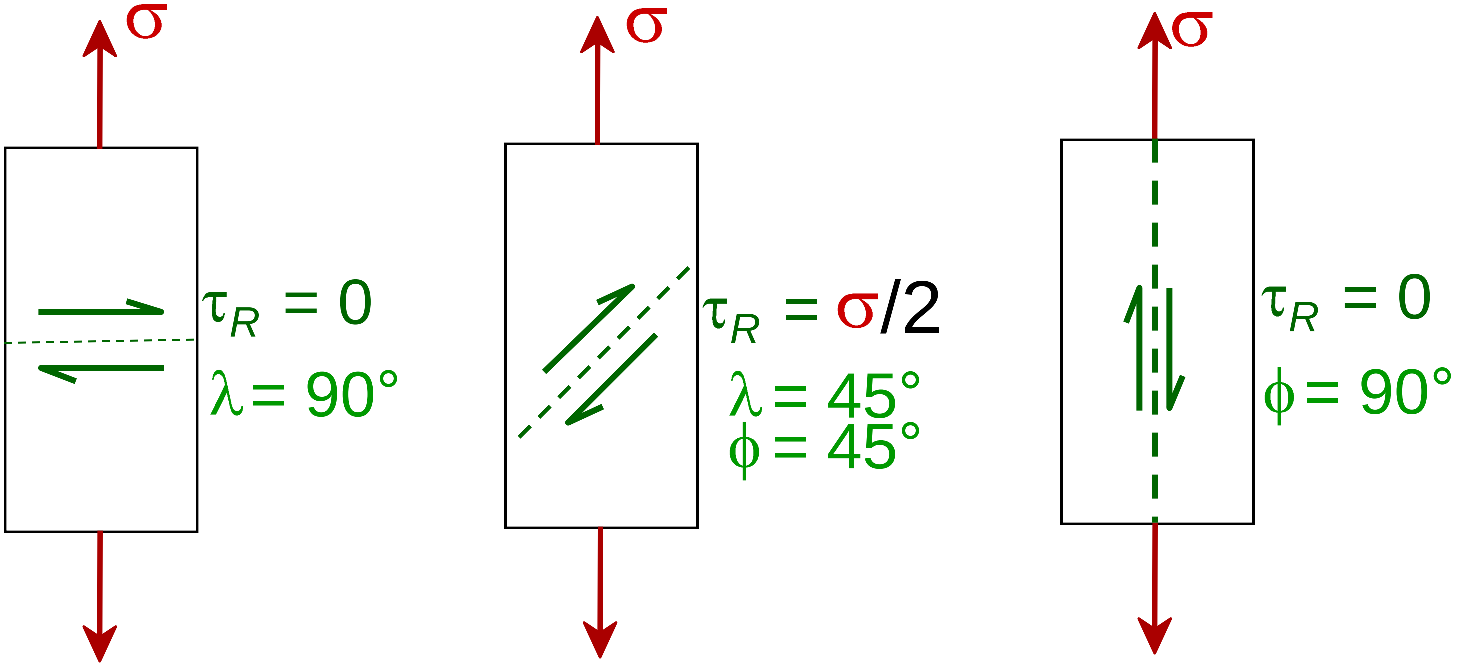
- Condition for dislocation motion: $\tau_R > \tau_{CRSS}$

typically

10^{-4} GPa to 10^{-2} GPa

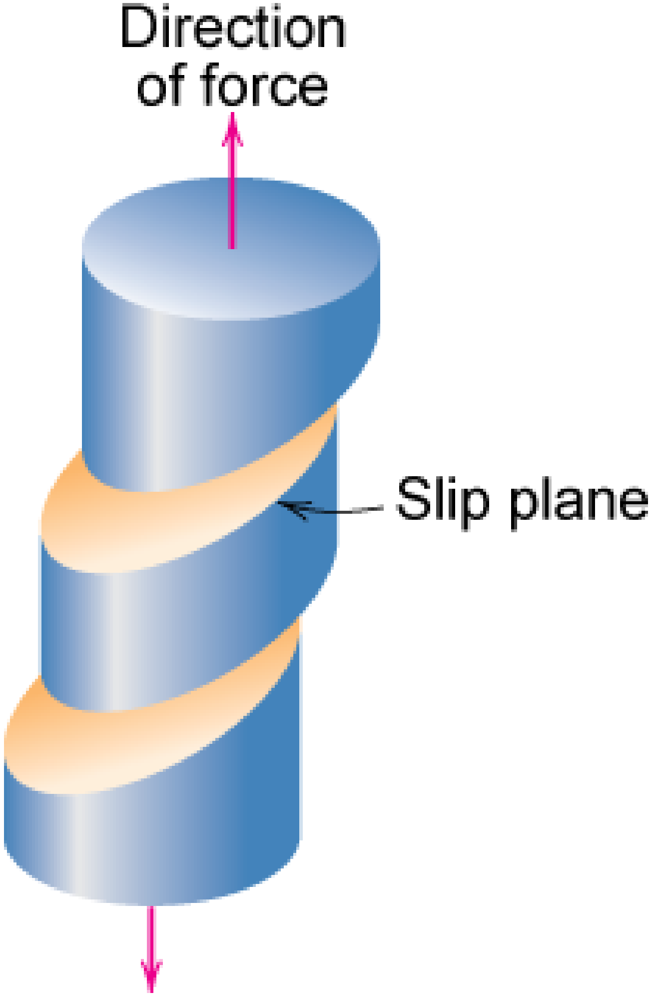
- Ease of dislocation motion depends on crystallographic orientation

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



τ maximum at $\lambda = \phi = 45°$

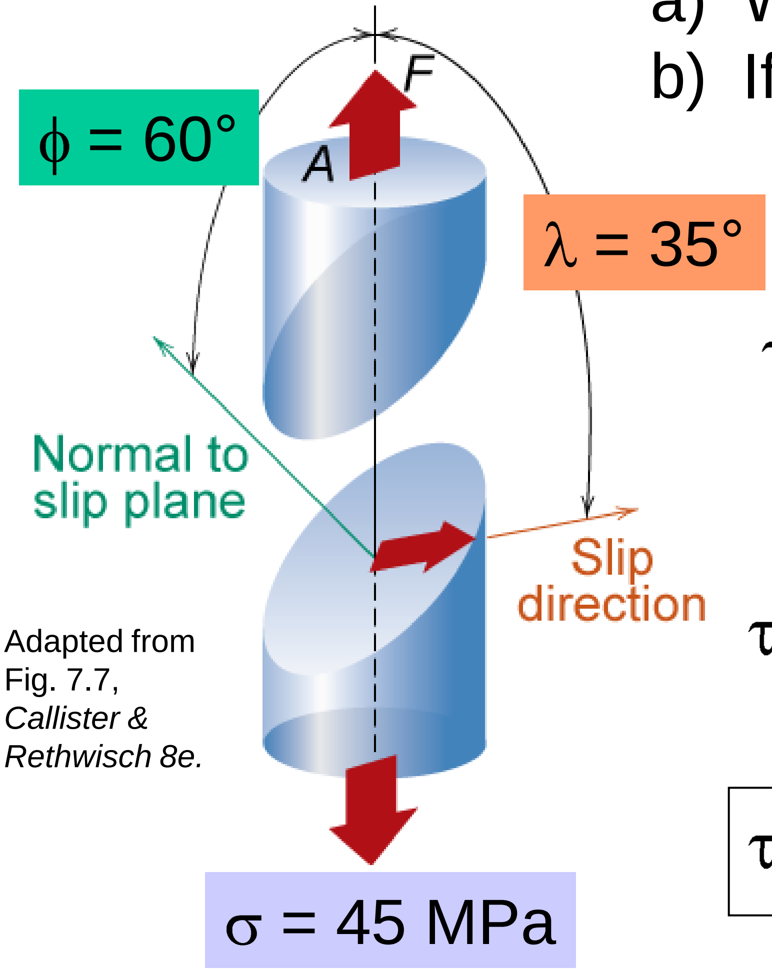
Single Crystal Slip



Adapted from Fig. 7.8, *Callister & Rethwisch 8e.*

Adapted from Fig. 7.9, *Callister & Rethwisch 8e.*

Ex: Deformation of single crystal



Adapted from Fig. 7.7, *Callister & Rethwisch 8e.*

a) Will the single crystal yield?

b) If not, what stress is needed?

$$\tau_{crss} = 20.7 \text{ MPa}$$

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

$$\sigma = 45 \text{ MPa}$$

$$\tau = (45 \text{ MPa})\,(\cos 35^\circ)(\cos 60^\circ)$$

$$= (45 \text{ MPa})\,(0.41)$$

$$\boxed{\tau = 18.4 \text{ MPa} \quad < \tau_{crss} = 20.7 \text{ MPa}}$$

So the applied stress of 45 MPa will not cause the crystal to yield.

Ex: Deformation of single crystal

What stress *is* necessary (i.e., what is the yield stress, σ_y)?

$$\tau_{crss} = 20.7\text{ MPa} = \sigma_y \cos\lambda \cos\phi = \sigma_y (0.41)$$

$$\therefore \sigma_y = \frac{\tau_{crss}}{\cos\lambda \cos\phi} = \frac{20.7\text{ MPa}}{0.41} = \underline{\underline{50.5\text{ MPa}}}$$

So for deformation to occur the applied stress must be greater than or equal to the yield stress

$$\boxed{\sigma \geq \sigma_y = 50.5\text{ MPa}}$$

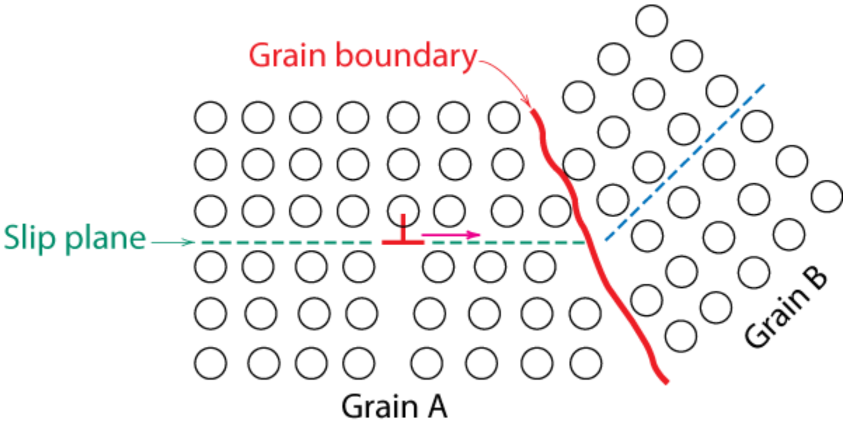
Slip Motion in Polycrystals

- Polycrystals stronger than single crystals – grain boundaries are barriers to dislocation motion.
- Slip planes & directions (λ, ϕ) change from one grain to another.
- τ_R will vary from one grain to another.
- The grain with the largest τ_R yields first.
- Other (less favorably oriented) grains yield later.

Adapted from Fig. 7.10, *Callister & Rethwisch 8e.* (Fig. 7.10 is courtesy of C. Brady, National Bureau of Standards [now the National Institute of Standards and Technology, Gaithersburg, MD].)

Strengthening Mechanisms:
1: Reduce Grain Size

- Grain boundaries are barriers to slip.
- Barrier "strength" increases with Increasing angle of misorientation.
- Smaller grain size: more barriers to slip.



Adapted from Fig. 7.14, *Callister & Rethwisch 8e.* (Fig. 7.14 is from *A Textbook of Materials Technology*, by Van Vlack, Pearson Education, Inc., Upper Saddle River, NJ.)

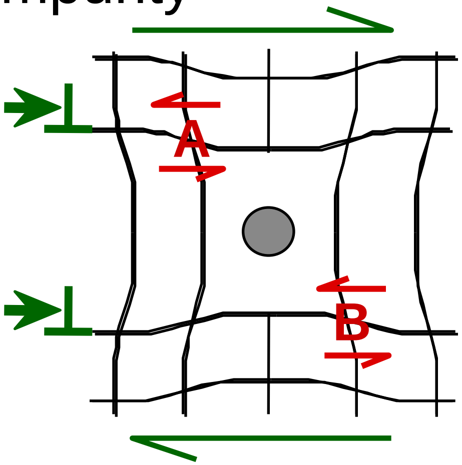
- Hall-Petch Equation:

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

Strengthening Mechanisms : 2: Form Solid Solutions

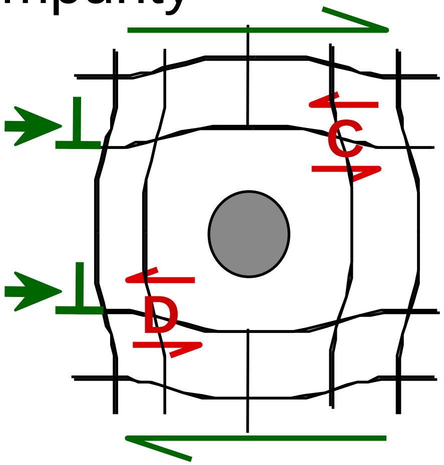
- Impurity atoms distort the lattice & generate lattice strains.
- These strains can act as barriers to dislocation motion.

- Smaller substitutional impurity



Impurity generates local stress at **A** and **B** that opposes dislocation motion to the right.

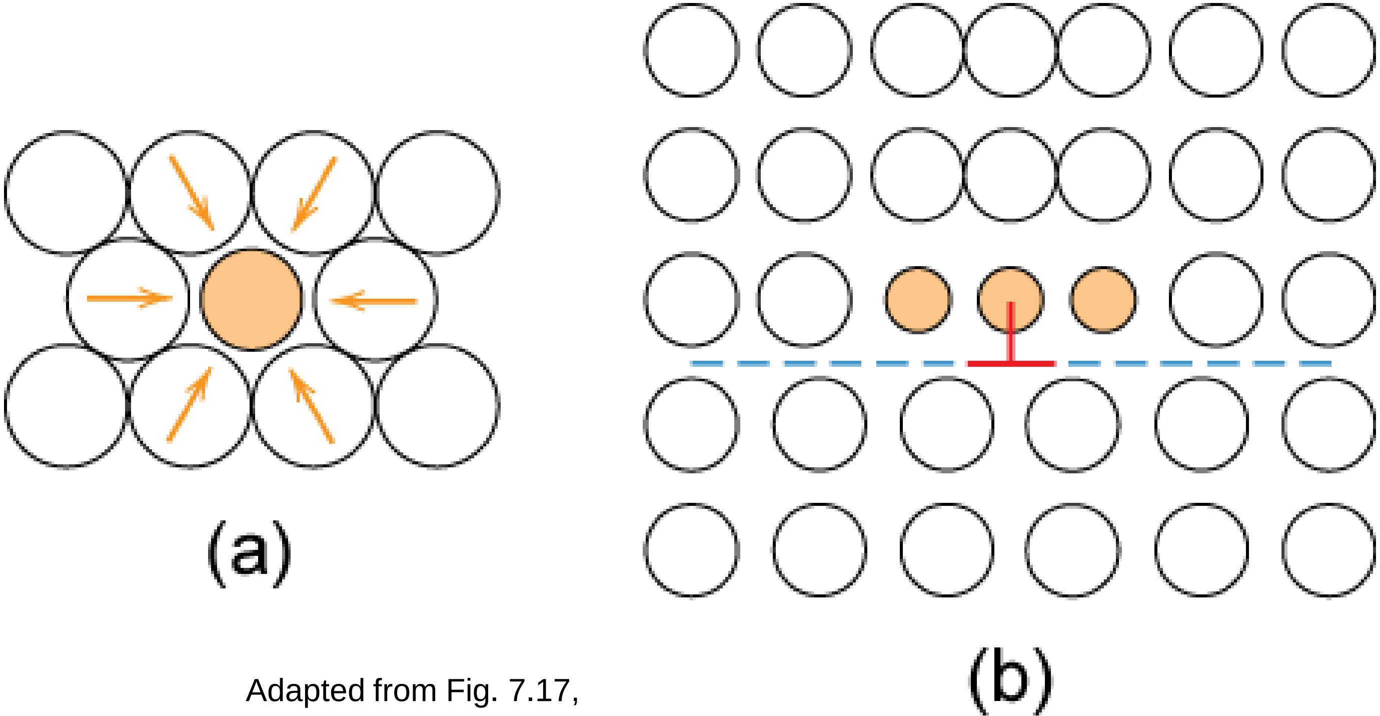
- Larger substitutional impurity



Impurity generates local stress at **C** and **D** that opposes dislocation motion to the right.

Strengthening by Solid Solution Alloying

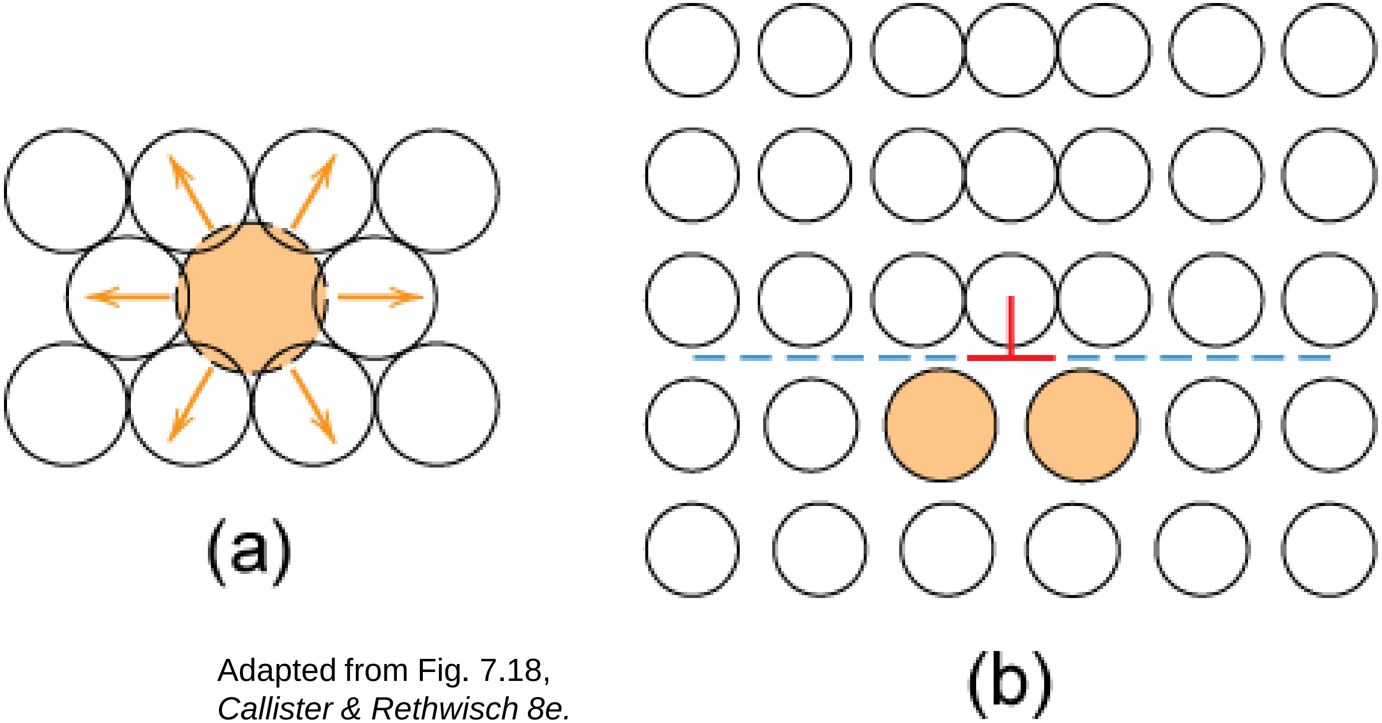
- Small impurities tend to concentrate at dislocations (regions of compressive strains) - partial cancellation of dislocation compressive strains and impurity atom tensile strains
- Reduce mobility of dislocations and increase strength



Adapted from Fig. 7.17,
Callister & Rethwisch 8e.

Strengthening by Solid Solution Alloying

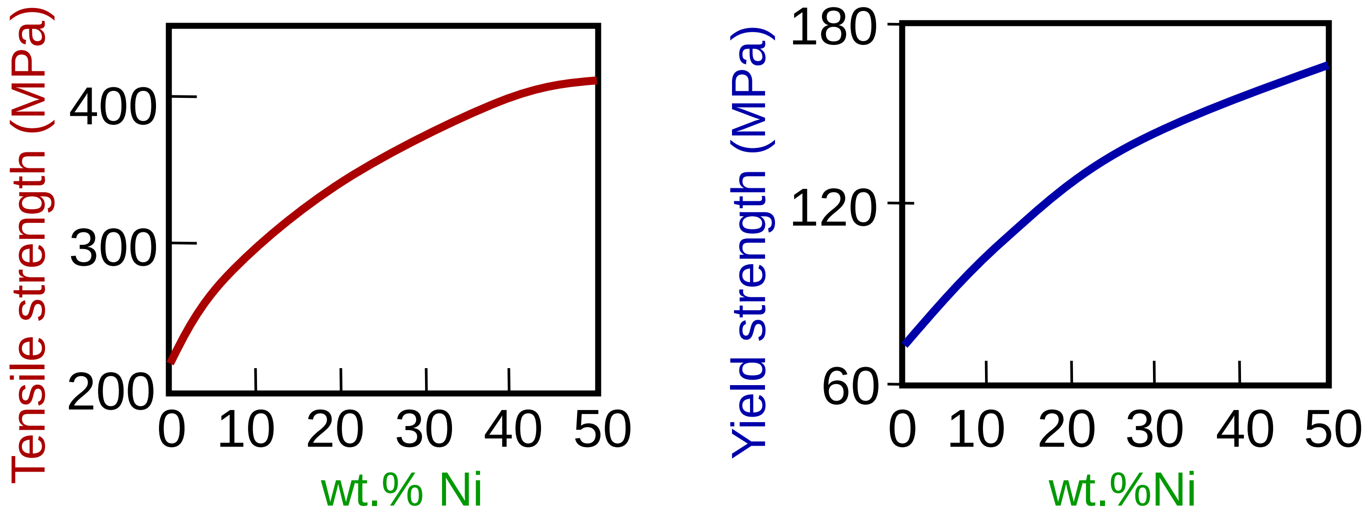
- Large impurities tend to concentrate at dislocations (regions of tensile strains)



Adapted from Fig. 7.18,
Callister & Rethwisch 8e.

Ex: Solid Solution Strengthening in Copper

- Tensile strength & yield strength increase with wt% Ni.

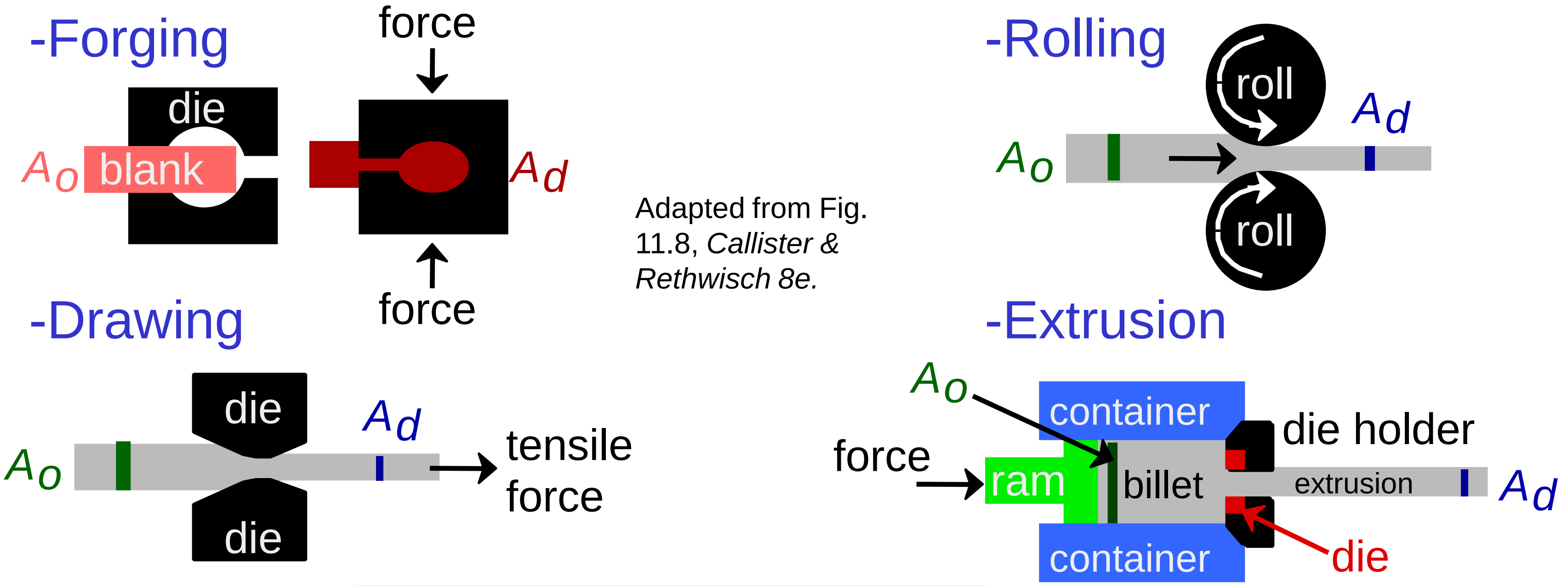


Adapted from Fig. 7.16(a) and (b), *Callister & Rethwisch 8e.*

- Alloying increases σ_y and *TS*.

Strengthening Mechanisms : 3: Cold Work (Strain Hardening)

- Deformation at room temperature (for most metals).
- Common forming operations reduce the cross-sectional area:

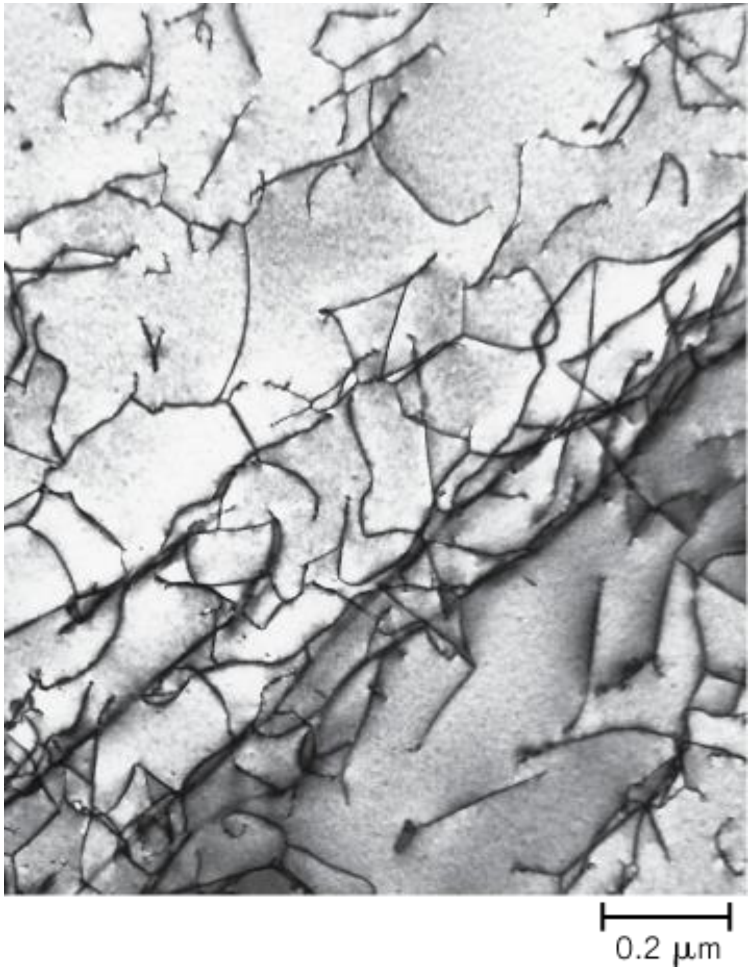


Adapted from Fig. 11.8, *Callister & Rethwisch 8e.*

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

Dislocation Structures Change During Cold Working

- Dislocation structure in Ti after cold working.



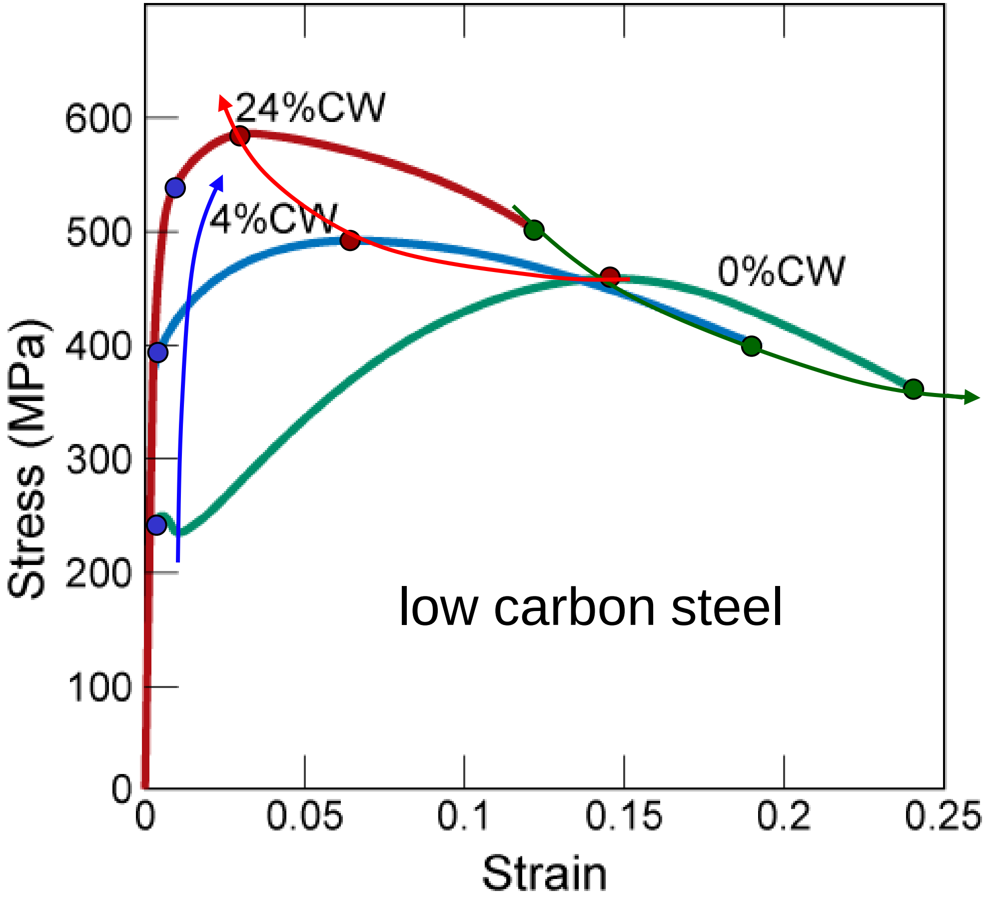
- Dislocations entangle with one another during cold work.
- Dislocation motion becomes more difficult.

Fig. 4.6, *Callister & Rethwisch 8e.*
(Fig. 4.6 is courtesy of M.R. Plichta, Michigan Technological University.)

Impact of Cold Work

As cold work is increased

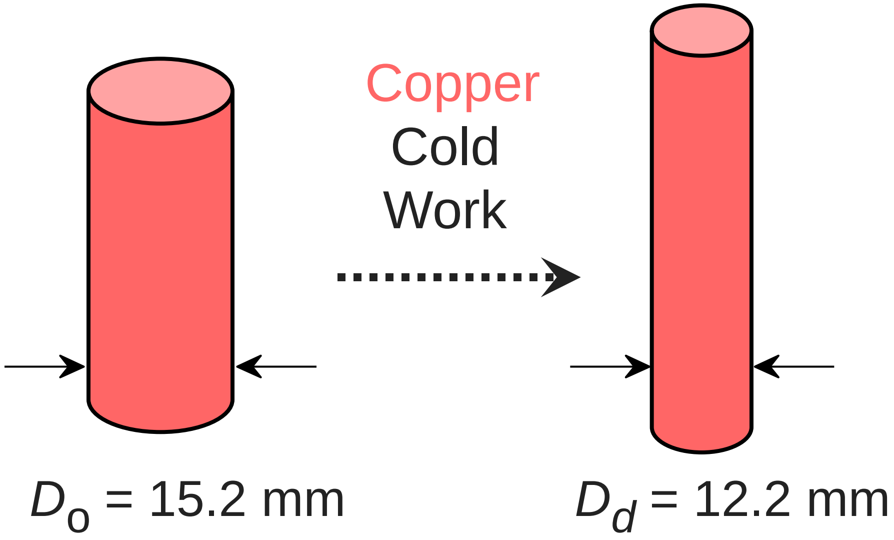
- Yield strength (σ_y) increases.
- Tensile strength (*TS*) increases.
- Ductility (%*EL* or %*AR*) decreases.



Adapted from Fig. 7.20, *Callister & Rethwisch 8e.*

Mechanical Property Alterations Due to Cold Working

- What are the values of yield strength, tensile strength & ductility after cold working Cu?



D_o = 15.2 mm

D_d = 12.2 mm

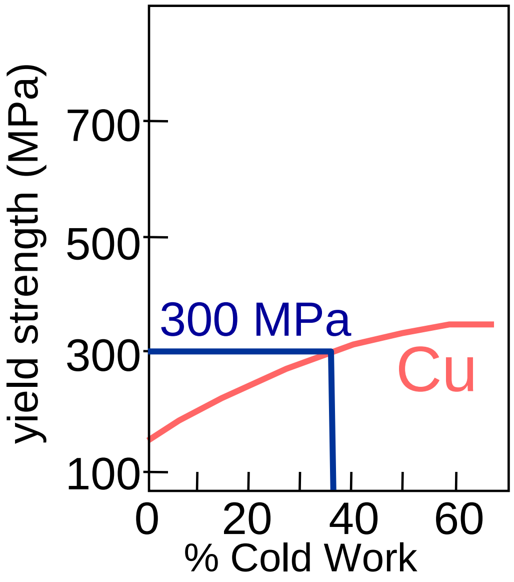
$$\%CW = \frac{\frac{\pi D_o^2}{4} - \frac{\pi D_d^2}{4}}{\frac{\pi D_o^2}{4}} \text{ x } 100$$

$$= \frac{D_o^2 - D_d^2}{D_o^2} \text{ x } 100$$

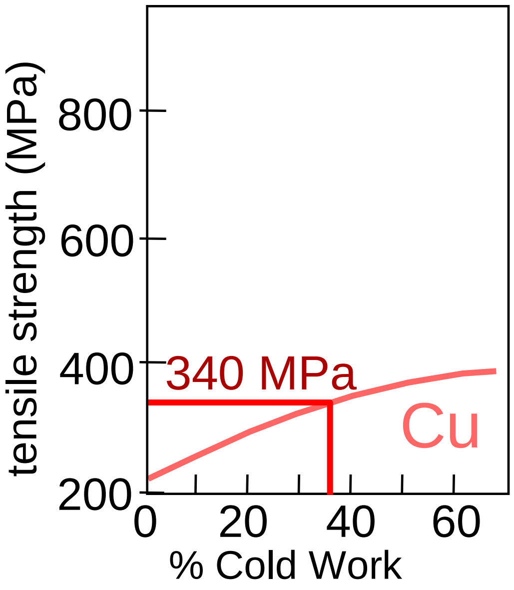
$$\%CW = \frac{(15.2 \text{ mm})^2 - (12.2 \text{ mm})^2}{(15.2 \text{ mm})^2} \text{ x } 100 = 35.6\%$$

Mechanical Property Alterations Due to Cold Working

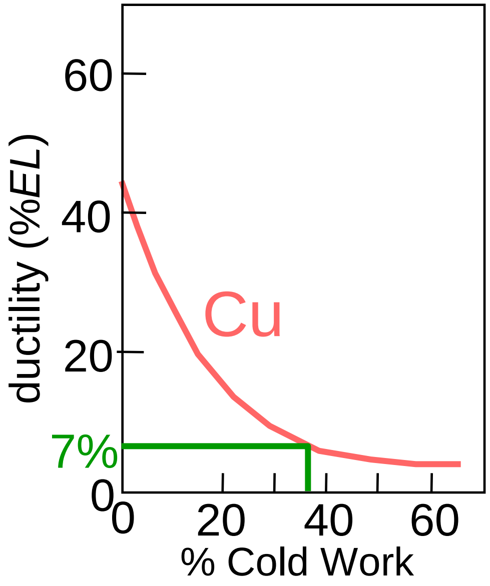
- What are the values of yield strength, tensile strength & ductility for Cu for %CW = 35.6%?



σ_y = 300 MPa



TS = 340 MPa

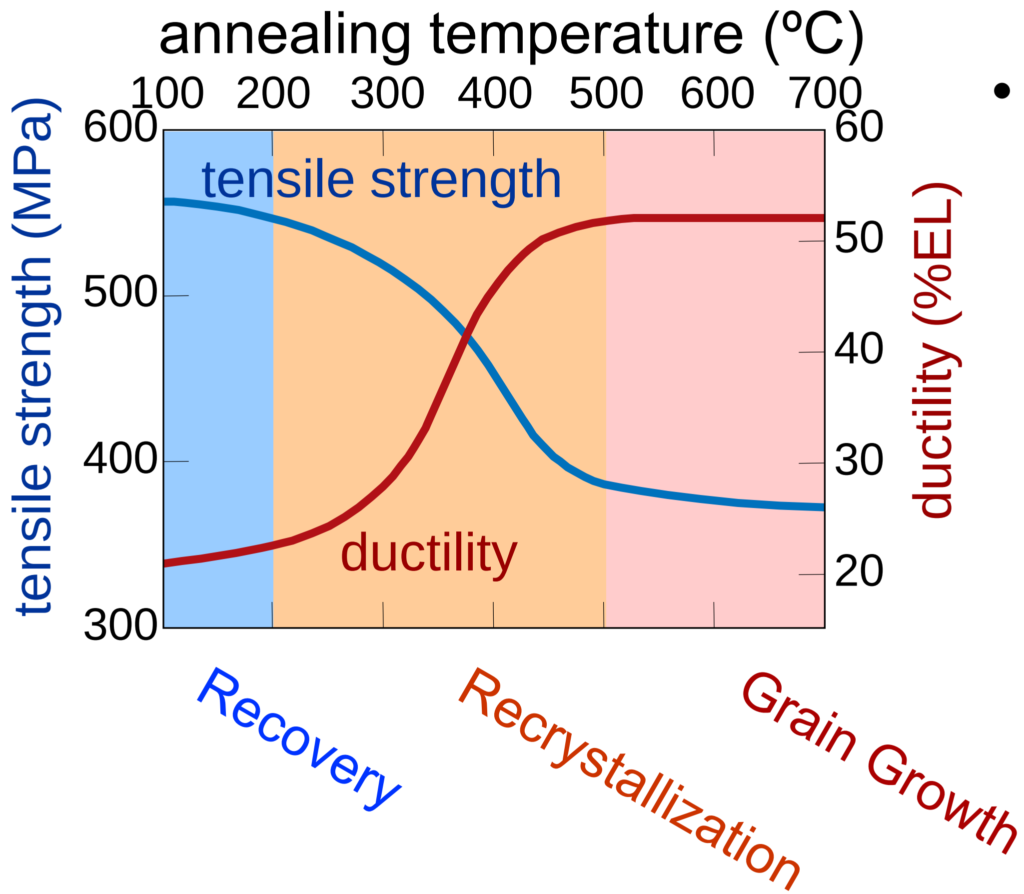


%*EL* = 7%

Adapted from Fig. 7.19, *Callister & Rethwisch 8e.* (Fig. 7.19 is adapted from *Metals Handbook: Properties and Selection: Iron and Steels*, Vol. 1, 9th ed., B. Bardes (Ed.), American Society for Metals, 1978, p. 226; and *Metals Handbook: Properties and Selection: Nonferrous Alloys and Pure Metals*, Vol. 2, 9th ed., H. Baker (Managing Ed.), American Society for Metals, 1979, p. 276 and 327.)

Effect of Heat Treating After Cold Working

- 1 hour treatment at T_{anneal}...
  decreases *TS* and increases %*EL*.
- Effects of cold work are nullified!



- Three Annealing stages:
  1. Recovery
  2. Recrystallization
  3. Grain Growth

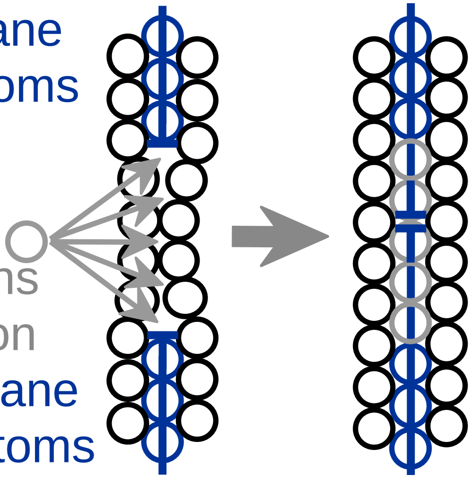
Adapted from Fig. 7.22, *Callister & Rethwisch 8e.* (Fig. 7.22 is adapted from G. Sachs and K.R. van Horn, *Practical Metallurgy, Applied Metallurgy, and the Industrial Processing of Ferrous and Nonferrous Metals and Alloys*, American Society for Metals, 1940, p. 139.)

Three Stages During Heat Treatment:
1. Recovery

Reduction of dislocation density by annihilation.

- Scenario 1

  Results from diffusion



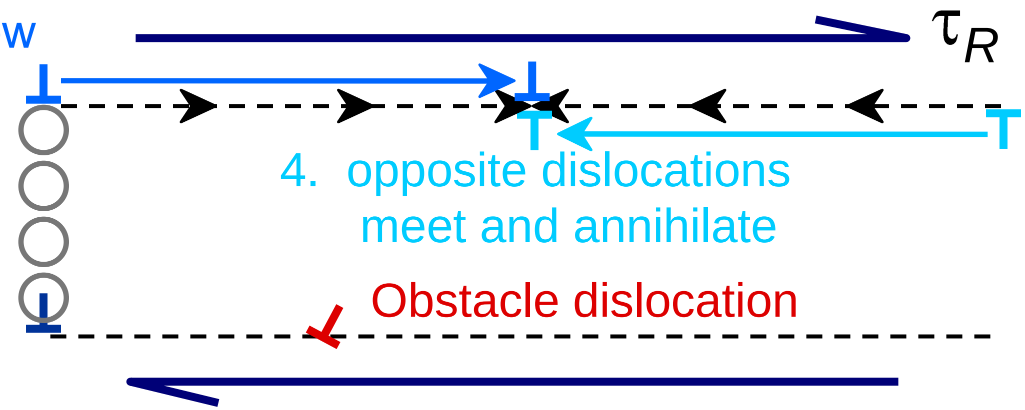
extra half-plane of atoms

atoms diffuse to regions of tension

extra half-plane of atoms

Dislocations annihilate and form a perfect atomic plane.

- Scenario 2



3. “Climbed” disl. can now move on new slip plane

2. grey atoms leave by vacancy diffusion allowing disl. to “climb”

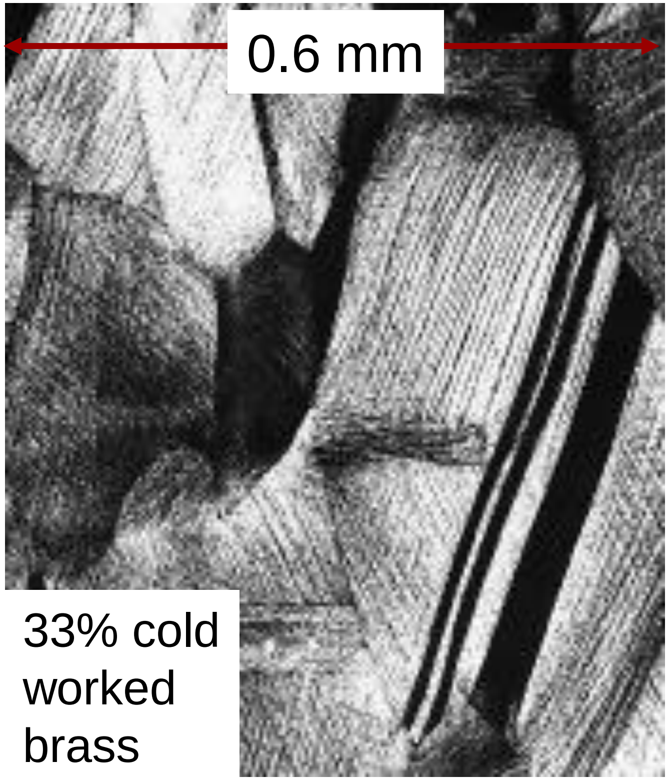
1. dislocation blocked; can’t move to the right

4. opposite dislocations meet and annihilate

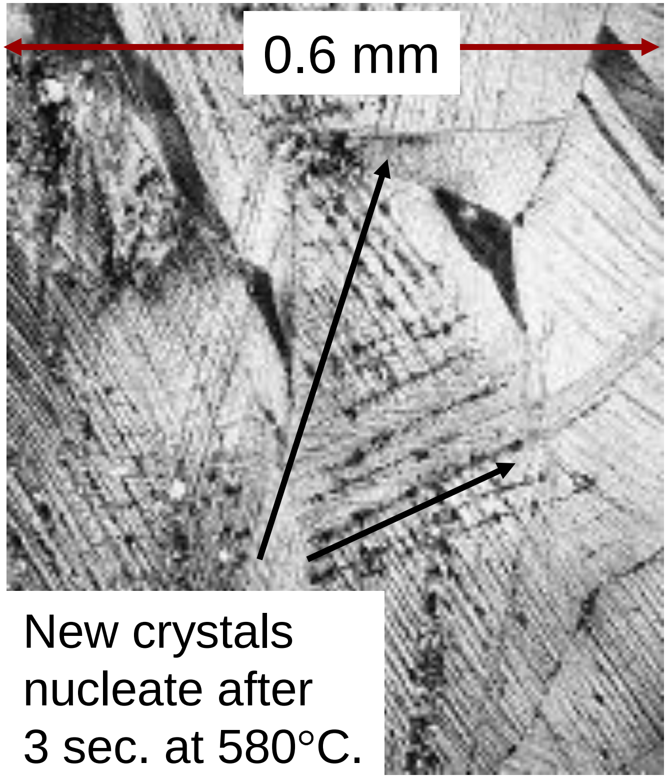
Obstacle dislocation

Three Stages During Heat Treatment:
2. Recrystallization

- New grains are formed that:
  - -- have low dislocation densities
  - -- are small in size
  - -- consume and replace parent cold-worked grains.



33% cold worked brass

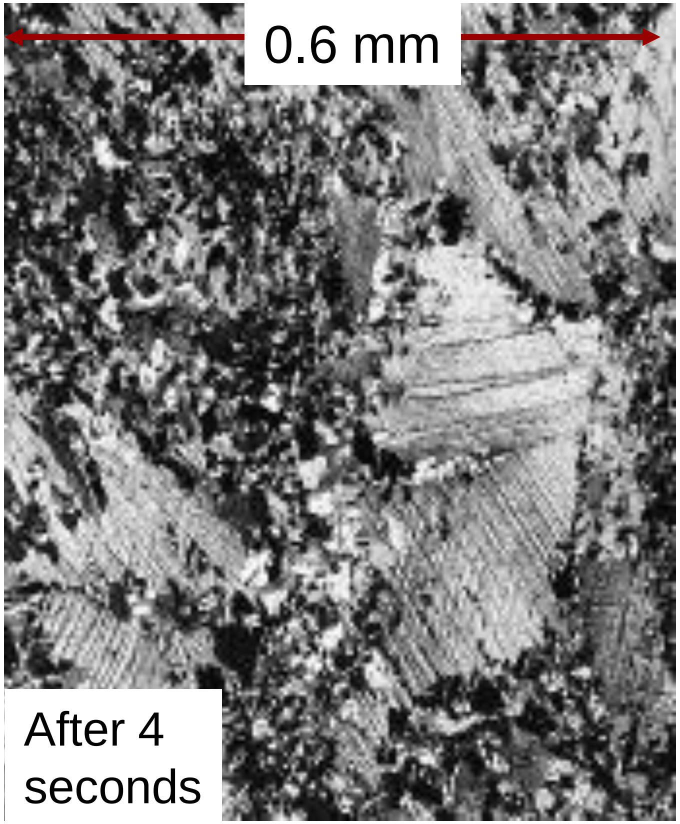


New crystals nucleate after 3 sec. at 580°C.

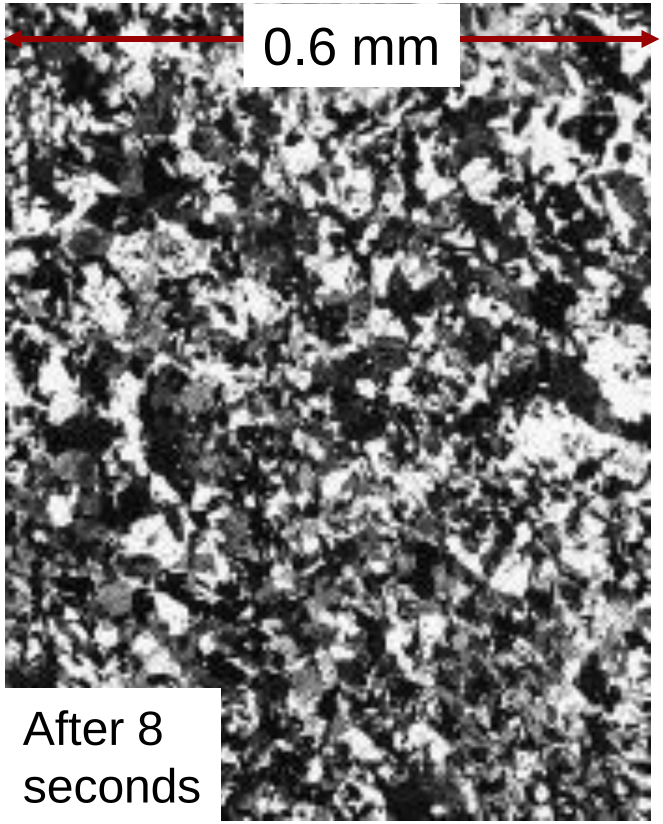
Adapted from Fig. 7.21(a),(b), *Callister & Rethwisch 8e.* (Fig. 7.21(a),(b) are courtesy of J.E. Burke, General Electric Company.)

As Recrystallization Continues…

- All cold-worked grains are eventually consumed/replaced.



After 4 seconds

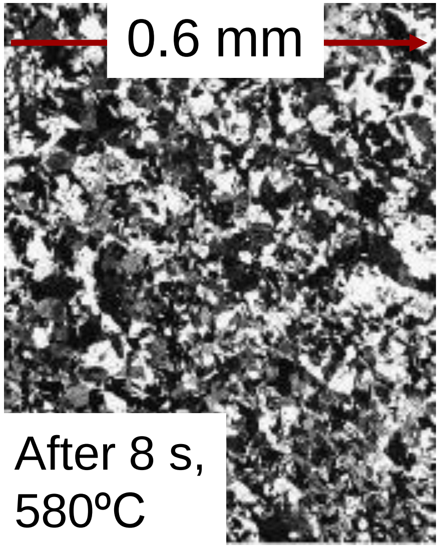


After 8 seconds

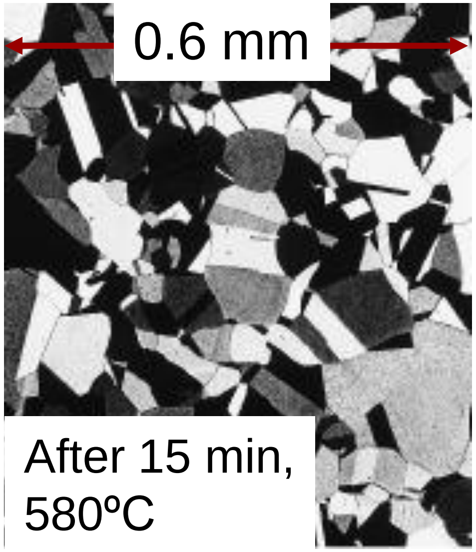
Adapted from Fig. 7.21(c),(d), *Callister & Rethwisch 8e.* (Fig. 7.21(c),(d) are courtesy of J.E. Burke, General Electric Company.)

Three Stages During Heat Treatment: 3. Grain Growth

- At longer times, average grain size increases.
  - -- Small grains shrink (and ultimately disappear)
  - -- Large grains continue to grow



After 8 s, 580ºC



After 15 min, 580ºC

Adapted from Fig. 7.21(d),(e), *Callister & Rethwisch 8e.* (Fig. 7.21(d),(e) are courtesy of J.E. Burke, General Electric Company.)

- Empirical Relation:

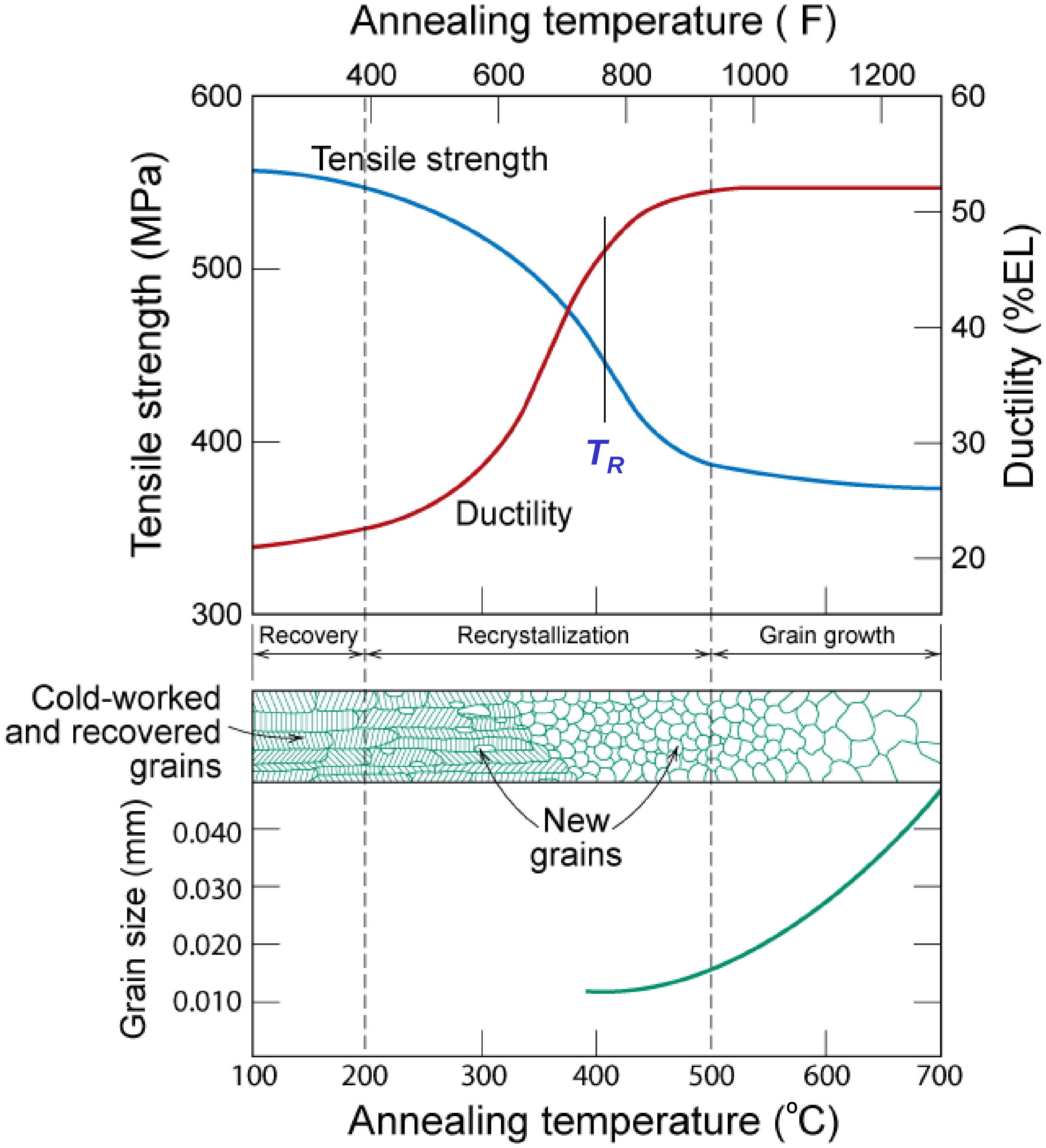
exponent typ. ~ 2

grain diam. at time t.

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

coefficient dependent on material and *T*.

elapsed time



T_R = recrystallization temperature

Adapted from Fig. 7.22, *Callister & Rethwisch 8e.*

Recrystallization Temperature

T_R = recrystallization temperature = temperature at which recrystallization just reaches completion in 1 h.

$$0.3T_m < T_R < 0.6T_m$$

For a specific metal/alloy, T_R depends on:

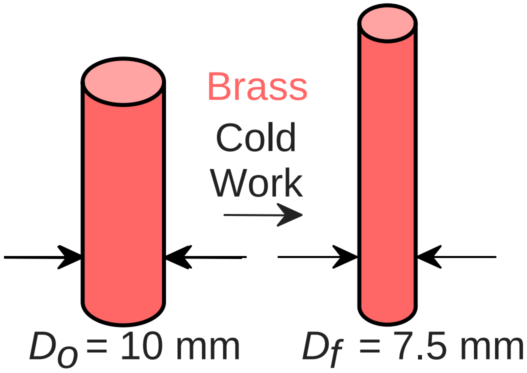
- %CW -- T_R decreases with increasing %CW
- Purity of metal -- T_R decreases with increasing purity

Diameter Reduction Procedure - Problem

A cylindrical rod of brass originally 10 mm (0.39 in) in diameter is to be cold worked by drawing. The circular cross section will be maintained during deformation. A cold-worked tensile strength in excess of 380 MPa (55,000 psi) and a ductility of at least 15 %*EL* are desired. Furthermore, the final diameter must be 7.5 mm (0.30 in). Explain how this may be accomplished.

Diameter Reduction Procedure - Solution

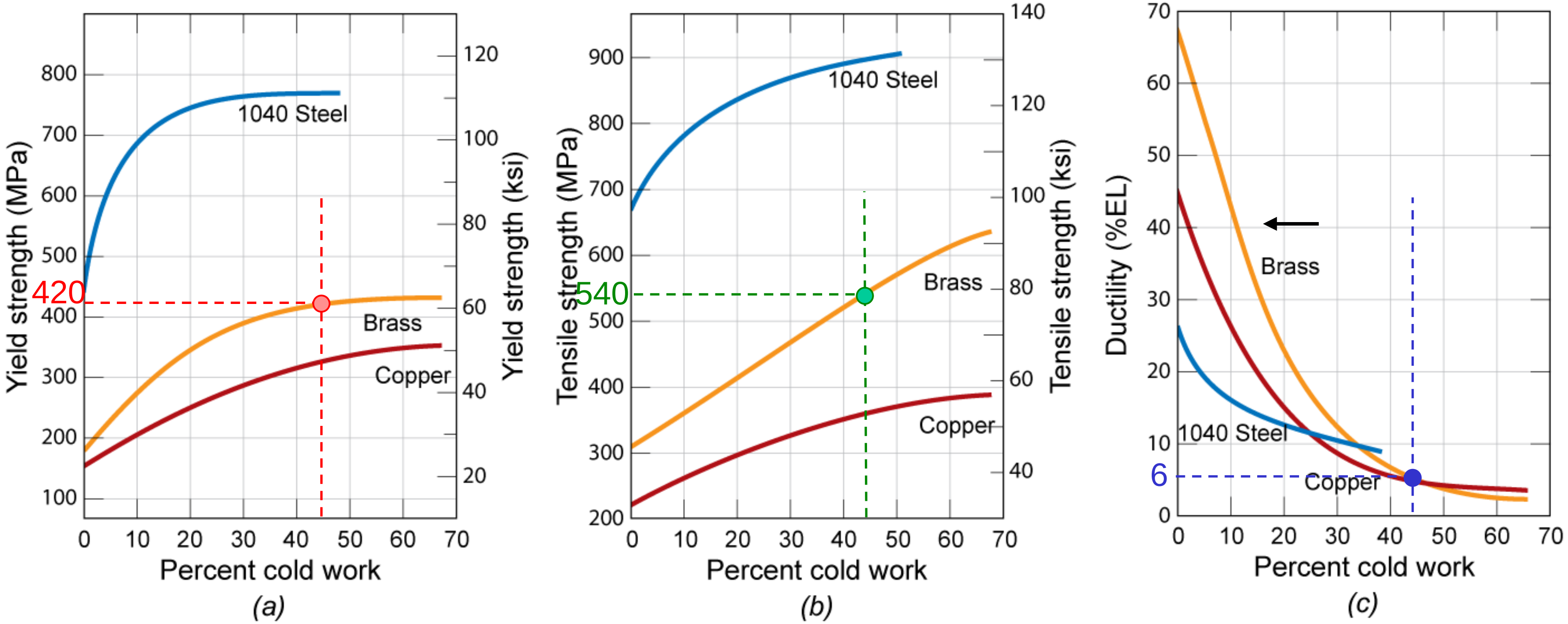
What are the consequences of directly drawing to the final diameter?



$$\%CW = \left(\frac{A_o - A_f}{A_o}\right) \text{x}\,100 = \left(1 - \frac{A_f}{A_o}\right) x\,100$$

$$= \left(1 - \frac{\pi D_f^2/4}{\pi D_o^2/4}\right) \text{x}\,100 = \left(1 - \left(\frac{7.5}{10}\right)^2\right) \text{x}\,100 = 43.8\%$$

Diameter Reduction Procedure – Solution (Cont.)

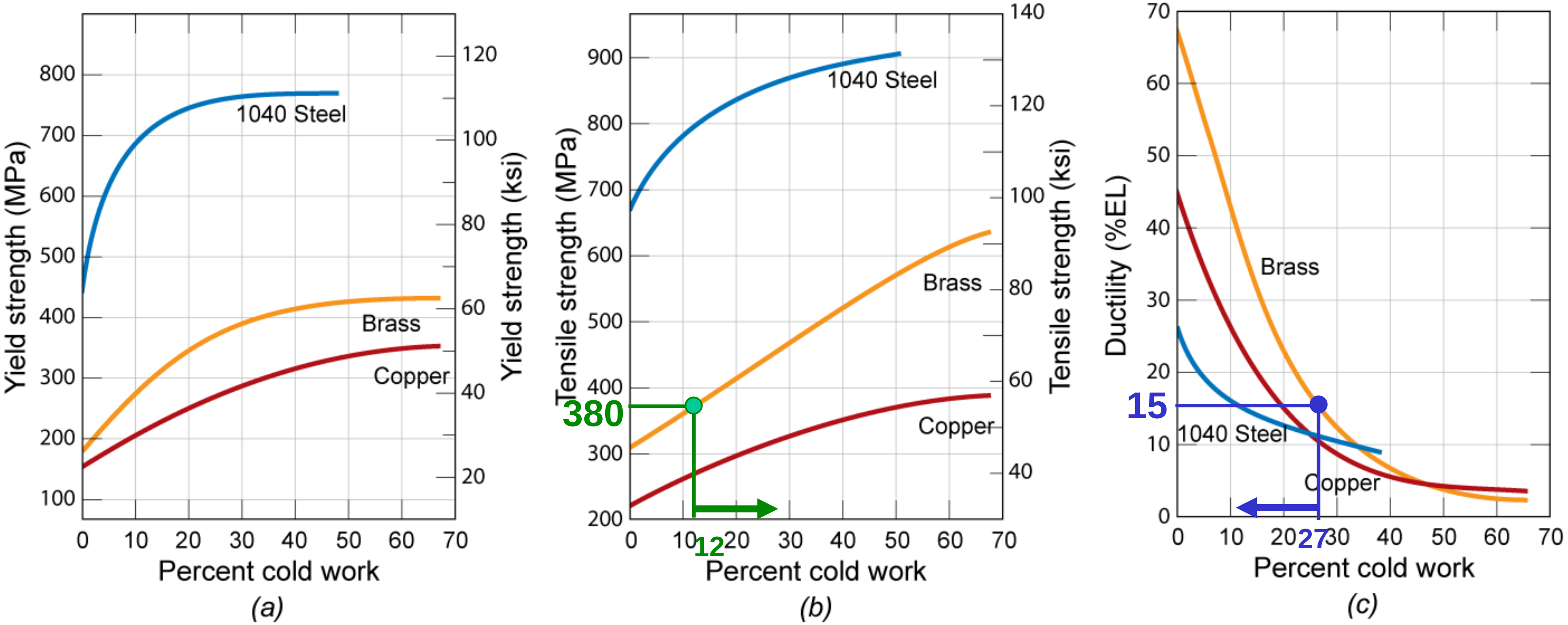


(a) (b) (c)

Adapted from Fig. 7.19, *Callister & Rethwisch 8e.*

- For %CW = 43.8%
  - σ_y = 420 MPa
  - *TS* = 540 MPa > 380 MPa
  - %*EL* = 6 < 15
- This doesn’t satisfy criteria… what other options are possible?

Diameter Reduction Procedure – Solution (cont.)



Adapted from Fig. 7.19, *Callister & Rethwisch 8e.*

For *TS* > 380 MPa → > 12 %CW

For %*EL* > 15 → < 27 %CW

∴ our working range is limited to 12 < %CW < 27

Diameter Reduction Procedure – Solution (cont.)

Cold work, then anneal, then cold work again

- For objective we need a cold work of $12 < \%CW < 27$
  - We'll use 20 %CW
- Diameter after first cold work stage (but before 2nd cold work stage) is calculated as follows:

$$\%CW = \left(1-\frac{D_{f2}{}^2}{D_{02}{}^2}\right) x\, 100 \quad \Rightarrow \quad 1-\frac{D_{f2}{}^2}{D_{02}{}^2} = \frac{\%CW}{100}$$

$$\frac{D_{f2}}{D_{02}} = \left(1-\frac{\%CW}{100}\right)^{0.5} \quad \Rightarrow \quad D_{02} = \frac{D_{f2}}{\left(1-\frac{\%CW}{100}\right)^{0.5}}$$

Intermediate diameter = $D_{f1} = D_{02} = 7.5\,\text{mm} \Big/ \left(1-\frac{20}{100}\right)^{0.5} = \boxed{8.39\,\text{mm}}$

Diameter Reduction Procedure – Summary

Stage 1: Cold work – reduce diameter from 10 mm to 8.39 mm

$$\%CW_1 = \left(1 - \left(\frac{8.39\text{ mm}}{10\text{ mm}}\right)^2\right) x\, 100 = 29.6$$

Stage 2: Heat treat (allow recrystallization)

Stage 3: Cold work – reduce diameter from 8.39 mm to 7.5 mm

$$\%CW_2 = \left(1 - \left(\frac{7.5}{8.49}\right)^2\right) x\, 100 = 20$$

Fig 7.19 $\Rightarrow$

$$\sigma_y = 340\text{ MPa}$$

$$TS = 400\text{ MPa}$$

$$\%EL = 24$$

Therefore, all criteria satisfied

Cold Working vs. Hot Working

- Hot working → deformation above T_R

- Cold working → deformation below T_R

Summary

- Dislocations are observed primarily in metals and alloys.
- Strength is increased by making dislocation motion difficult.
- Strength of metals may be increased by:
  - -- decreasing grain size
  - -- solid solution strengthening
  - -- precipitate hardening
  - -- cold working
- A cold-worked metal that is heat treated may experience recovery, recrystallization, and grain growth – its properties will be altered.