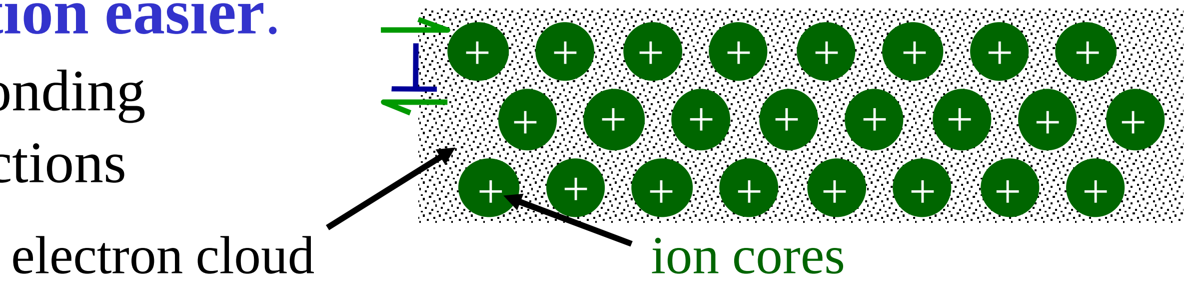
Chapter 9: Dislocations & Strengthening Mechanisms in metals

ISSUES TO ADDRESS...

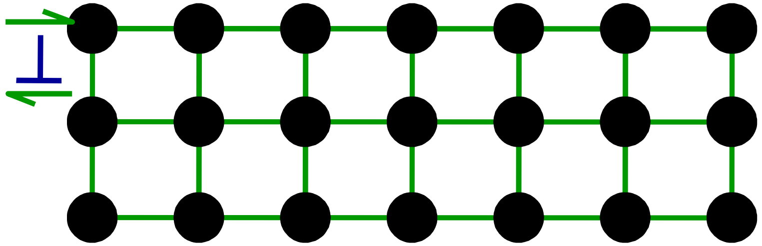
- How are strength and dislocation motion related?
- How do we **increase strength**?
- How can **heating change strength and other properties**?

Dislocations & Materials Classes

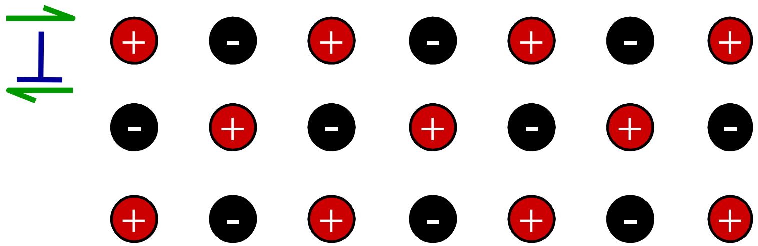
- Metals: Disl. **motion easier**.
  - -non-directional bonding
  - -close-packed directions for slip.



- Covalent Ceramics (Si, diamond): **Motion hard**.
  - -directional (angular) bonding

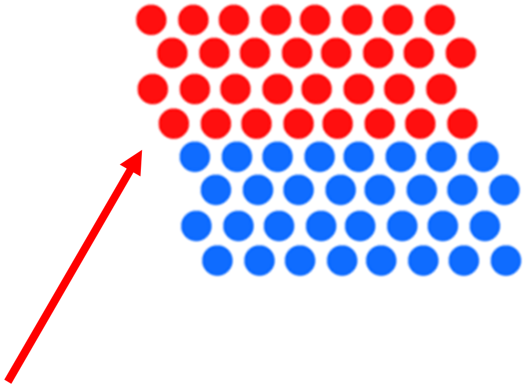


- Ionic Ceramics (NaCl): **Motion hard**.
  - -need to avoid ++ and - - neighbors.



Deformation Mechanisms for Metals

Material	Theoretical Strength (MPa)	Measured Strength (MPa)
Copper	20000	0.5
Iron	34000	28

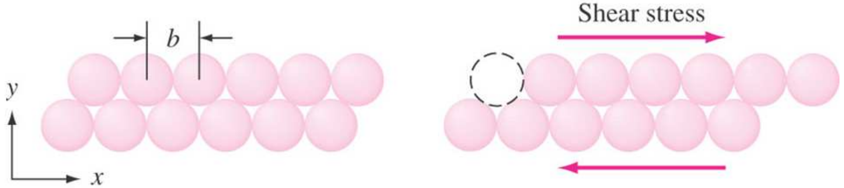


Slip Plane

The **theoretical strength** can be calculated from the number of **all** atomic bonds that must be broken at the same time

The measured strength is much lower than the theoretical strength

There must another, easier mechanism for slip

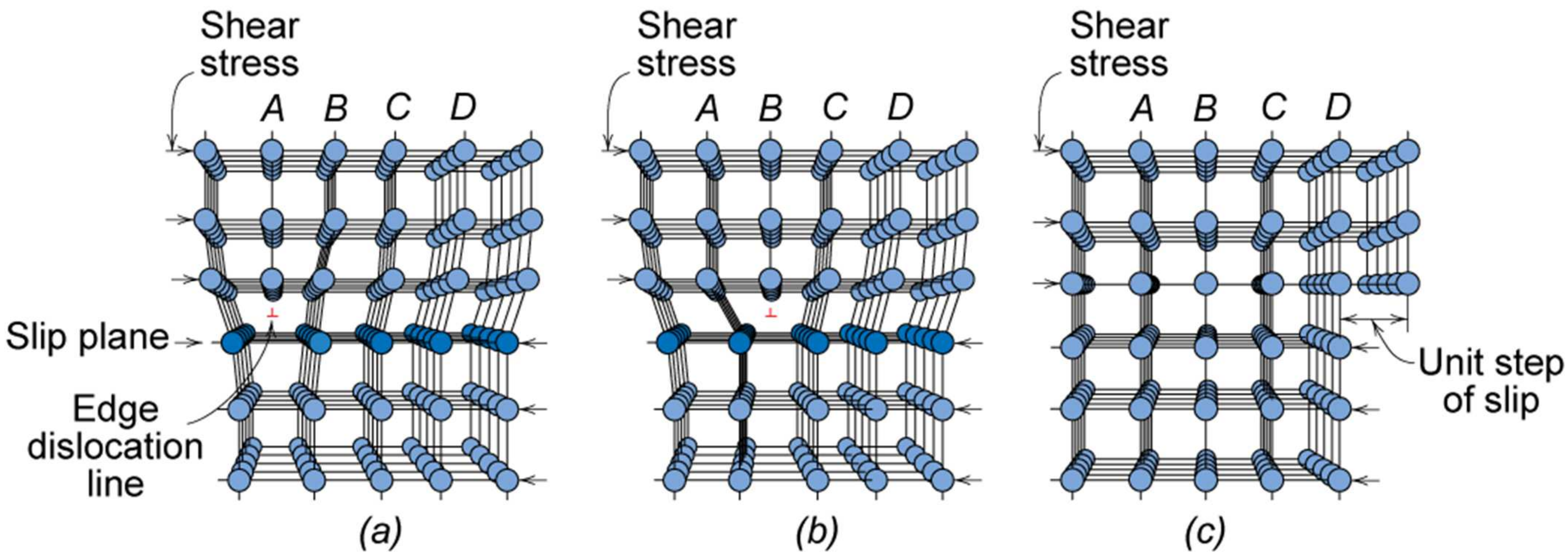


(a) (b)

Dislocation Motion

Dislocations & plastic deformation

- Cubic & hexagonal metals - plastic deformation by plastic shear or slip where one plane of atoms slides over adjacent plane by defect motion (dislocations).

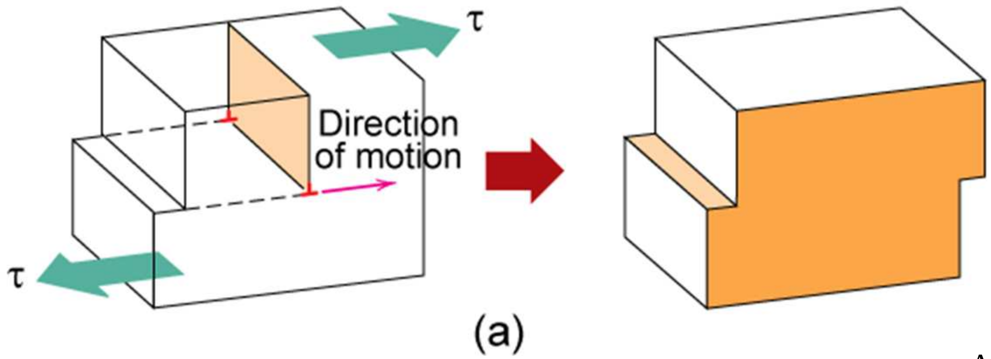


- If dislocations don't move, deformation doesn't occur!

Adapted from Fig. 7.1, *Callister 7e.*

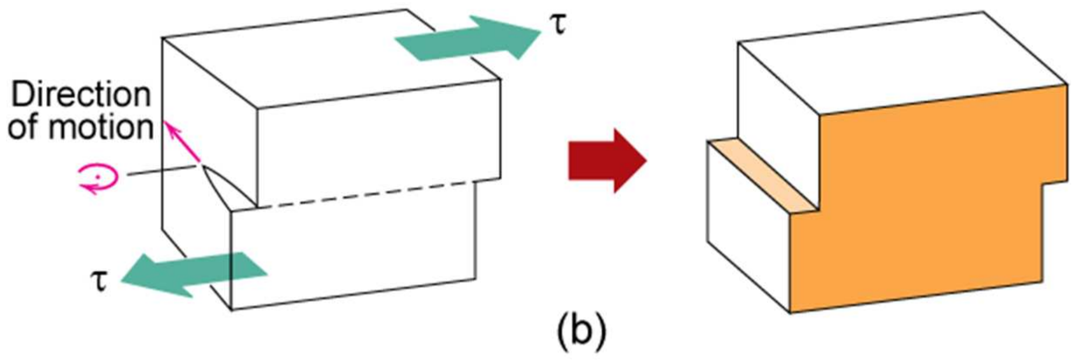
Dislocation Motion

- Dislocation moves along **slip plane** in **slip direction** perpendicular to dislocation line



Edge dislocation

Adapted from Fig. 7.2, *Callister 7e.*



Screw dislocation

Model of Dislocation Movement

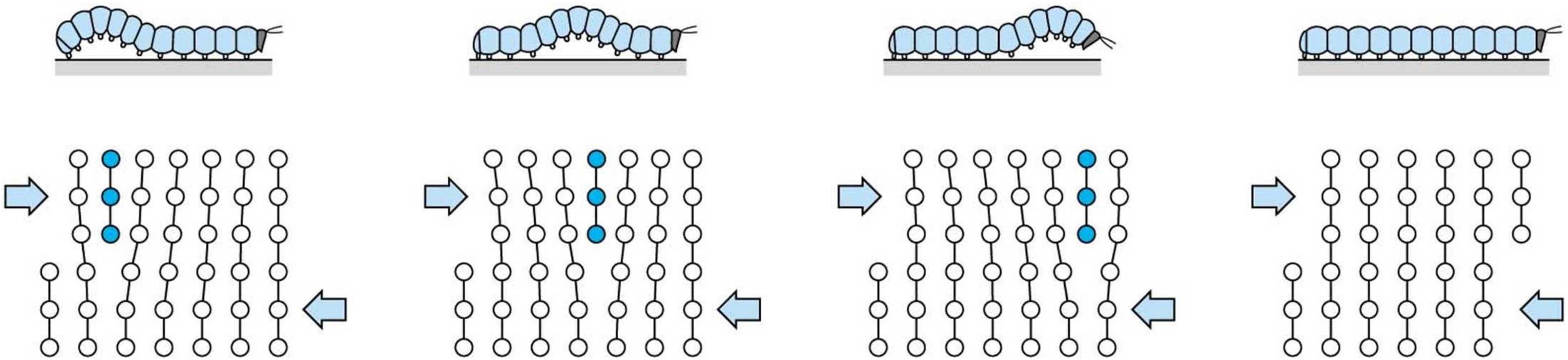
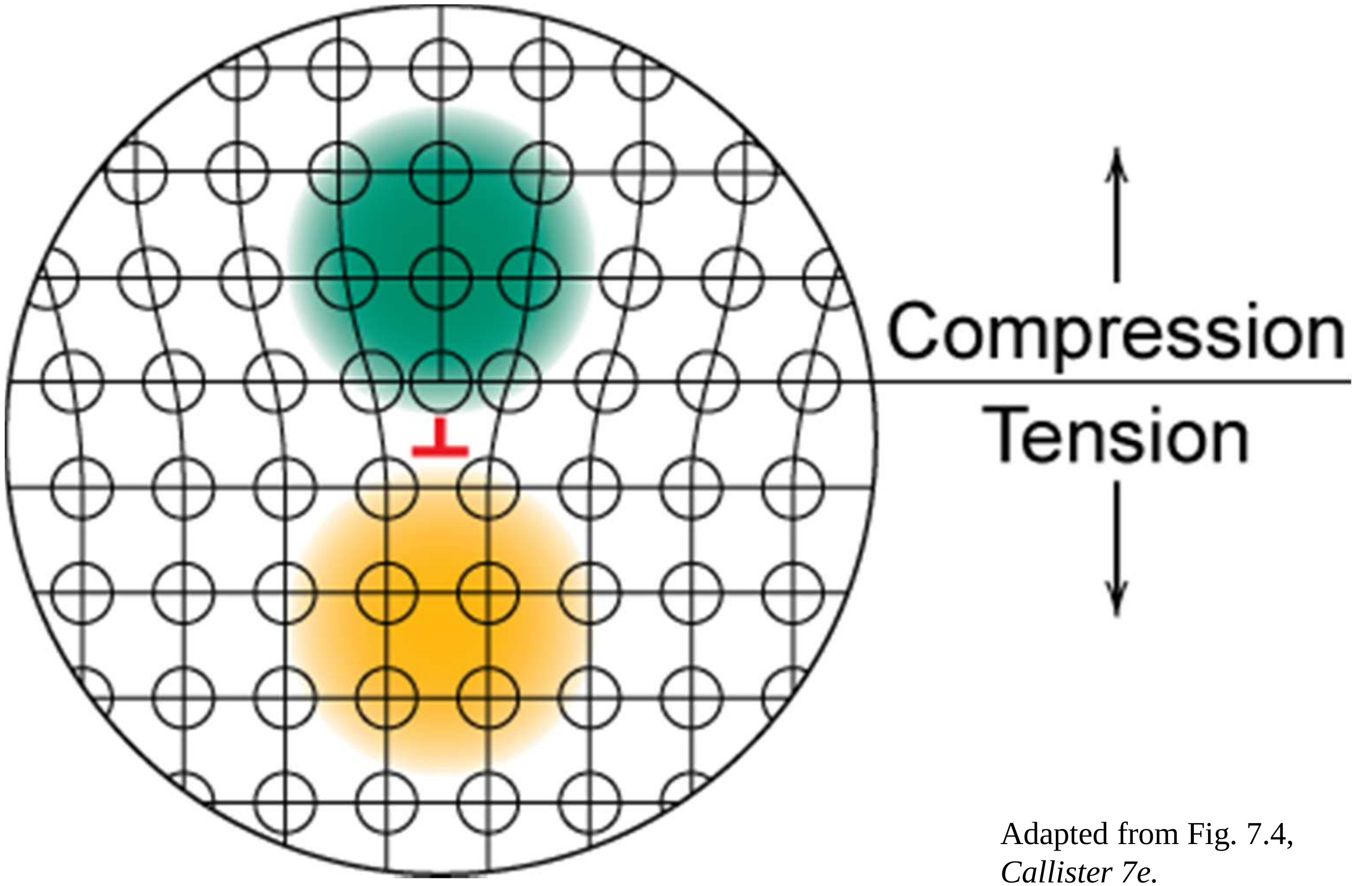


FIGURE 7.3 Representation of the analogy between caterpillar and dislocation motion.

Video caterpil

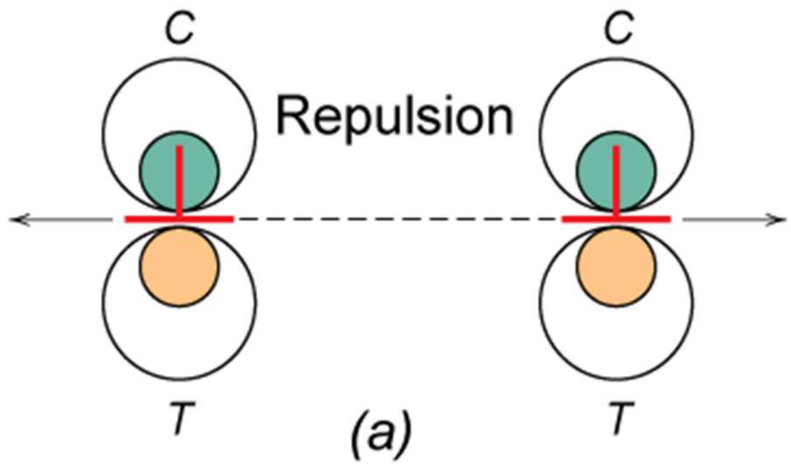
Stress Concentration at Dislocations

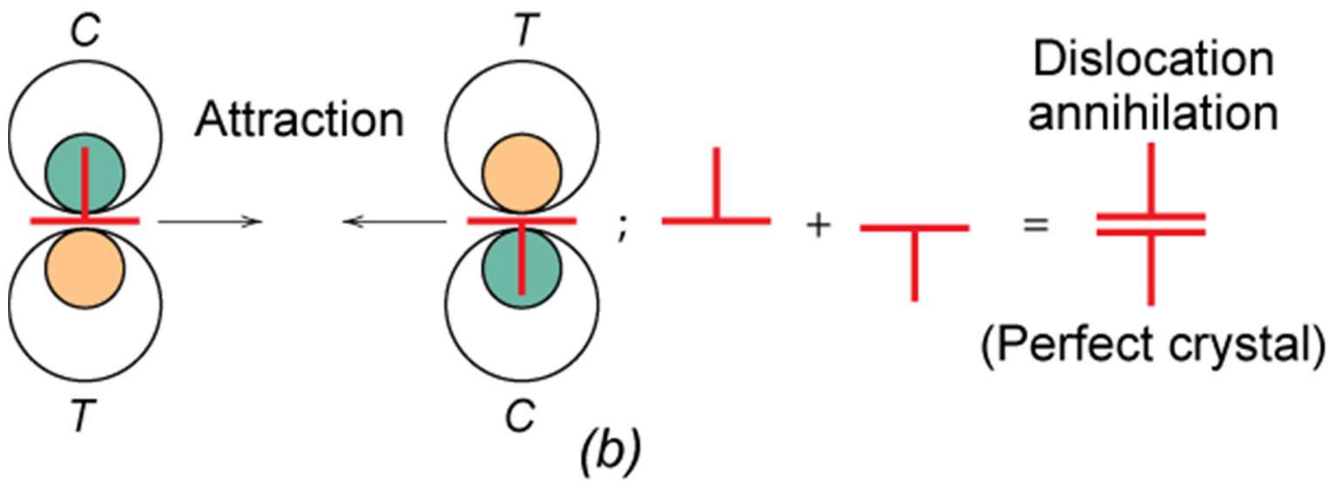


Adapted from Fig. 7.4,
Callister 7e.

Effects of Stress at Dislocations

Adapted from Fig. 7.5, *Callister 7e.*

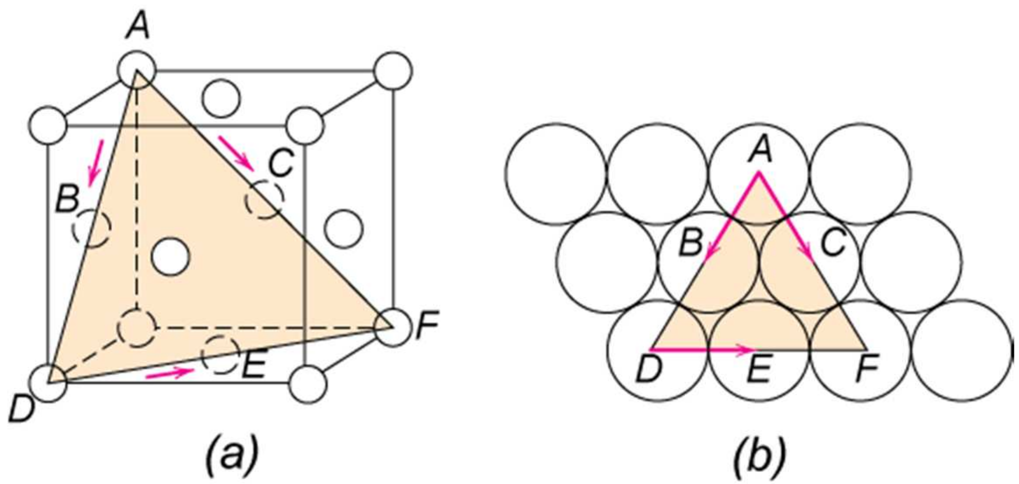




Deformation Mechanisms

Slip System

– Slip plane - plane allowing easiest slippage
  - Wide interplanar spacings - highest planar densities
– Slip direction - direction of movement - Highest linear densities



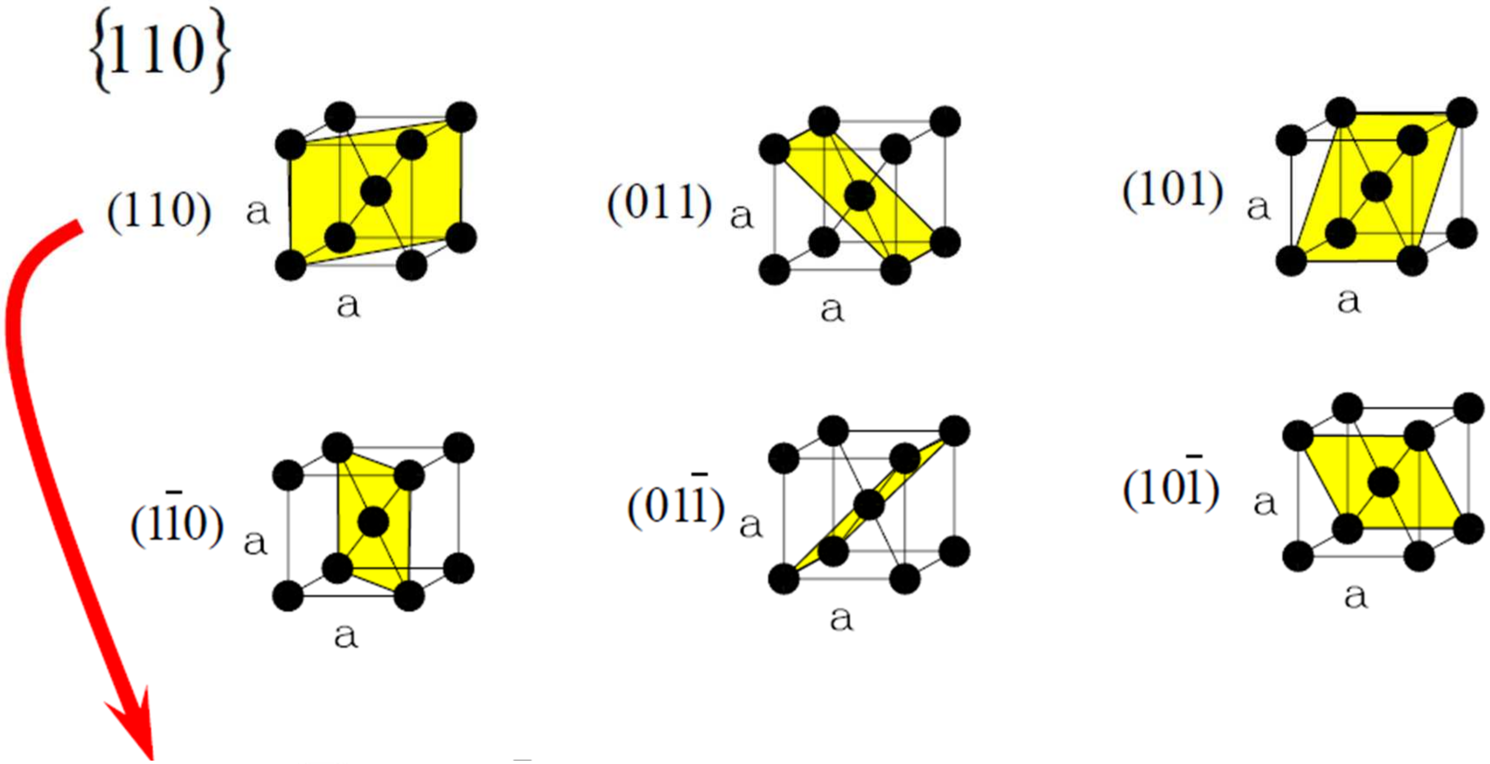
Adapted from Fig. 7.6, *Callister 7e.*

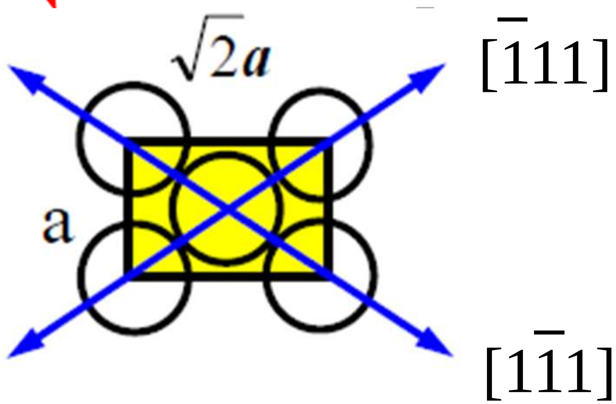
– FCC Slip occurs on {111} planes (close-packed) in <110> directions (close-packed) => total of 12 slip systems in FCC

– in BCC & HCP other slip systems occur

http://joelgordon.photoshelter.com/image/I0000R36uTwITiok

Stress and Dislocation Motion





BCC Slip occurs on {110} planes in
<111> directions (close-packed)
=> total of 12 slip systems in BCC

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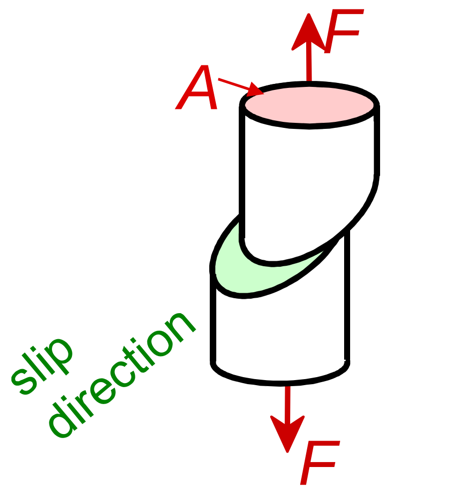
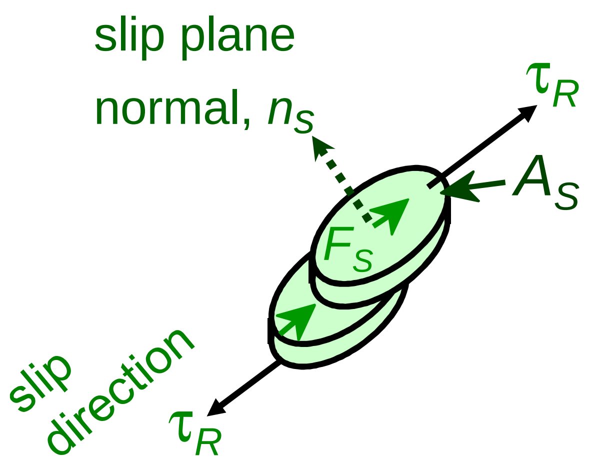
Stress and Dislocation Motion

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

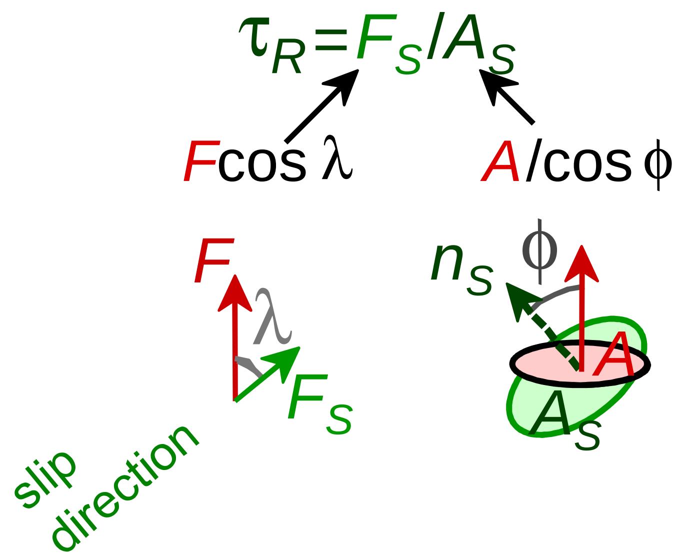
Applied **tensile** stress: $\sigma = F/A$



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

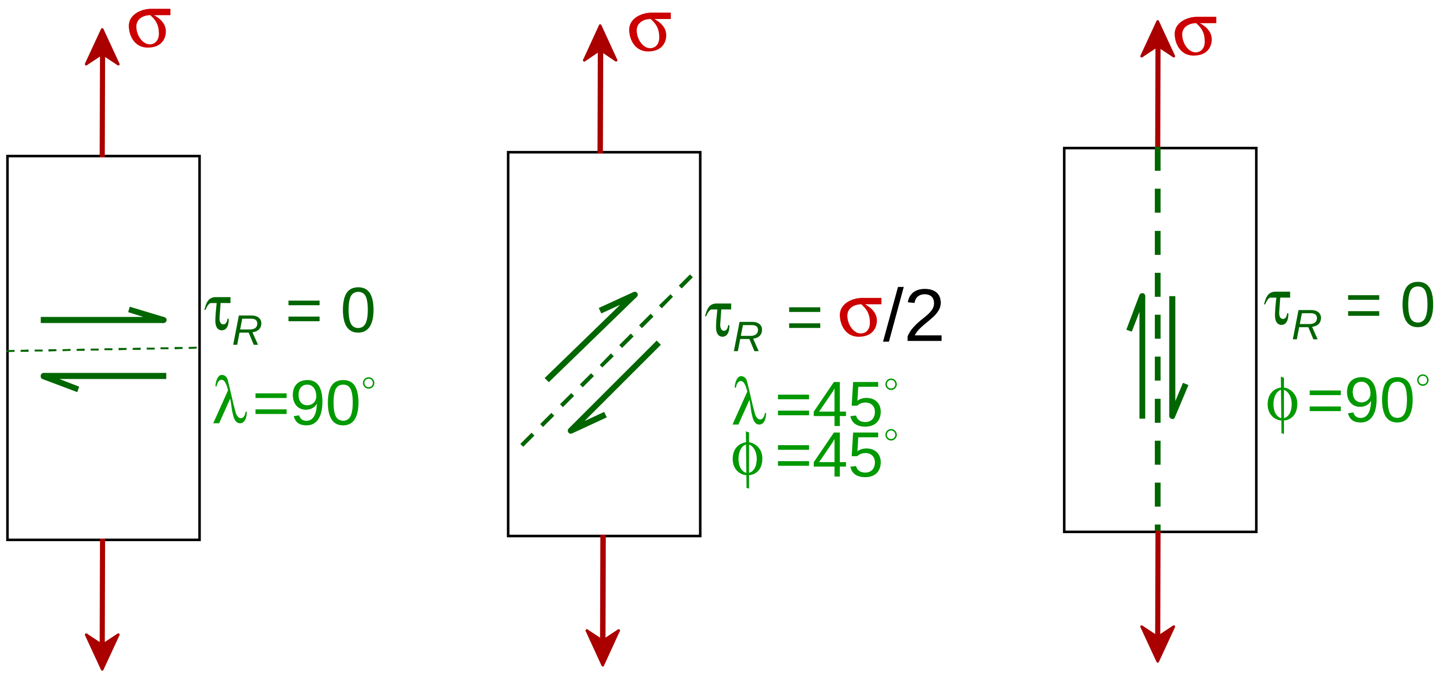
- Condition for dislocation motion: $\tau_R > \tau_{CRSS}$

typically

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

- Crystal orientation can make it easy or hard to move dislocation

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



τ maximum at $\lambda = \phi = 45^o$

Example 7.1

Resolved Shear Stress and Stress-to-Initiate-Yielding Computations

Consider a single crystal of BCC iron oriented such that a tensile stress is applied along a [010] direction.

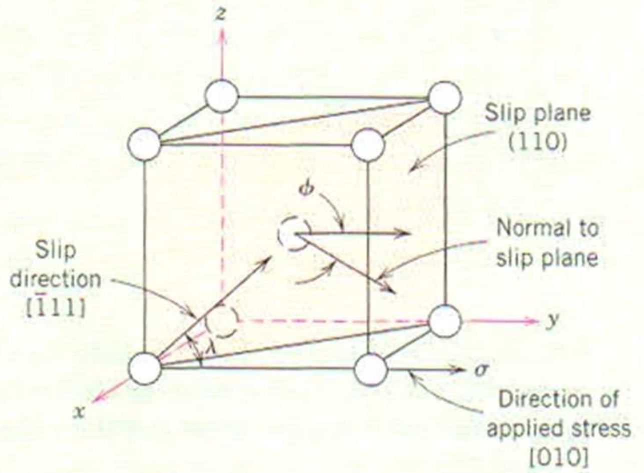
(a) Compute the resolved shear stress along a (110) plane and in a $[\bar{1}11]$ direction when a tensile stress of 52 MPa is applied.

(b) If slip occurs on a (110) plane and in a $[\bar{1}11]$ direction, and the critical resolved shear stress is 30 MPa, calculate the magnitude of the applied tensile stress necessary to initiate yielding.

Solution

(a) A BCC unit cell along with the slip direction and plane as well as the direction of the applied stress are shown in the accompanying diagram. In order to solve this problem we must use Equation 7.2. However, it is first necessary to determine values for ϕ and λ, where, from the preceding diagram, ϕ is the angle between the normal to the (110) slip plane (i.e., the [110] direction) and the [010] direction, and λ represents the angle between the $[\bar{1}11]$ and [010] directions. In general, for cubic unit cells, an angle θ between directions 1 and 2, represented by $[u_1v_1w_1]$ and $[u_2v_2w_2]$, respectively, is equal to

$$\theta = \cos^{-1}\left[\frac{u_1u_2 + v_1v_2 + w_1w_2}{\sqrt{(u_1^2 + v_1^2 + w_1^2)(u_2^2 + v_2^2 + w_2^2)}}\right] \tag{7.6}$$



For the determination of the value of ϕ, let $[u_1v_1w_1] = [110]$ and $[u_2v_2w_2] = [010]$ such that

$$\phi = \cos^{-1}\left\{\frac{(1)(0) + (1)(1) + (0)(0)}{\sqrt{[(1)^2 + (1)^2 + (0)^2][(0)^2 + (1)^2 + (0)^2]}}\right\}$$

$$= \cos^{-1}\left(\frac{1}{\sqrt{2}}\right) = 45°$$

However, for λ, we take $[u_1v_1w_1] = [\bar{1}11]$ and $[u_2v_2w_2] = [010]$, and

$$\lambda = \cos^{-1}\left[\frac{(-1)(0) + (1)(1) + (1)(0)}{\sqrt{[(-1)^2 + (1)^2 + (1)^2][(0)^2 + (1)^2 + (0)^2]}}\right]$$

$$= \cos^{-1}\left(\frac{1}{\sqrt{3}}\right) = 54.7°$$

Thus, according to Equation 7.2,

$$\tau_R = \sigma \cos\phi \cos\lambda = (52 \text{ MPa})(\cos 45°)(\cos 54.7°)$$

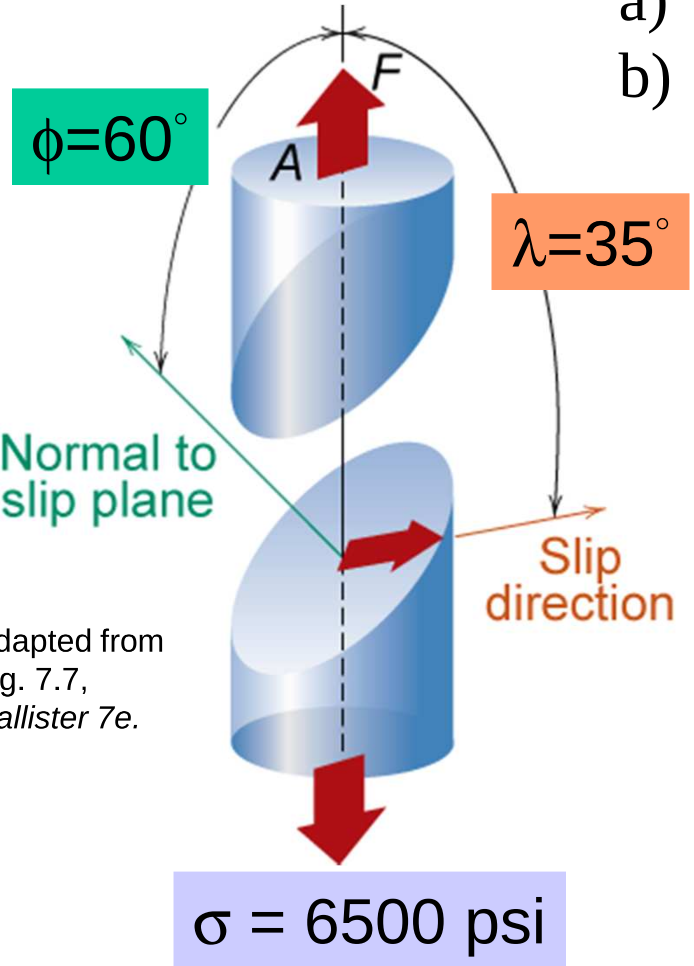
$$= (52 \text{ MPa})\left(\frac{1}{\sqrt{2}}\right)\left(\frac{1}{\sqrt{3}}\right)$$

$$= 21.3 \text{ MPa}$$

(b) The yield strength σ_y may be computed from Equation 7.4; ϕ and λ will be the same as for part (a), and

$$\sigma_y = \frac{30 \text{ MPa}}{(\cos 45°)(\cos 54.7°)} = 73.4 \text{ MPa}$$

Ex: Deformation of single crystal



Adapted from Fig. 7.7, *Callister 7e.*

a) Will the single crystal yield?

b) If not, what stress is needed?

$$\tau_{crss} = 3000 \text{ psi}$$

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

$$\sigma = 6500 \text{ psi}$$

$$\tau = (6500 \text{ psi})\,(\cos 35^\circ)(\cos 60^\circ)$$

$$= (6500 \text{ psi})\,(0.41)$$

$$\boxed{\tau = 2662 \text{ psi} \quad < \tau_{crss} = 3000 \text{ psi}}$$

So the applied stress of 6500 psi 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)?

$$\tau_{crss} = 3000 \text{ psi} = \sigma_y \cos\lambda \cos\phi = \sigma_y (0.41)$$

$$\therefore \sigma_y = \frac{\tau_{crss}}{\cos\lambda \cos\phi} = \frac{3000 \text{ psi}}{0.41} = \underline{\underline{7325 \text{ psi}}}$$

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

$$\boxed{\sigma \geq \sigma_y = 7325 \text{ psi}}$$

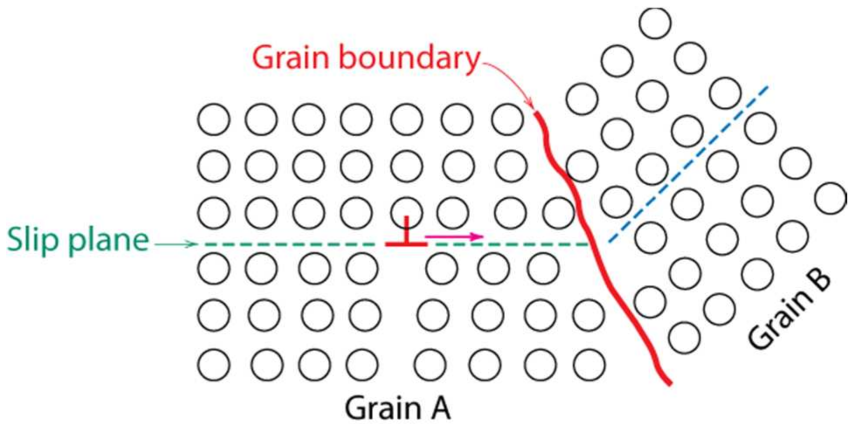
Slip Motion in Polycrystals

- Stronger - grain boundaries **pin** deformations
- Slip planes & directions (l, f) change from one crystal to another.
- t_R will vary from one crystal to another.
- The crystal with the largest t_R yields first.
- Other (less favorably oriented) crystals yield later.

Adapted from Fig. 7.10, *Callister 7e.* (Fig. 7.10 is courtesy of C. Brady, National Bureau of Standards [now the National Institute of Standards and Technology, Gaithersburg, MD].)

Four Strategies for Strengthening: 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**.

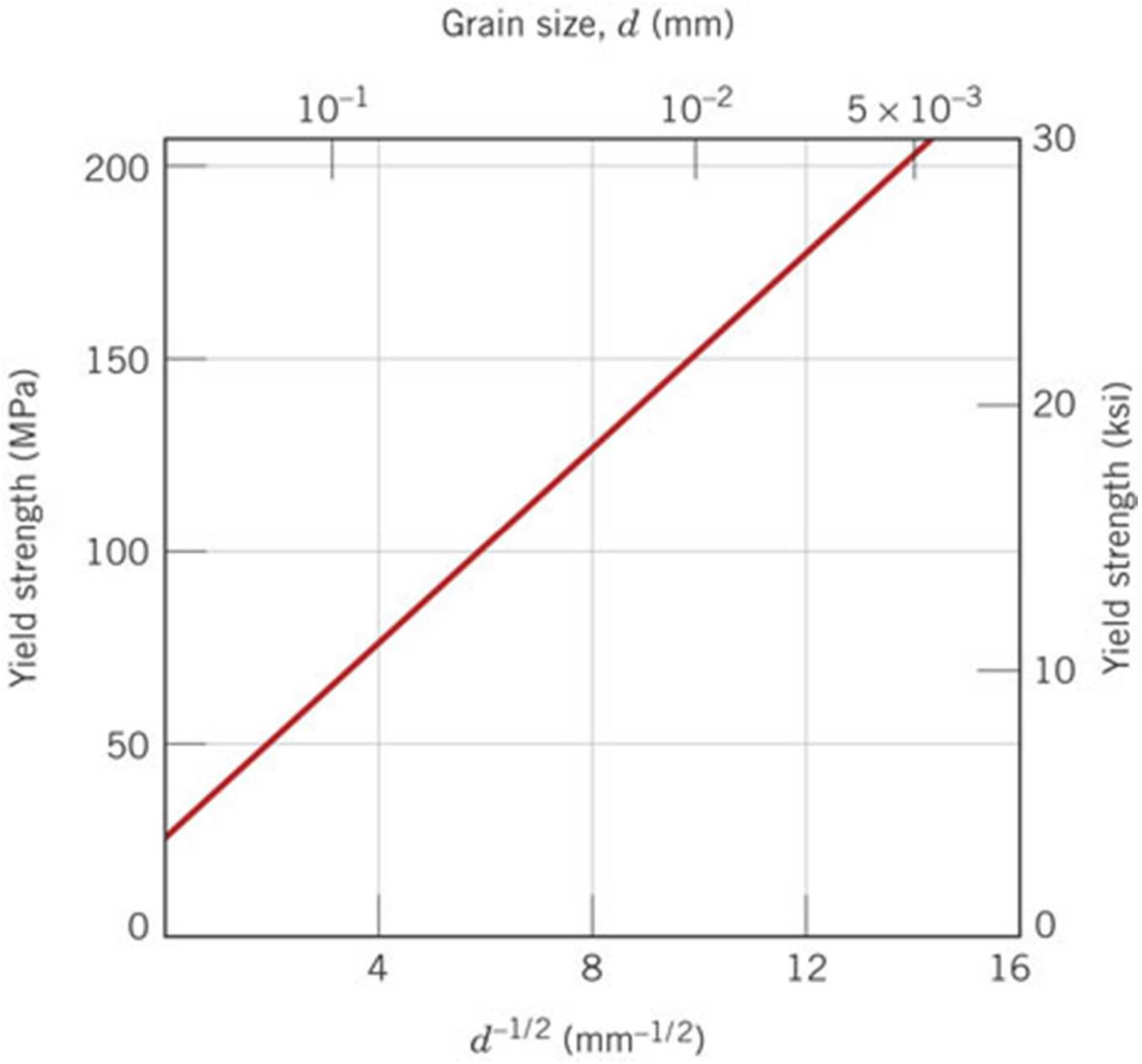


Adapted from Fig. 7.14, *Callister 7e.*
(Fig. 7.14 is from *A Textbook of Materials Technology*, by Van Vlack, Pearson Education, Inc., Upper Saddle River, NJ.)

- **Hall-Petch Equation**:

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

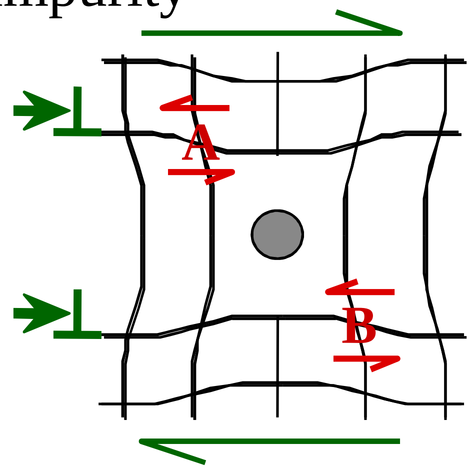
Grain Siza v.s. Yield Strength



Four Strategies for Strengthening: 2: Solid Solutions

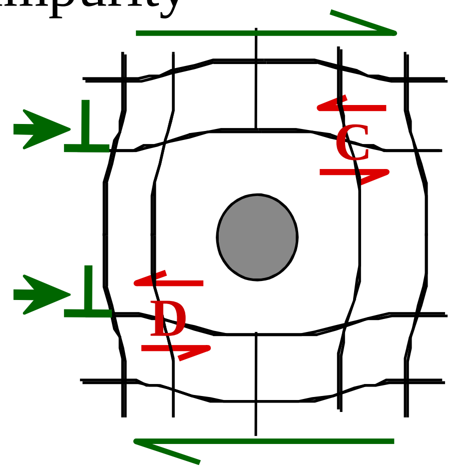
- Impurity atoms distort the lattice & generate stress.
- Stress can produce a barrier to dislocation motion.

- Smaller substitutional impurity



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

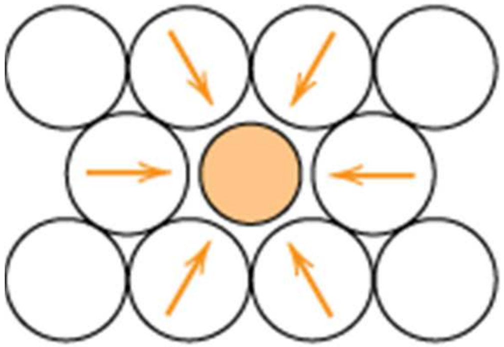
- Larger substitutional impurity



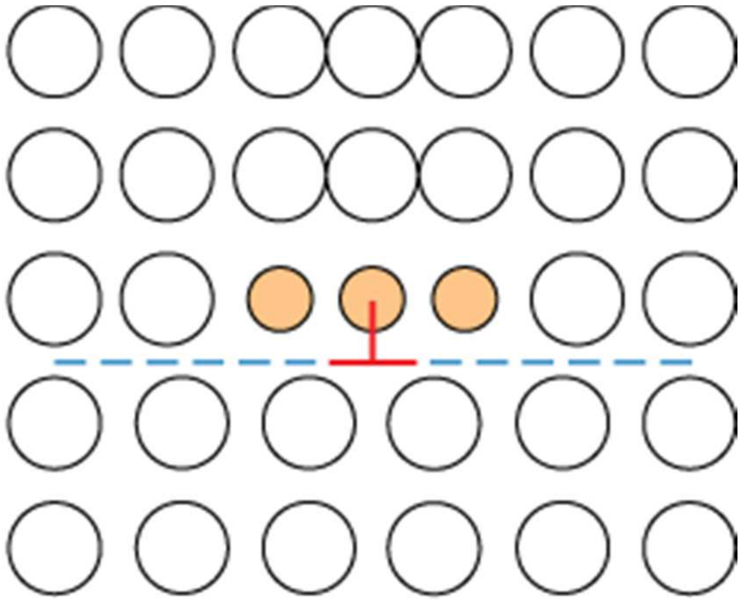
Impurity generates local stress at **C** and **D** that opposes dislocation motion to the right.

Strengthening by Alloying

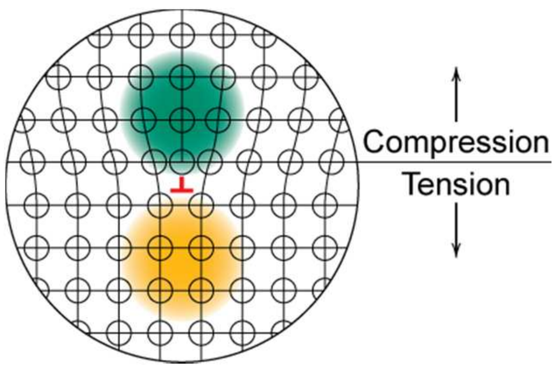
- small impurities tend to concentrate at dislocations
- reduce mobility of dislocation ∴ increase strength



(a)

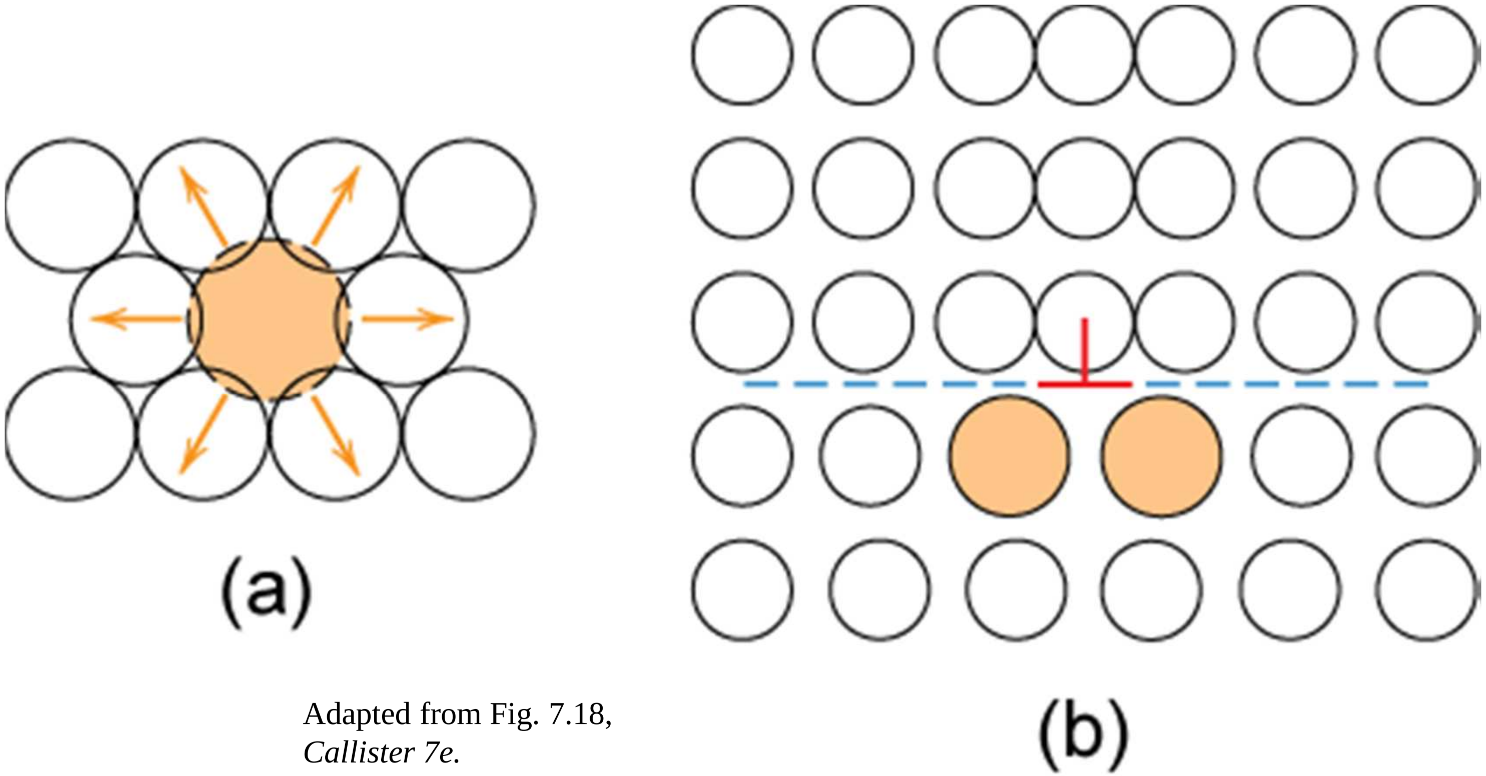


(b)



Strengthening by alloying

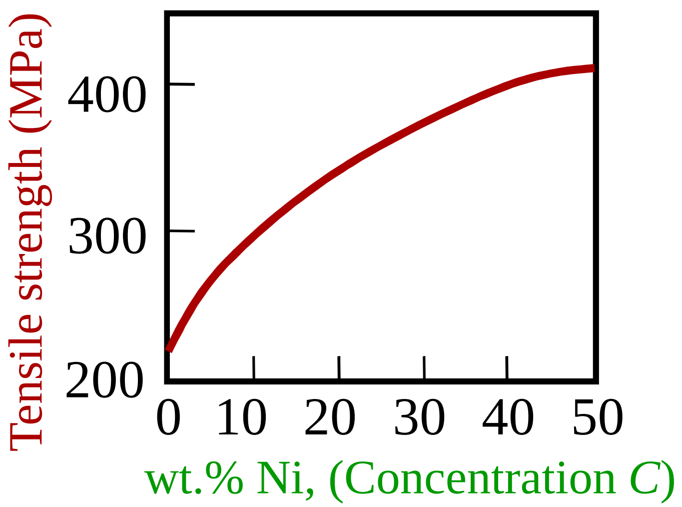
- large impurities concentrate at dislocations on low density side

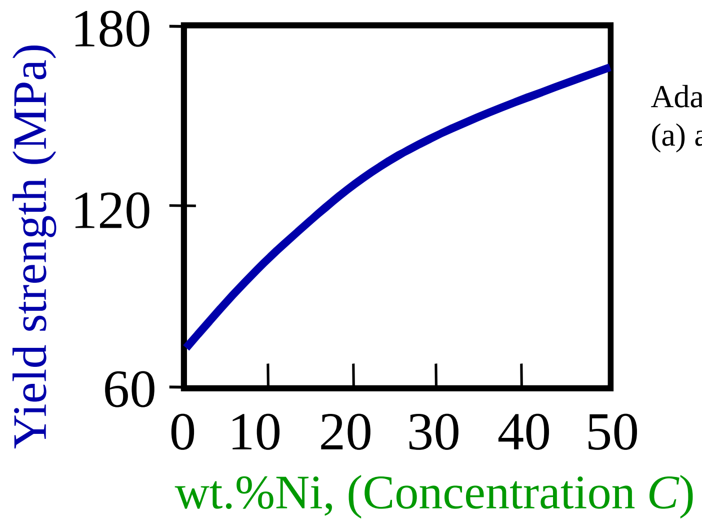


Adapted from Fig. 7.18, *Callister 7e.*

Ex: Solid Solution Strengthening in Copper

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





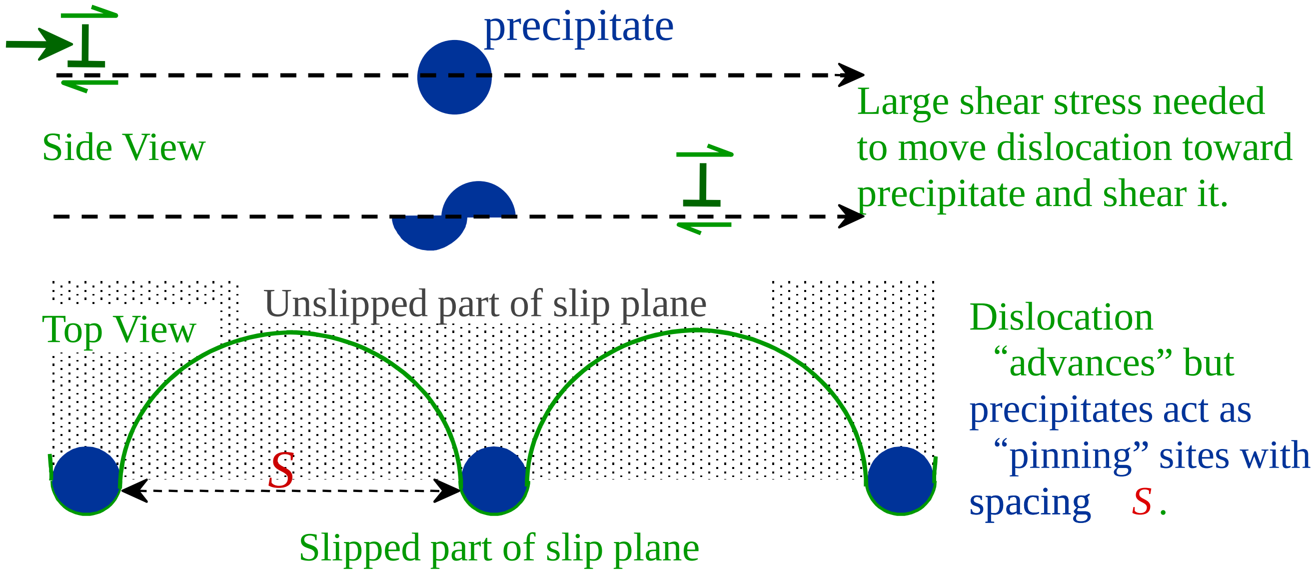
Adapted from Fig. 7.16 (a) and (b), *Callister 7e.*

- Empirical relation: $\sigma_y \sim C^{1/2}$

- **Alloying increases s_y and *TS*.**

Four Strategies for Strengthening: 3: Precipitation Strengthening

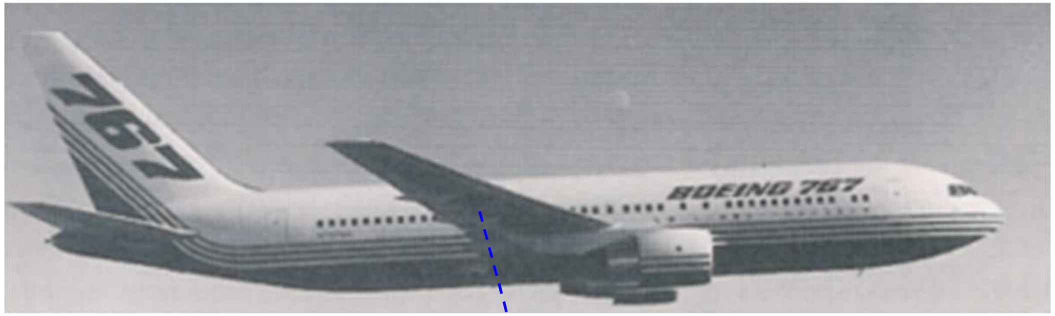
- Hard precipitates are difficult to shear.
  Ex: Ceramics in metals (SiC in Iron or Aluminum).



- Result: $\sigma_y \sim \frac{1}{S}$

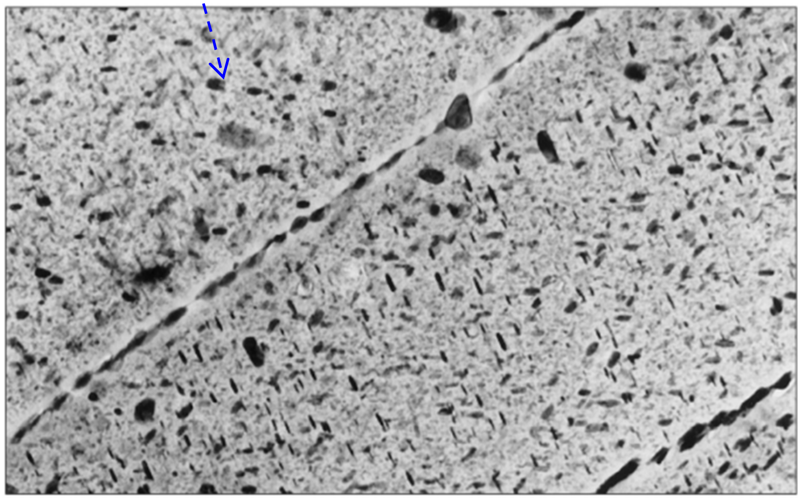
Application: Precipitation Strengthening

- Internal wing structure on Boeing 767



Adapted from chapter-opening photograph, Chapter 11, *Callister 5e.* (courtesy of G.H. Narayanan and A.G. Miller, Boeing Commercial Airplane Company.)

- Aluminum is strengthened with precipitates formed by alloying.



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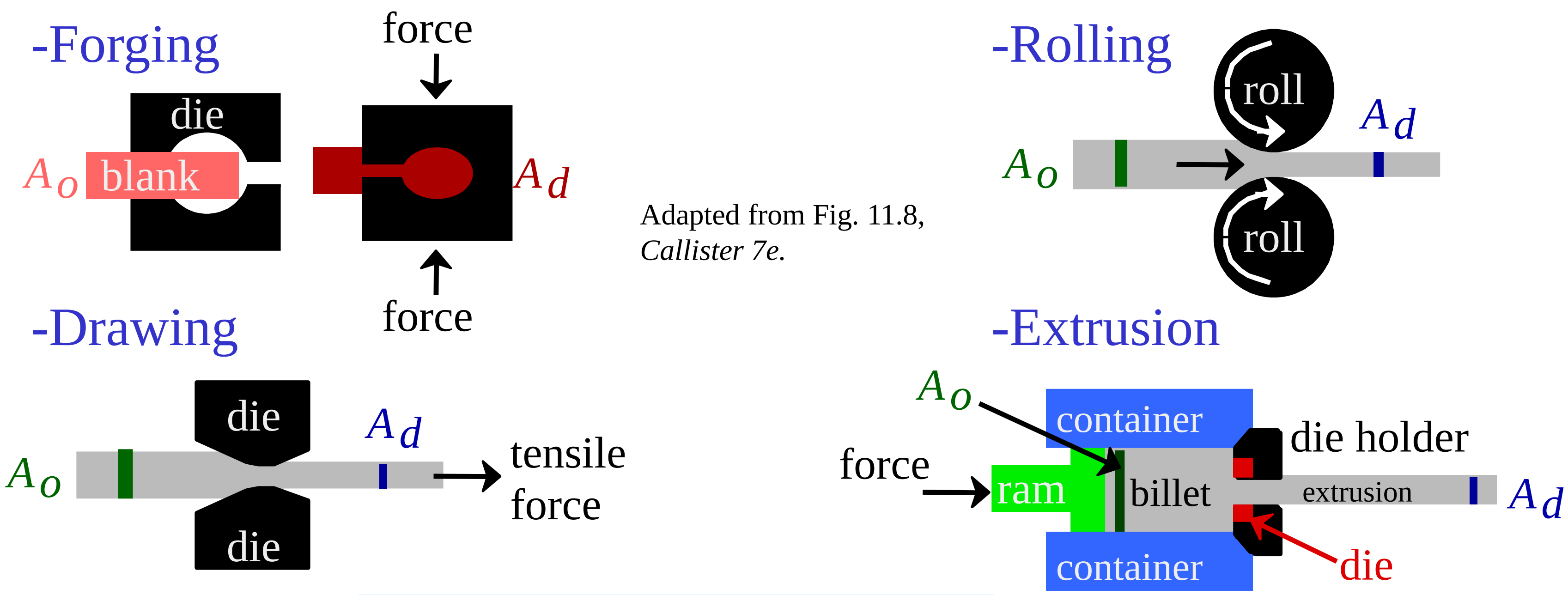
Adapted from Fig. 11.26, *Callister 7e.* (Fig. 11.26 is courtesy of G.H. Narayanan and A.G. Miller, Boeing Commercial Airplane Company.)

Four Strategies for Strengthening: 4: Cold Work (%*CW*)

- **Room temperature** deformation.
- Common forming operations change the cross sectional area:

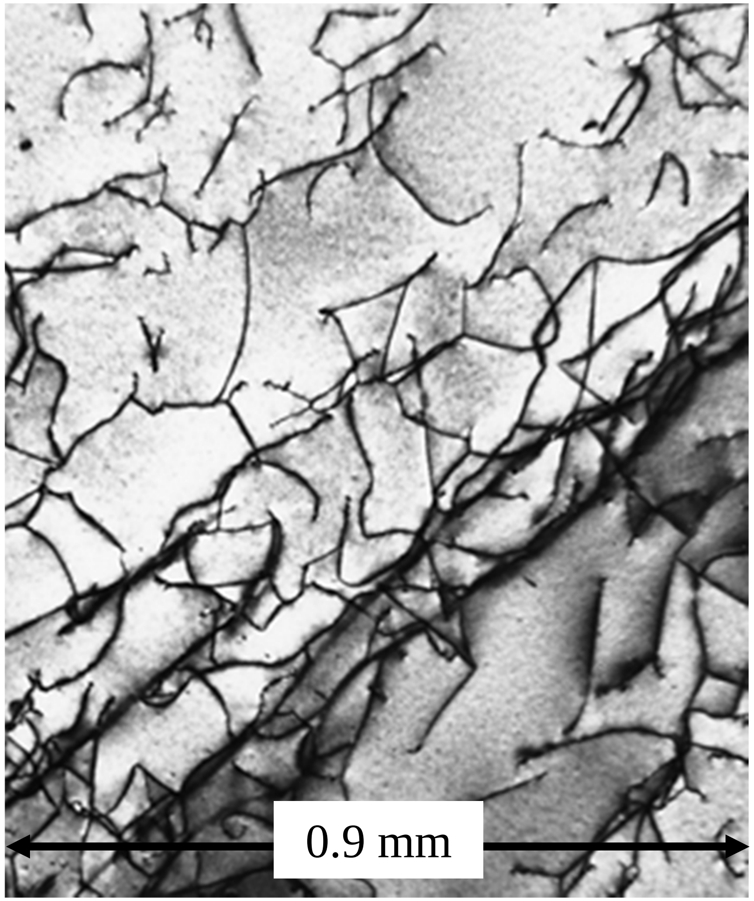


Adapted from Fig. 11.8, *Callister 7e.*

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

Dislocations During Cold Work

- Ti alloy after cold working:



Carefully grown single crystal

→ 10^3 mm^{-2}

Deforming sample increases density

→ 10^9-10^{10} mm^{-2}

Heat treatment reduces density

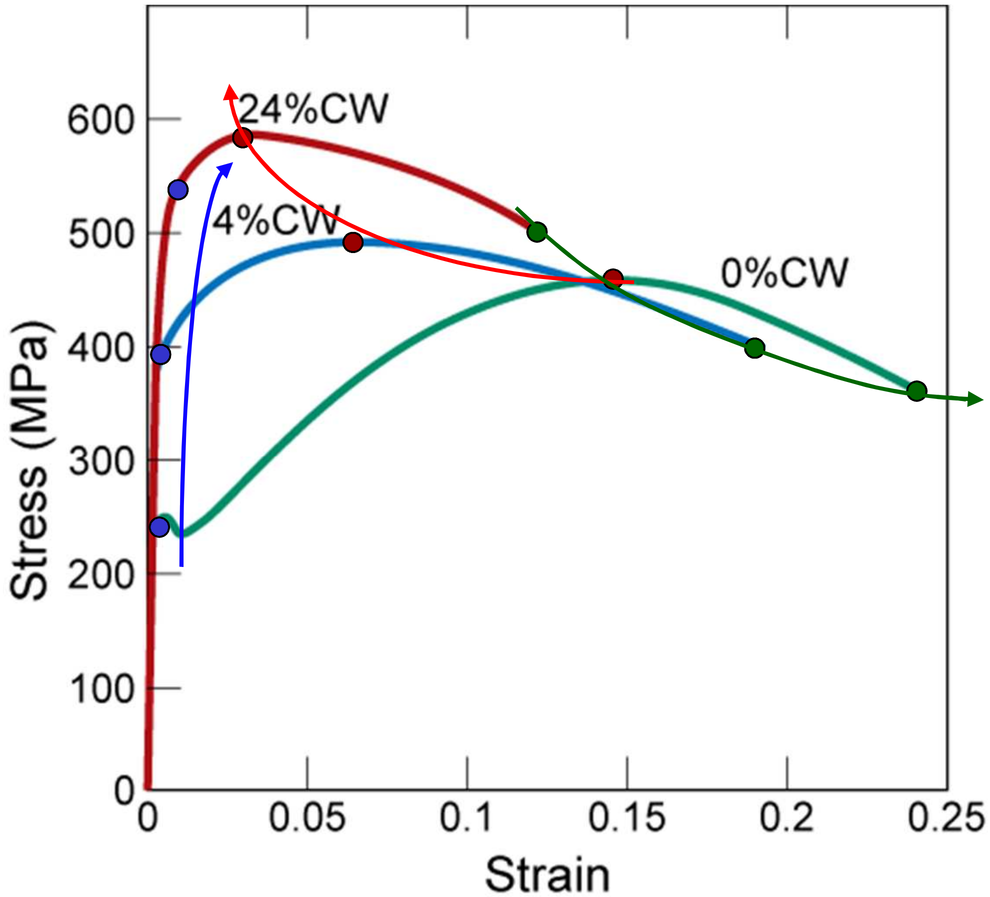
→ 10^5-10^6 mm^{-2}

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

Impact of Cold Work

As cold work is increased

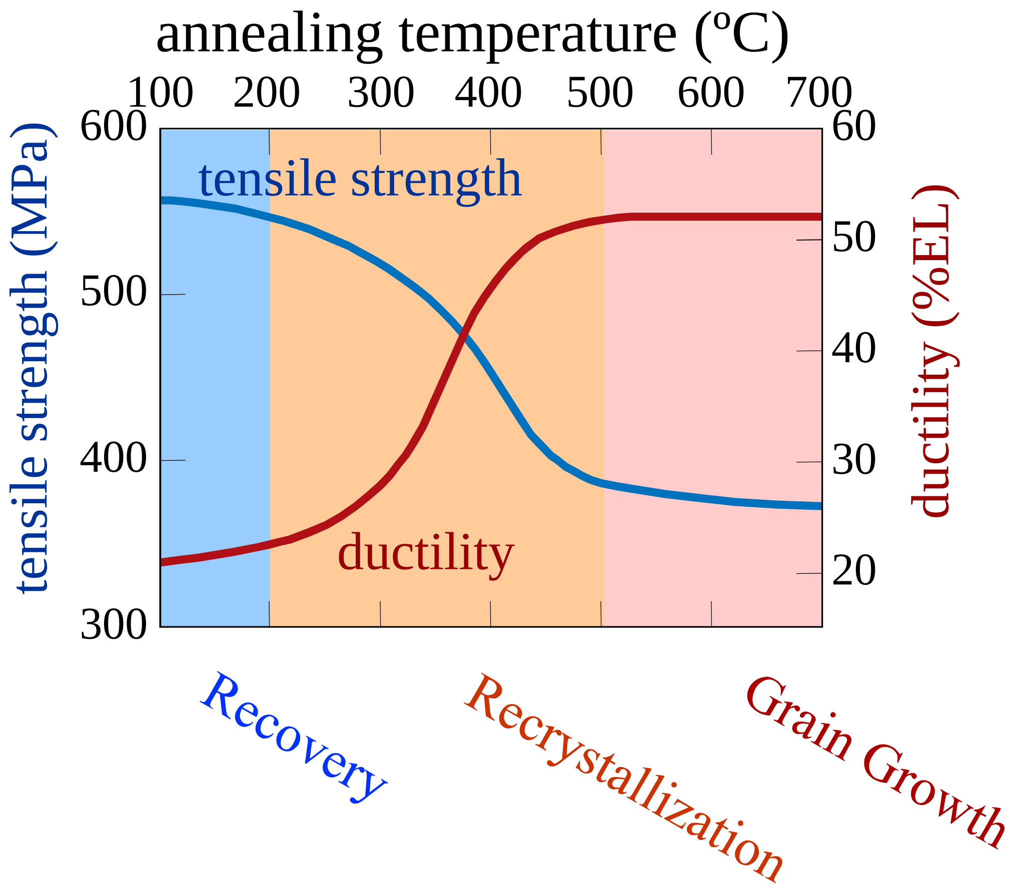
- Yield strength (σ_y) increases.
- Tensile strength (*TS*) increases.
- Ductility (*%EL* or *%AR*) decreases.



Adapted from Fig. 7.20, *Callister 7e.*

Effect of Heating After %*CW*

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

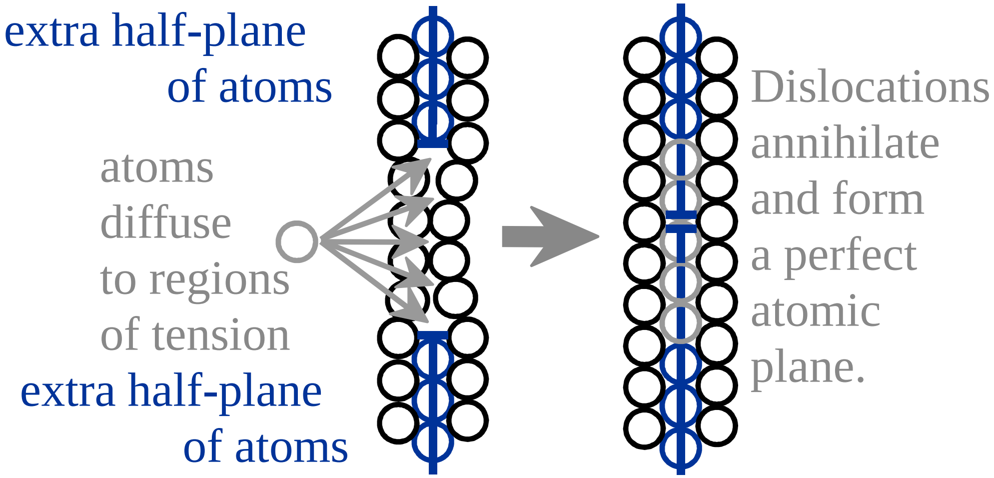


- 3 Annealing stages to discuss...

Adapted from Fig. 7.22, *Callister 7e.* (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.)

Recovery

- If you only add a small amount of thermal energy (heat it up at little) the **dislocations rearrange themselves** into networks to **relieve residual stresses**
- Polyganized subgrain structure
- Ductility is improved



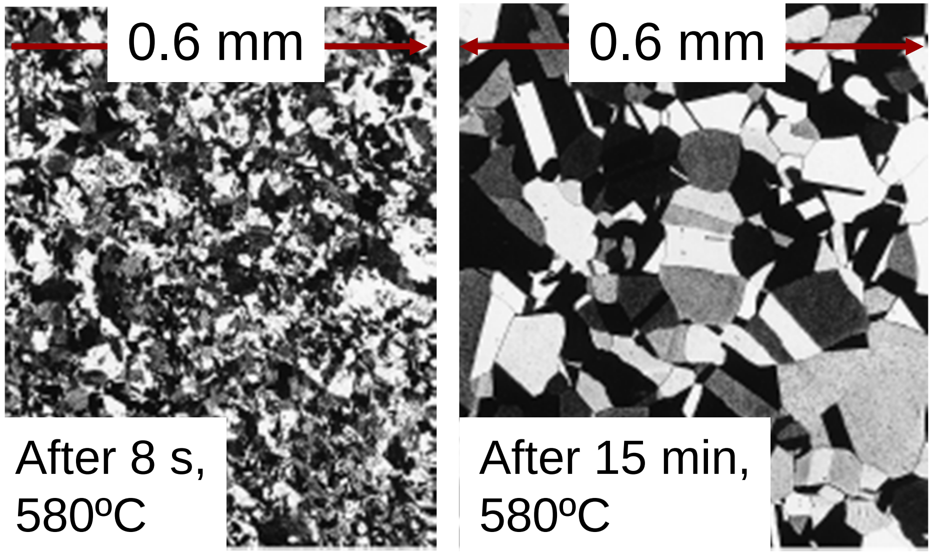
Annihilation ***reduces dislocation density***.

Recrystallization

- Add more heat, and **new grains start to grow** at the grain boundaries.
- The new grains have not been strain hardened
- The recrystallized metal is ductile and has low strength

Grain Growth

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



Adapted from Fig. 7.21 (d),(e), *Callister 7e.* (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

Ostwald Ripening

Summary

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