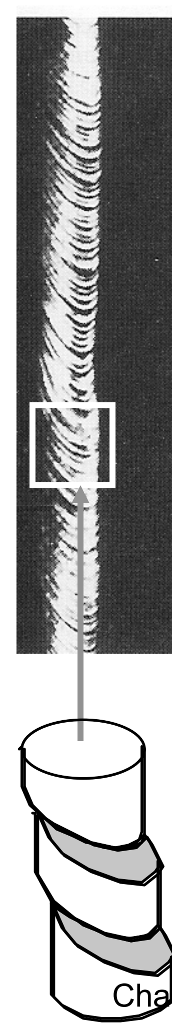
# Chapter 7: Dislocations and strengthening mechanisms

- Introduction
- Basic concepts
- Characteristics of dislocations
- Slip systems
- Slip in single crystals
- Plastic deformation of polycrystalline materials

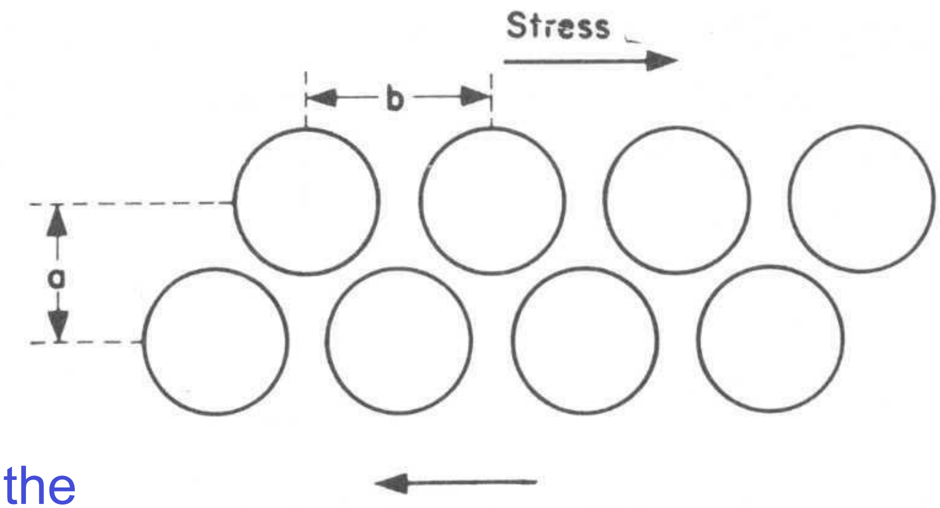


Plastically stretched zinc single crystal.

# Theoretical stress

**Theoretical stress (Frenkel in 1926)**

$$\tau = \frac{Gb}{2\pi a}\sin\frac{2\pi x}{b}$$




G: shear modulus
b: spacing between atoms in the direction of shear stress
a: spacing of the rows of atoms
x: shear translation

# Theoretical stress (*continued*)

**Hook's law**

**assumption: small strain**

$$\tau = \frac{Gb}{2\pi a} \times \frac{2\pi x}{b} = G\frac{x}{a} = G\gamma$$

Theoretical critical shear stress (maximum stress):

$$\tau_{th} = \frac{b}{a}\frac{G}{2\pi}$$

# Theoretical & experimental strength

**There is much difference between theoretical and experimental strength**

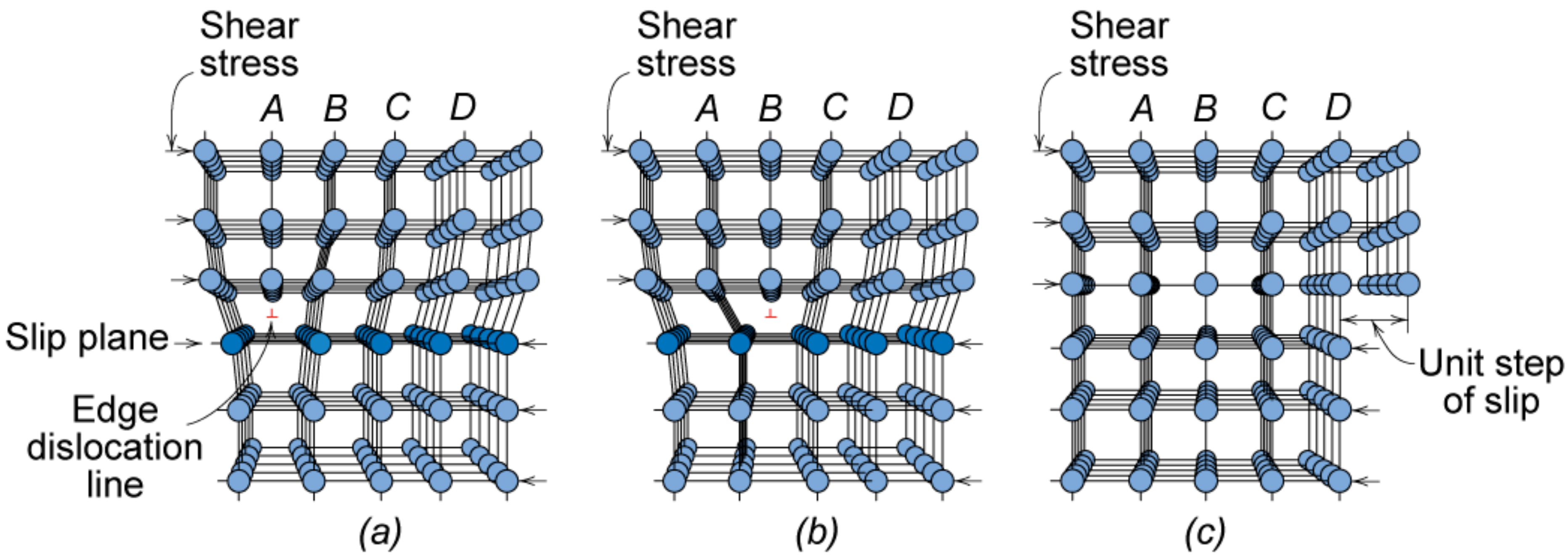
**Reasons are:**

- **Defects are present in all perfect crystal**
- **Dislocation movement makes plastic deformation easier than that predicted by the Frenkel calculation**

# 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).

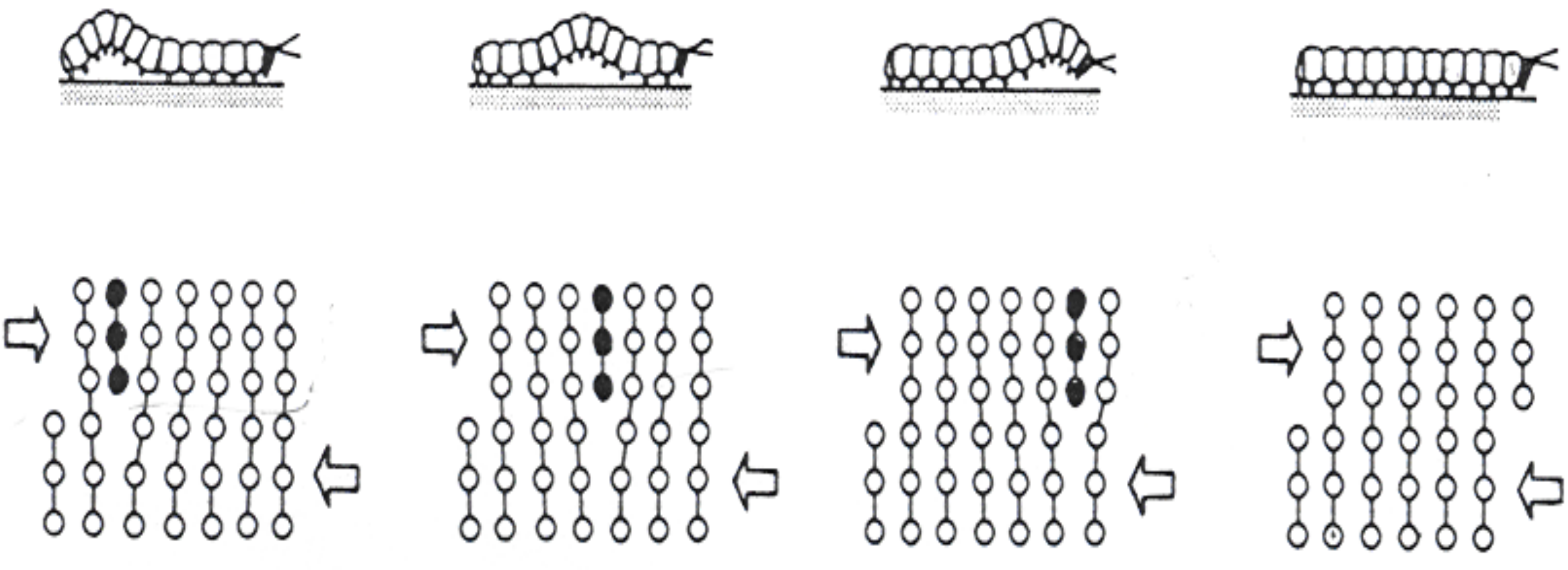



- If dislocations don't move, deformation doesn't occur!

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

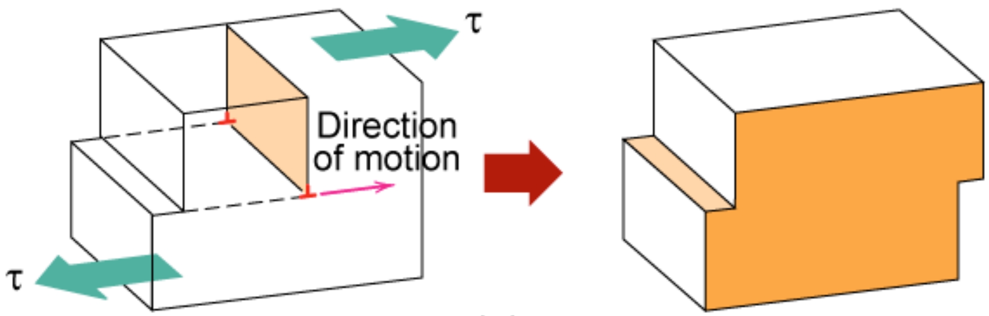
# Analogy between caterpillar and dislocation motion

- Dislocation density: total dislocation length per unit volume
- $10^3$ mm$^{-2}$ for pure metal crystals; $10^9$-$10^{10}$mm$^{-2}$ for heavily deformed metals; $10^5$-$10^6$mm$^{-2}$ for heat-treated deformed metals



# Dislocation Motion

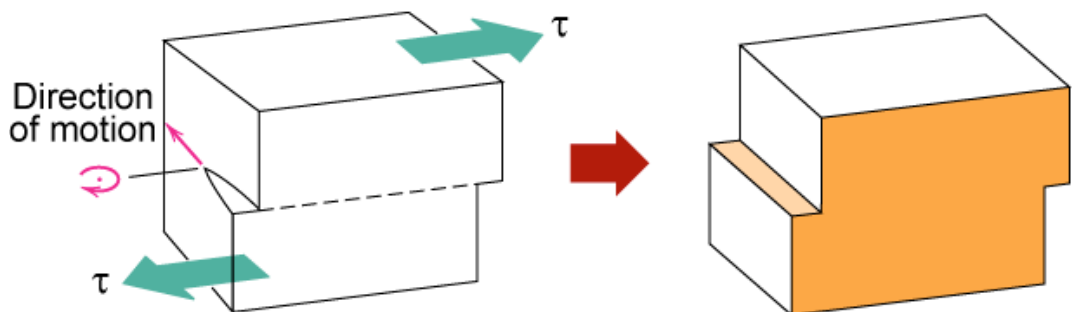
- Dislocation moves along slip plane in slip direction perpendicular to dislocation line
- Slip direction same direction as Burgers vector




(a)

**Edge dislocation**

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



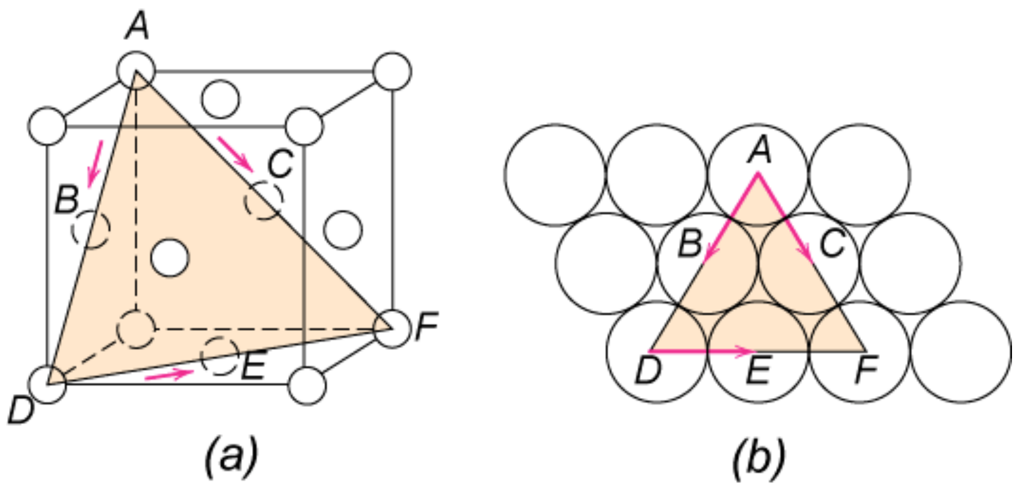

(b)

**Screw dislocation**

# 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

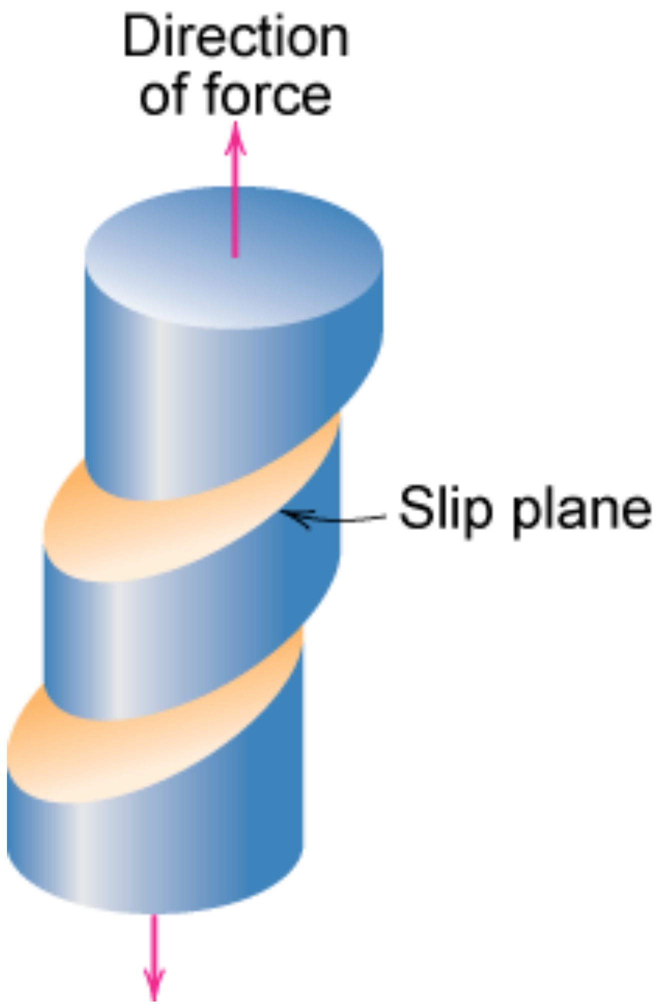
– in BCC & HCP other slip systems occur

# Slip planes and directions for common crystal structure

**Table 7.1** Slip Systems for Face-Centered Cubic, Body-Centered Cubic, and Hexagonal Close-Packed Metals

| *Metals* | *Slip Plane* | *Slip Direction* | *Number of Slip Systems* |
|---|---|---|---|
| | **Face-Centered Cubic** | | |
| Cu, Al, Ni, Ag, Au | {111} | $\langle 1\bar{1}0 \rangle$ | 12 |
| | **Body-Centered Cubic** | | |
| $\alpha$-Fe, W, Mo | {110} | $\langle \bar{1}11 \rangle$ | 12 |
| $\alpha$-Fe, W | {211} | $\langle \bar{1}11 \rangle$ | 12 |
| $\alpha$-Fe, K | {321} | $\langle \bar{1}11 \rangle$ | 24 |
| | **Hexagonal Close-Packed** | | |
| Cd, Zn, Mg, Ti, Be | {0001} | $\langle 11\bar{2}0 \rangle$ | 3 |
| Ti, Mg, Zr | $\{10\bar{1}0\}$ | $\langle 11\bar{2}0 \rangle$ | 3 |
| Ti, Mg | $\{10\bar{1}1\}$ | $\langle 11\bar{2}0 \rangle$ | 6 |

# Single Crystal Slip




Adapted from Fig. 7.8, *Callister 7e.*

Adapted from Fig. 7.9, *Callister 7e.*

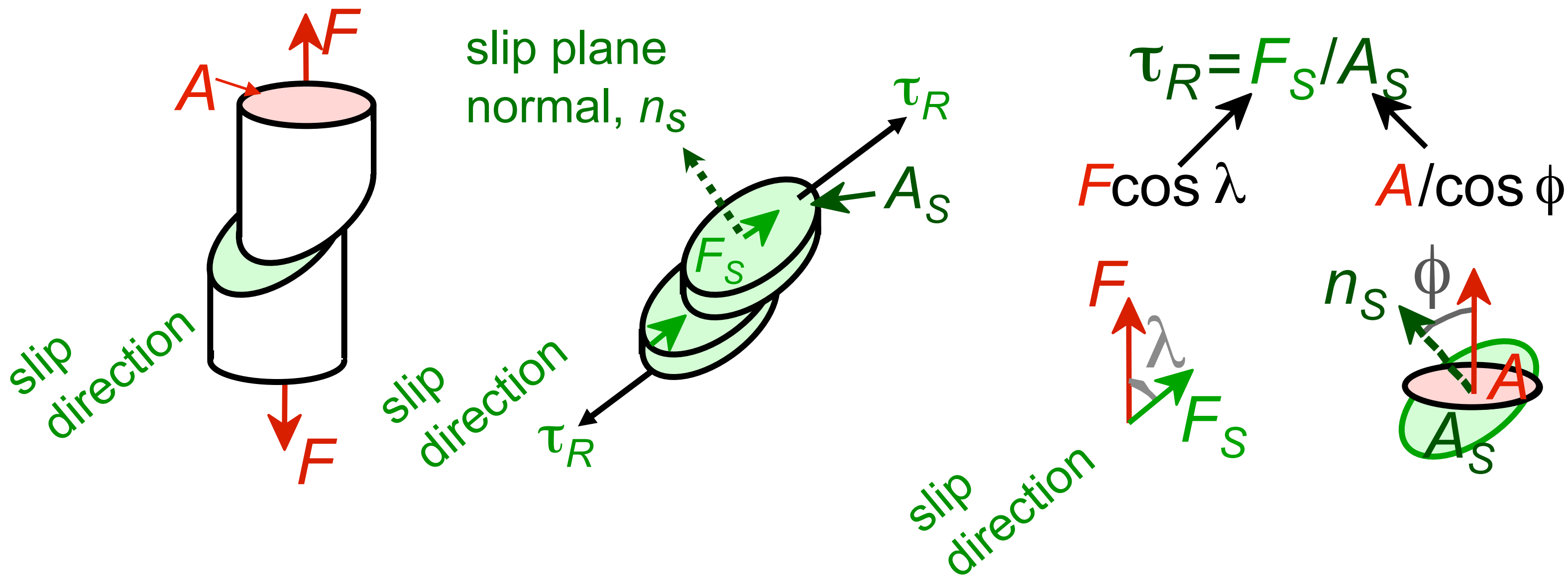
# Stress and Dislocation Motion

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

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

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

Relation between $\sigma$ and $\tau_R$




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

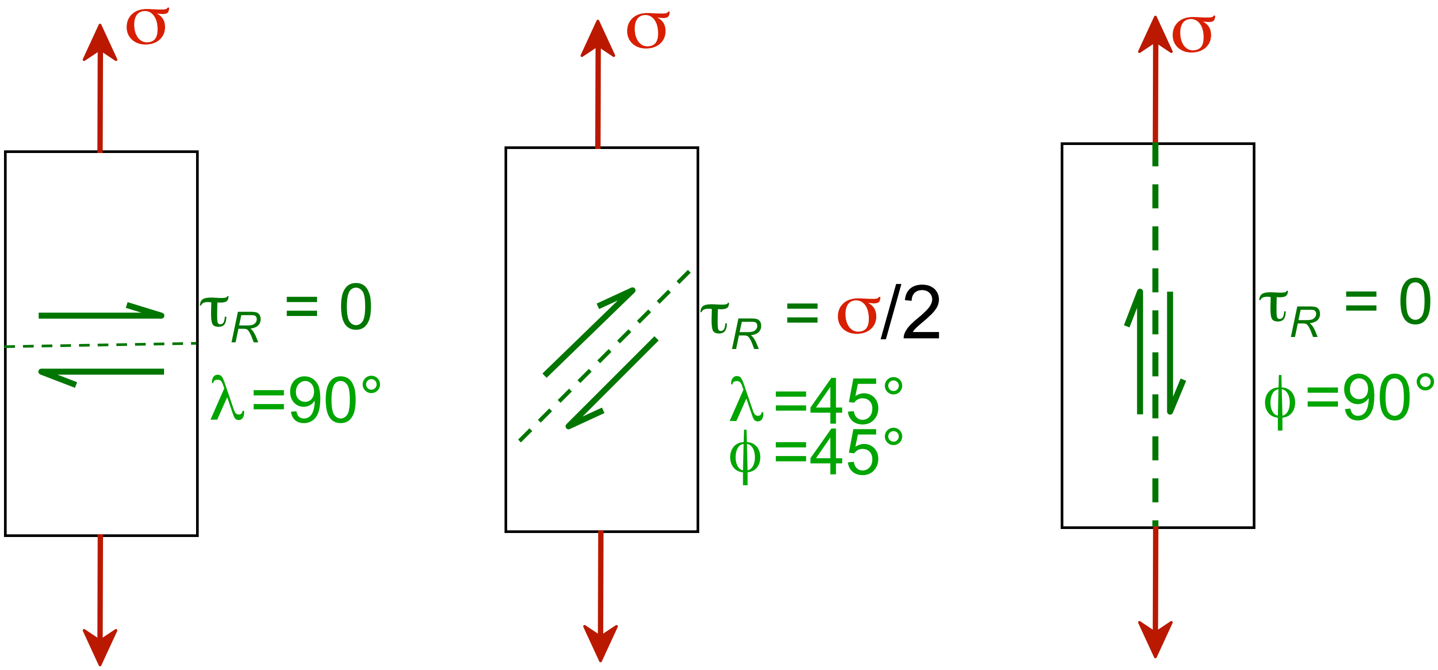
# Critical Resolved Shear Stress

- 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

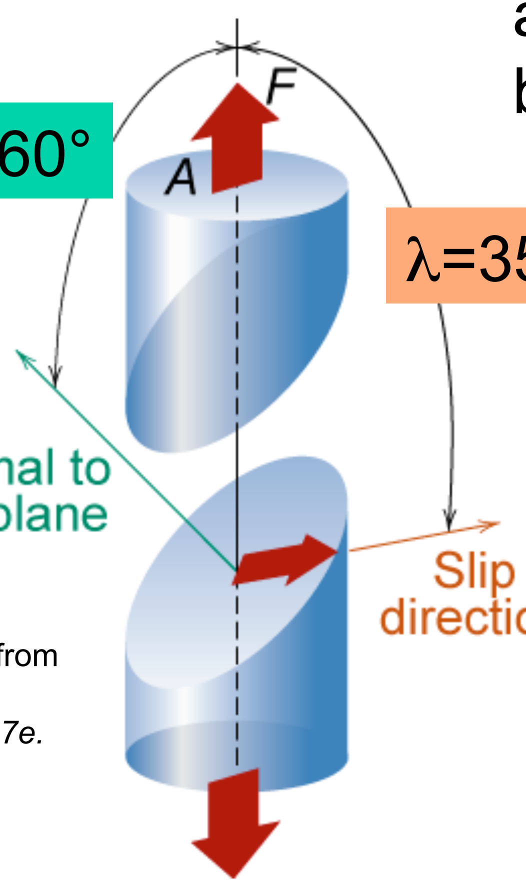
$$\tau_R = \sigma \cos\lambda \cos\phi$$




$\tau$ maximum at $\lambda = \phi = 45°$

# Ex: Deformation of single crystal

a) Will the single crystal yield?
b) If not, what stress is needed?




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

$\sigma$ = 6500 psi

$\tau_{crss}$ = 3000 psi

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

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

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

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

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

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, $\sigma_y$)?

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

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

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

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

# Slip Motion in Polycrystals

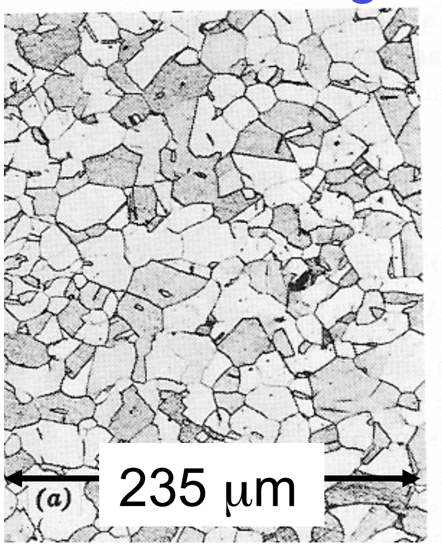
- Stronger - grain boundaries pin deformations
- Slip planes & directions ($\lambda$, $\phi$) change from one crystal to another.
- $\tau_R$ will vary from one crystal to another.
- The crystal with the largest $\tau_R$ yields first.
- Other (less favorably oriented) crystals yield later.


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].)

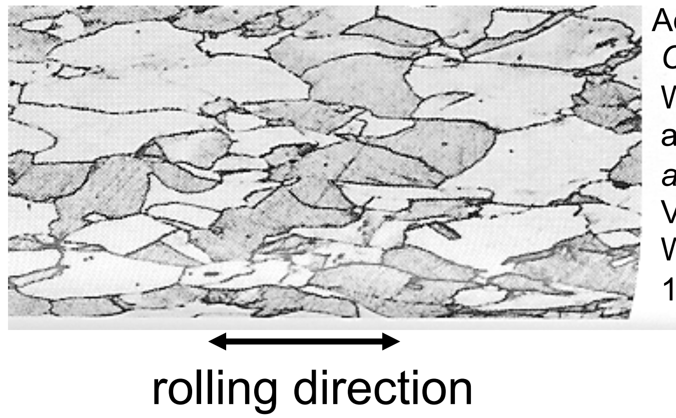
# Anisotropy in $\sigma_y$

- Can be induced by rolling a polycrystalline metal

- before rolling




- after rolling



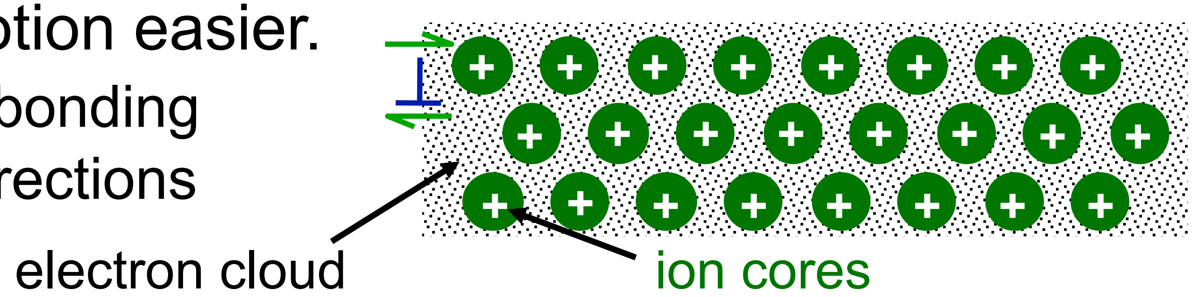

Adapted from Fig. 7.11, *Callister 7e.* (Fig. 7.11 is from W.G. Moffatt, G.W. Pearsall, and J. Wulff, *The Structure and Properties of Materials*, Vol. I, *Structure*, p. 140, John Wiley and Sons, New York, 1964.)

- isotropic
  since grains are approx. spherical & randomly oriented.

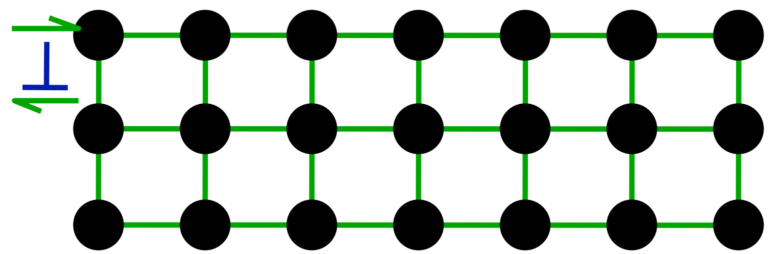
- anisotropic
  since rolling affects grain orientation and shape.

# 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.