Chapter 7:

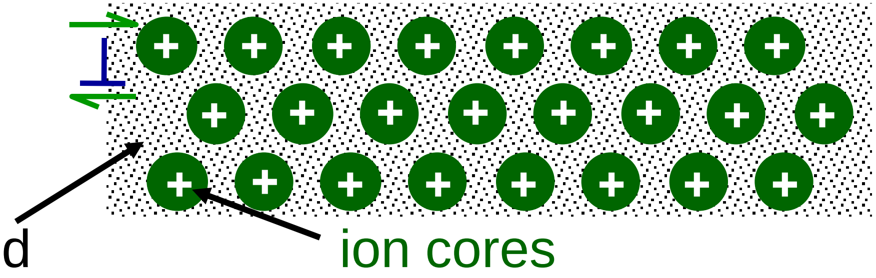
Dislocations & Strengthening Mechanisms

ISSUES TO ADDRESS...

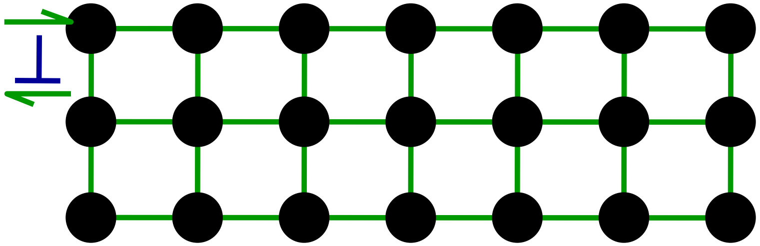
- Why are dislocations observed primarily in metals and alloys?
- How are strength and dislocation motion related?
- How do we increase strength?
- How can heating change strength and other properties?

Dislocations & Materials Classes

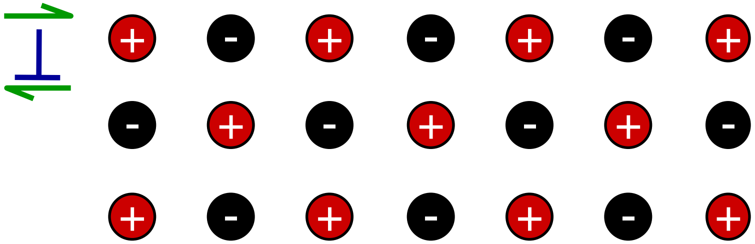
- Metals: Disl. motion easier.
  - -non-directional bonding
  - -close-packed directions for slip.



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



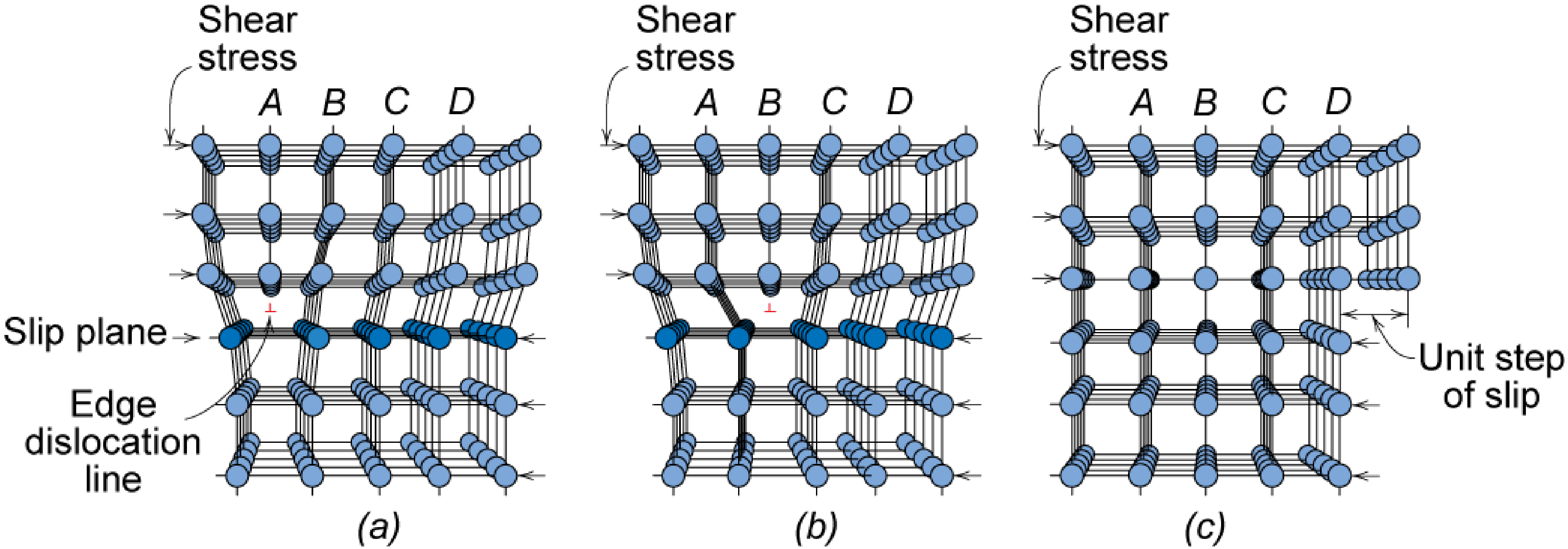
- Ionic Ceramics (NaCl):
  - Motion hard.
  - -need to avoid ++ and - - neighbors.



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).

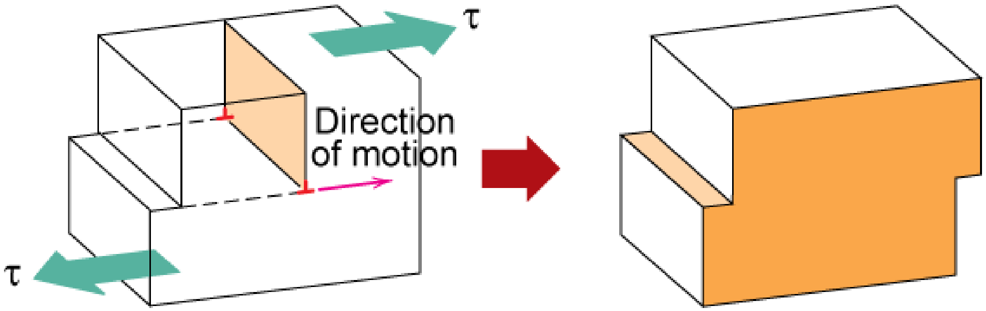


- If dislocations don't move, deformation doesn't occur!

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

Dislocation Motion

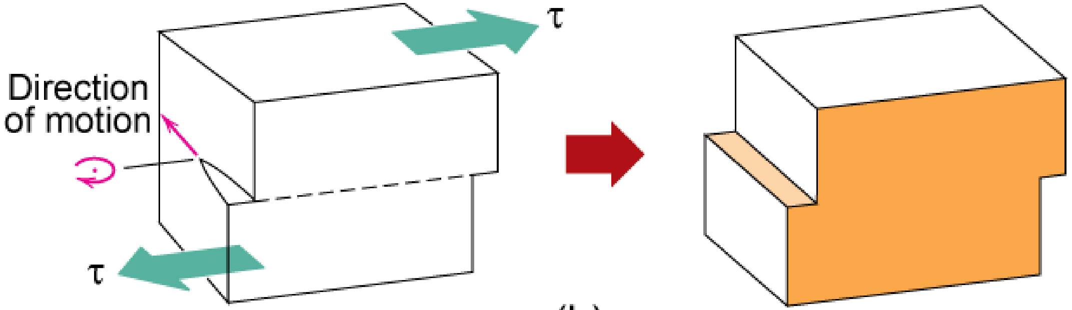
- Dislocation moves along slip plane in slip direction perpendicular to dislocation line
- Slip direction same direction as Burgers vector



(a)

Edge dislocation

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



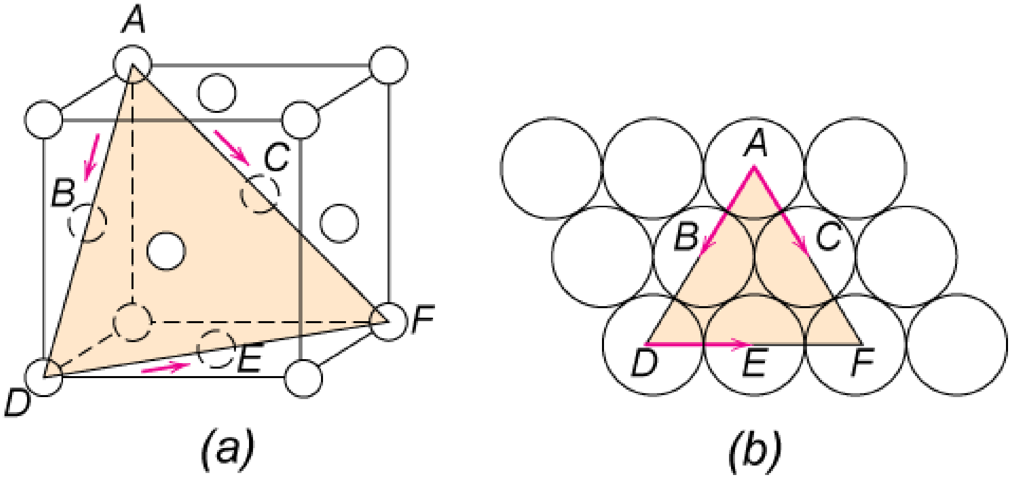
(b)

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

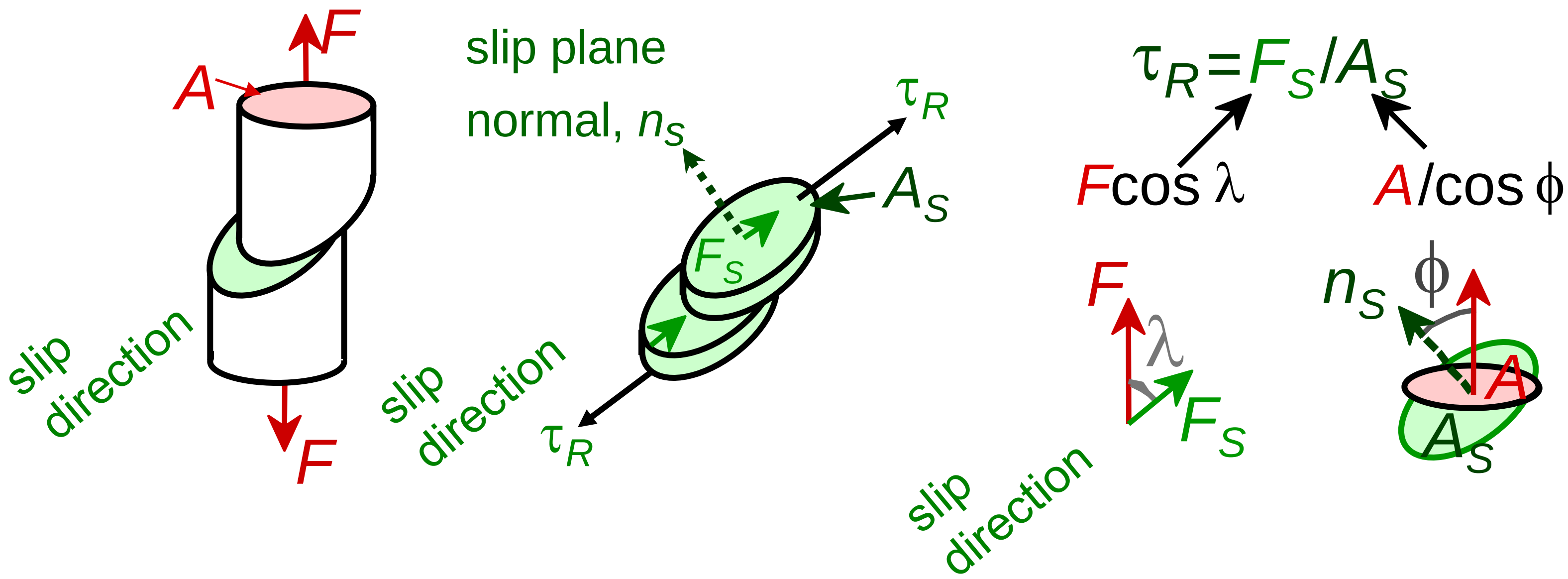
Stress and Dislocation Motion

- 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

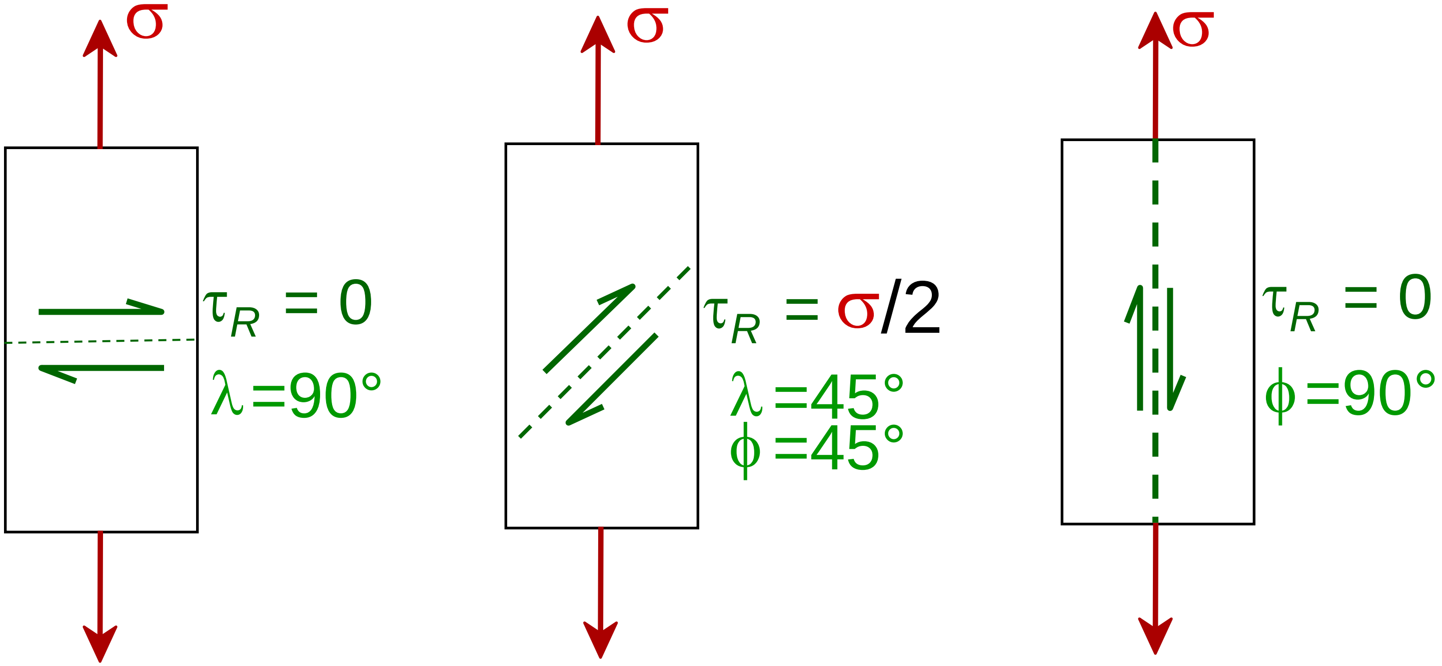
- Condition for dislocation motion: $\tau_R > \tau_{CRSS}$

typically

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

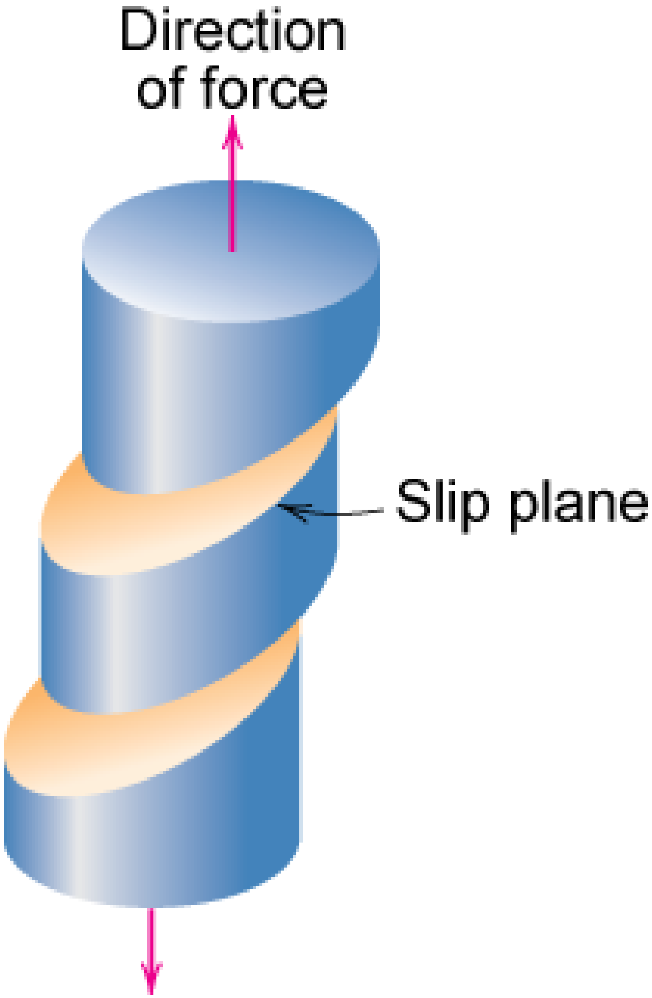
- Crystal orientation can make it easy or hard to move dislocation

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



τ maximum at $\lambda = \phi = 45^{o}$

Single Crystal Slip

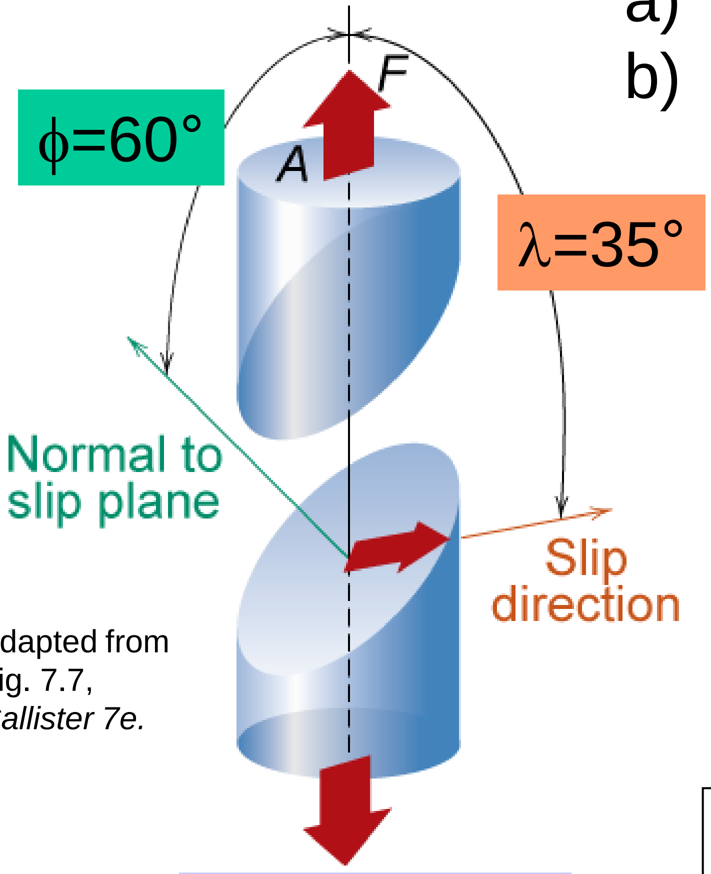


Adapted from Fig. 7.8, *Callister 7e.*

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

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.

τ_{crss} = 3000 psi

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

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

σ = 6500 psi

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

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

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

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

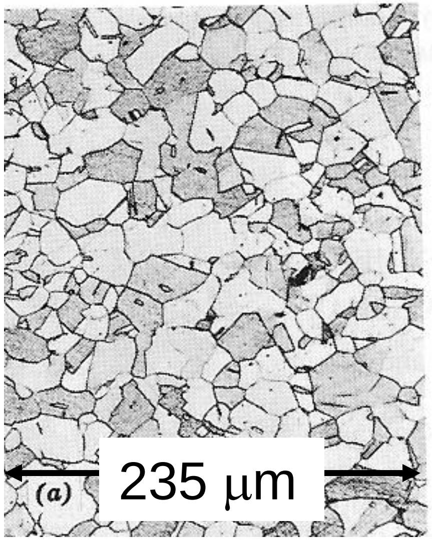
- Stronger - grain boundaries pin deformations
- Slip planes & directions (λ, ϕ) change from one crystal to another.
- τ_R will vary from one crystal to another.
- The crystal with the largest τ_R yields first.
- Other (less favorably oriented) crystals yield later.

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 σ_y

- Can be induced by rolling a polycrystalline metal

- before rolling



- after rolling

rolling direction

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.

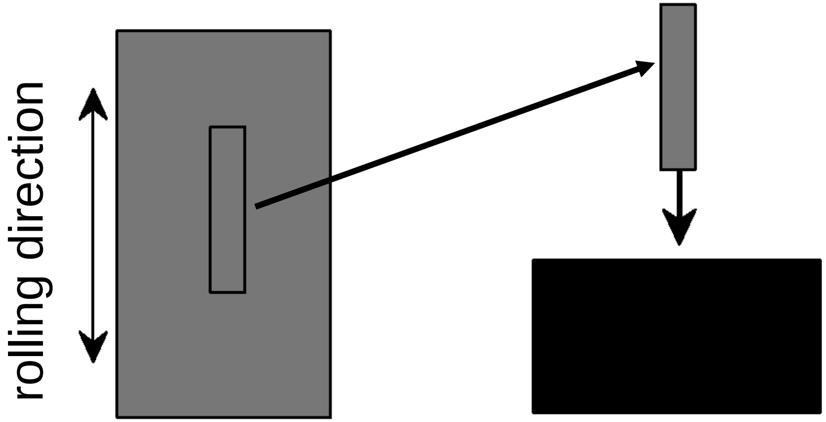
- anisotropic
  since rolling affects grain orientation and shape.

Anisotropy in Deformation

1. Cylinder of Tantalum machined from a rolled plate:

2. Fire cylinder at a target.

3. Deformed cylinder



Photos courtesy of G.T. Gray III, Los Alamos National Labs. Used with permission.

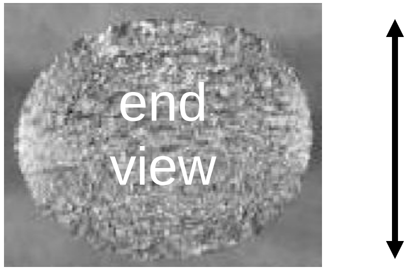
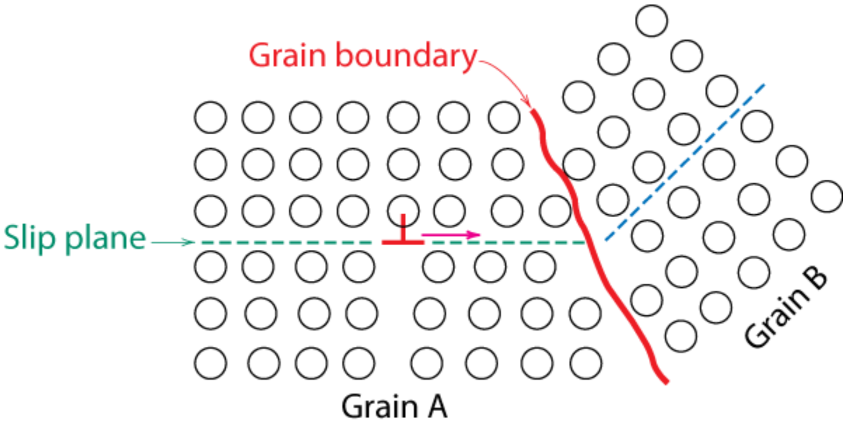


plate thickness direction

- The noncircular end view shows anisotropic deformation of rolled material.

4 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.)

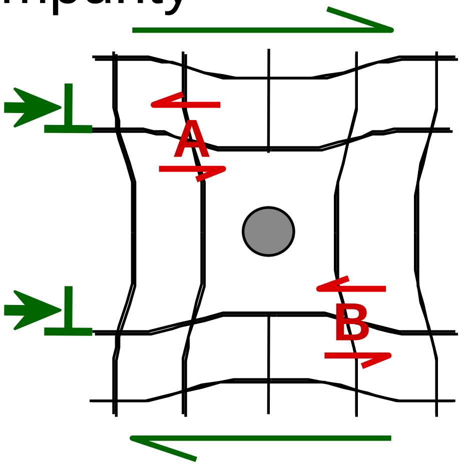
- Hall-Petch Equation:

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

4 Strategies for Strengthening:
2: Solid Solutions

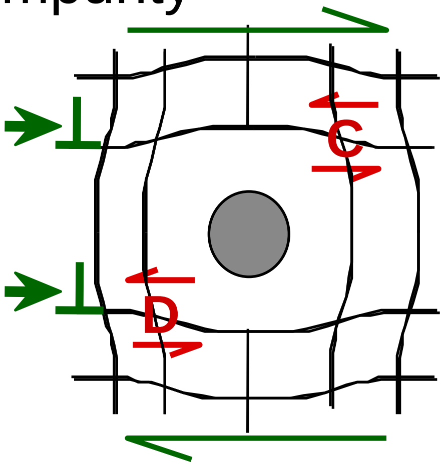
- Impurity atoms distort the lattice & generate stress.
- Stress can produce a barrier to dislocation motion.

- Smaller substitutional impurity



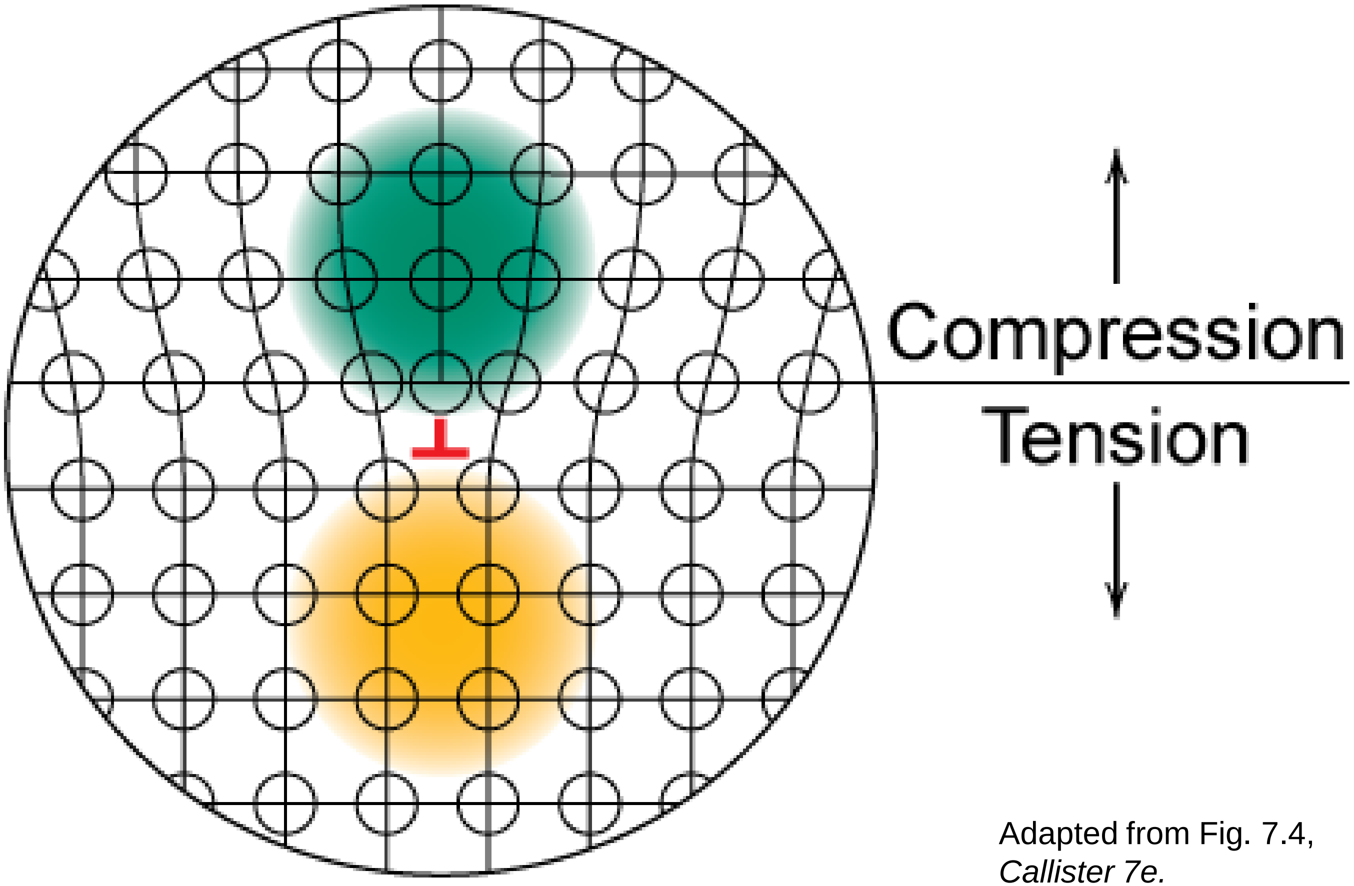
Impurity generates local stress at **A** and **B** that opposes dislocation motion to the right.

- Larger substitutional impurity



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

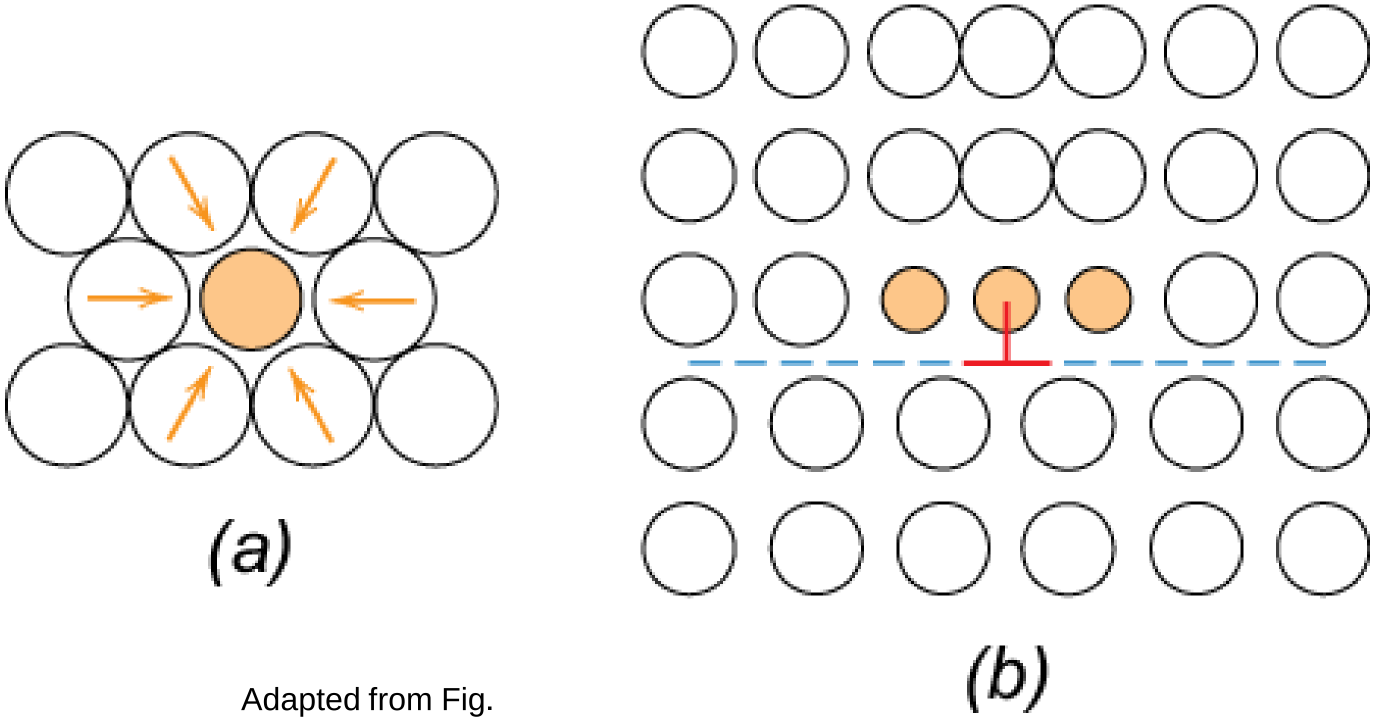
Stress Concentration at Dislocations



Adapted from Fig. 7.4, *Callister 7e.*

Strengthening by Alloying

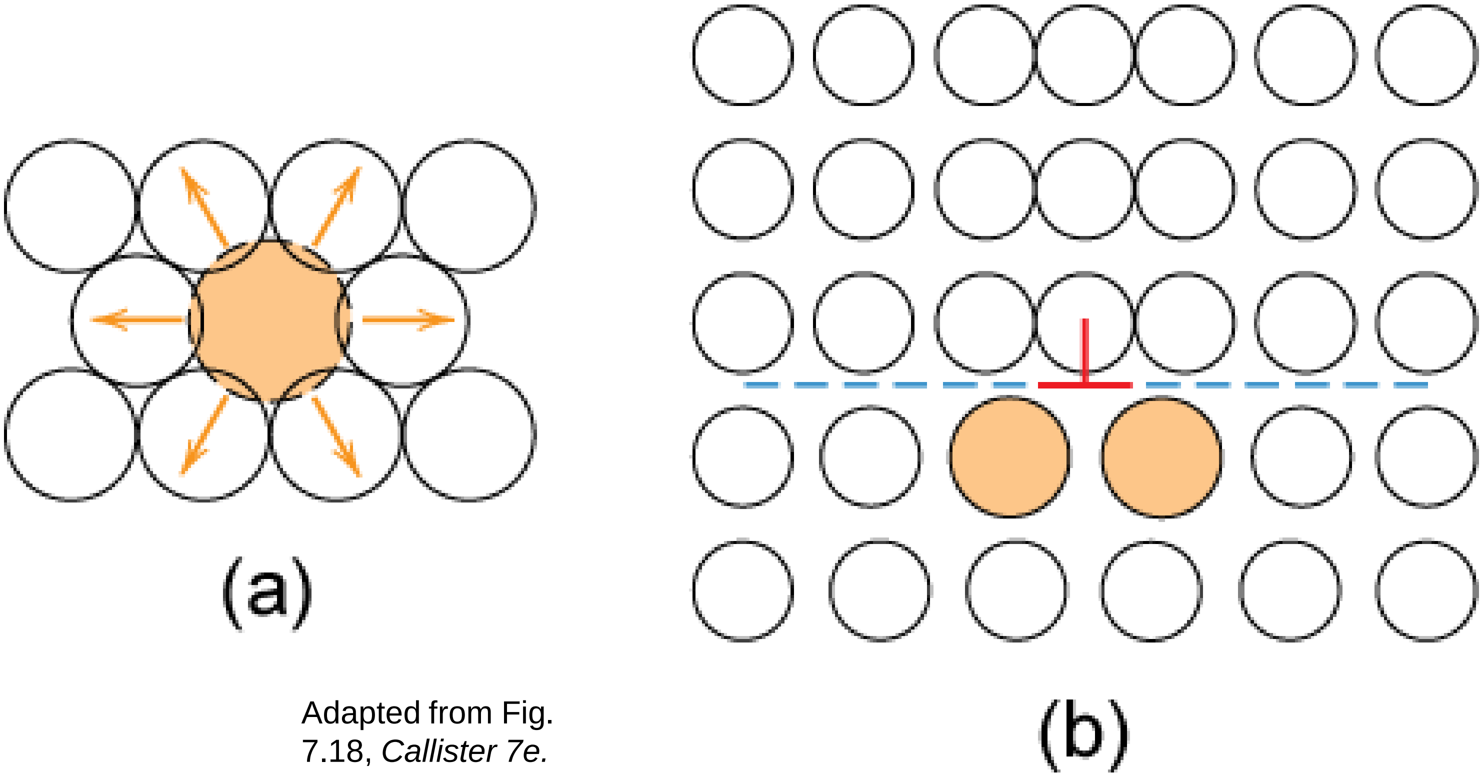
- small impurities tend to concentrate at dislocations
- reduce mobility of dislocation ∴ increase strength



Adapted from Fig. 7.17, *Callister 7e.*

Strengthening by alloying

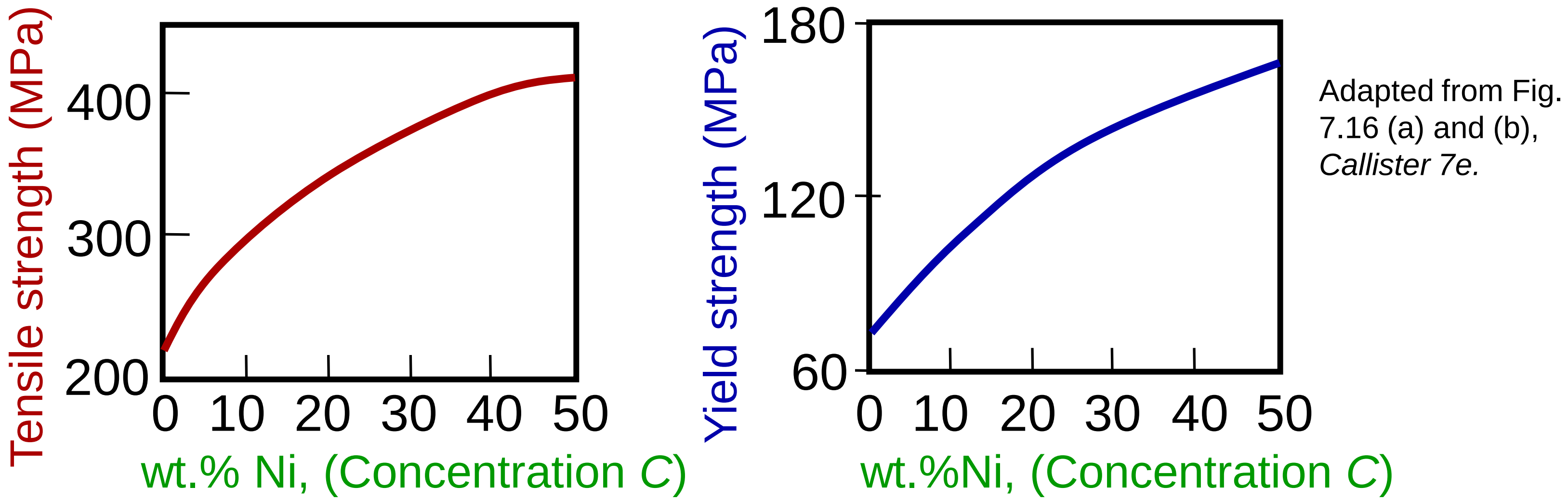
- large impurities concentrate at dislocations on low density side



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

Ex: Solid Solution Strengthening in Copper

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



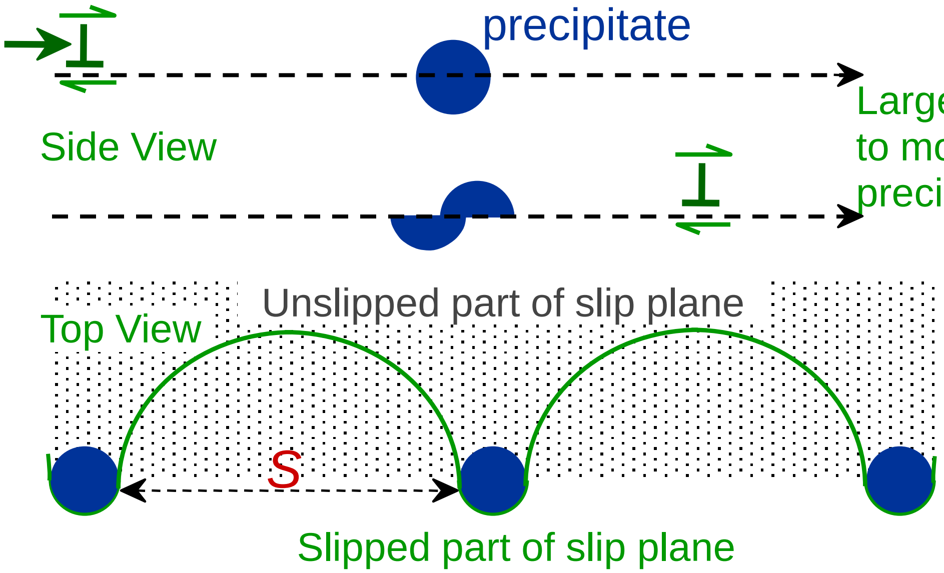
Adapted from Fig. 7.16 (a) and (b), *Callister 7e.*

- Empirical relation: $\sigma_y \sim C^{1/2}$
- Alloying increases σ_y and *TS*.

4 Strategies for Strengthening: 3: Precipitation Strengthening

- Hard precipitates are difficult to shear.

  Ex: Ceramics in metals (SiC in Iron or Aluminum).



Large shear stress needed to move dislocation toward precipitate and shear it.

Dislocation "advances" but precipitates act as "pinning" sites with spacing *S*.

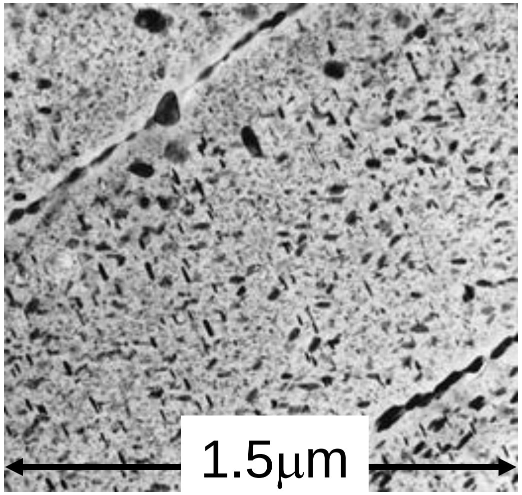
- Result: $$\sigma_y \sim \frac{1}{S}$$

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.)

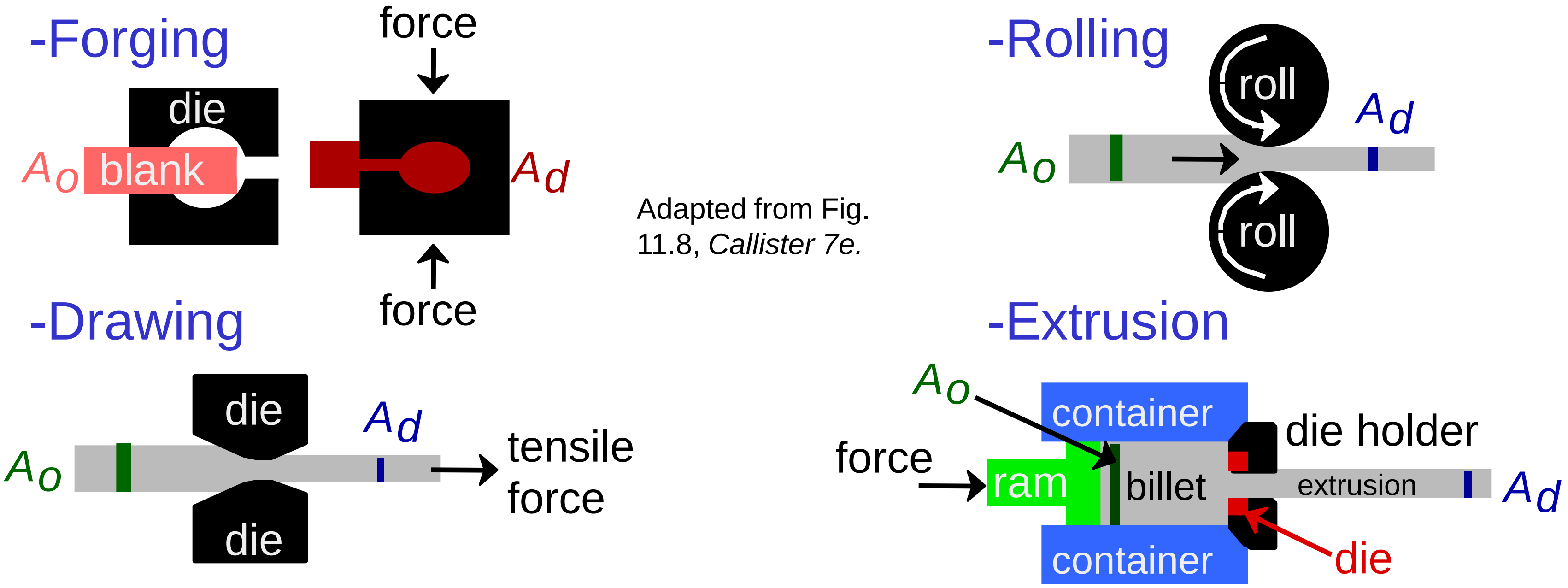
- Aluminum is strengthened with precipitates formed by alloying.



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

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

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

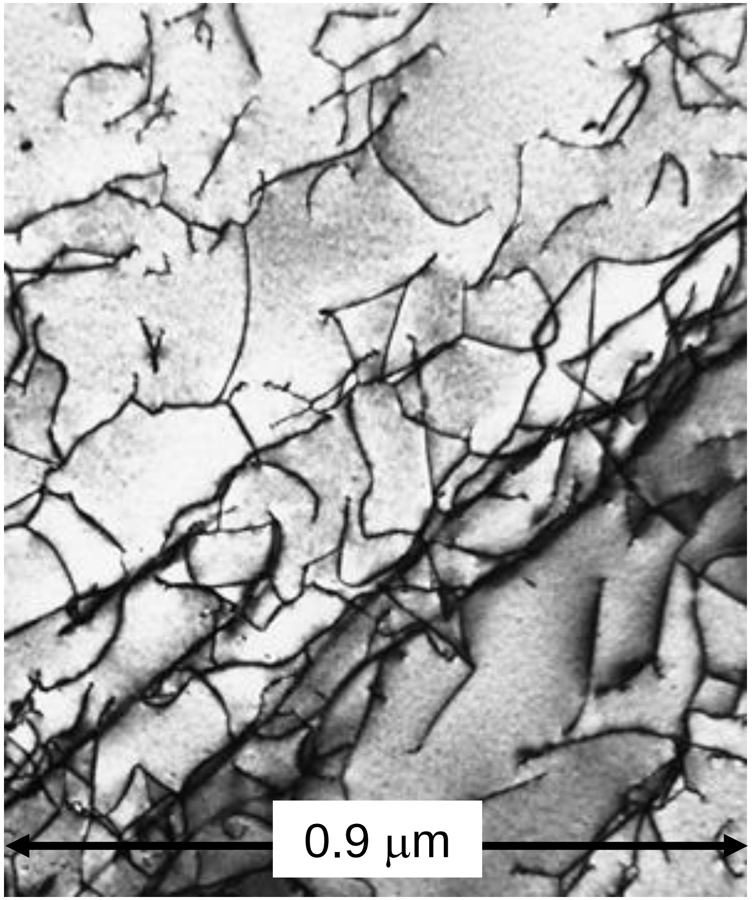


Adapted from Fig. 11.8, *Callister 7e.*

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

Dislocations During Cold Work

- Ti alloy after cold working:



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

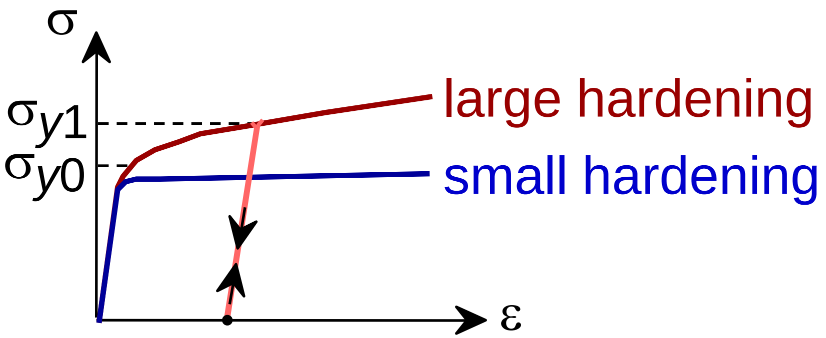
Adapted from Fig. 4.6, *Callister 7e.* (Fig. 4.6 is courtesy of M.R. Plichta, Michigan Technological University.)

Result of Cold Work

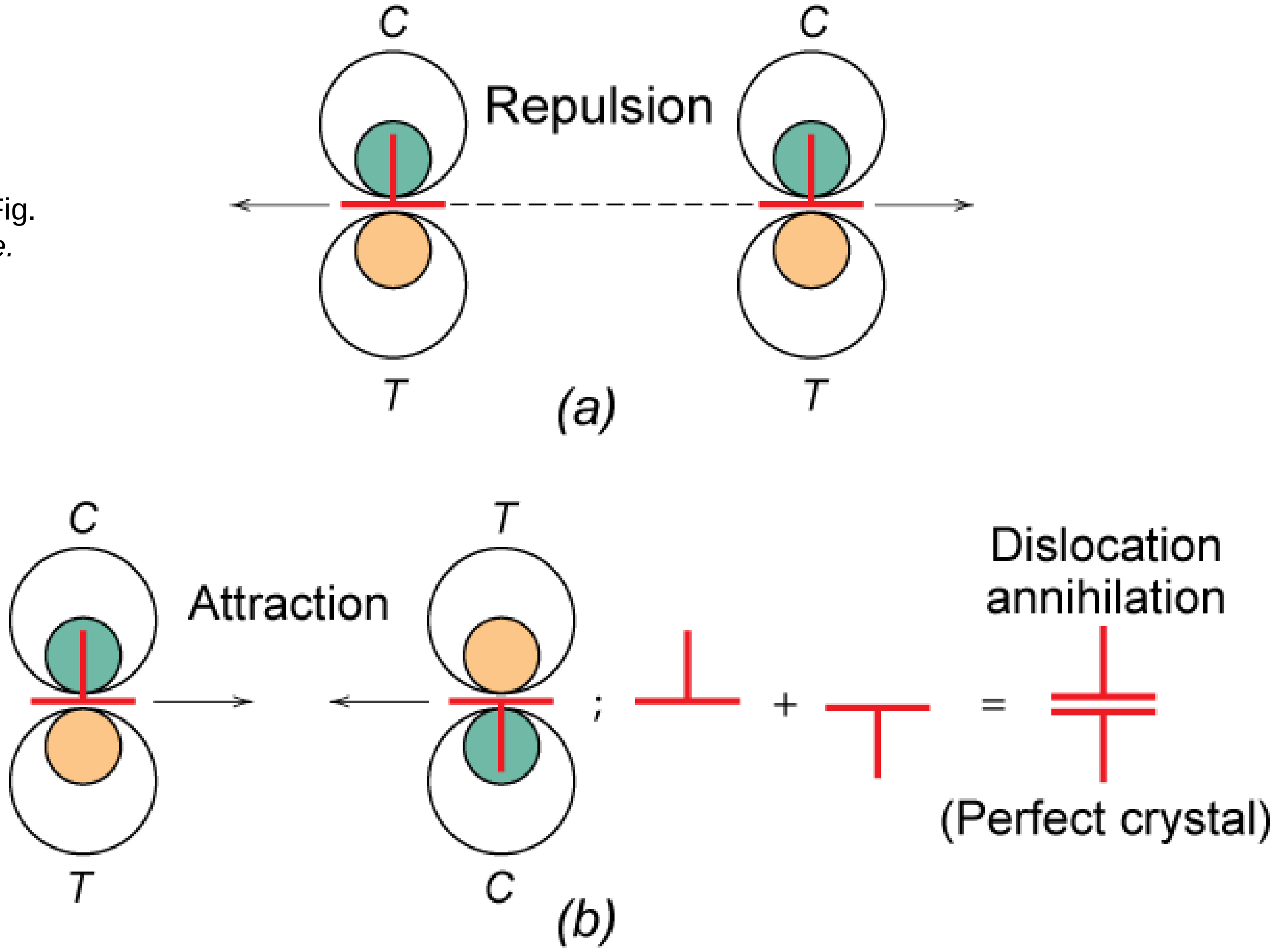
$$\text{Dislocation density} = \frac{\text{total dislocation length}}{\text{unit volume}}$$

- Carefully grown single crystal
  - → ca. 10^3 mm^{-2}
- Deforming sample increases density
  - → 10^9-10^{10} mm^{-2}
- Heat treatment reduces density
  - → 10^5-10^6 mm^{-2}

- Yield stress increases as ρ_d increases:



Effects of Stress at Dislocations

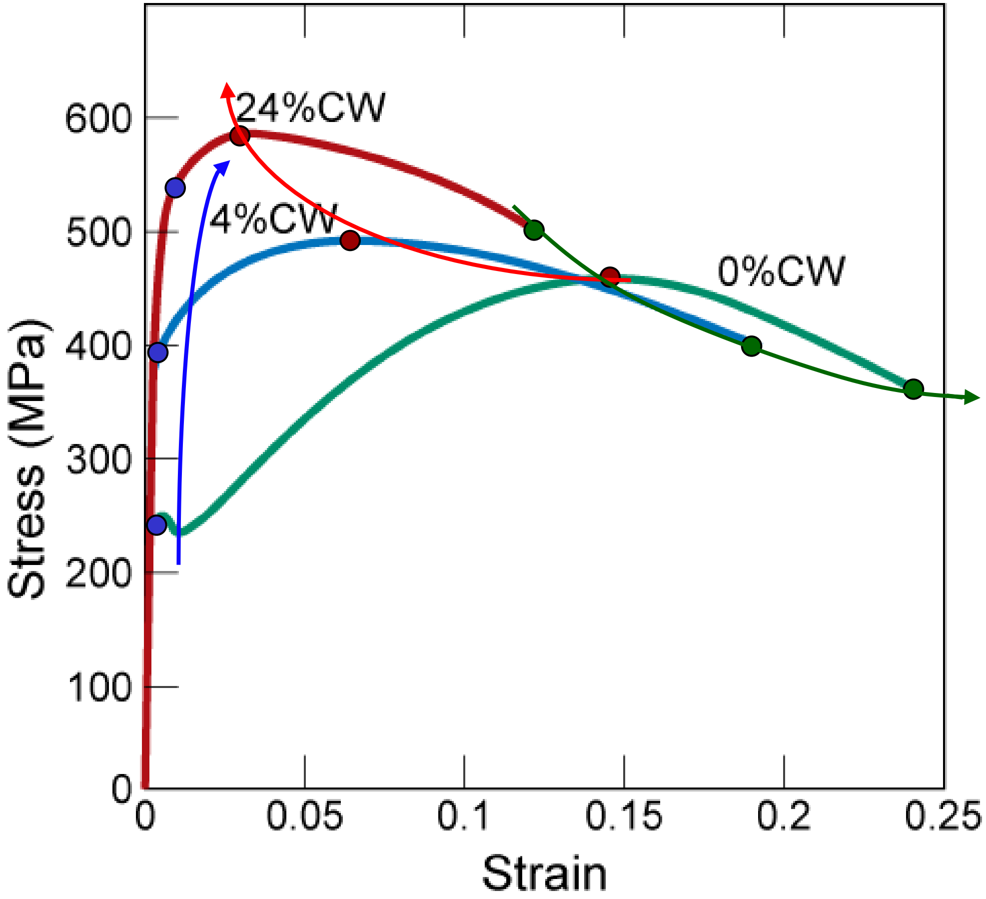


Adapted from Fig. 7.5, *Callister 7e.*

Impact of Cold Work

As cold work is increased

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

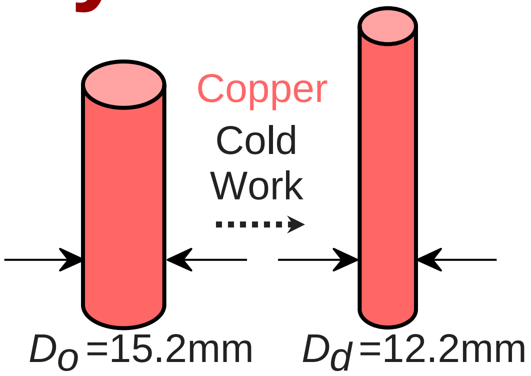


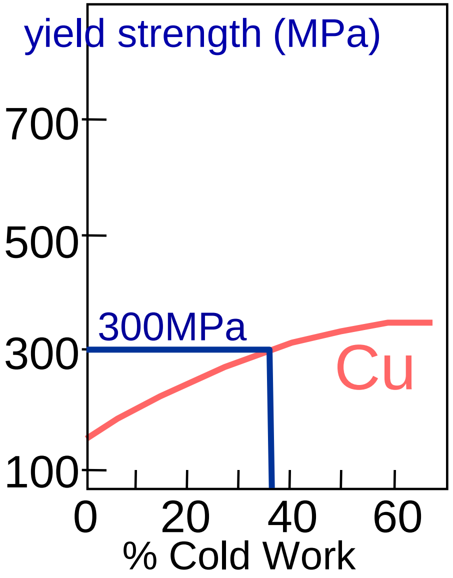
Adapted from Fig. 7.20, *Callister 7e.*

Cold Work Analysis

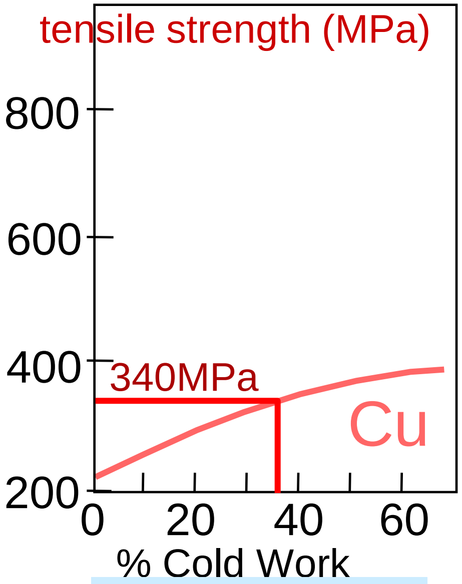
- What is the tensile strength & ductility after cold working?

$$\%CW = \frac{\pi r_o^2 - \pi r_d^2}{\pi r_o^2} \times 100 = 35.6\%$$

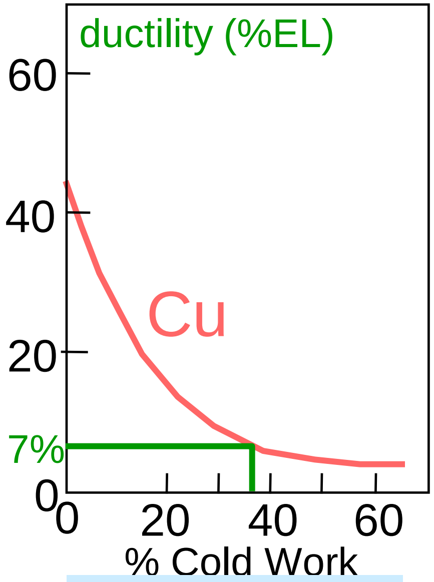




$\sigma_y = 300$MPa



TS = 340MPa

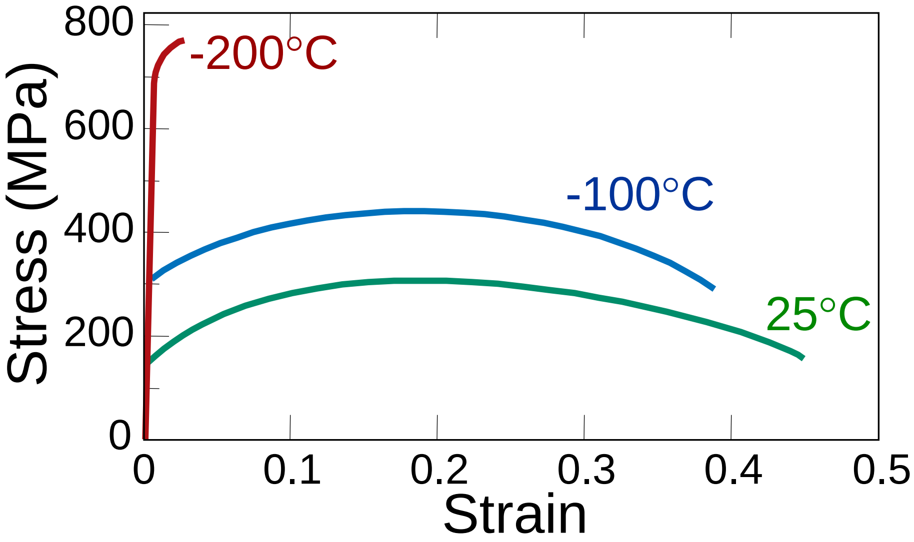


%EL = 7%

Adapted from Fig. 7.19, *Callister 7e.* (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.)

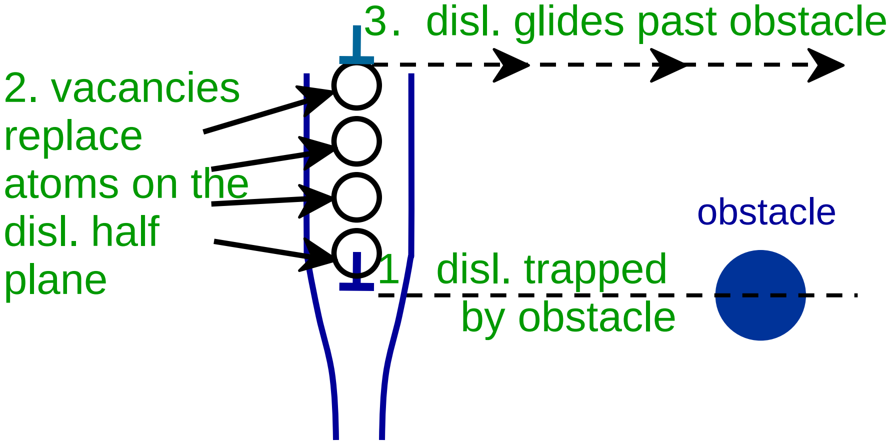
σ-ε Behavior vs. Temperature

- Results for polycrystalline iron:



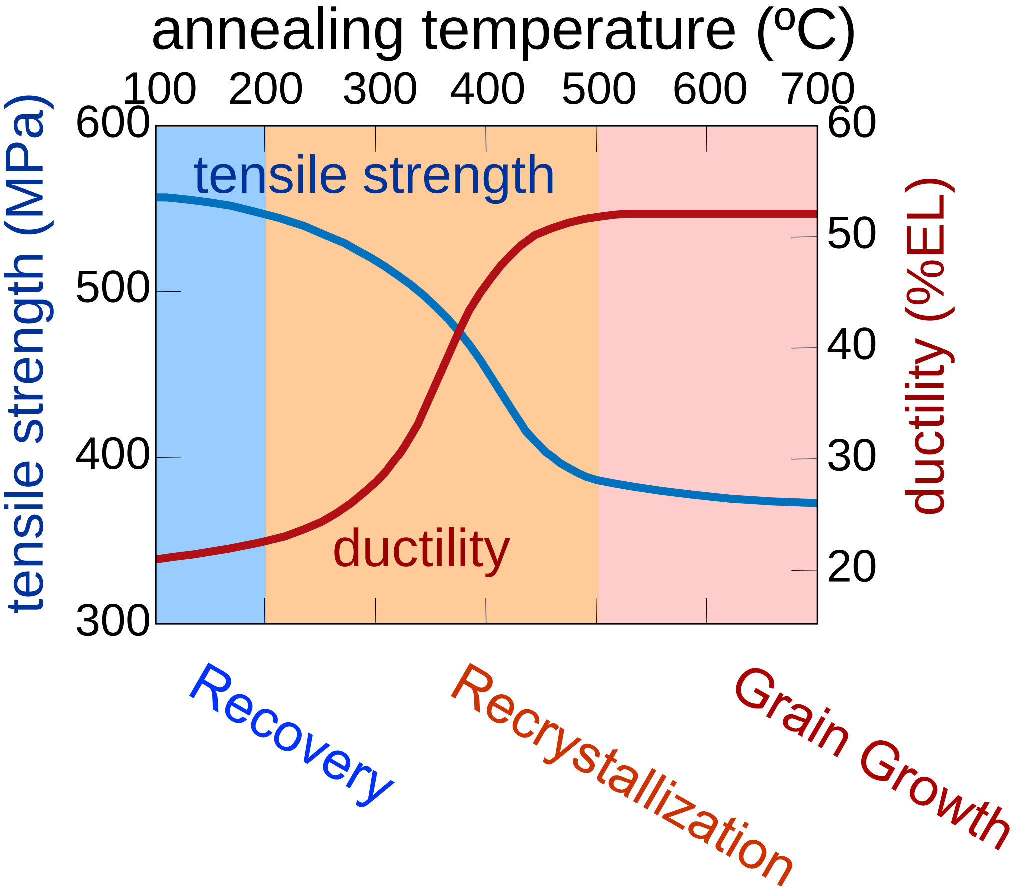
Adapted from Fig. 6.14, *Callister 7e.*

- σ_y and *TS* *decrease* with increasing test temperature.
- %*EL* *increases* with increasing test temperature.
- Why? Vacancies help dislocations move past obstacles.



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...

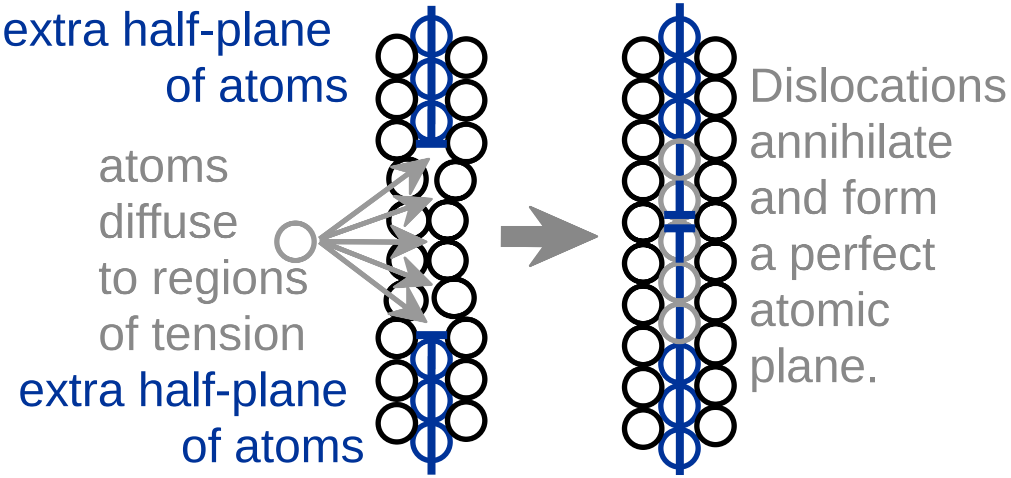
Adapted from Fig. 7.22, *Callister 7e.* (Fig. 7.22 is adapted from G. Sachs and K.R. van Horn, *Practical Metallurgy, Applied Metallurgy, and the Industrial Processing of Ferrous and Nonferrous Metals and Alloys*, American Society for Metals, 1940, p. 139.)

Recovery

Annihilation reduces dislocation density.

- Scenario 1

  Results from diffusion



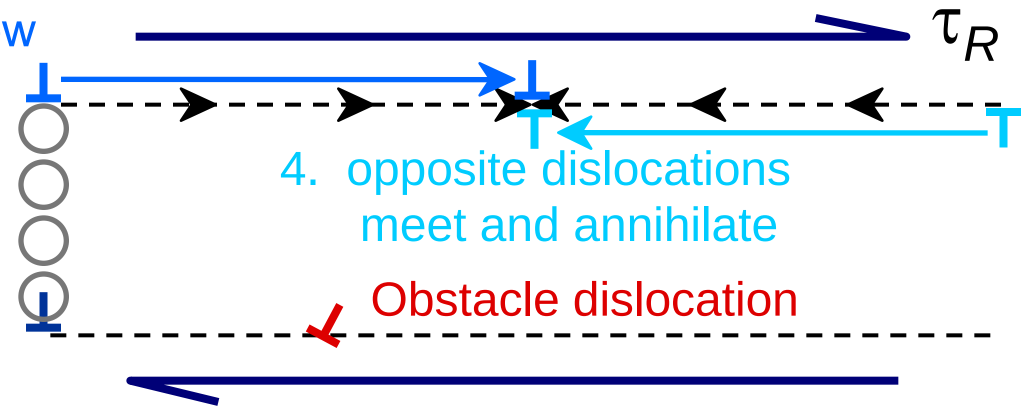
extra half-plane of atoms

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"

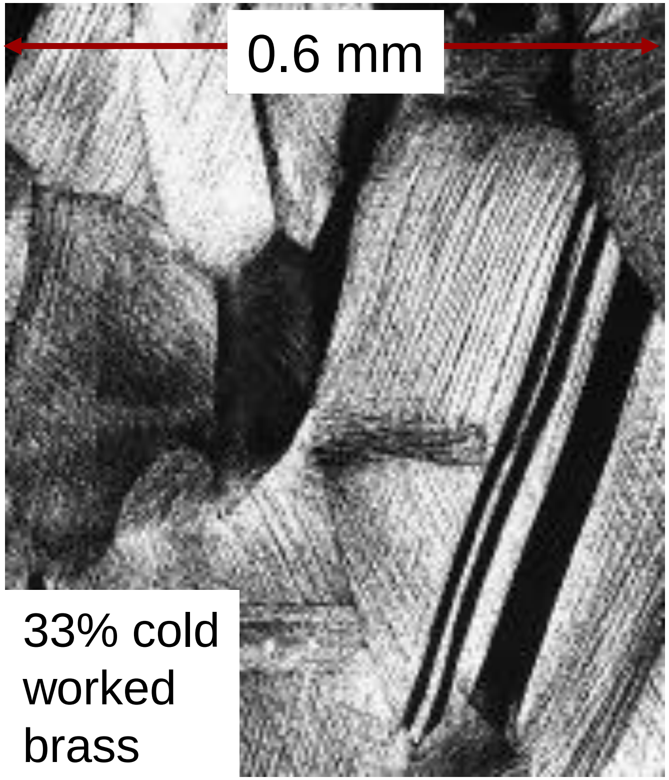
1. dislocation blocked; can't move to the right

4. opposite dislocations meet and annihilate

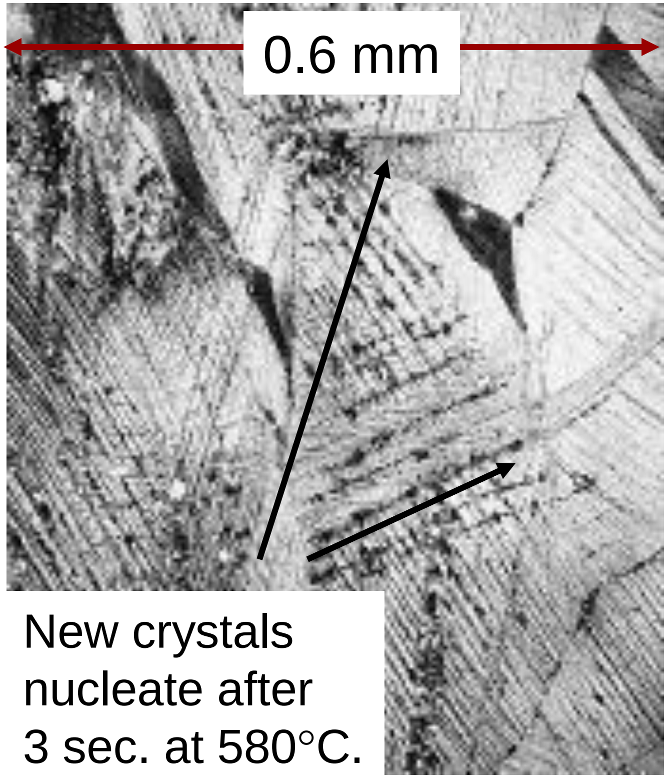
Obstacle dislocation

Recrystallization

- New grains are formed that:
  - -- have a small dislocation density
  - -- are small
  - -- consume cold-worked grains.



33% cold worked brass

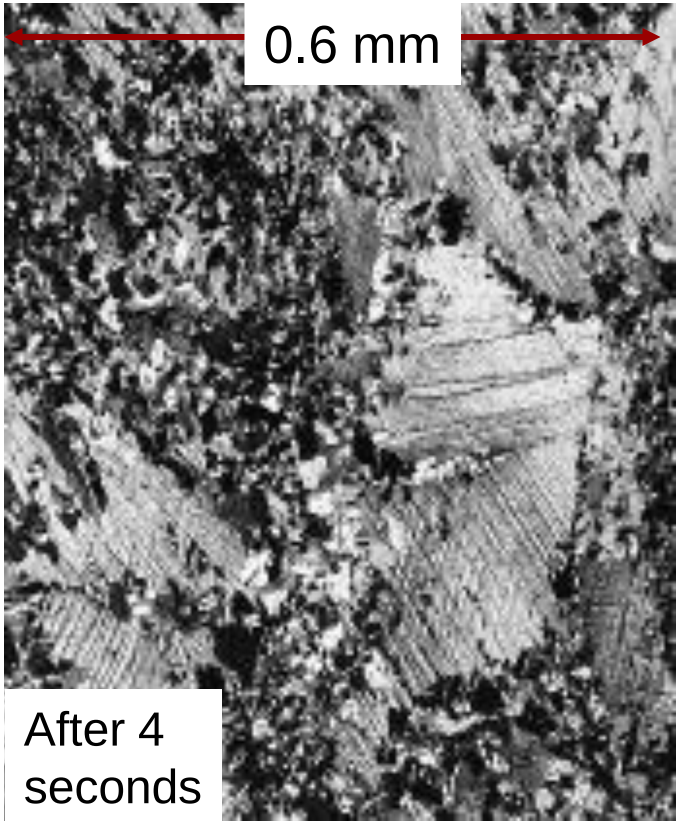


New crystals nucleate after 3 sec. at 580°C.

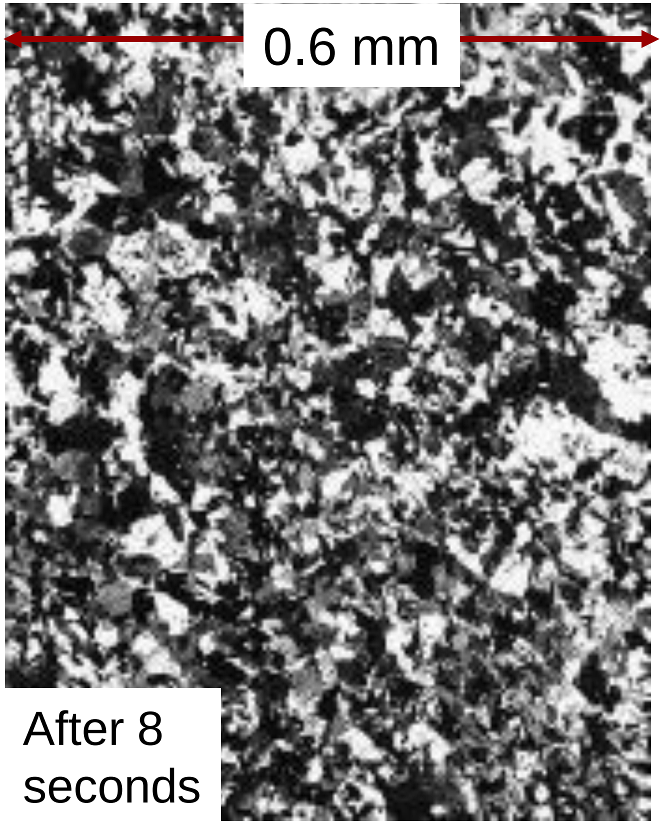
Adapted from Fig. 7.21 (a),(b), *Callister 7e.* (Fig. 7.21 (a),(b) are courtesy of J.E. Burke, General Electric Company.)

Further Recrystallization

- All cold-worked grains are consumed.



After 4 seconds

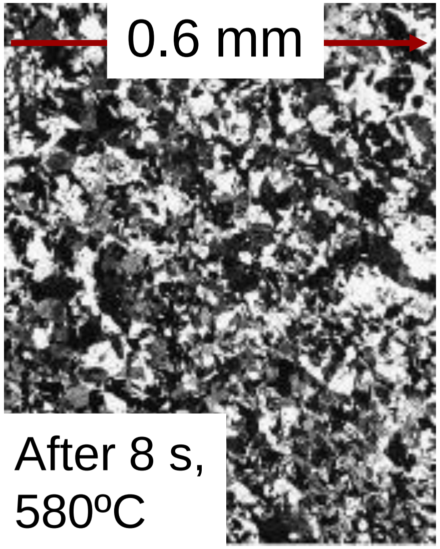


After 8 seconds

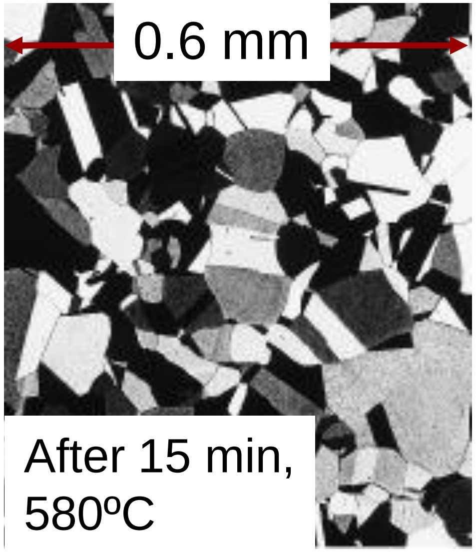
Adapted from Fig. 7.21 (c),(d), *Callister 7e.* (Fig. 7.21 (c),(d) are courtesy of J.E. Burke, General Electric Company.)

Grain Growth

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



After 8 s, 580ºC



After 15 min, 580ºC

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

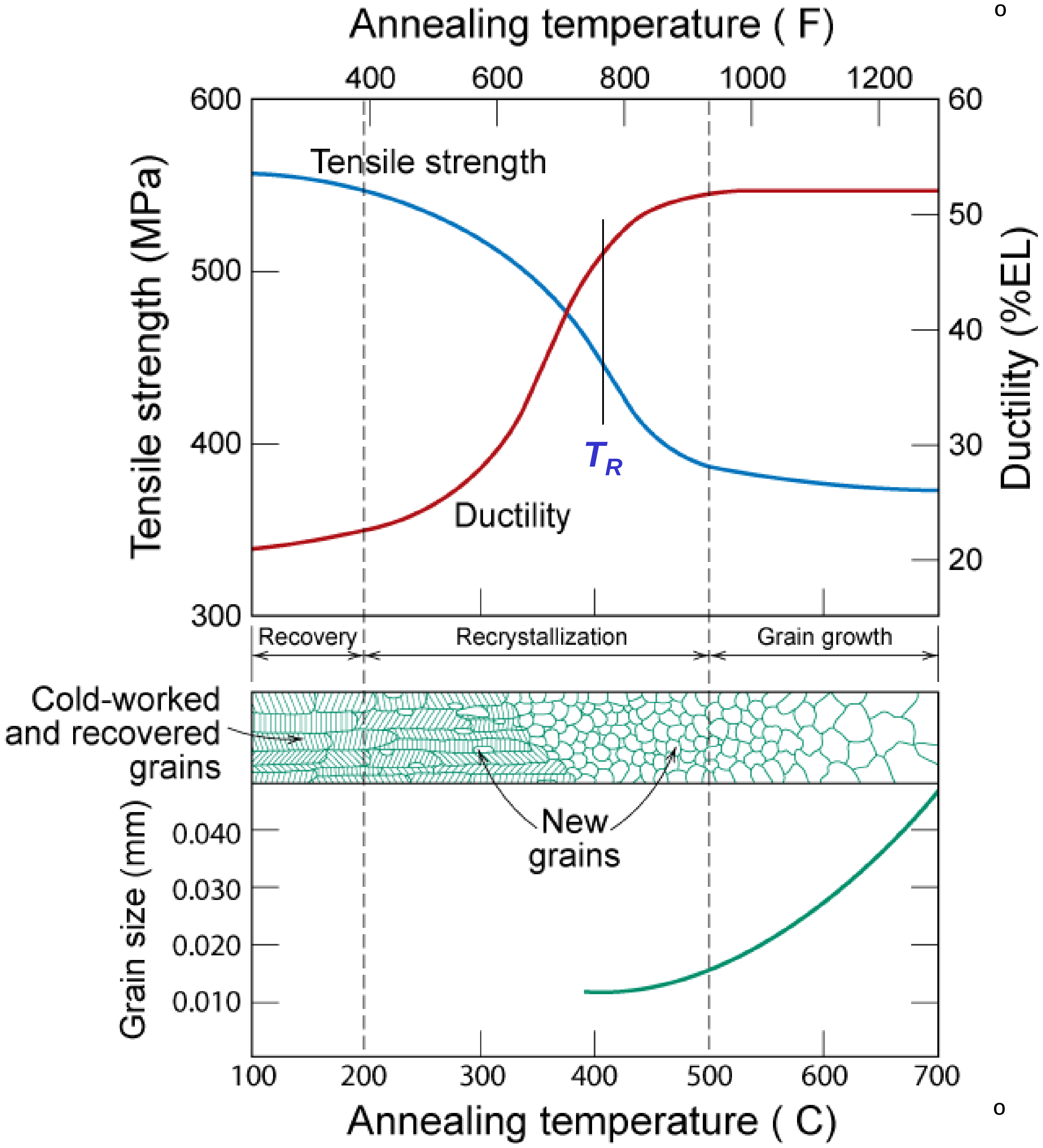
grain diam. at time t.

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

coefficient dependent on material and *T*.

elapsed time

Ostwald Ripening



T_R = recrystallization temperature

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

Recrystallization Temperature, T_R

T_R = recrystallization temperature = point of highest rate of property change

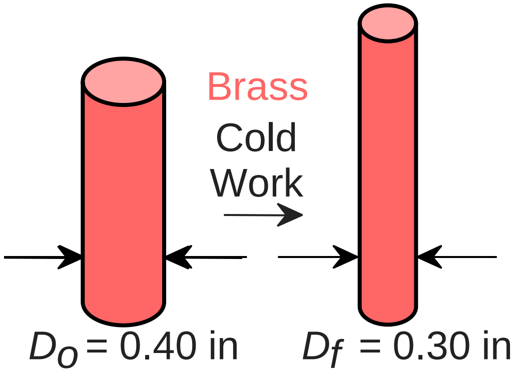
1. T_m => $T_R \approx 0.3\text{-}0.6\ T_m$ (K)
2. Due to diffusion → annealing time → $T_R = f(t)$
   shorter annealing time => higher T_R
3. Higher %CW => lower T_R – strain hardening
4. Pure metals lower T_R due to dislocation movements
   - Easier to move in pure metals => lower T_R

Coldwork Calculations

A cylindrical rod of brass originally 0.40 in (10.2 mm) 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 55,000 psi (380 MPa) and a ductility of at least 15 %*EL* are desired. Further more, the final diameter must be 0.30 in (7.6 mm). Explain how this may be accomplished.

Coldwork Calculations Solution

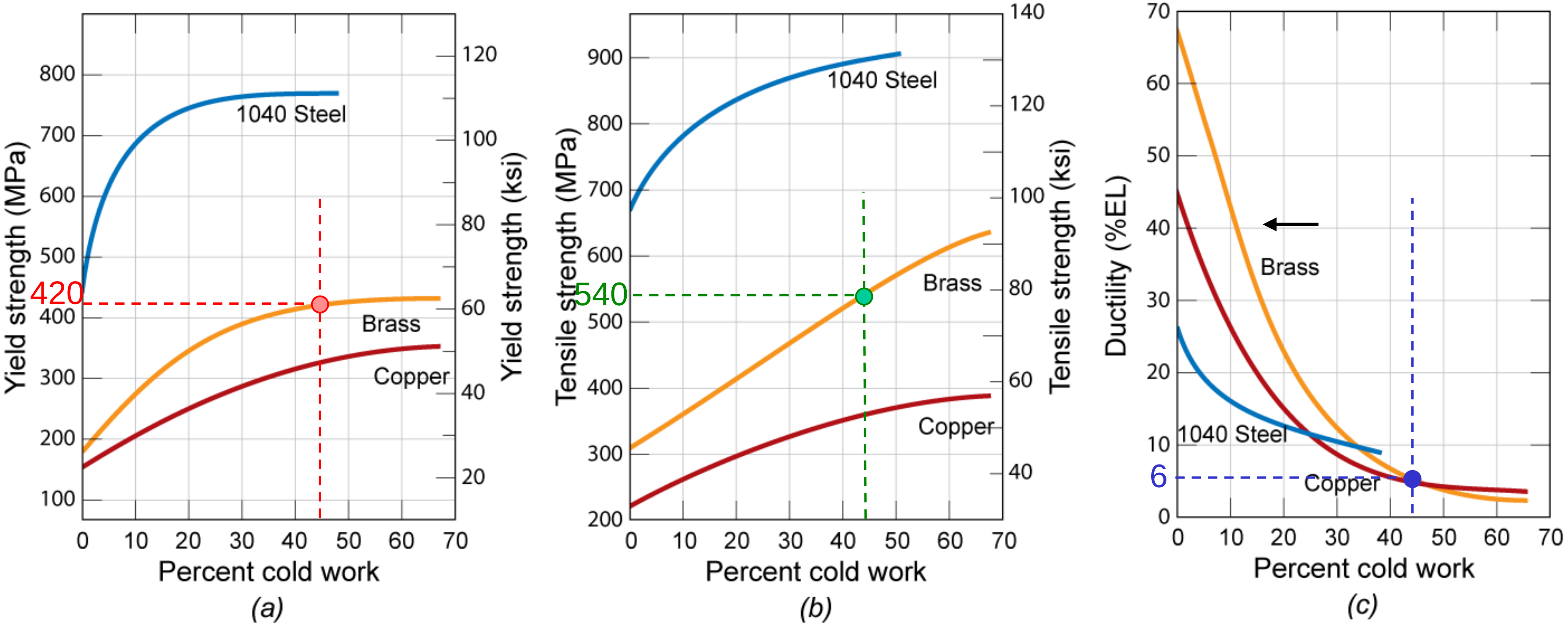
If we directly draw to the final diameter what happens?



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

$$= \left(1 - \frac{\pi D_f^2/4}{\pi D_o^2/4}\right) x\,100 = \left(1 - \left(\frac{0.30}{0.40}\right)^2\right) x\,100 = 43.8\%$$

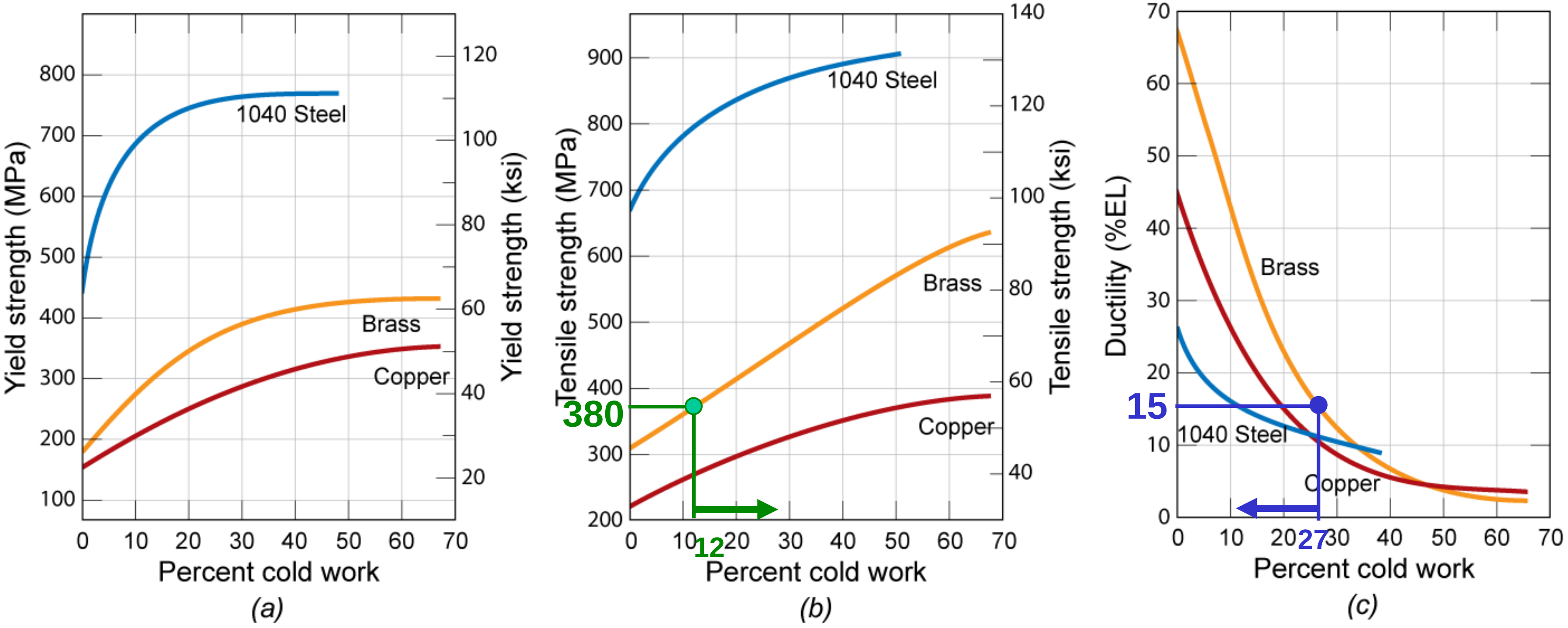
Coldwork Calc Solution: Cont.



Adapted from Fig. 7.19, *Callister 7e.*

- For %*CW* = 43.8%
  - σ_y = 420 MPa
  - *TS* = 540 MPa > 380 MPa
  - %*EL* = 6 < 15
- This doesn't satisfy criteria…… what can we do?

Coldwork Calc Solution: Cont.



Adapted from Fig. 7.19, *Callister 7e.*

For *TS* > 380 MPa → > 12 %*CW*

For %*EL* < 15 → < 27 %*CW*

∴ our working range is limited to %*CW* = 12-27

Coldwork Calc Soln: Recrystallization

Cold draw-anneal-cold draw again

- For objective we need a cold work of $\%CW \cong$ 12-27
  - We'll use $\%CW = 20$
- Diameter after first cold draw (before 2nd cold draw)?
  - must be calculated as follows:

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

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

Intermediate diameter = $D_{f1} = D_{02} = 0.30 \Big/ \left(1 - \frac{20}{100}\right)^{0.5} = \underline{\underline{0.335\,\text{m}}}$

Coldwork Calculations Solution

Summary:

1. Cold work D_{01}= 0.40 in → D_{f1} = 0.335 m

$$\%CW_1 = \left(1 - \left(\frac{0.335}{0.4}\right)^2\right) x\,100 = 30$$

2. Anneal above $D_{02} = D_{f1}$
3. Cold work D_{02}= 0.335 in → D_{f2} =0.30 m

$$\%CW_2 = \left(1 - \left(\frac{0.3}{0.335}\right)^2\right) x\,100 = 20$$

Fig 7.19 $\Rightarrow$

$$\sigma_y = 340\,\text{MPa}$$
$$TS = 400\,\text{MPa}$$
$$\%EL = 24$$

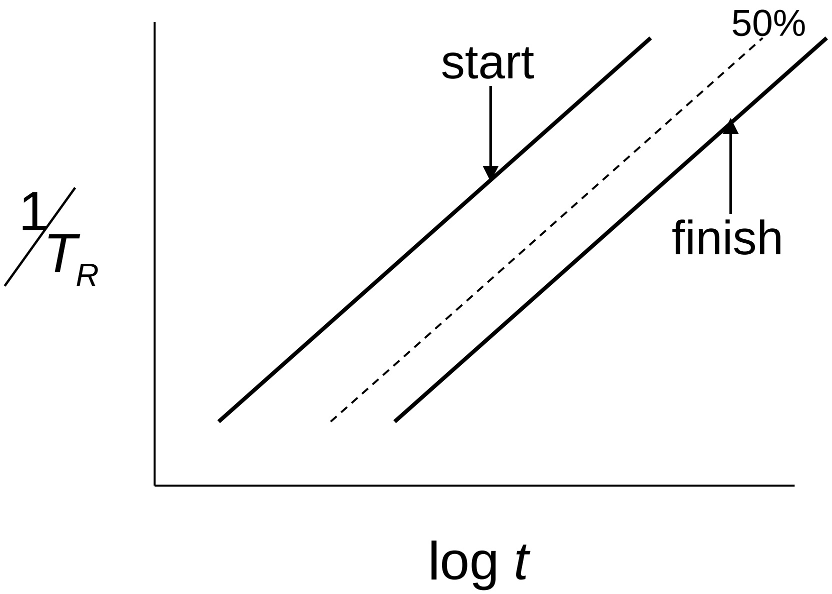
Therefore, meets all requirements

Rate of Recrystallization

$$\log R = -\log t = \log R_0 - \frac{E}{kT}$$

$$\log t = C + \frac{B}{T}$$

$$\text{note}: R = 1/\,t$$



- Hot work → above T_R
- Cold work → below T_R
- Smaller grains
  - – stronger at low temperature
  - – weaker at high temperature

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.

ANNOUNCEMENTS

Reading:

Core Problems:

Self-help Problems: