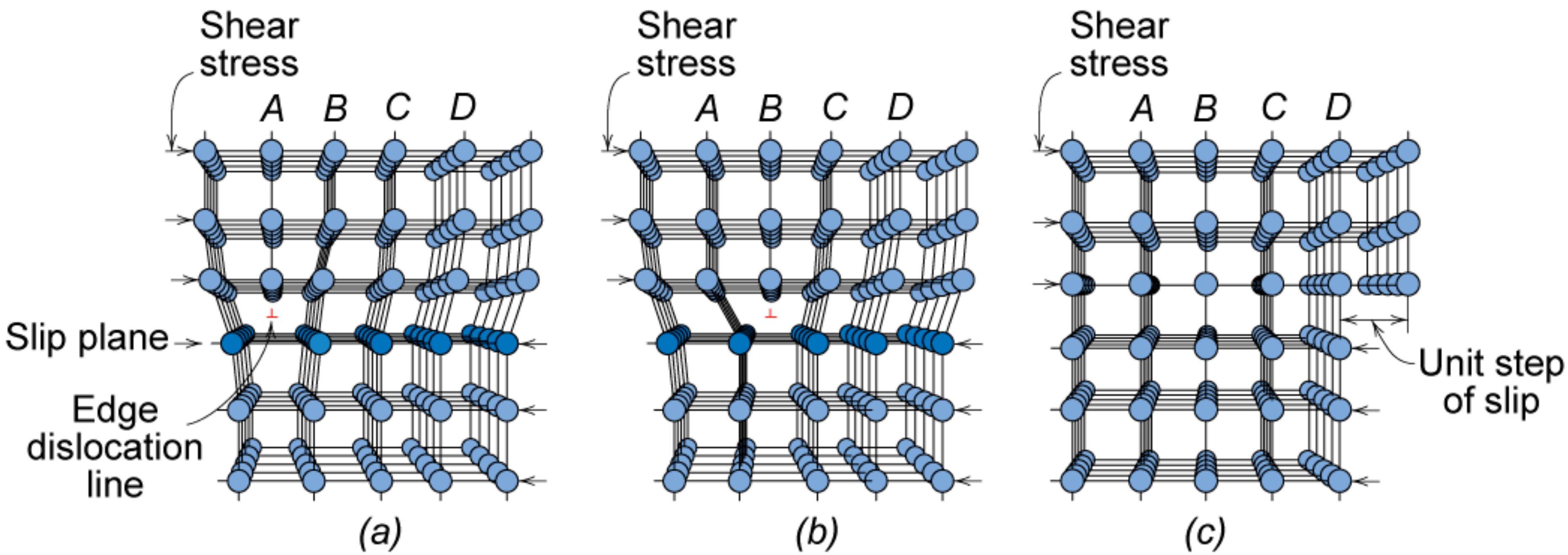
Chapter 7:
Dislocations & Strengthening Mechanisms

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).

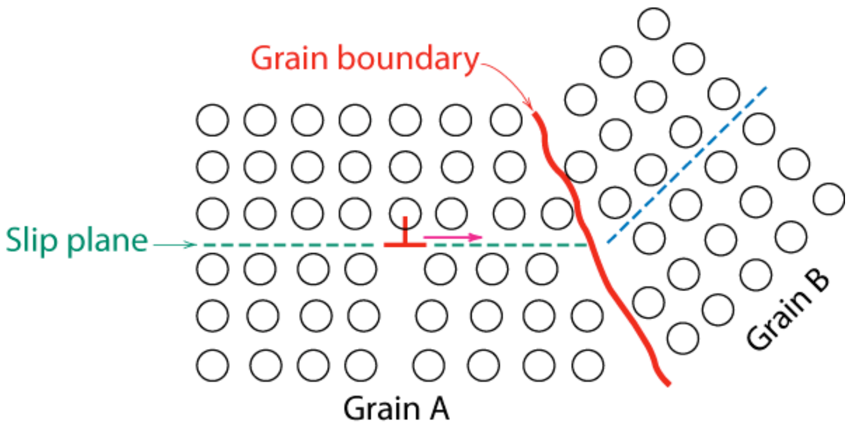


- If dislocations don't move, deformation doesn't occur!

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

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.)

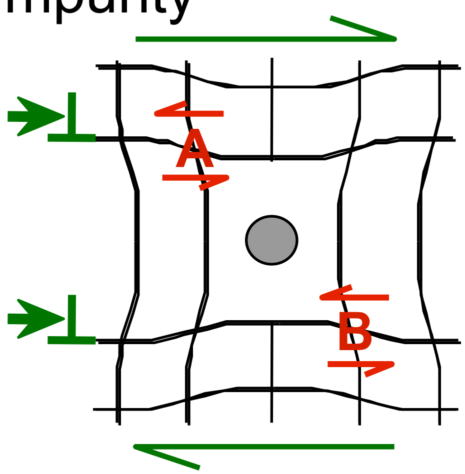
- Hall-Petch Equation:

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

4 Strategies for Strengthening: 2: Solid Solutions

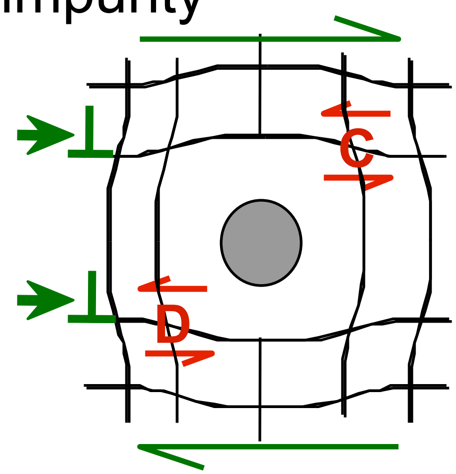
- Impurity atoms distort the lattice & generate stress.
- Stress can produce a barrier to dislocation motion.

- Smaller substitutional impurity



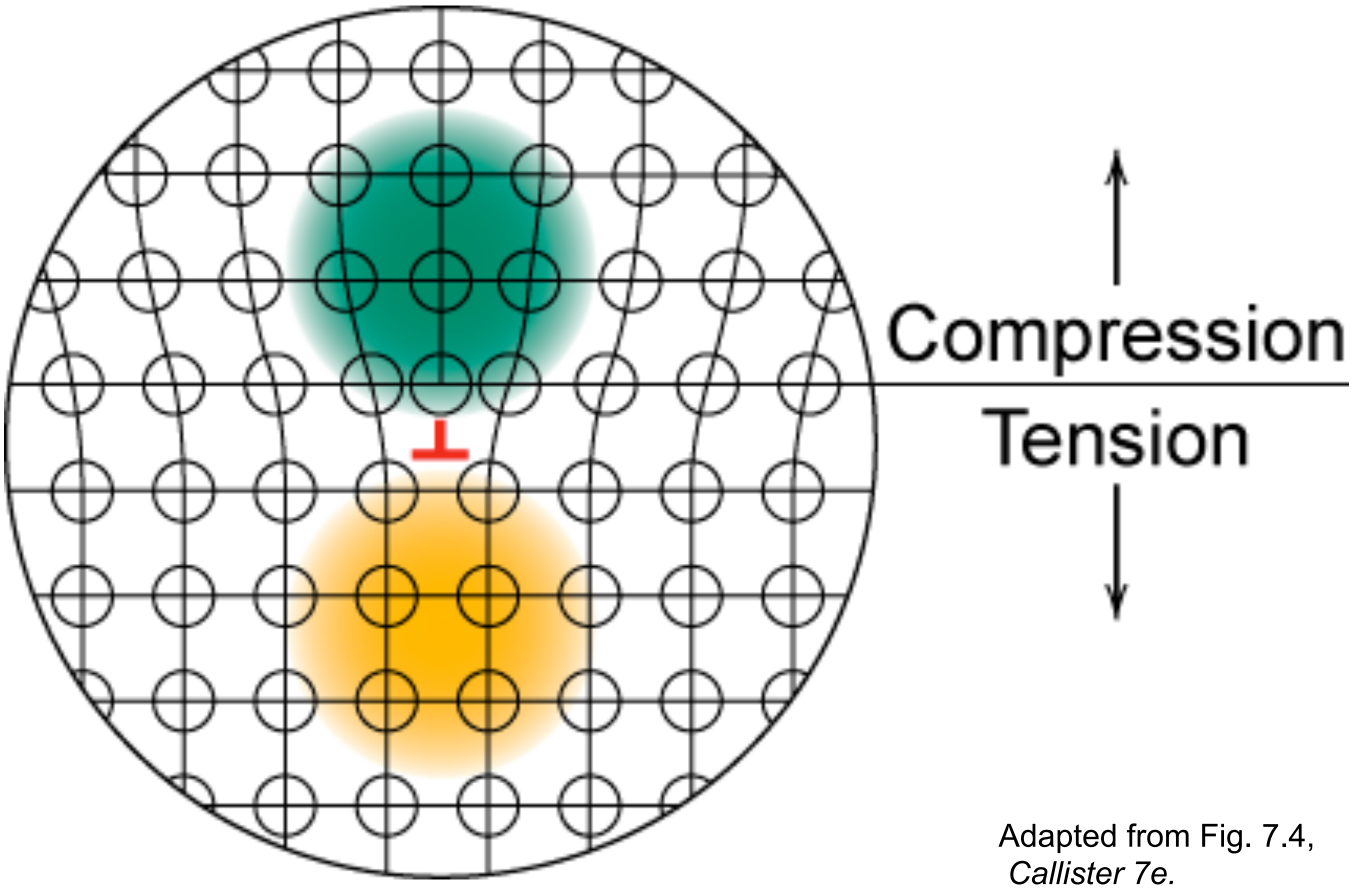
Impurity generates local stress at **A** and **B** that opposes dislocation motion to the right.

- Larger substitutional impurity



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

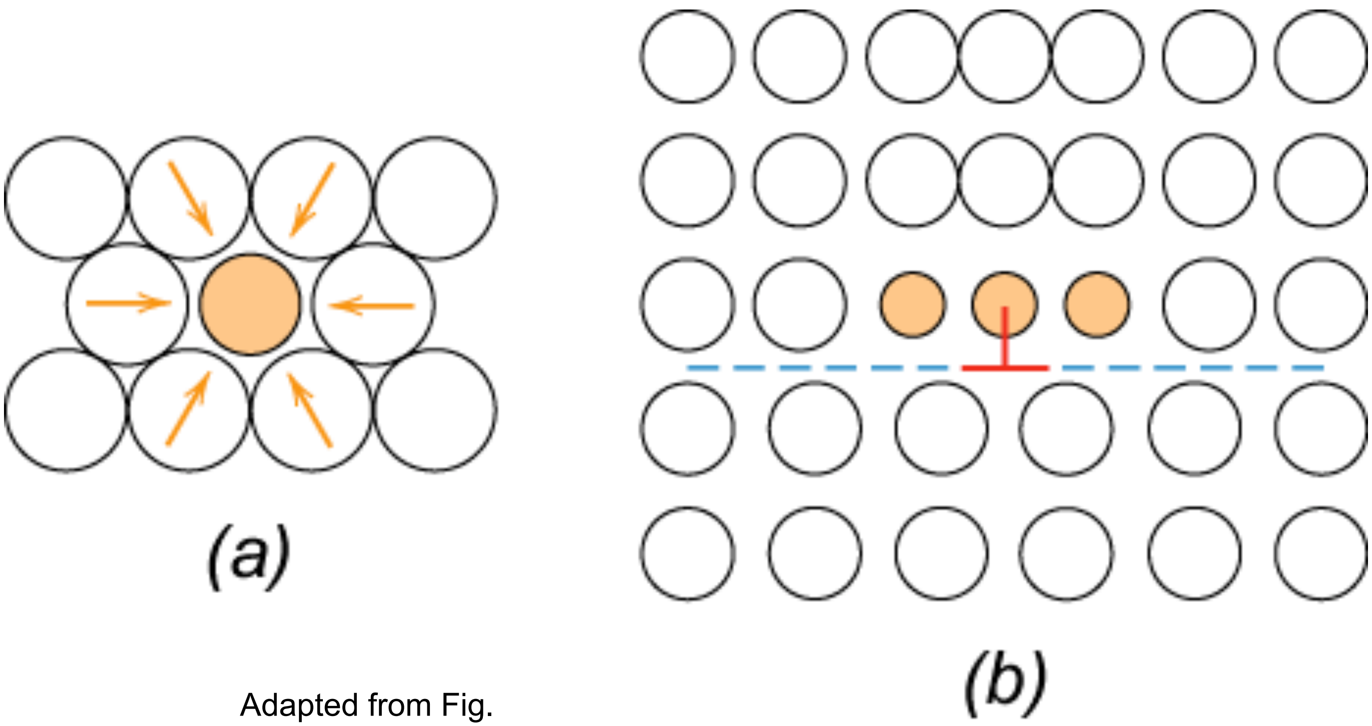
Stress Concentration at Dislocations



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

Strengthening by Alloying

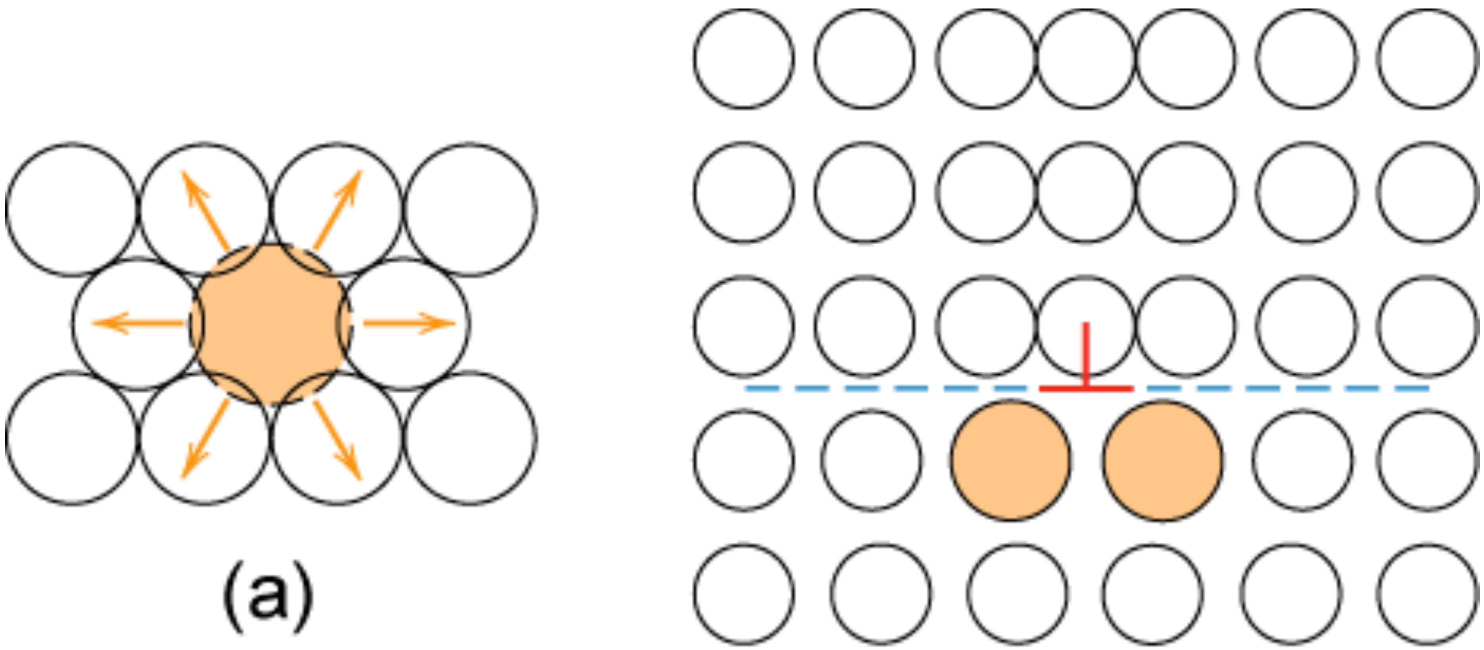
- small impurities tend to concentrate at dislocations
- reduce mobility of dislocation ∴ increase strength



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

Strengthening by alloying

- large impurities concentrate at dislocations on low density side

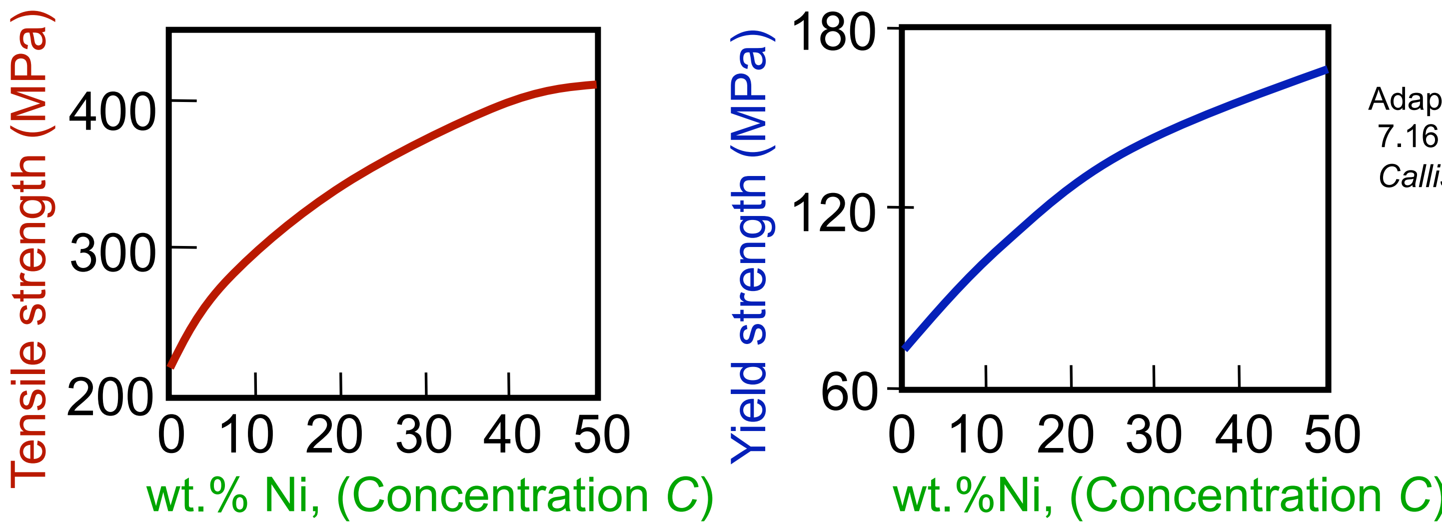


(a) (b)

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

Ex: Solid Solution Strengthening in Copper

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



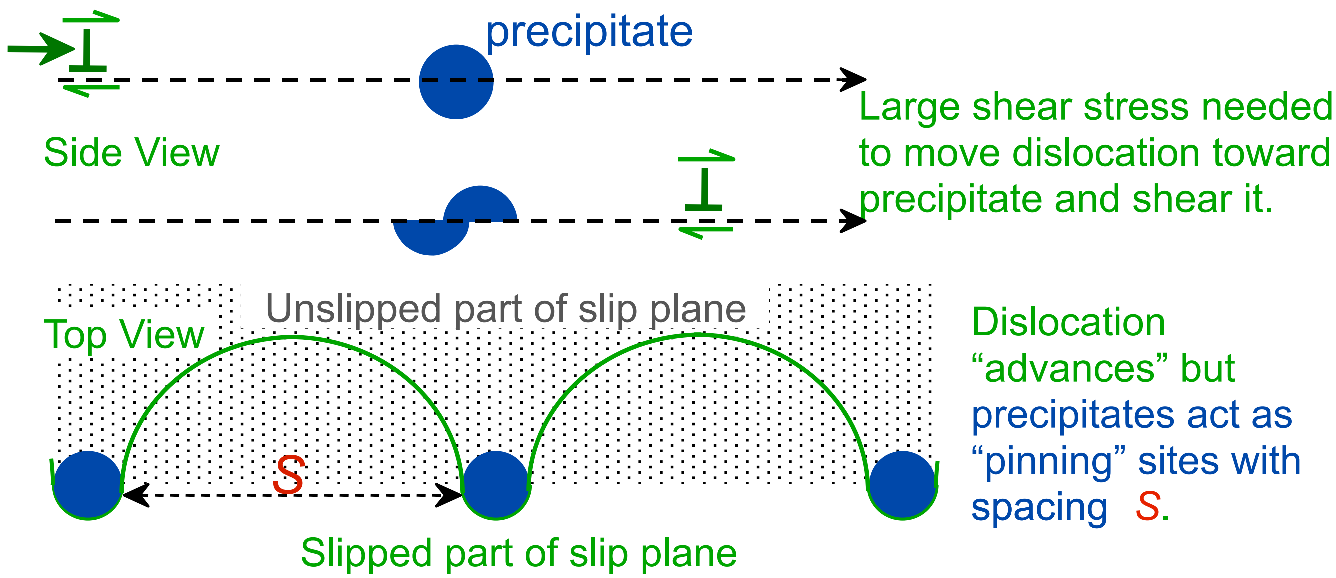
Adapted from Fig. 7.16 (a) and (b), *Callister 7e.*

- 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).



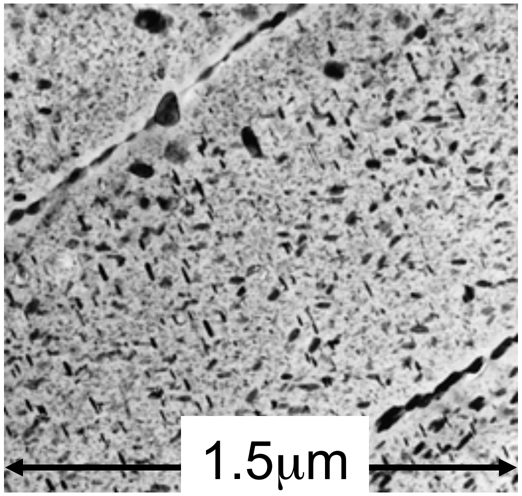
- Result: $\sigma_y \sim \dfrac{1}{S}$

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.)

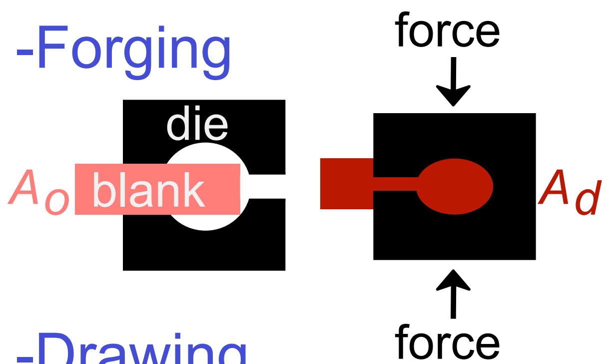
- Aluminum is strengthened with precipitates formed by alloying.

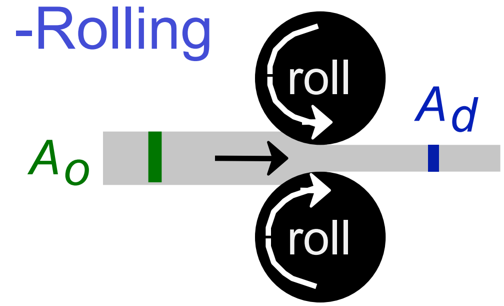


Adapted from Fig. 11.26, *Callister 7e.* (Fig. 11.26 is courtesy of G.H. Narayanan and A.G. Miller, Boeing Commercial Airplane Company.)

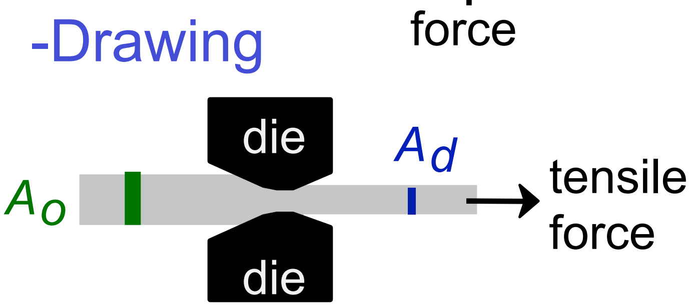
4 Strategies for Strengthening: 4: Cold Work (%*CW*)

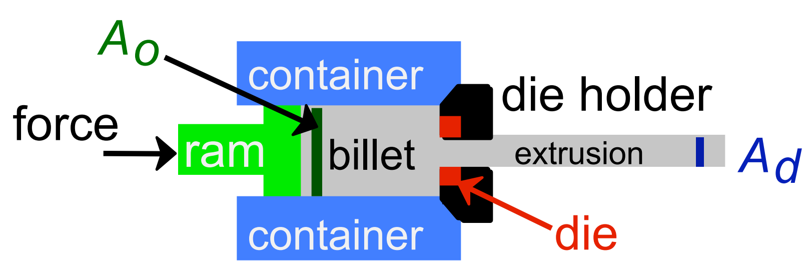
- Room temperature deformation.
- Common forming operations change the cross sectional area:





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

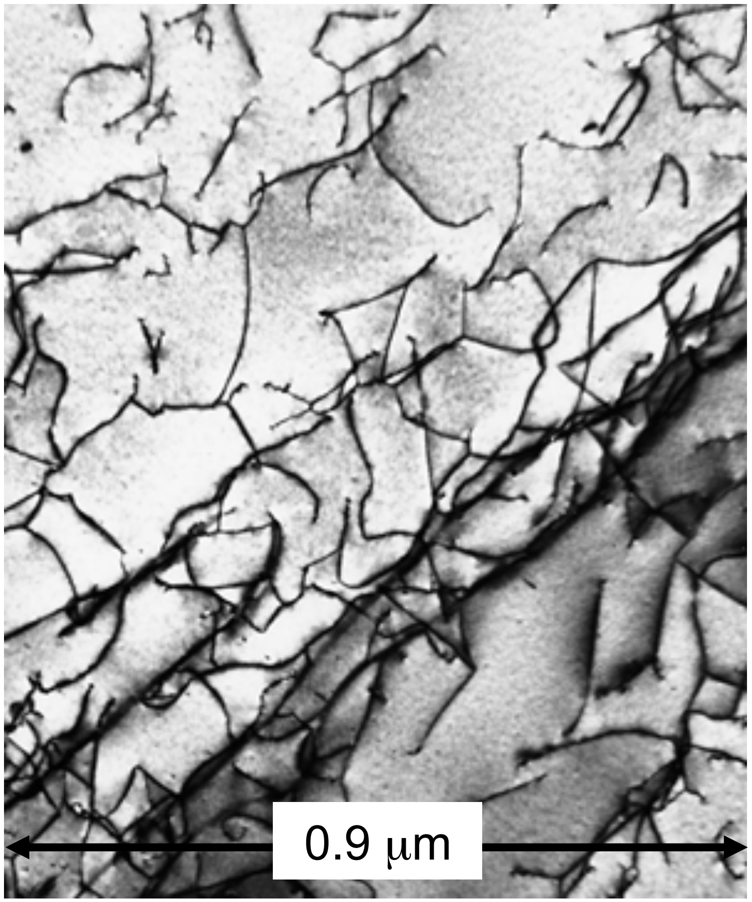




$$\%CW = \frac{A_o - A_d}{A_o} \times 100$$

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

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

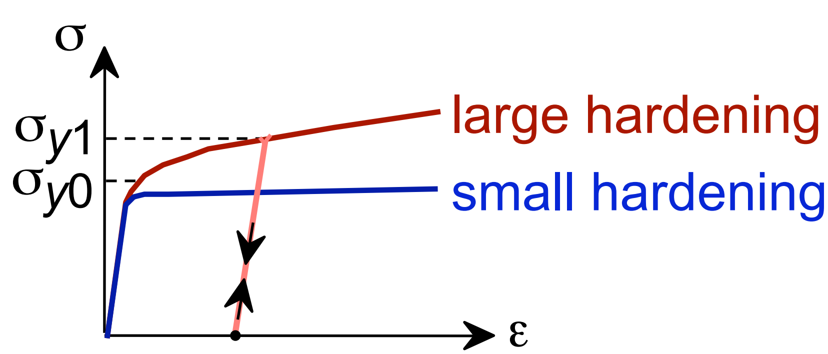
– Carefully grown single crystal

→ ca. 10^3 mm^{-2}

– Deforming sample increases density

→ 10^9-10^{10} mm^{-2}

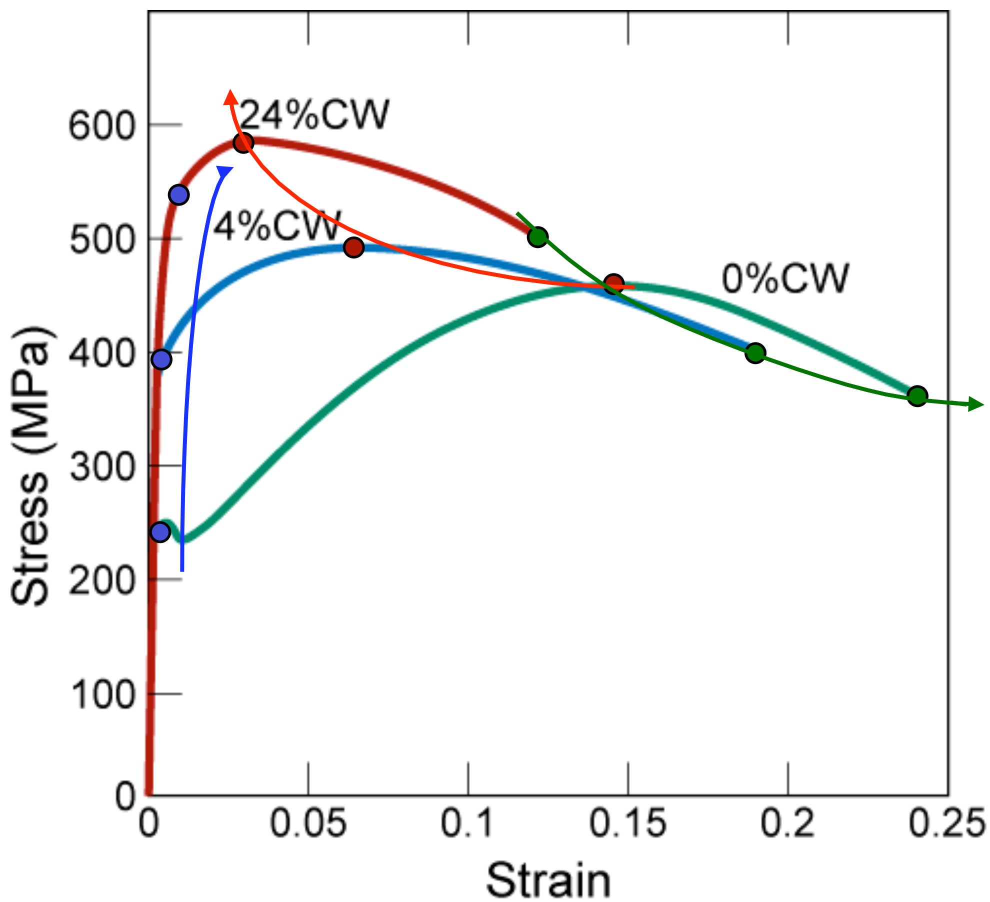
• Yield stress increases as ρ_d increases:



Impact of Cold Work

As cold work is increased

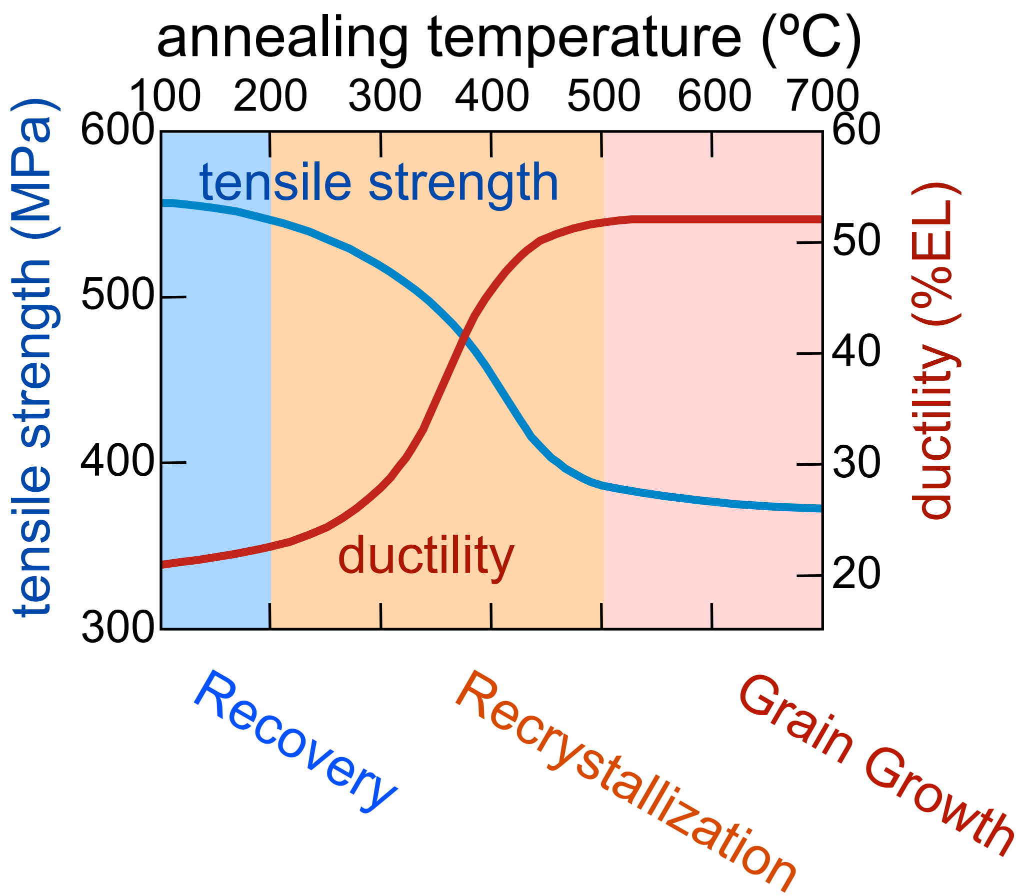
- Yield strength (σ_y) increases.
- Tensile strength (*TS*) increases.
- Ductility (*%EL* or *%AR*) decreases.



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...

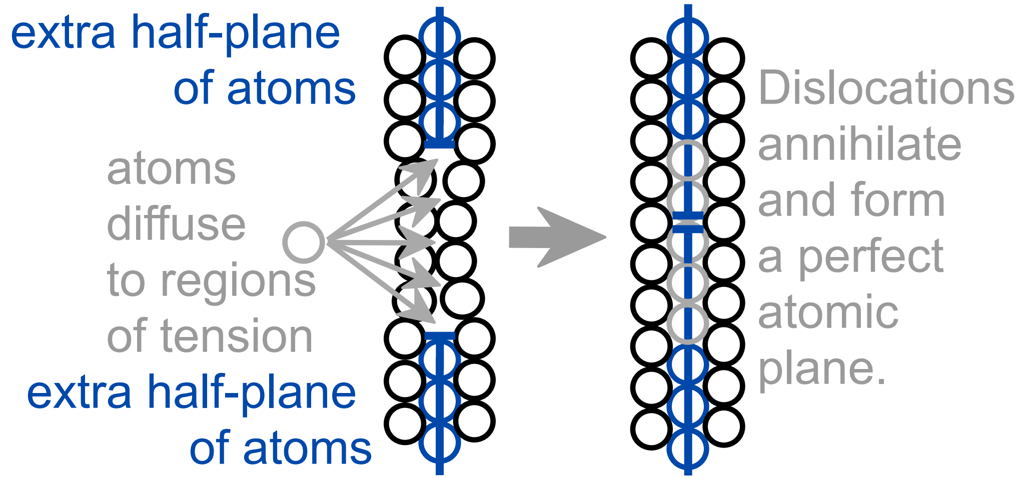
Adapted from Fig. 7.22, *Callister 7e.* (Fig. 7.22 is adapted from G. Sachs and K.R. van Horn, *Practical Metallurgy, Applied Metallurgy, and the Industrial Processing of Ferrous and Nonferrous Metals and Alloys*, American Society for Metals, 1940, p. 139.)

Recovery

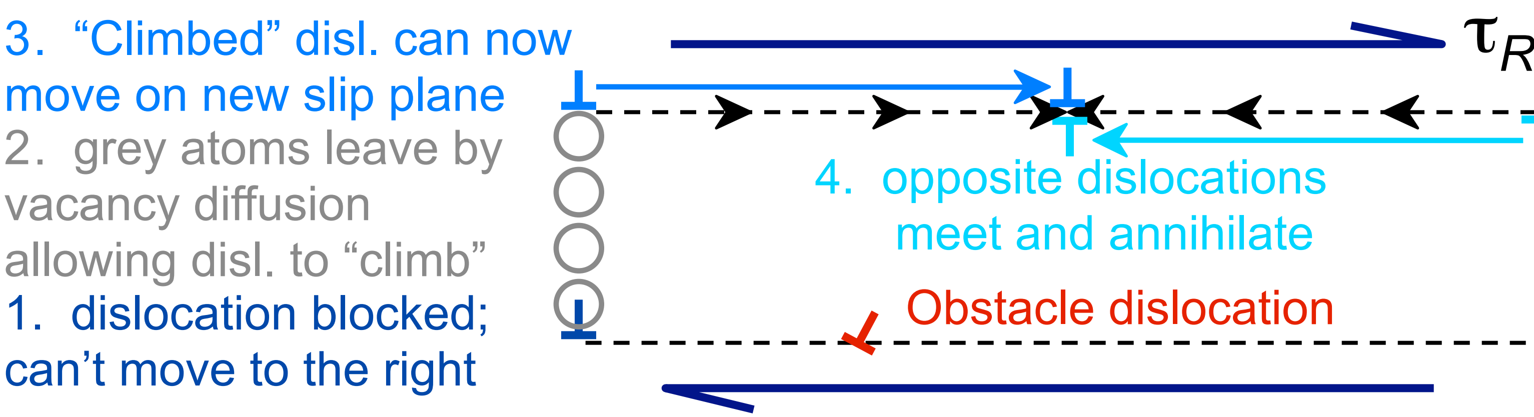
Annihilation reduces dislocation density.

- Scenario 1

  Results from diffusion

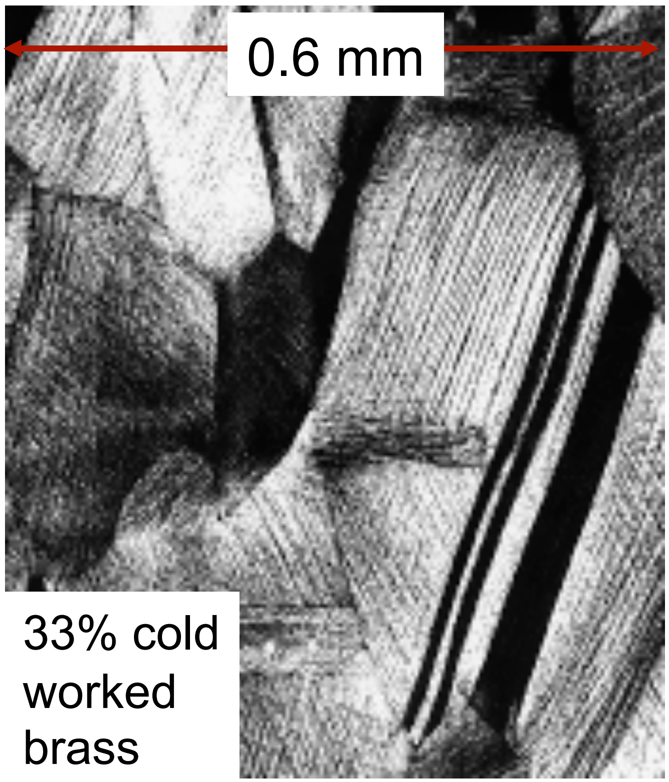


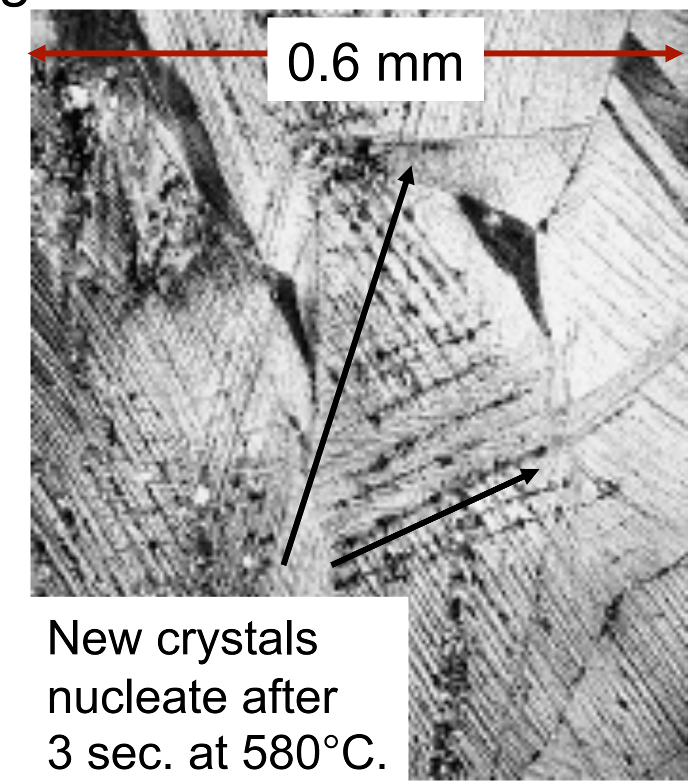
- Scenario 2



Recrystallization

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

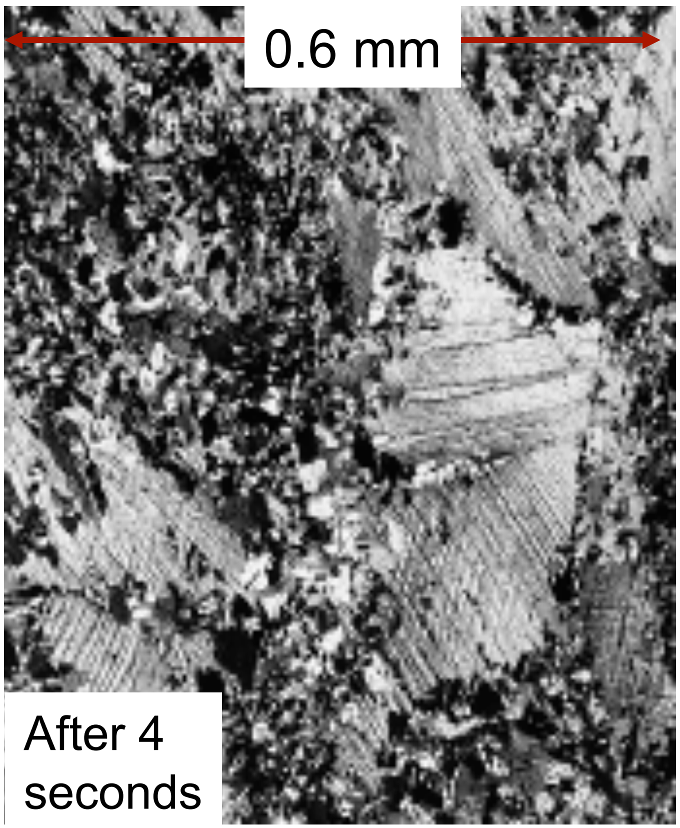


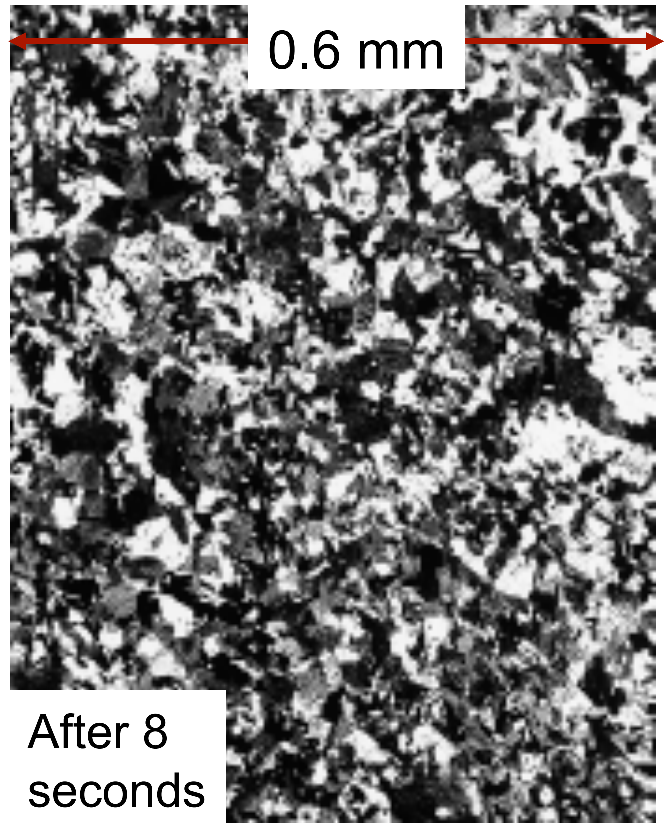


Adapted from Fig. 7.21 (a),(b), *Callister 7e.* (Fig. 7.21 (a),(b) are courtesy of J.E. Burke, General Electric Company.)

Further Recrystallization

- All cold-worked grains are consumed.

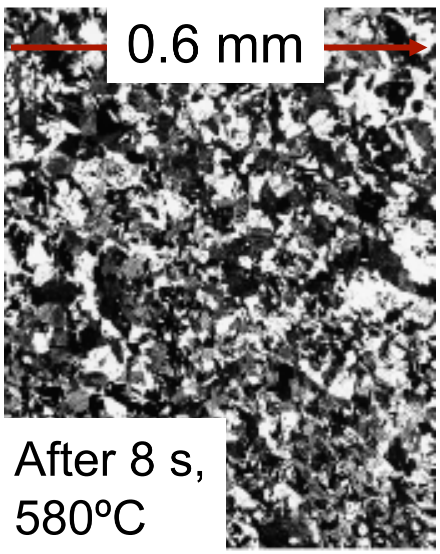


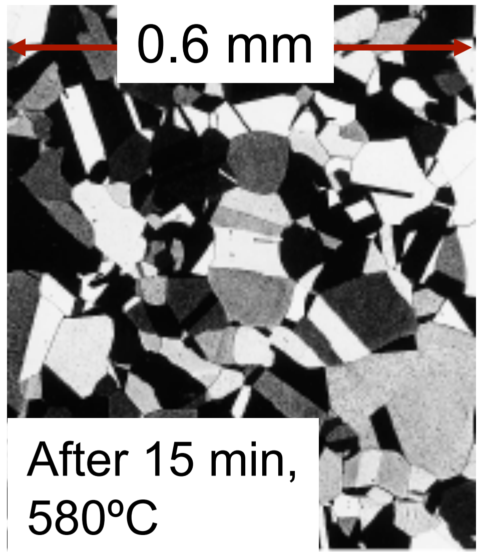


Adapted from Fig. 7.21 (c),(d), *Callister 7e.* (Fig. 7.21 (c),(d) are courtesy of J.E. Burke, General Electric Company.)

Grain Growth

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





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

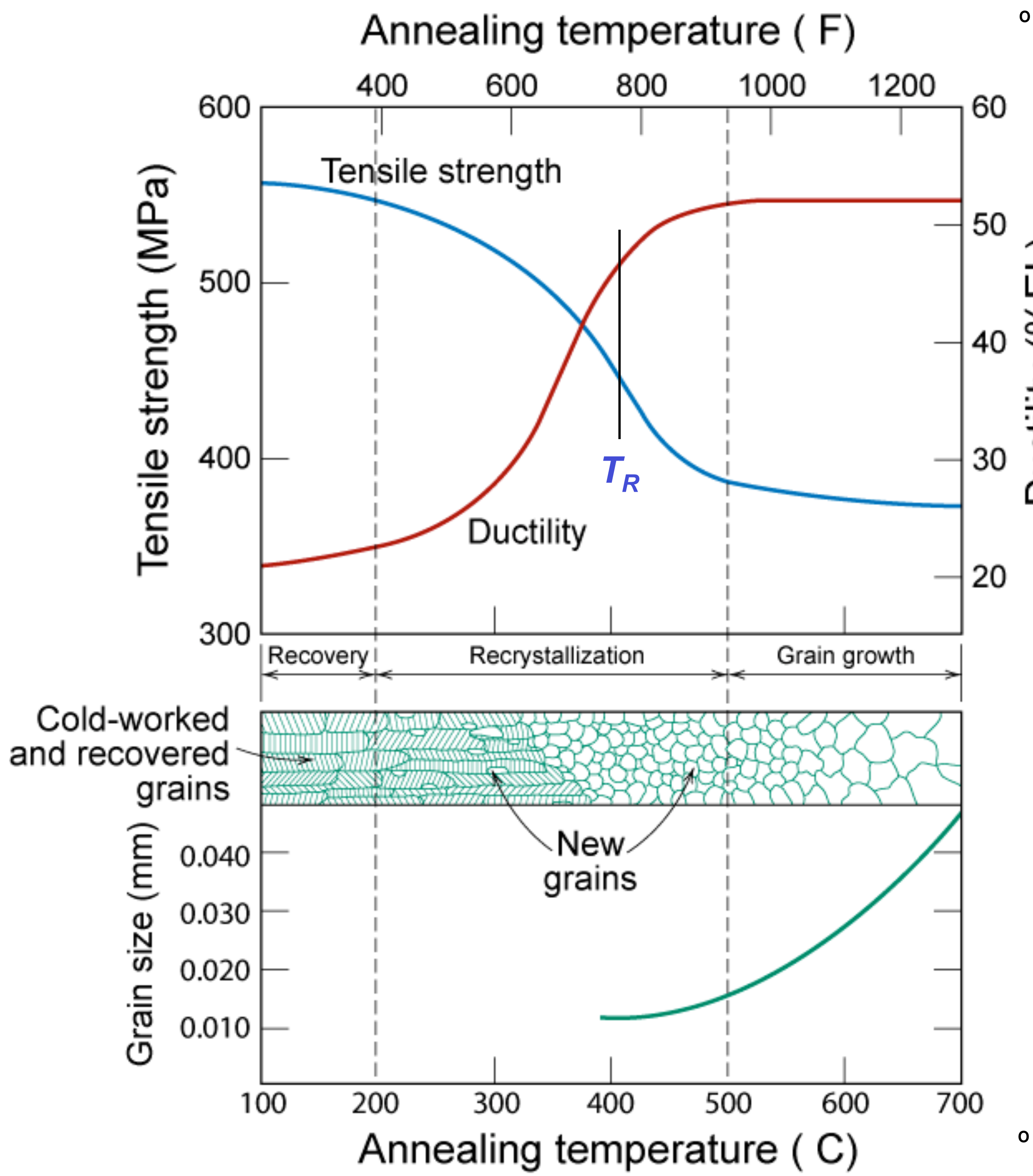
grain diam. at time t.

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

coefficient dependent on material and *T*.

elapsed time

Ostwald Ripening



T_R = recrystallization temperature

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

Summary

- 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.