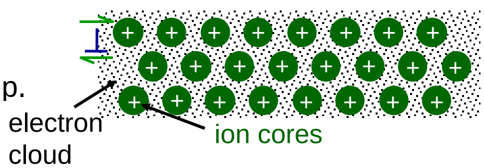
Dislocations & Strengthening Mechanisms

ISSUES TO ADDRESS...

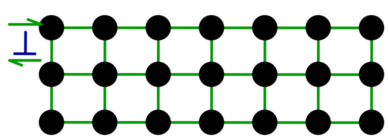
- **Why are dislocations observed primarily in metals and alloys?**
- **How are strength and dislocation motion related?**
- **How do we increase strength?**
- **How can heating change strength and other properties?**

Dislocations & Materials Classes

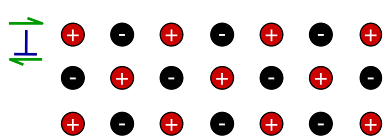
- Metals: Disl. motion easier.
  non-directional bonding
  close-packed directions for slip.



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



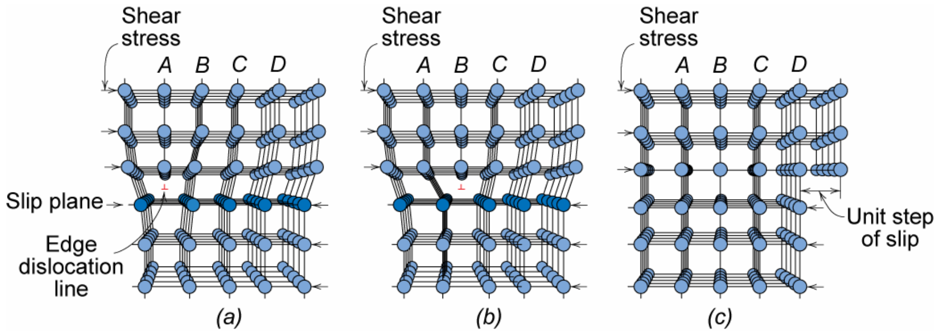
- Ionic Ceramics (NaCl):
  Motion hard.
  Need to avoid
  ++ and - - neighbors.



Dislocation Motion

Dislocations & plastic deformation

Cubic & hexagonal metals - plastic 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!

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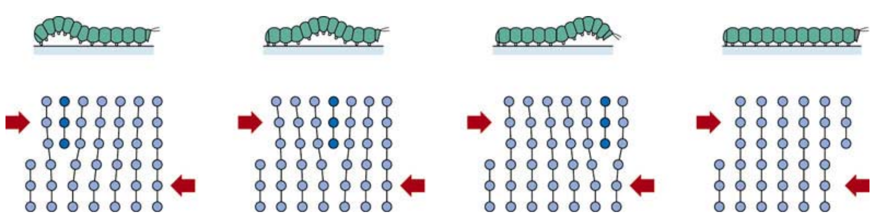
Deformation Mechanisms



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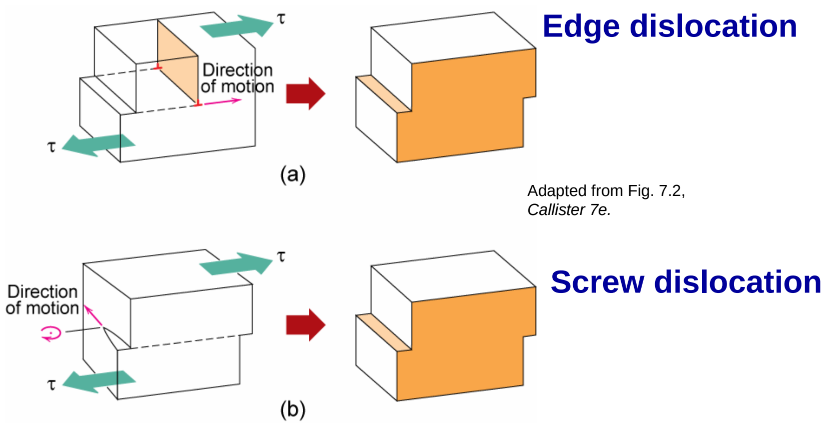
Dislocation Motion

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



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

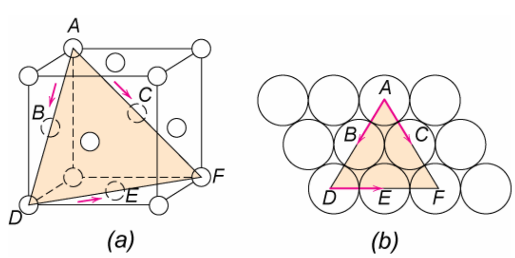
Deformation Mechanisms

Slip plane - plane allowing easiest slippage

Wide interplanar spacings - highest planar densities

Slip direction - direction of movement:

Highest linear densities



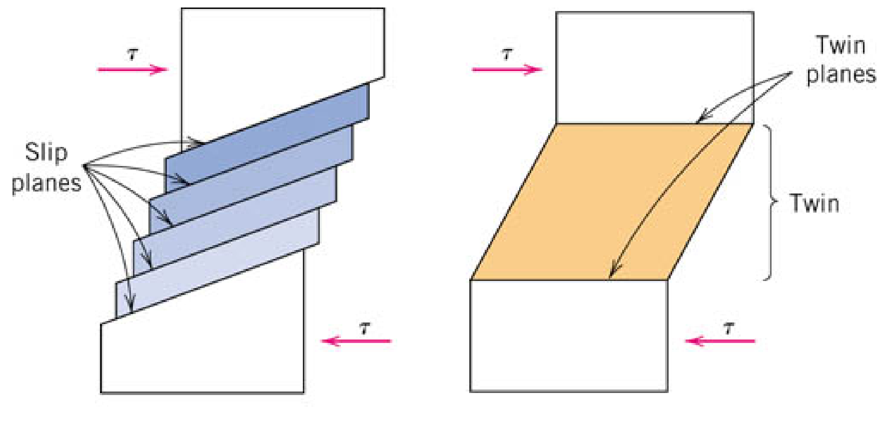
FCC (close-packed) Slip occurs on {111} planes in <110> directions

=> 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.



(a) (b)

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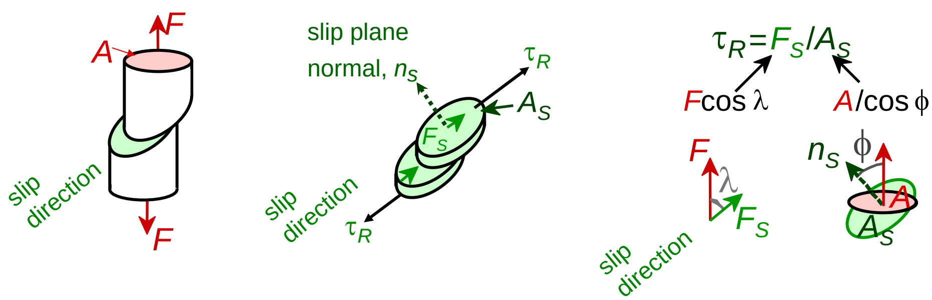
Stress and Dislocation Motion

- 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



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

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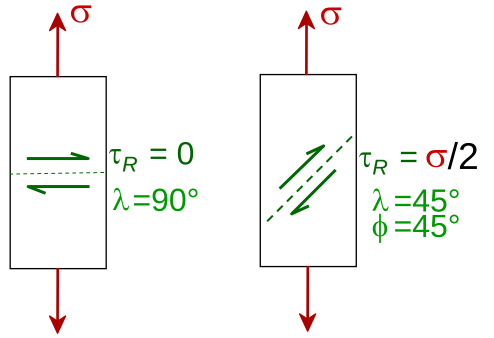
Critical Resolved Shear Stress

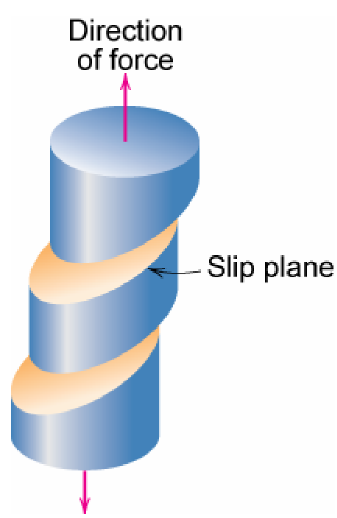
- Condition for dislocation motion: $\tau_R > \tau_{CRSS}$
  - typically 10^{-4} GPa to 10^{-2} GPa
- Crystal orientation can make it easy or hard to move dislocation

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

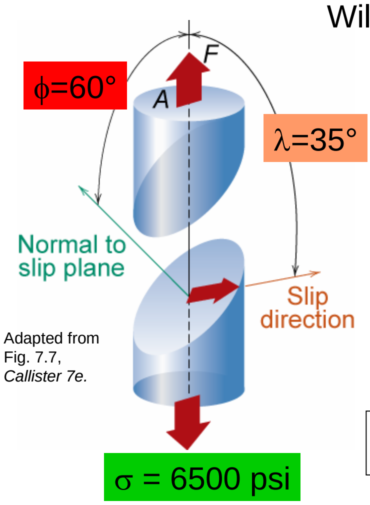


τ maximum at $\lambda = \phi = 45º$

Single Crystal Slip



Ex: Deformation of single crystal



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

Will the single crystal yield?

τ_{crss} = 3000 psi

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

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

$$\tau = (6500 \text{ psi})(\cos 35^\circ)(\cos 60^\circ)$$
$$= (6500 \text{ psi})(0.41)$$

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

So the applied stress of 6500 psi will not cause the crystal to yield.

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Ex: Deformation of single crystal

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

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

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

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

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

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Slip Motion in Polycrystals

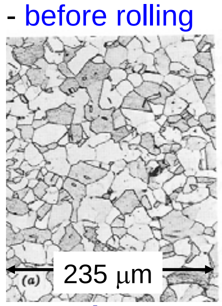
- Stronger - grain boundaries pin deformations
- Slip planes & directions (λ, ϕ) change from one crystal to another.
- τ_R will vary from one crystal to another.
- The crystal with the largest τ_R yields first.
- Other (less favorably oriented) crystals yield later.

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

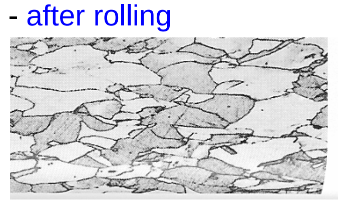
- before rolling



isotropic

since grains are approx. spherical & randomly oriented.

- after rolling



rolling direction

anisotropic

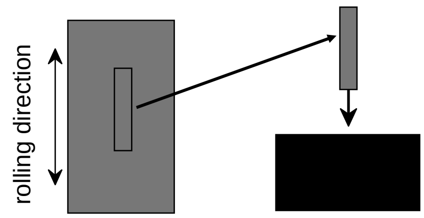
since rolling affects grain orientation and shape.

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.

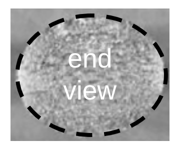
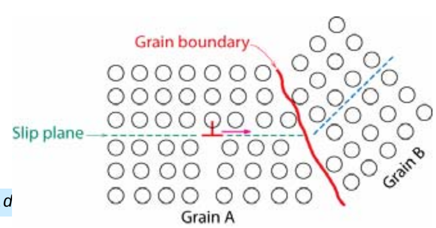


plate thickness direction

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

Four Strategies for Strengthening: 1: Reduce Grain Size

- Grain boundaries are barriers to slip.
- Barrier "strength" increases with Increasing angl $\sigma_{yield} = \sigma_o + k_y d$ mis-orientation.
- Smaller grain size: more barriers to slip.



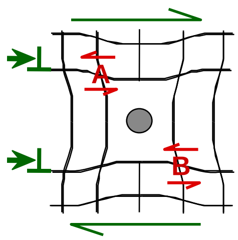
Adapted from Fig. 7.14, *Callister 7e.*
(Fig. 7.14 is from *A Textbook of Materials Technology*, by Van Vlack, Pearson Education, Inc., Upper Saddle River, NJ.)

- Hall-Petch Equation:

Four Strategies for Strengthening: 2: Solid Solutions

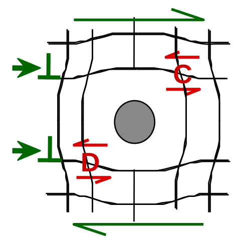
- Impurity atoms distort the lattice & generate stress.
- Stress can produce a barrier to dislocation motion.

- 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.

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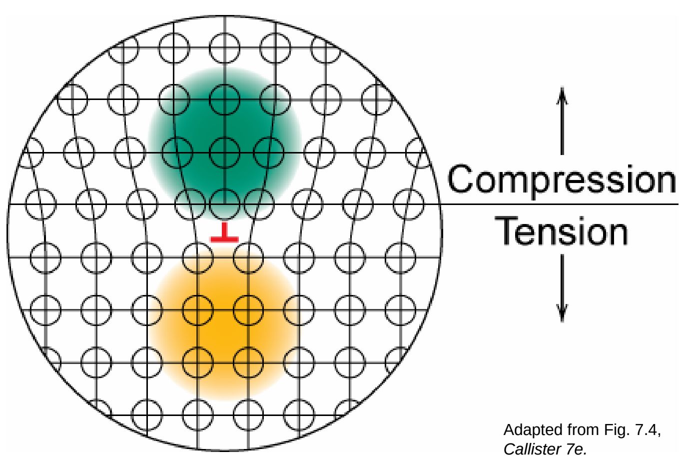
Stress Concentration at Dislocations



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

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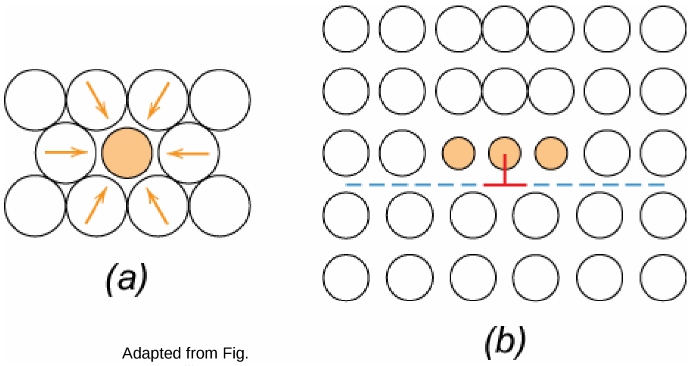
Strengthening by Alloying

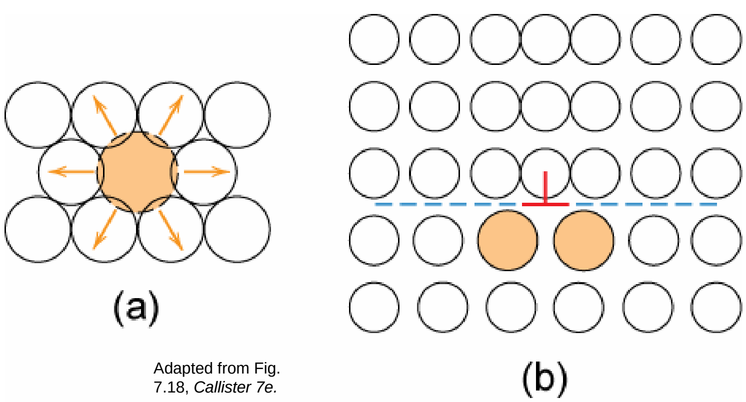
- small impurities tend to concentrate at dislocations
- reduce mobility of dislocation ∴ increase strength



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

Strengthening by alloying

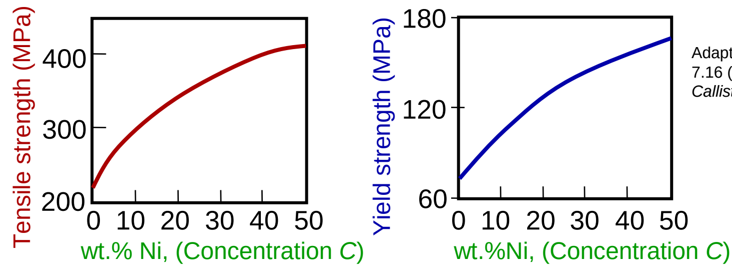
- large impurities concentrate at dislocations on low density side



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

Example: Solid Solution Strengthening in Copper

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

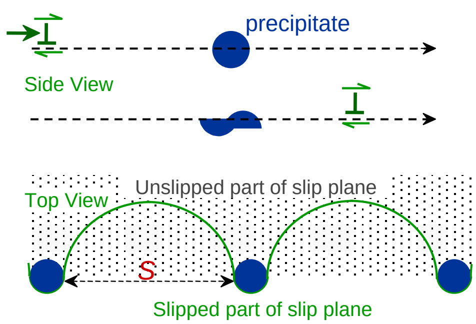


Adapted from Fig. 7.16 (a) and (b), *Callister 7e.*

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

Four Strategies for Strengthening: 3: Precipitation Strengthening

- Hard precipitates are difficult to shear.
  e.g., 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

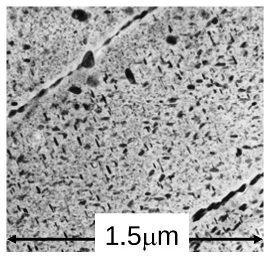
- Result: $\sigma_y \sim \frac{1}{S}$

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.)

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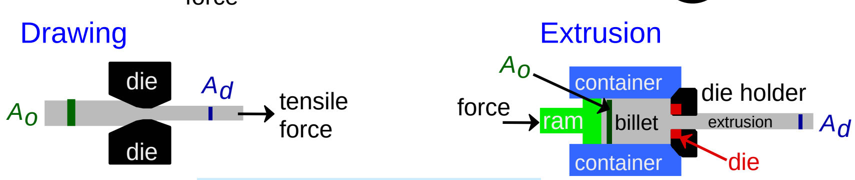
Four Strategies for Strengthening:
4: Cold Work (%*CW*)

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



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

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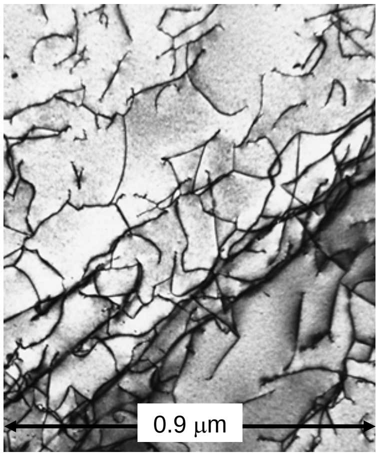
Dislocations During Cold Work

• 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.)

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Result of Cold Work

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

Carefully grown single crystal

→ ca. 10^3 mm^{-2}

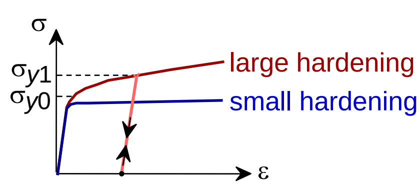
Deforming sample increases density

→ 10^9-10^{10} mm^{-2}

Heat treatment reduces density

→ 10^5-10^6 mm^{-2}

• Yield stress increases as ρ_d increases:



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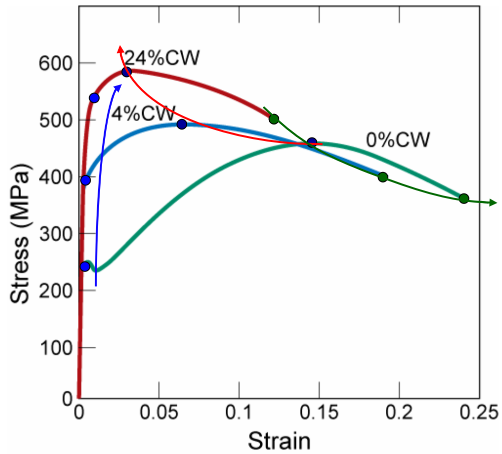
Impact of Cold Work

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.*

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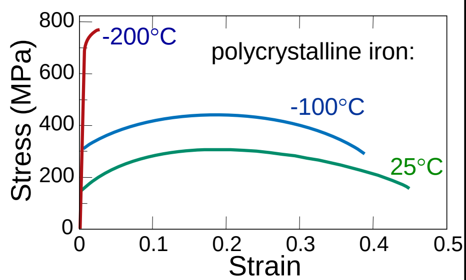
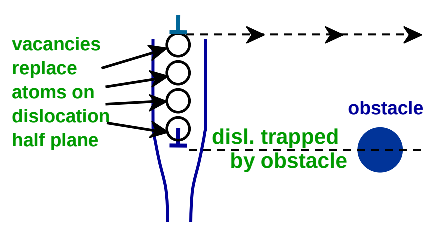
σ-ε Behavior vs. Temperature

- σ_y and *TS* *decrease* with increasing test temperature.
- %*EL* *increases* with increasing test temperature.



Why?

Temp. increases vacancies; Vacancies help dislocations move past obstacles.



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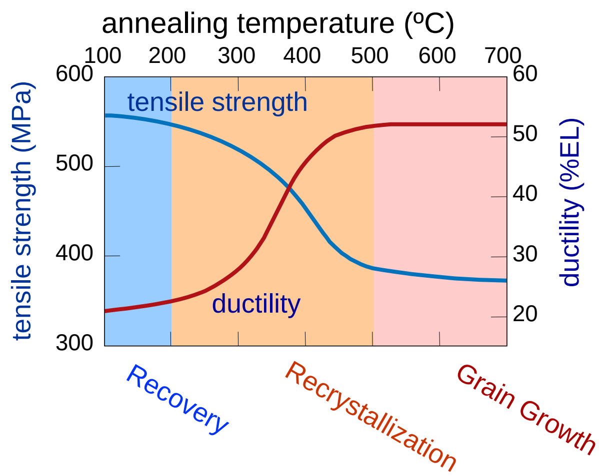
Effect of Heating After *Cold Work*

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



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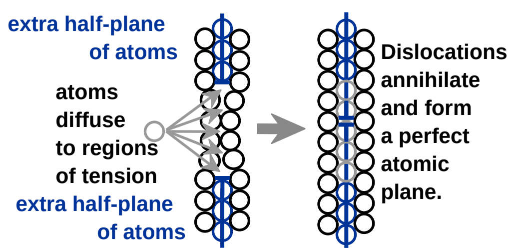
Recovery

Annihilation reduces dislocation density.

Results from diffusion



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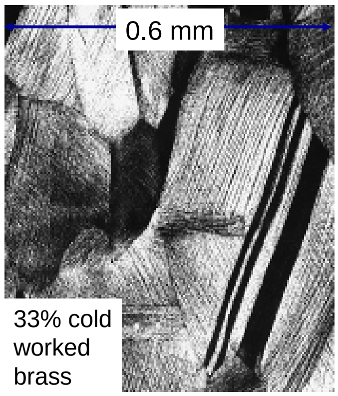
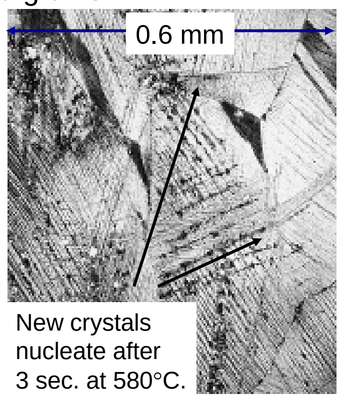
Recrystallization

- 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.)

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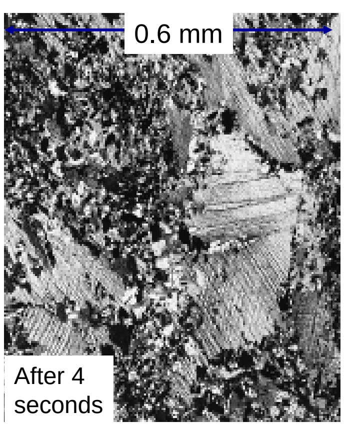
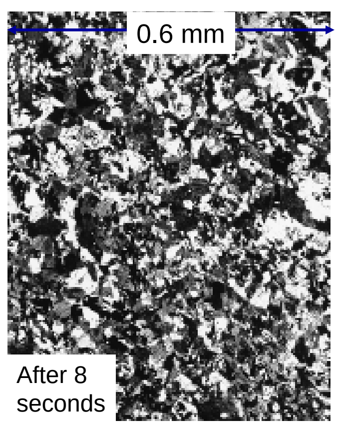
Further Recrystallization

- 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.)

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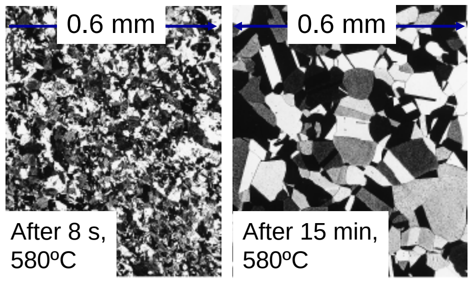
Grain Growth

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



- 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

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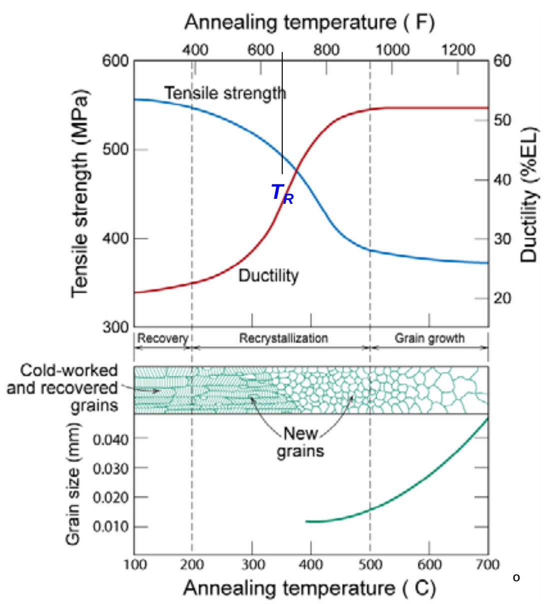
Grain Growth



T_R = recrystallization temperature

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

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Recrystallization Temperature, T_R

T_R = recrystallization temperature

= point of highest rate of property change

T_m => $T_R \approx$ 0.3-0.6 T_m (K)

Due to diffusion → annealing time→ T_R = f(t)

shorter annealing time => higher T_R

Higher %*CW* => lower T_R – strain hardening

Pure metals lower T_R due to dislocation movements

Easier to move in pure metals => lower T_R

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Recrystallization Temperature, T_R

Metal	*Recrystallization Temperature* °C	*Recrystallization Temperature* °F	*Melting Temperature* °C	*Melting Temperature* °F
Lead	−4	25	327	620
Tin	−4	25	232	450
Zinc	10	50	420	788
Aluminum (99.999 wt%)	80	176	660	1220
Copper (99.999 wt%)	120	250	1085	1985
Brass (60 Cu–40 Zn)	475	887	900	1652
Nickel (99.99 wt%)	370	700	1455	2651
Iron	450	840	1538	2800
Tungsten	1200	2200	3410	6170

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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.

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