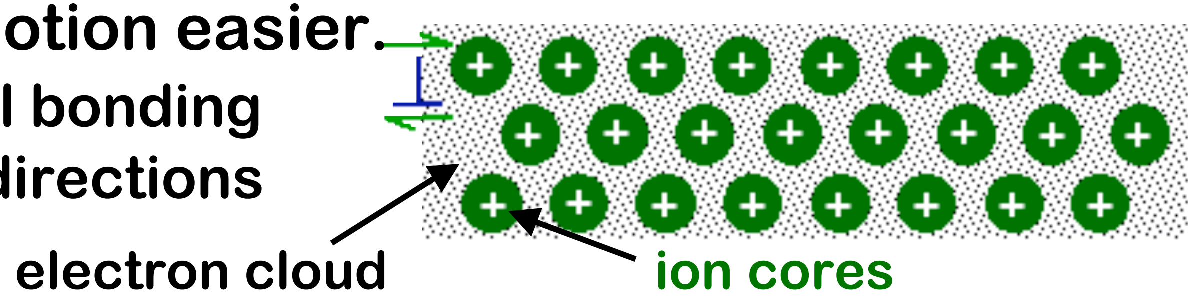
CHAPTER 7:
DISLOCATIONS AND STRENGTHENING

ISSUES TO ADDRESS...

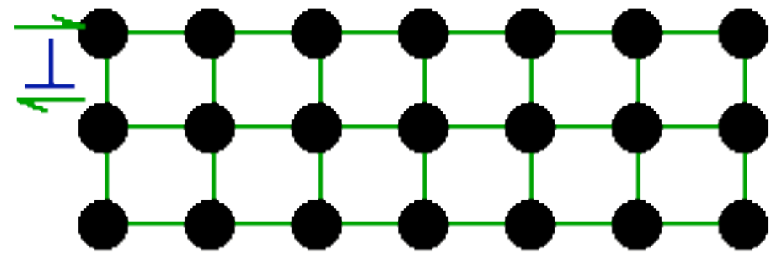
- **Why are dislocations observed primarily in metals and alloys?**
- **How are strength and dislocation motion related?**
- **How do we increase strength?**
- **How can heating change strength and other properties?**

DISLOCATIONS & MATERIALS CLASSES

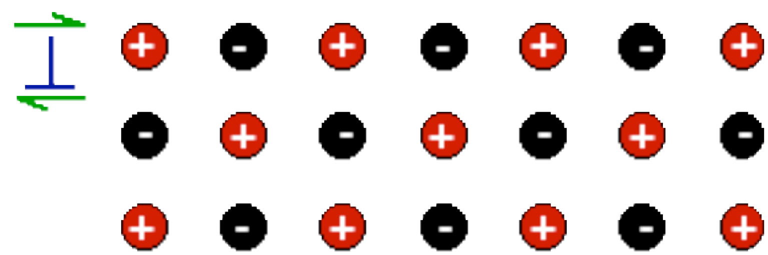
- **Metals: Disl. motion easier.**
  - -non-directional bonding
  - -close-packed directions for slip.



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

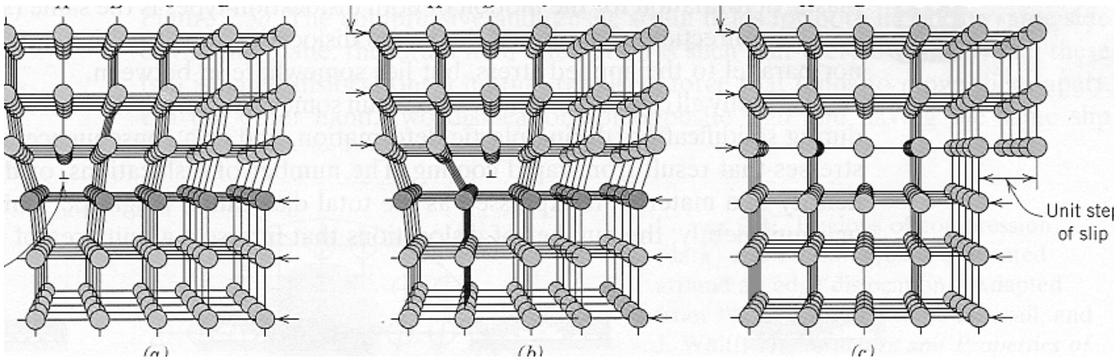


- **Ionic Ceramics (NaCl): Motion hard.**
  - -need to avoid ++ and -- neighbors.



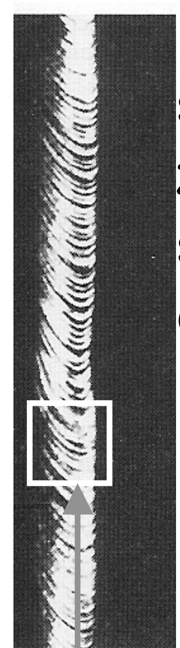
DISLOCATION MOTION

- Produces plastic deformation,
- Depends on incrementally breaking bonds.



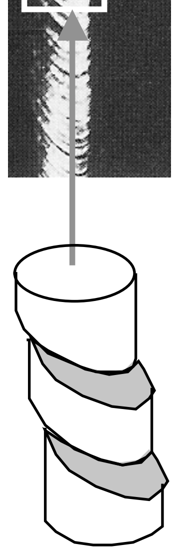
Adapted from Fig. 7.1, *Callister 6e.* (Fig. 7.1 is adapted from A.G. Guy, *Essentials of Materials Science*, McGraw-Hill Book Company, New York, 1976. p. 153.)

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



Plastically stretched zinc single crystal.

Adapted from Fig. 7.9, *Callister 6e.* (Fig. 7.9 is from C.F. Elam, *The Distortion of Metal Crystals*, Oxford University Press, London, 1935.)



Adapted from Fig. 7.8, *Callister 6e.*

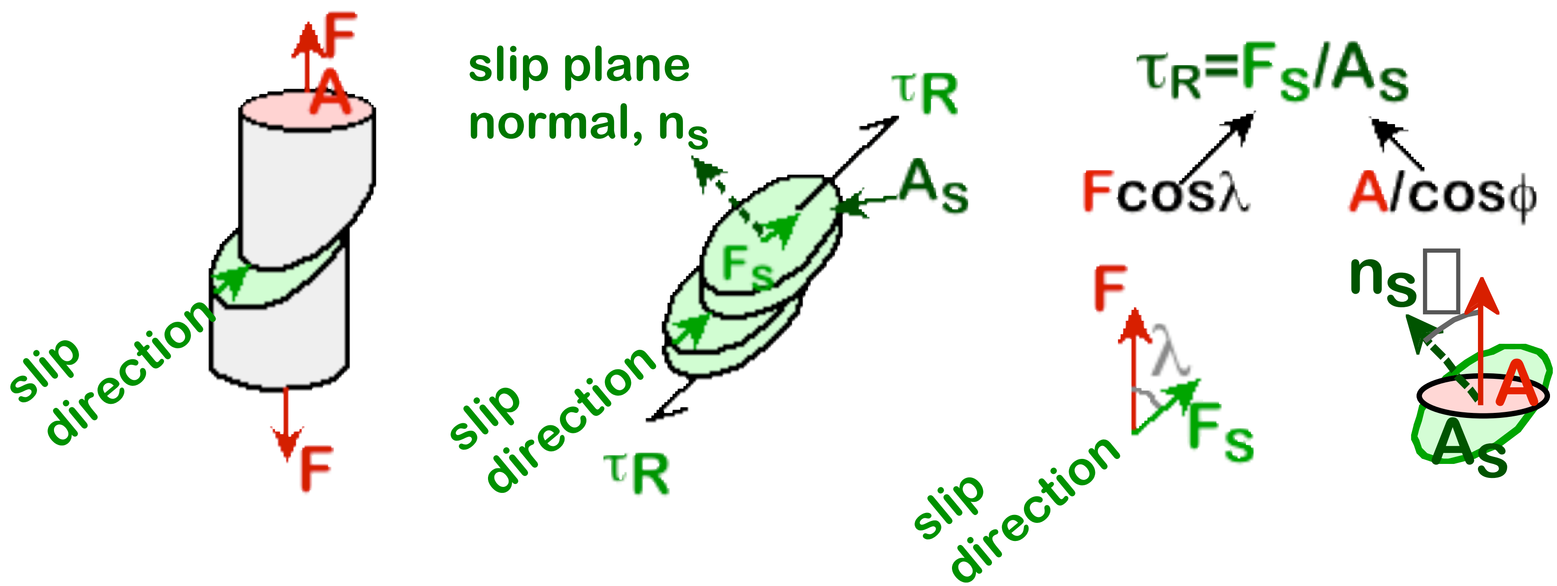
STRESS AND DISLOCATION MOTION

- 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



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

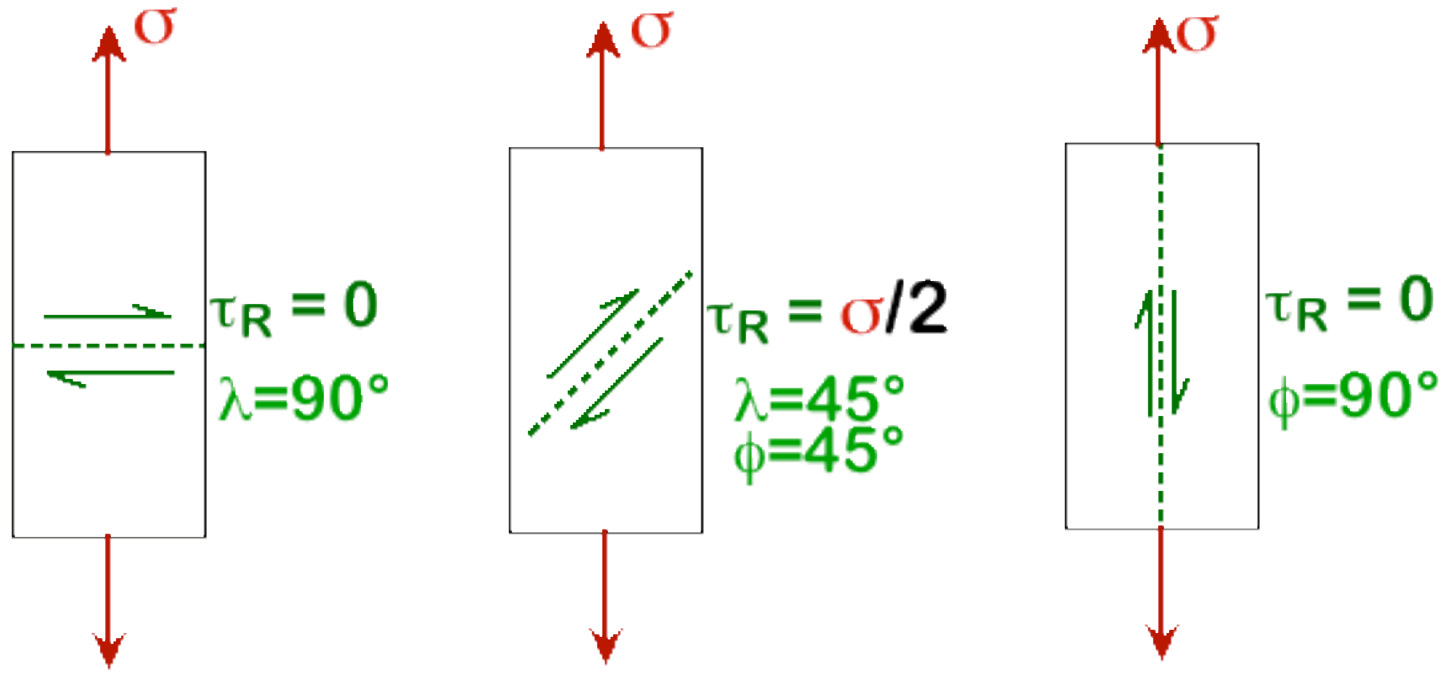
CRITICAL RESOLVED SHEAR STRESS

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

typically $10^{-4}G$ to $10^{-2}G$

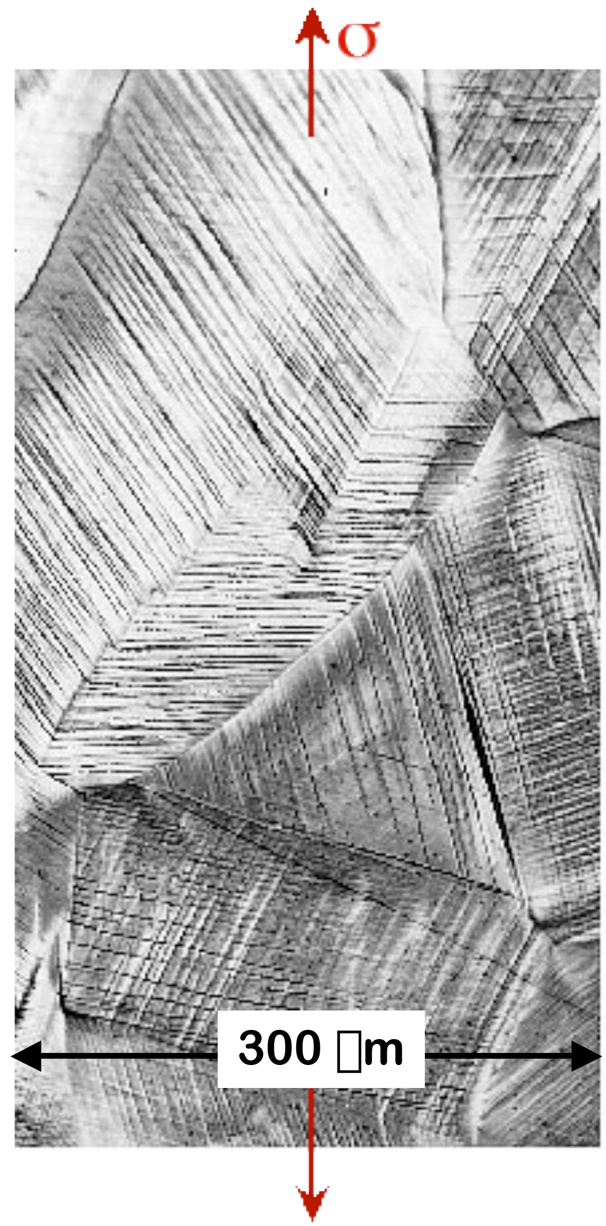
- Crystal orientation can make it easy or hard to move disl.

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



DISL. MOTION IN POLYCRYSTALS

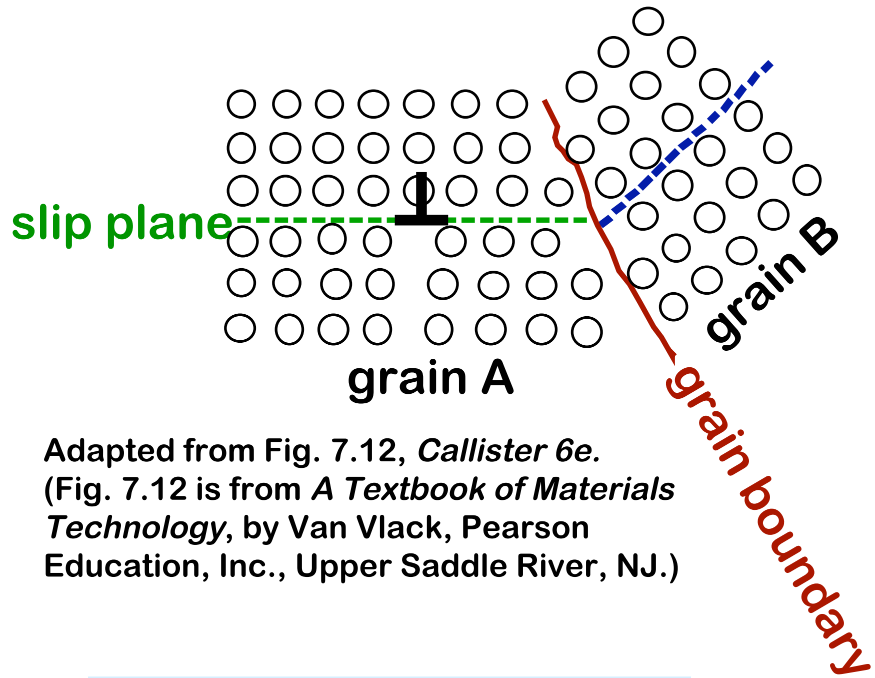
- Slip planes & directions (□, □) change from one crystal to another.
- □R will vary from one crystal to another.
- The crystal with the largest □R yields first.
- Other (less favorably oriented) crystals yield later.



Adapted from Fig. 7.10, *Callister 6e.* (Fig. 7.10 is courtesy of C. Brady, National Bureau of Standards [now the National Institute of Standards and Technology, Gaithersburg, MD].)

4 STRATEGIES FOR STRENGTHENING: 1: REDUCE GRAIN SIZE

- Grain boundaries are barriers to slip.
- Barrier "strength" increases with misorientation.
- Smaller grain size: more barriers to slip.



Adapted from Fig. 7.12, *Callister 6e.* (Fig. 7.12 is from *A Textbook of Materials Technology*, by Van Vlack, Pearson Education, Inc., Upper Saddle River, NJ.)

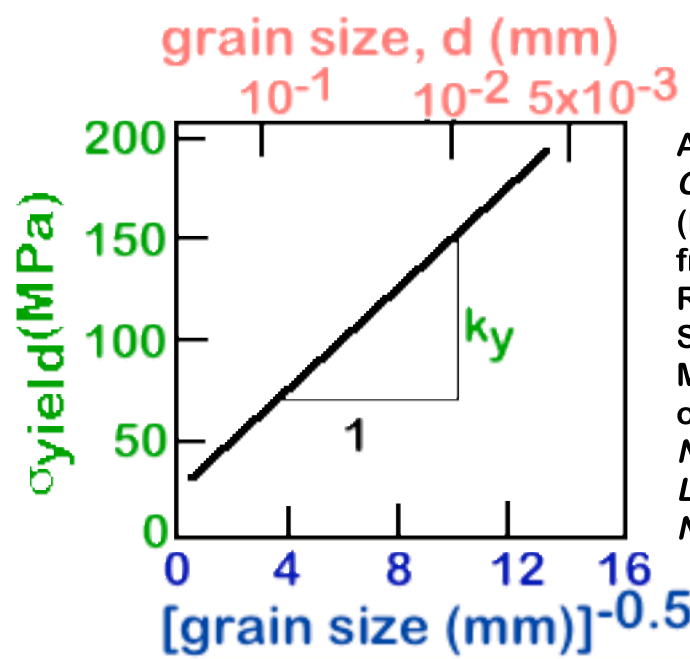
- Hall-Petch Equation: $\sigma_{yield} = \sigma_o + k_y d^{-1/2}$

GRAIN SIZE STRENGTHENING: AN EXAMPLE

- 70wt%Cu-30wt%Zn brass alloy

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

- Data:



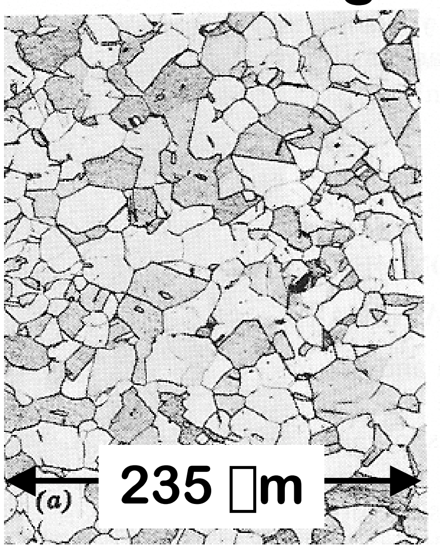
Adapted from Fig. 7.13, *Callister 6e.* (Fig. 7.13 is adapted from H. Suzuki, "The Relation Between the Structure and Mechanical Properties of Metals", Vol. II, *National Physical Laboratory Symposium No.* 15, 1963, p. 524.)

Adapted from Fig. 4.11(c), *Callister 6e.* (Fig. 4.11(c) is courtesy of J.E. Burke, General Electric Co.

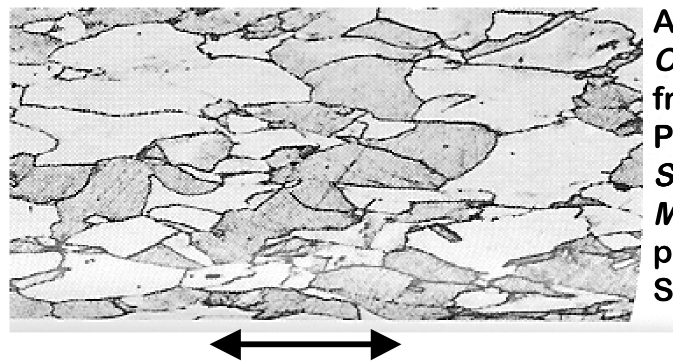
ANISOTROPY IN σ_{yield}

- Can be induced by rolling a polycrystalline metal

-before rolling



-after rolling



Adapted from Fig. 7.11, *Callister 6e.* (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

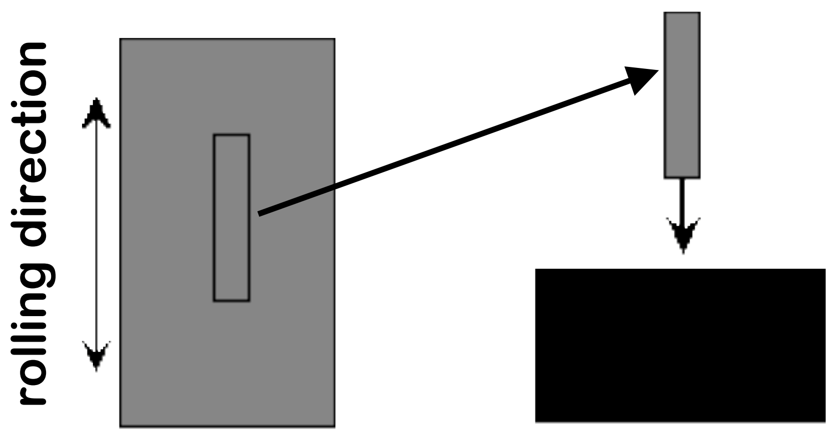
since rolling affects grain orientation and shape.

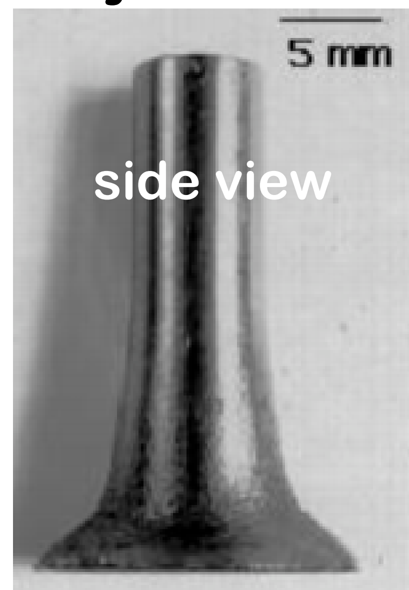
ANISOTROPY IN DEFORMATION

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.

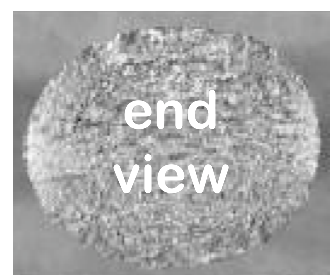


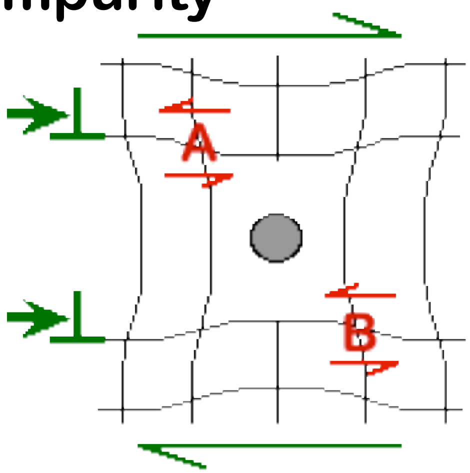
plate thickness direction

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

STRENGTHENING STRATEGY 2: SOLID SOLUTIONS

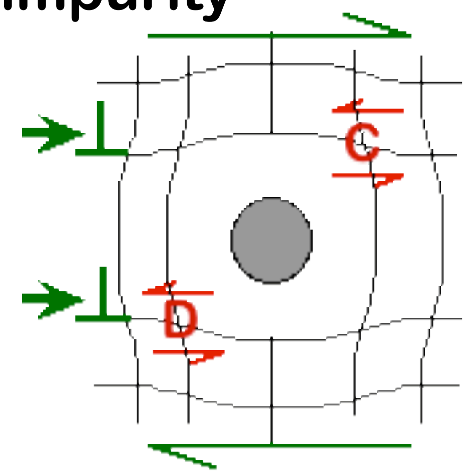
- Impurity atoms distort the lattice & generate stress.
- Stress can produce a barrier to dislocation motion.

- Smaller substitutional impurity



Impurity generates local shear at A and B that opposes disl motion to the right.

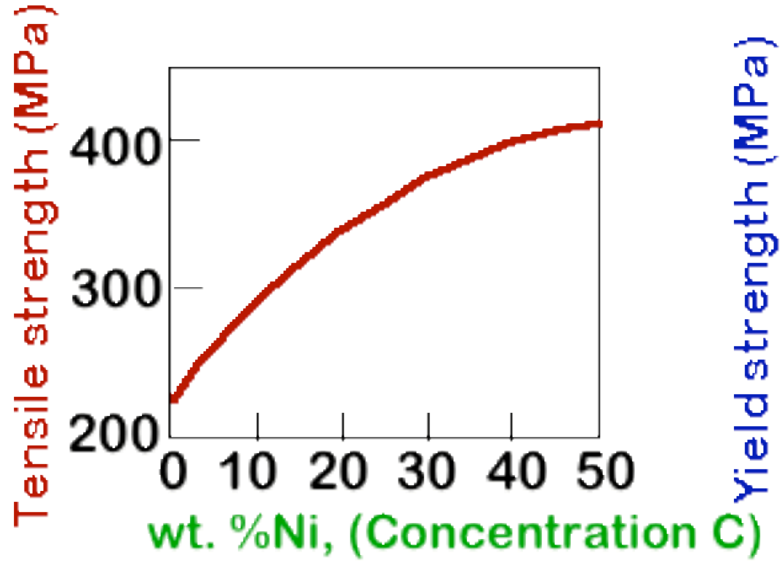
- Larger substitutional impurity

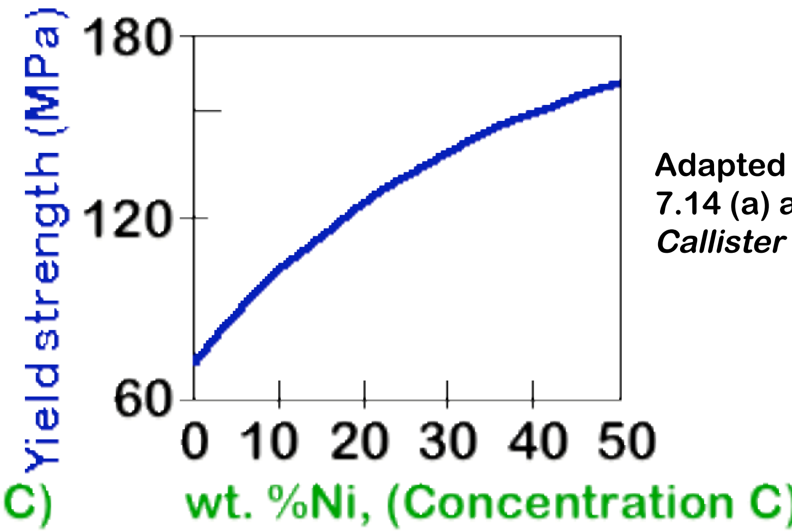


Impurity generates local shear at C and D that opposes disl motion to the right.

EX: SOLID SOLUTION STRENGTHENING IN COPPER

- Tensile strength & yield strength increase w/wt% Ni.



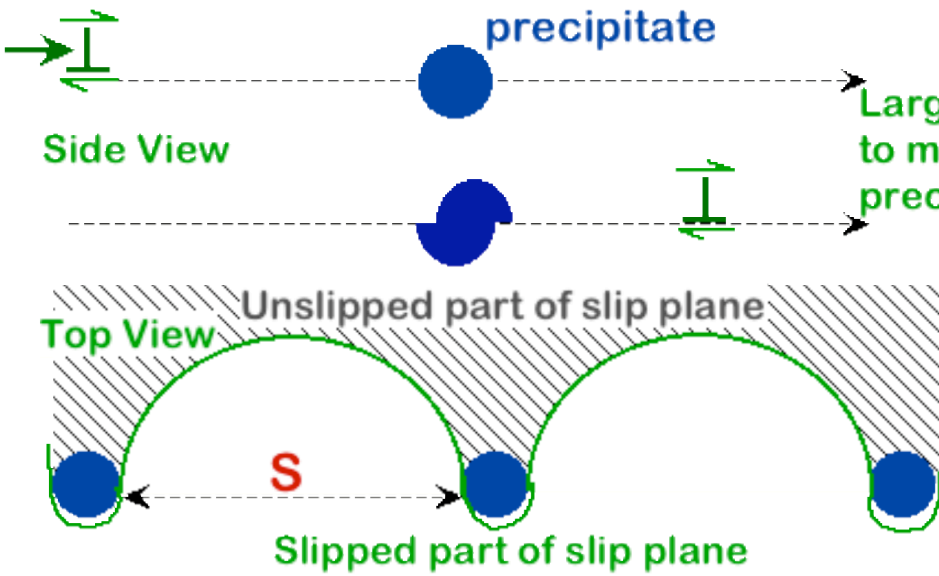


Adapted from Fig. 7.14 (a) and (b), *Callister 6e.*

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

STRENGTHENING STRATEGY 3: PRECIPITATION STRENGTHENING

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



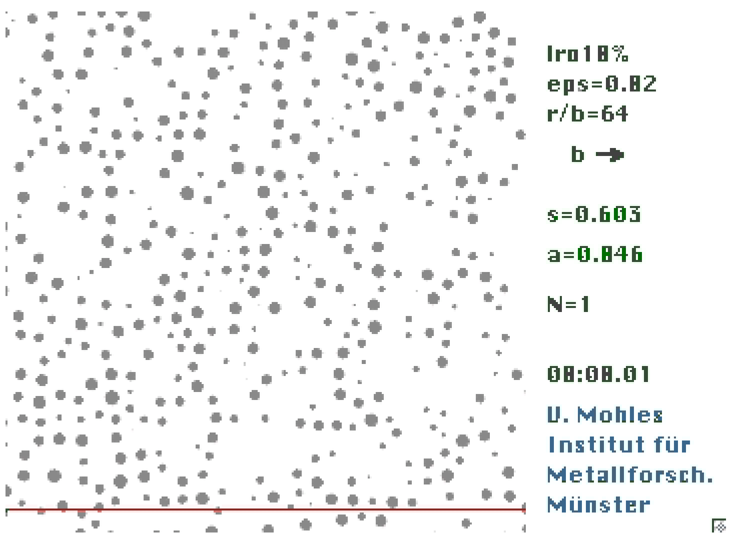
Large shear stress needed to move dislocation toward precipitate and shear it.

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

- **Result:** $\tau_y \sim \frac{1}{S}$

SIMULATION: PRECIPITATION STRENGTHENING

- View onto slip plane of Nimonic PE16
- Precipitate volume fraction: 10%
- Average precipitate size: 64 b (b = 1 atomic slip distance)



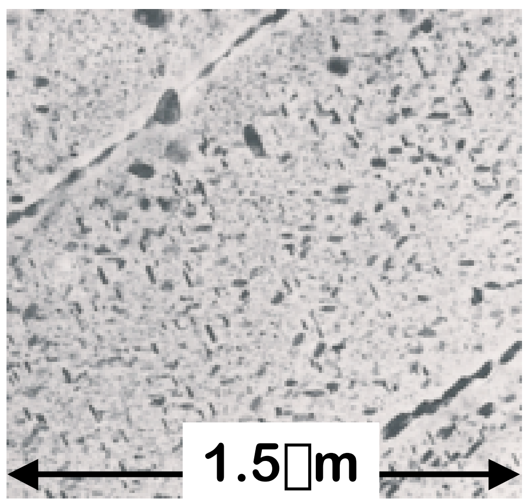
Simulation courtesy of Volker Mohles, Institut für Materialphysik der Universitåt, Münster, Germany (http://www.uni-munster.de/physik /MP/mohles/). Used with permission.

APPLICATION: PRECIPITATION STRENGTHENING

- Internal wing structure on Boeing 767

Adapted from Fig. 11.0, *Callister 5e.* (Fig. 11.0 is courtesy of G.H. Narayanan and A.G. Miller, Boeing Commercial Airplane Company.)

- Aluminum is strengthened with precipitates formed by alloying.

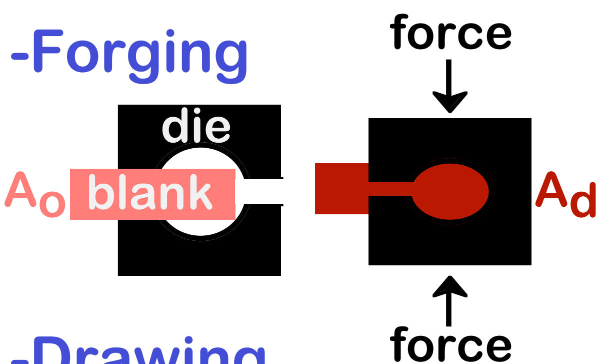


Adapted from Fig. 11.24, *Callister 6e.* (Fig. 11.24 is courtesy of G.H. Narayanan and A.G. Miller, Boeing Commercial Airplane Company.)

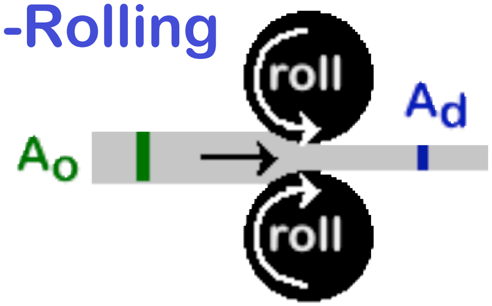
STRENGTHENING STRATEGY 4: COLD WORK (%CW)

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

-Forging

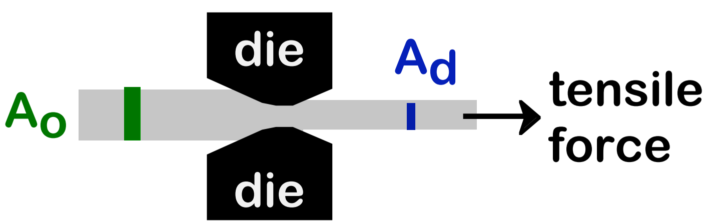


-Rolling

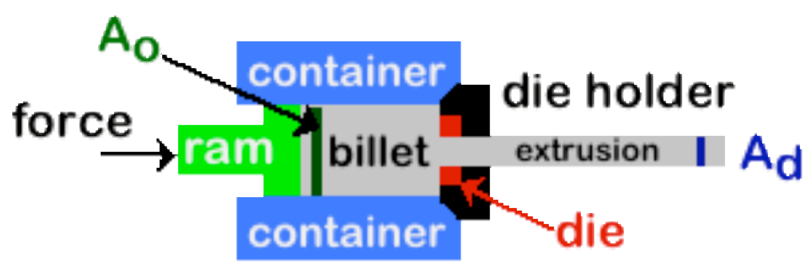


Adapted from Fig. 11.7, *Callister 6e.*

-Drawing



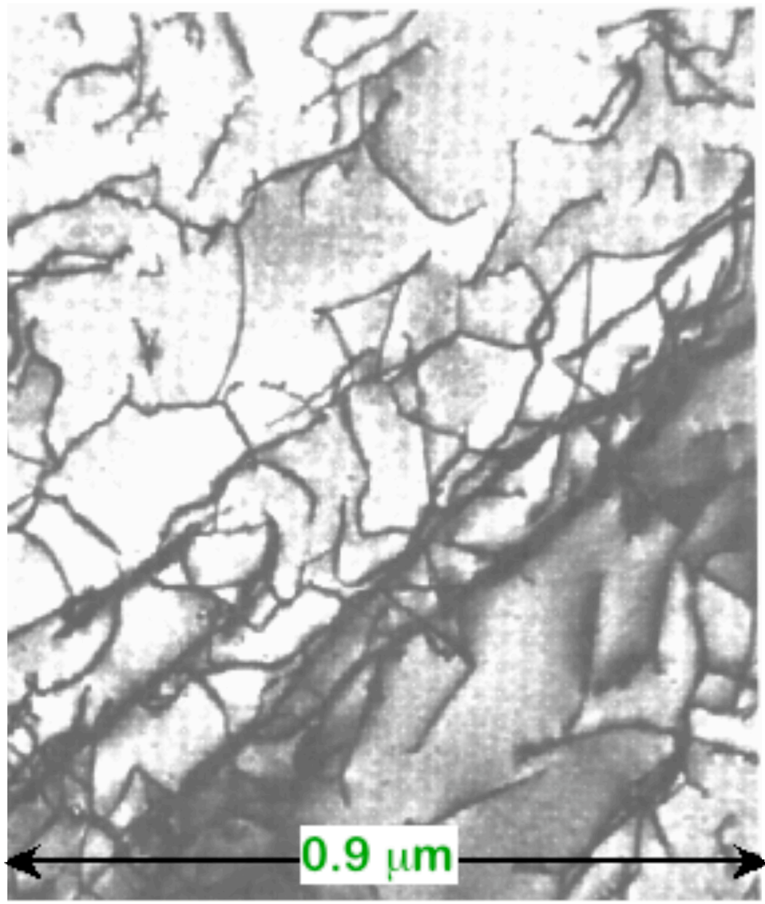
-Extrusion



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

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 6e.* (Fig. 4.6 is courtesy of M.R. Plichta, Michigan Technological University.)

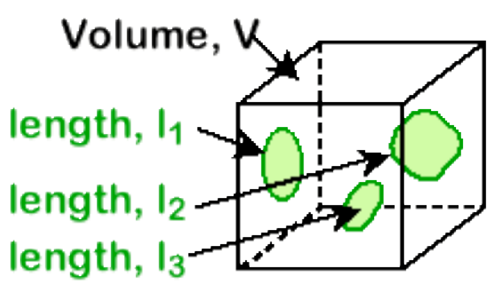
RESULT OF COLD WORK

- Dislocation density (ρ_d) goes up:

  Carefully prepared sample: $\rho_d \sim 10^3$ mm/mm^3

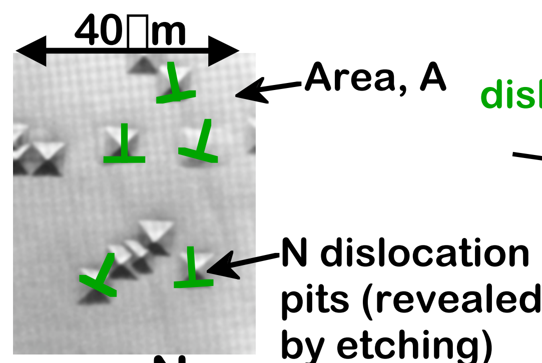
  Heavily deformed sample: $\rho_d \sim 10^{10}$ mm/mm^3

- Ways of measuring dislocation density:

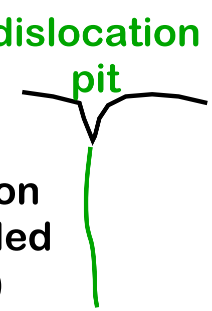


$$\rho_d = \frac{l_1 + l_2 + l_3}{V}$$

OR

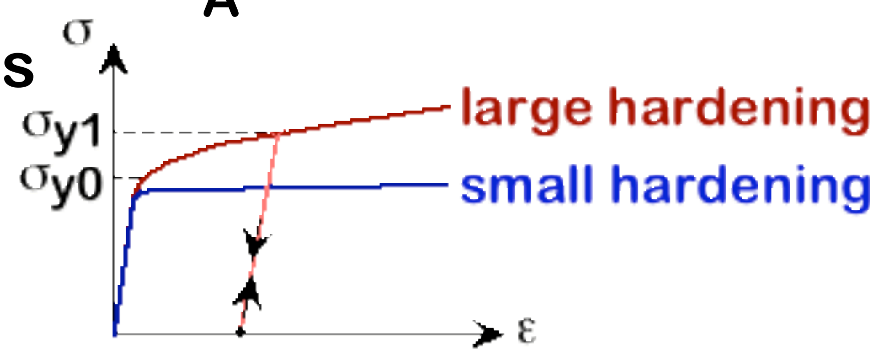


$$\rho_d = \frac{N}{A}$$



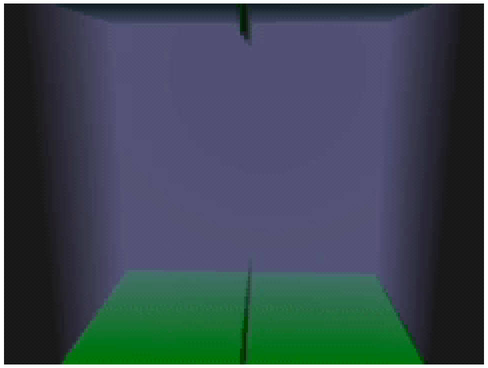
Micrograph adapted from Fig. 7.0, *Callister 6e.* (Fig. 7.0 is courtesy of W.G. Johnson, General Electric Co.)

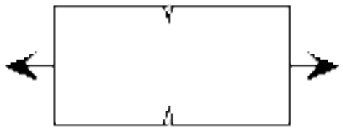
- Yield stress increases as ρ_d increases:



SIMULATION: DISLOCATION MOTION/GENERATION

- Tensile loading (horizontal dir.) of a FCC metal with notches in the top and bottom surface.
- Over 1 billion atoms modeled in 3D block.
- Note the large increase in disl. density.



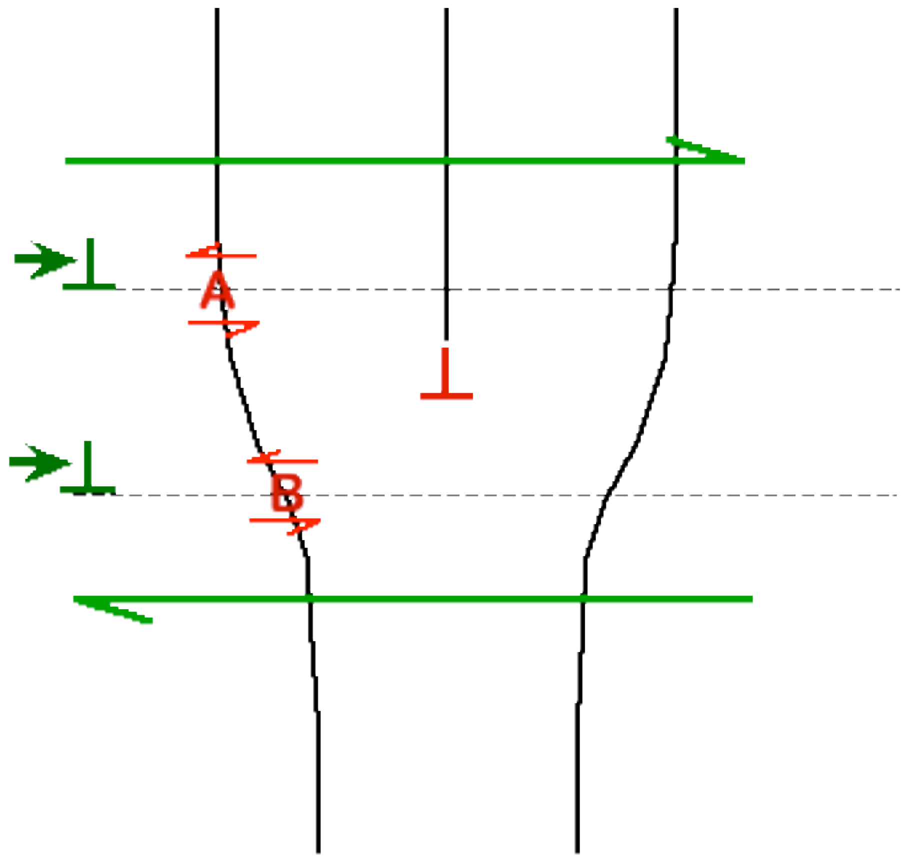


Simulation courtesy of Farid Abraham. Used with permission from International Business Machines Corporation.

DISLOCATION-DISLOCATION TRAPPING

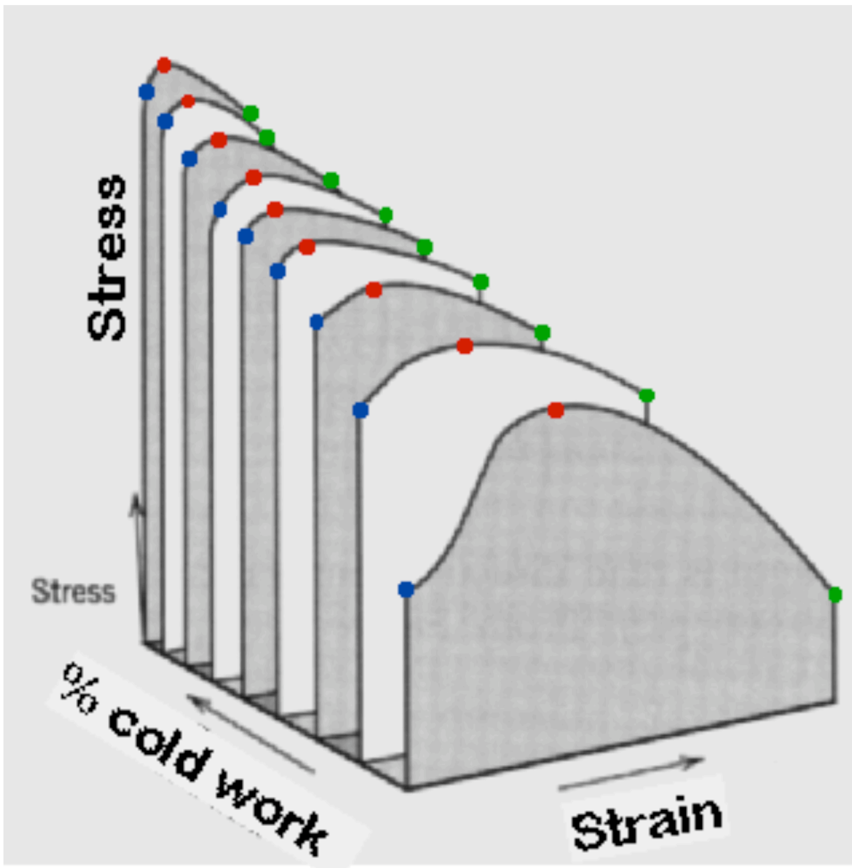
- Dislocation generate stress.
- This traps other dislocations.

Red dislocation generates shear at pts A and B that opposes motion of green disl. from left to right.



IMPACT OF COLD WORK

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

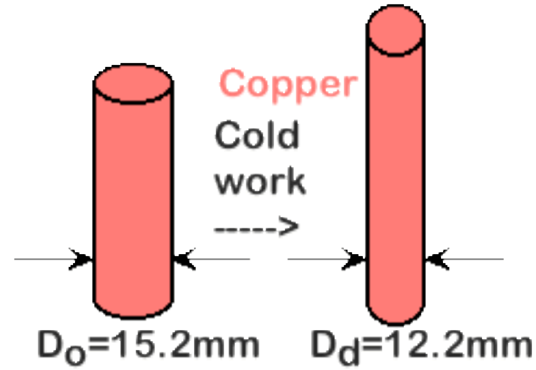


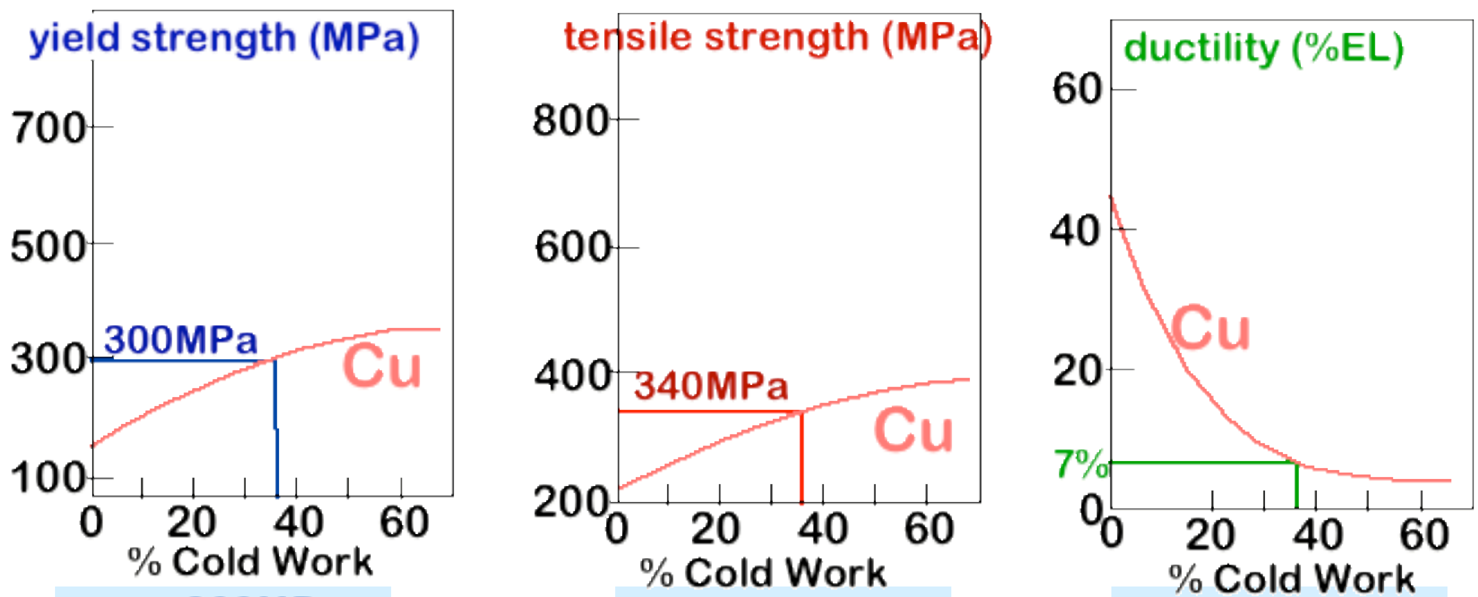
Adapted from Fig. 7.18, *Callister 6e.* (Fig. 7.18 is from *Metals Handbook: Properties and Selection: Iron and Steels*, Vol. 1, 9th ed., B. Bardes (Ed.), American Society for Metals, 1978, p. 221.)

COLD WORK ANALYSIS

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

$$\%CW = \frac{\pi r_o^2 - \pi r_d^2}{\pi r_o^2} x100 = 35.6\%$$





σ_y=300MPa

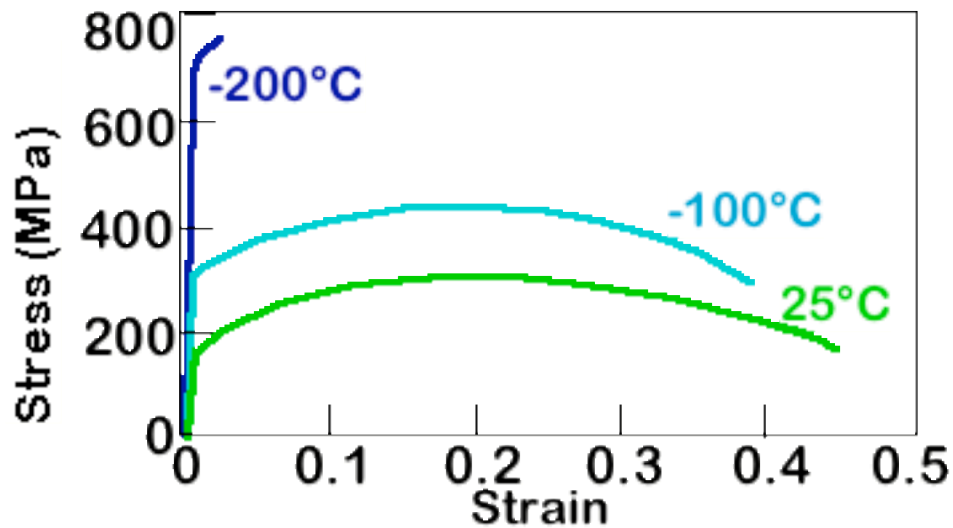
TS=340MPa

%EL=7%

Adapted from Fig. 7.17, *Callister 6e.* (Fig. 7.17 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.)

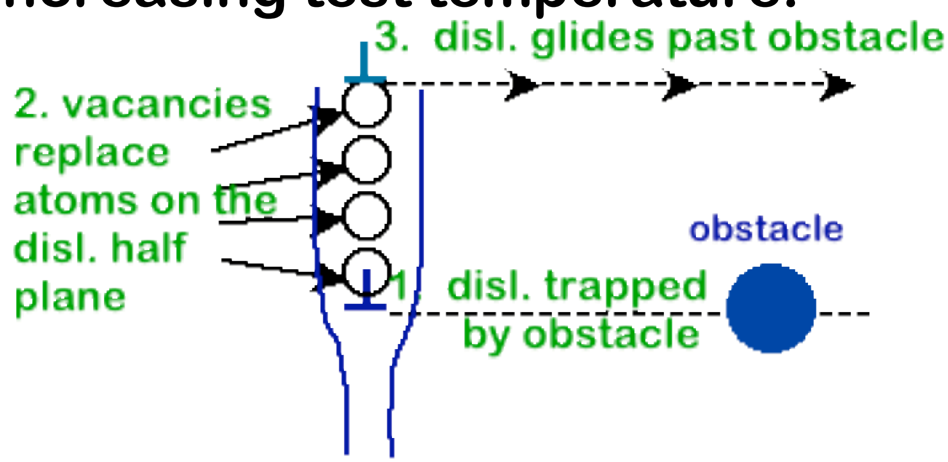
σ-ϵ BEHAVIOR VS TEMPERTURE

- Results for polycrystalline iron:



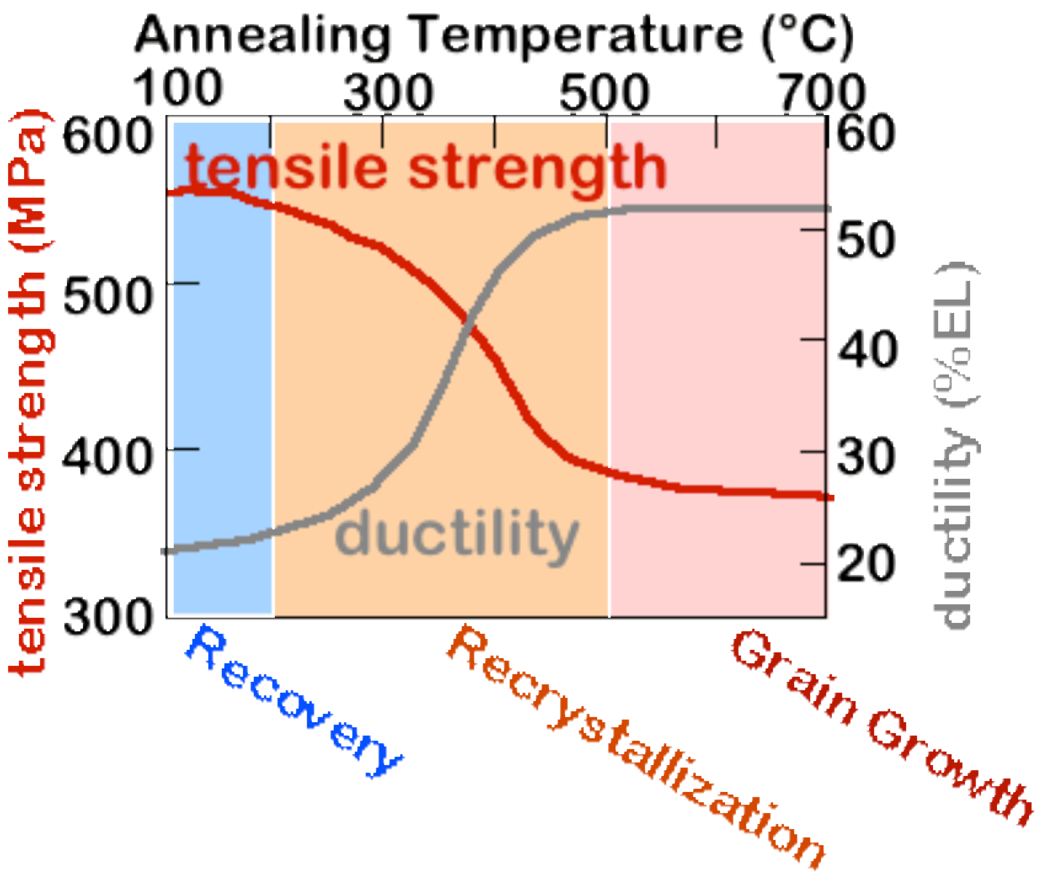
Adapted from Fig. 6.14, *Callister 6e.*

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



EFFECT OF HEATING AFTER %CW

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



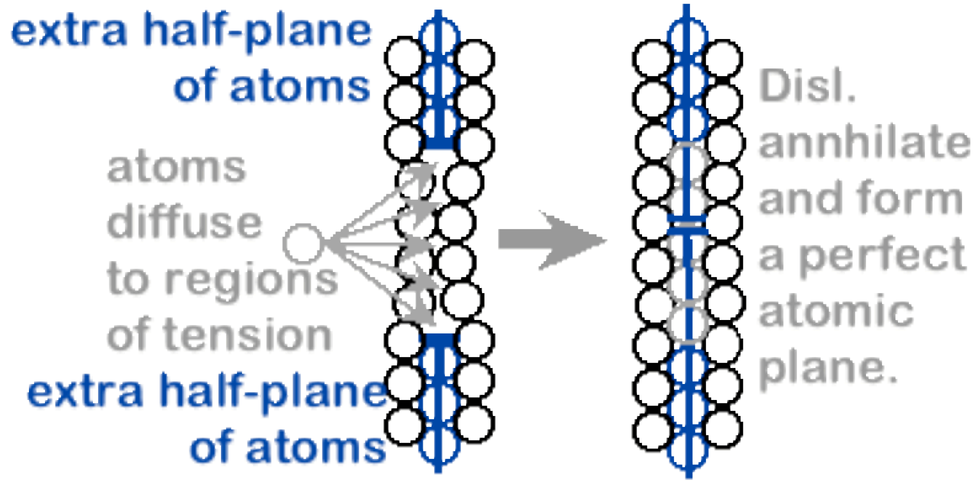
- 3 Annealing stages to discuss...

Adapted from Fig. 7.20, *Callister 6e.* (Fig. 7.20 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.)

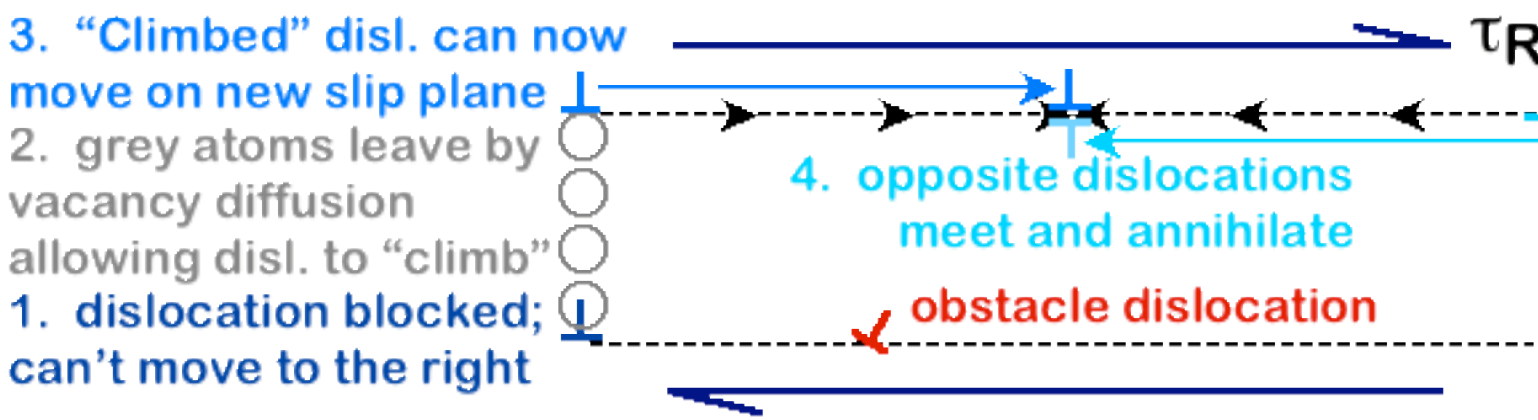
RECOVERY

Annihilation reduces dislocation density.

- **Scenario 1**

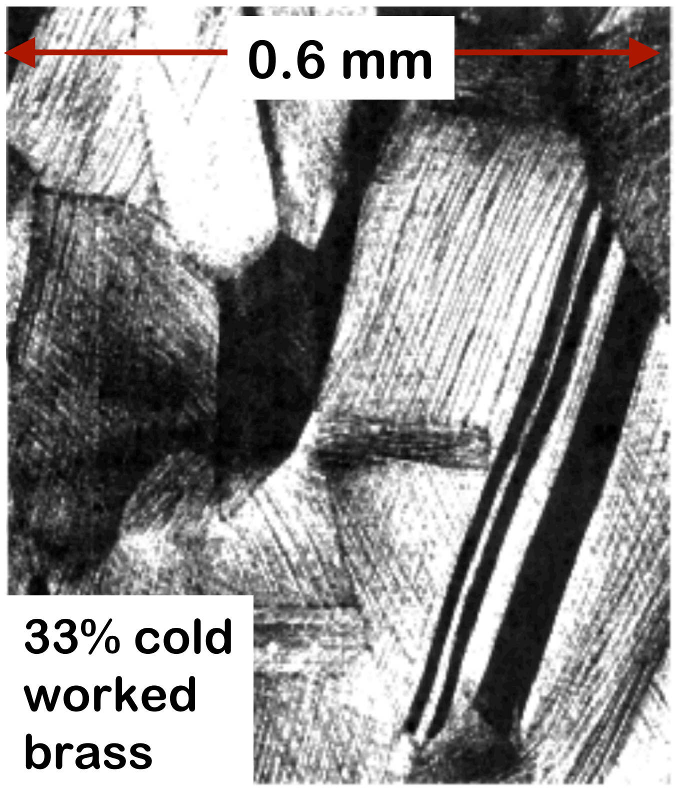


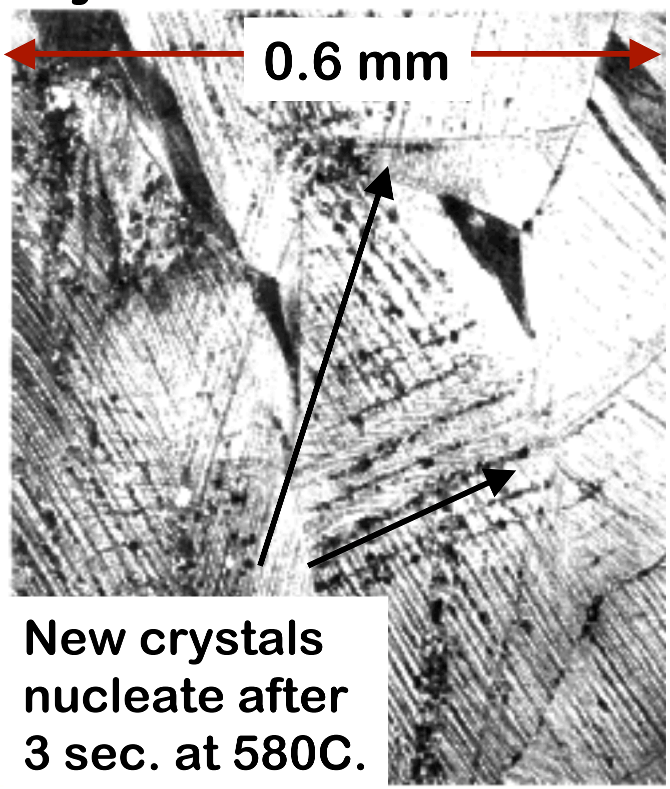
- **Scenario 2**



RECRYSTALLIZATION

- New crystals are formed that:
  - --have a small disl. density
  - --are small
  - --consume cold-worked crystals.

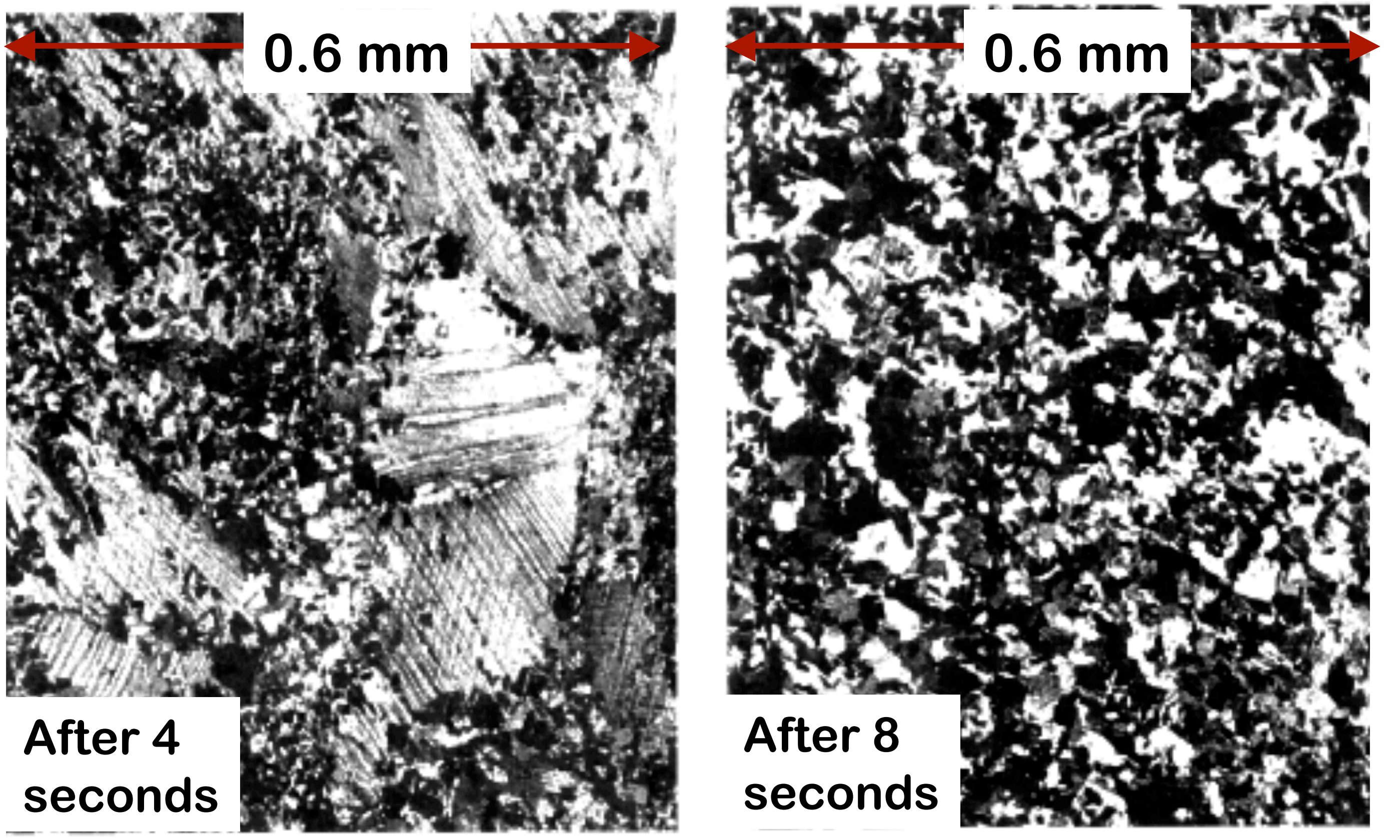




Adapted from Fig. 7.19 (a),(b), *Callister 6e.* (Fig. 7.19 (a),(b) are courtesy of J.E. Burke, General Electric Company.)

FURTHER RECRYSTALLIZATION

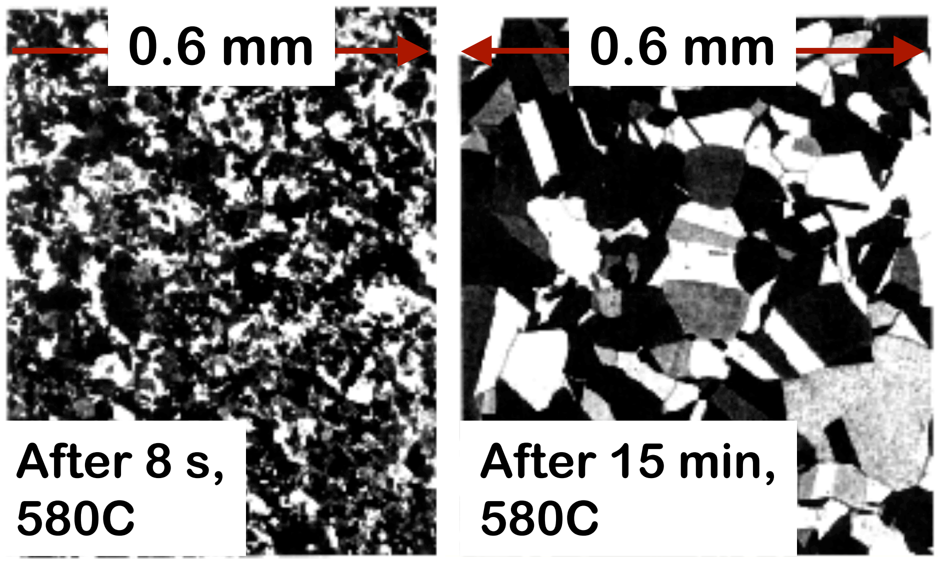
- All cold-worked crystals are consumed.



Adapted from Fig. 7.19 (c),(d), *Callister 6e.* (Fig. 7.19 (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. 7.19 (d),(e), *Callister 6e.* (Fig. 7.19 (d),(e) are courtesy of J.E. Burke, General Electric Company.)

- Empirical Relation:

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

exponent typ. ~ 2

grain diam. at time t.

coefficient dependent on material and T.

elapsed time

SUMMARY

- Dislocations are observed primarily in metals and alloys.
- Here, 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.

ANNOUNCEMENTS

Reading:

Core Problems:

Self-help Problems: