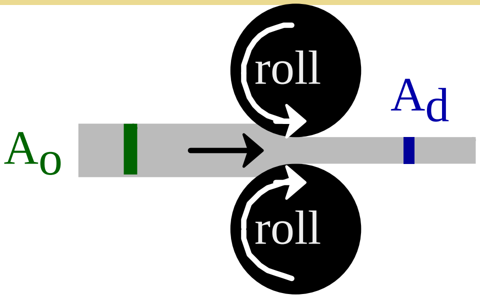
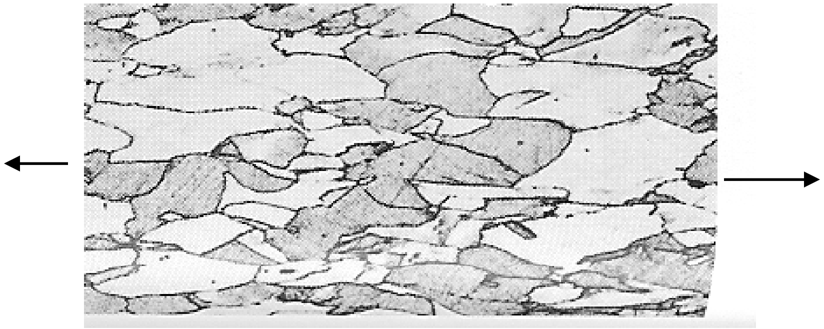
Cold Working

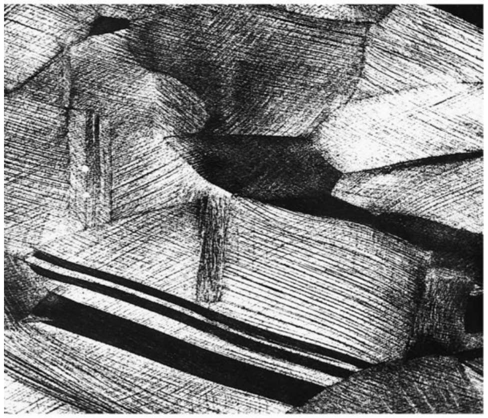


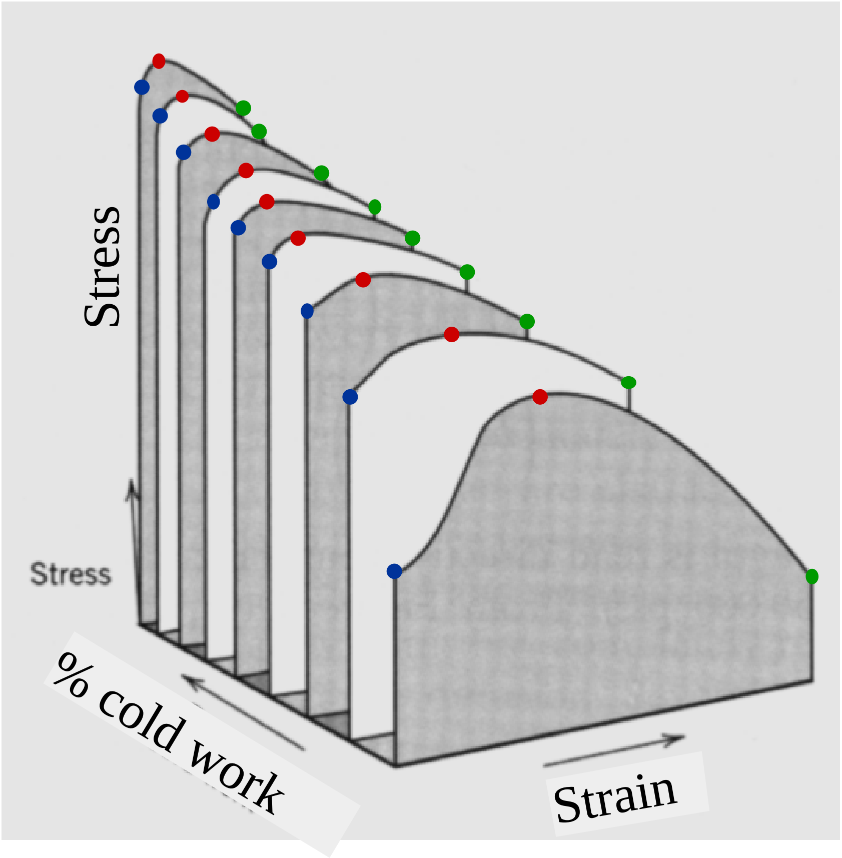
Rolling



Anisotropy

Traces of
Slip bands





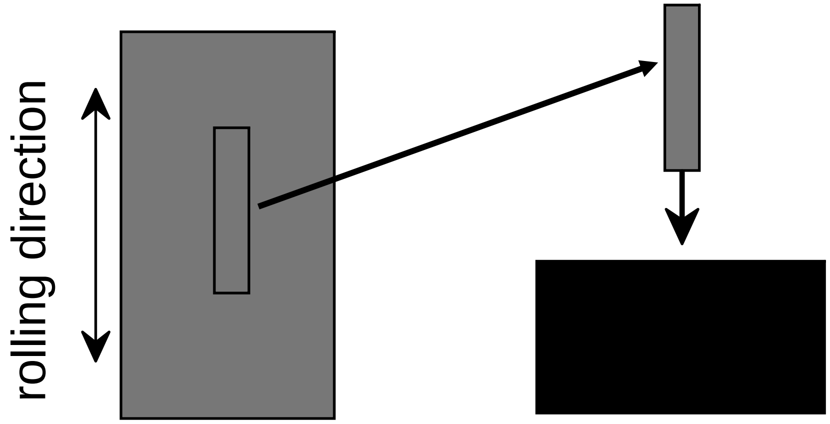
- **Yield strength increases**
- **Tensile strength increases**
- **Strain Hardening decreases**
- **Uniform Elongation decreases**
- **Ductility decreases**

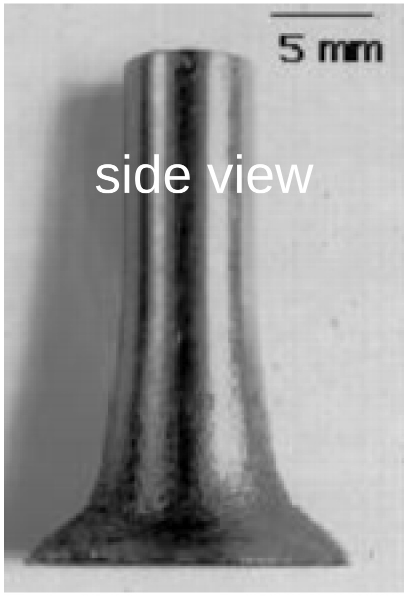
ANISOTROPY IN DEFORMATION

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.

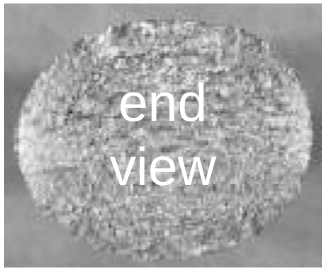
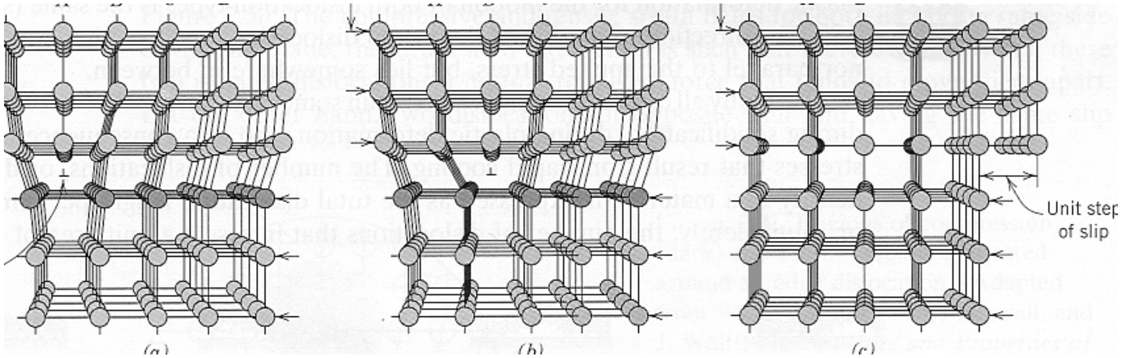


plate thickness direction

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

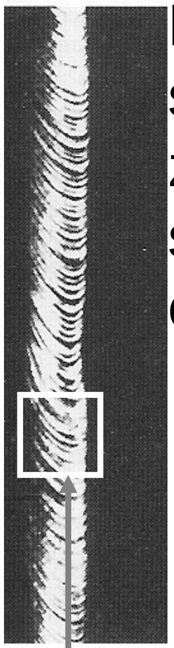
DISLOCATION MOTION

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



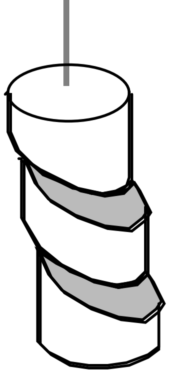
Adapted from Fig. 7.1, *Callister 6e.* (Fig. 7.1 is adapted from A.G. Guy, *Essentials of Materials Science*, McGraw-Hill Book Company, New York, 1976. p. 153.)

- 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.*

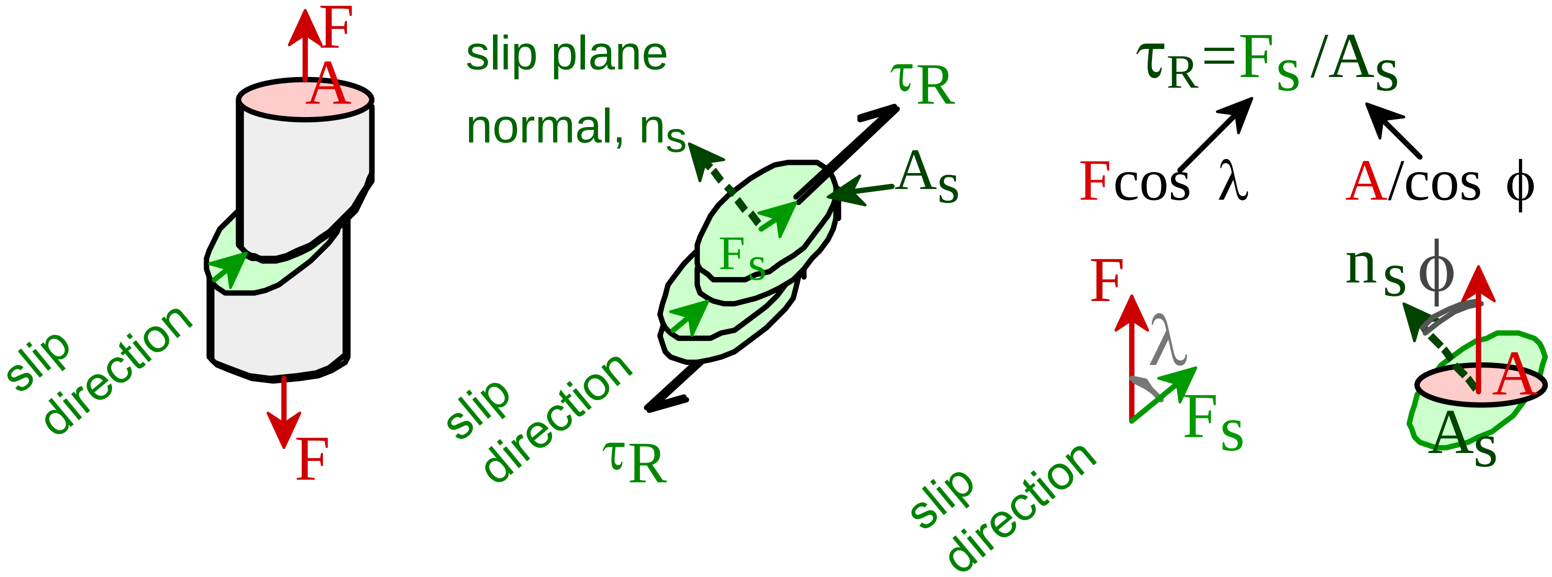
STRESS AND DISLOCATION MOTION

- 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



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

SLIP IN POLYCRYSTALS

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

CRITICAL RESOLVED SHEAR STRESS

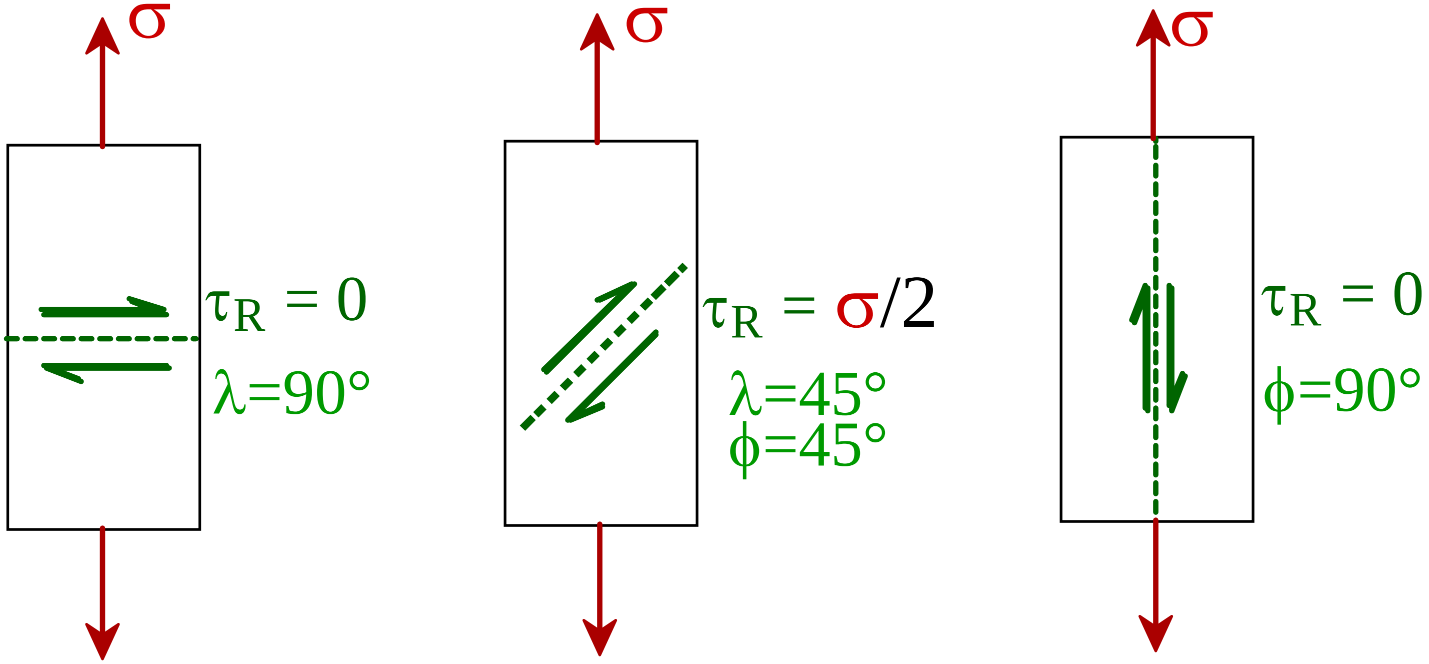
- Condition for dislocation motion: $\tau_R > \tau_{CRSS}$

typically

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

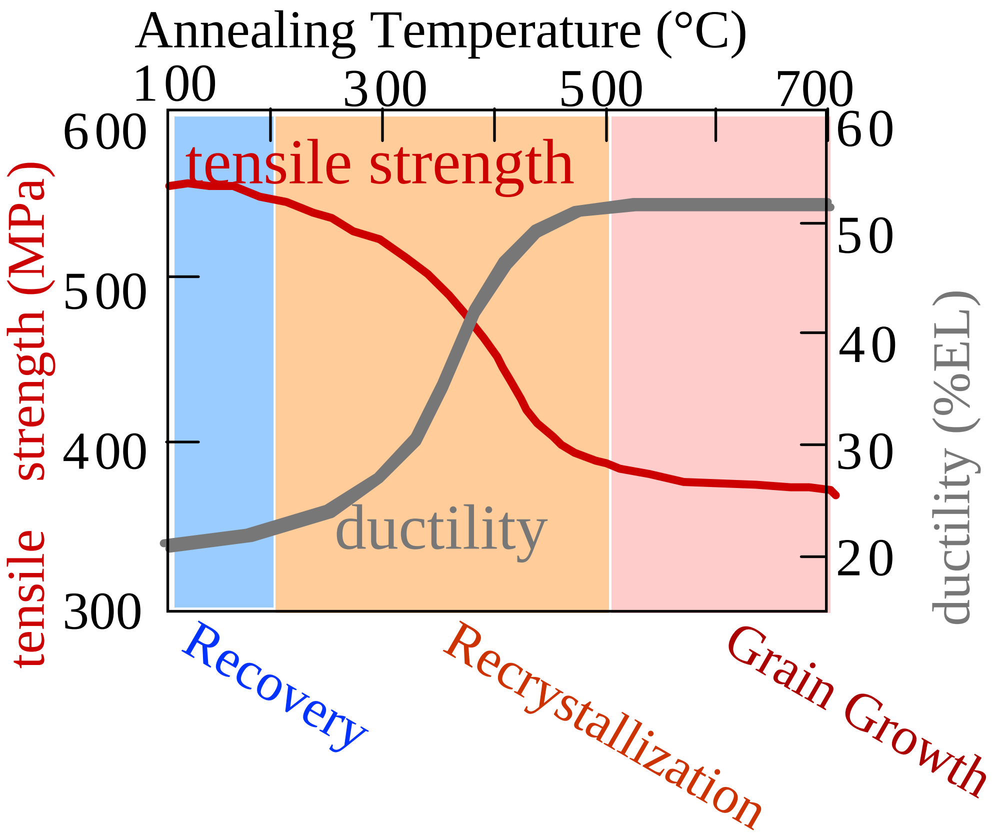
- Crystal orientation can make it easy or hard to move disl.

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



EFFECT OF HEATING AFTER %CW

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



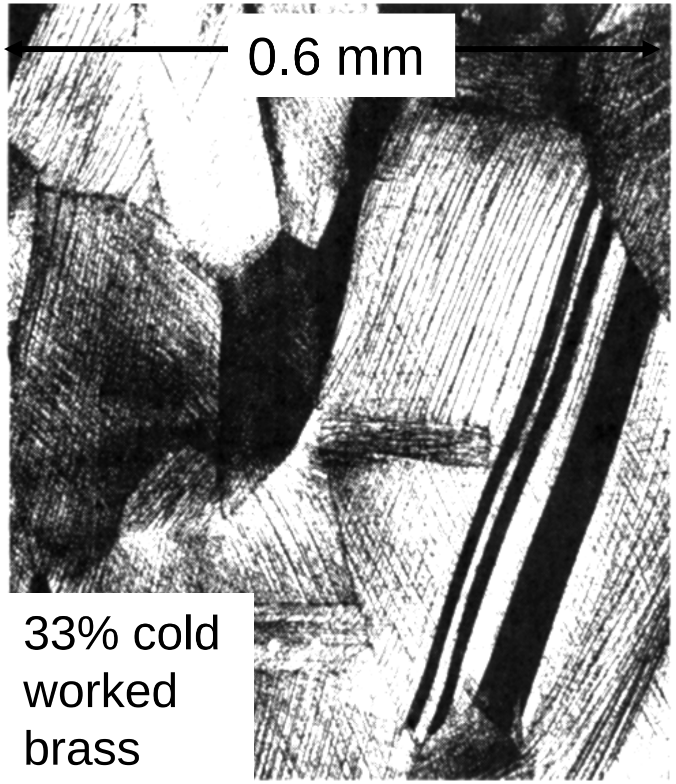
• During recovery the dislocations move slightly and find lower energy arrangements. Atoms diffuse and reduce the number of vacancies to its equilibrium concentration.

• After recovery, physical properties such as electrical conductivity and corrosion resistance are recovered, but the strength is not!

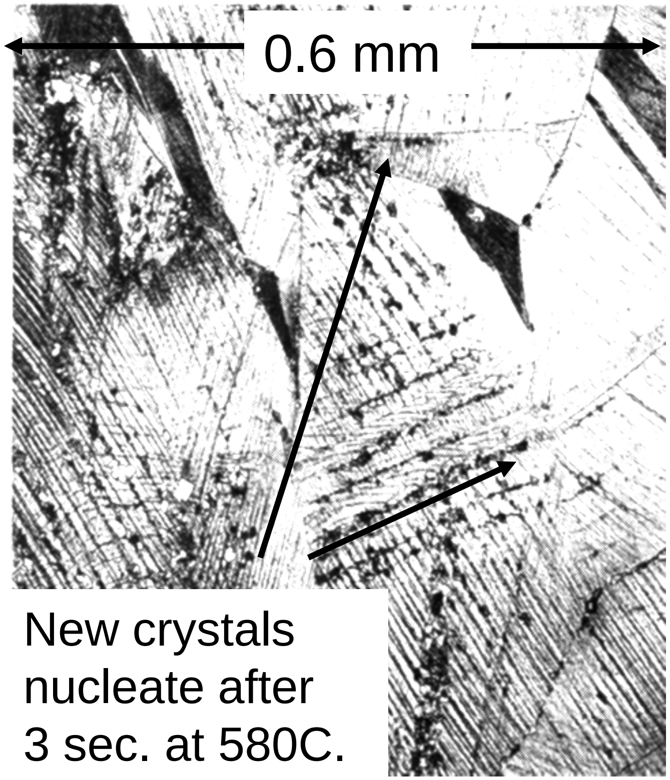
Adapted from Fig. 7.20, *Callister 6e.* (Fig. 7.20 is adapted from G. Sachs and K.R. van Horn, *Practical Metallurgy, Applied Metallurgy, and the Industrial Processing of Ferrous and Nonferrous Metals and Alloys*, American Society for Metals, 1940, p. 139.)

RECRYSTALLIZATION

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



33% cold worked brass

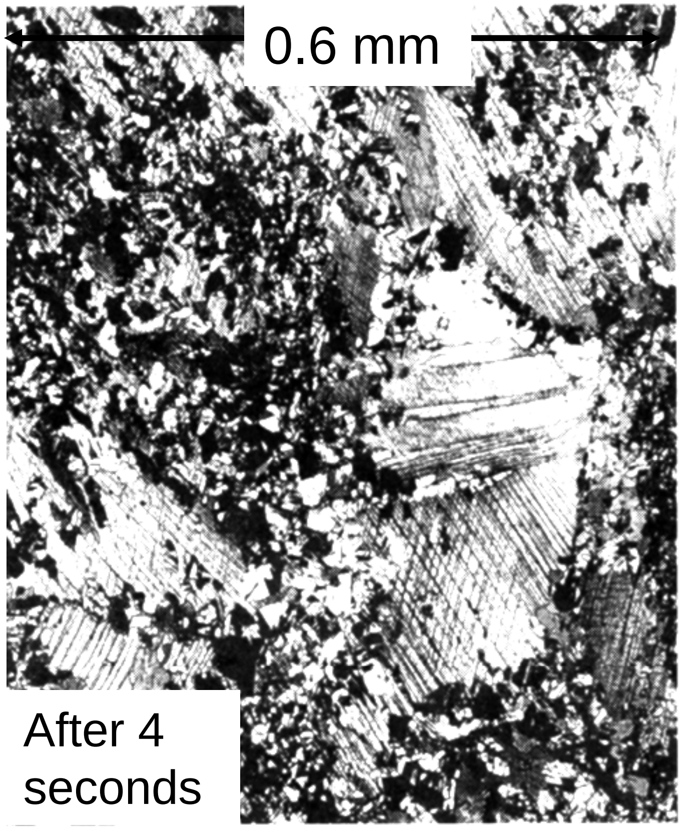


New crystals nucleate after 3 sec. at 580C.

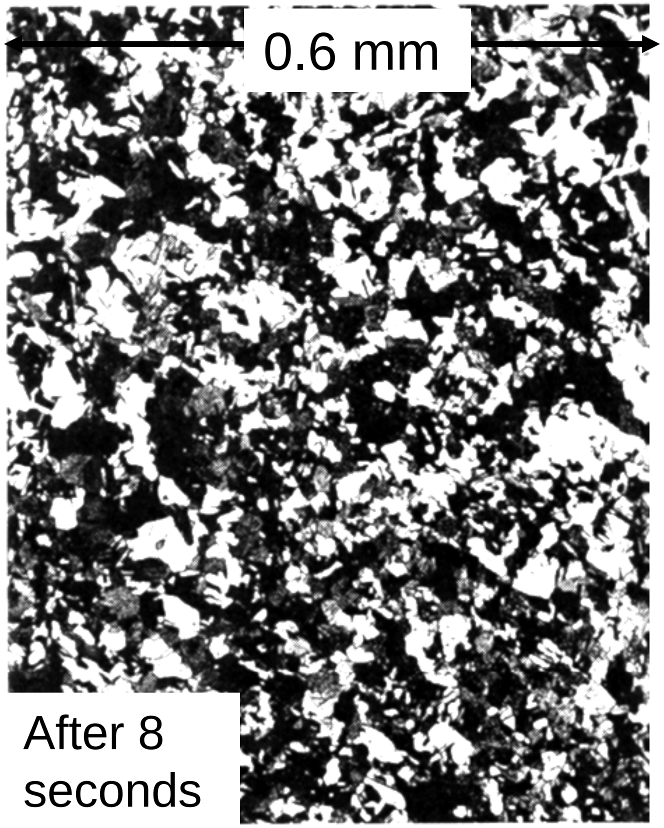
Adapted from Fig. 7.19 (a),(b), *Callister 6e.* (Fig. 7.19 (a),(b) are courtesy of J.E. Burke, General Electric Company.)

FURTHER RECRYSTALLIZATION

- All cold-worked crystals are consumed.



After 4 seconds



After 8 seconds

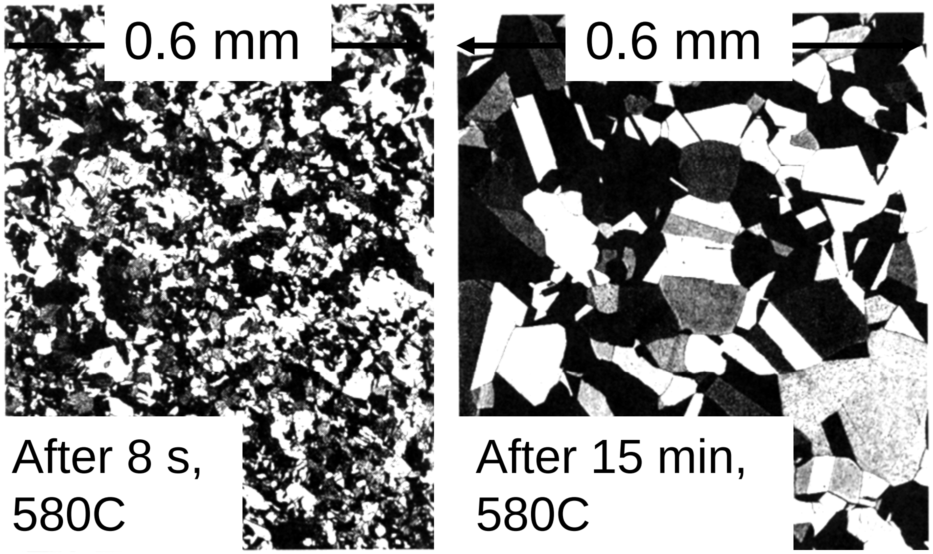
Adapted from Fig. 7.19 (c),(d), *Callister 6e.* (Fig. 7.19 (c),(d) are courtesy of J.E. Burke, General Electric Company.)

$Y = 1-\exp(-Kt^n)$, Y = Fraction transformed

Avrami Equation

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:

exponent typ. ~ 2

grain diam. at time t.

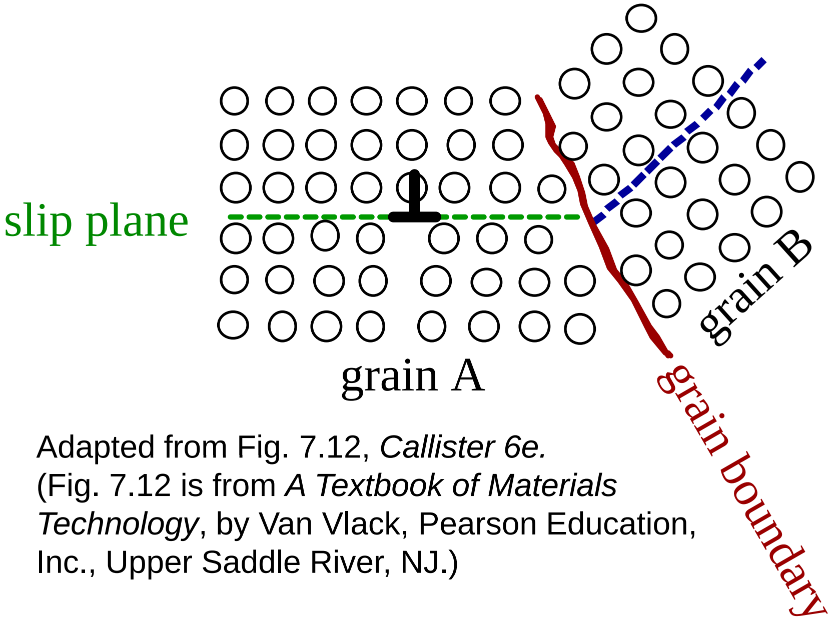
$$d^n - d_o^n = Kt$$

coefficient dependent on material and T.

elapsed time

GRAIN BOUNDARY STRENGTHENING

- 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:

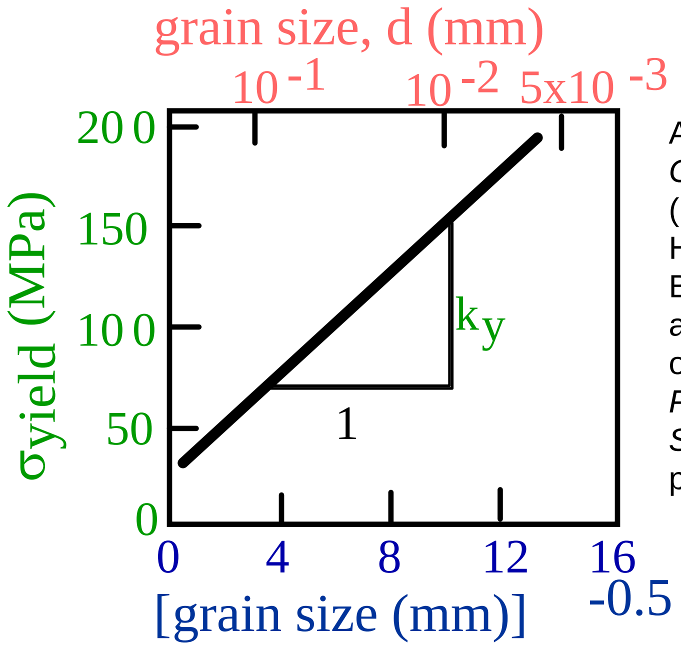
$$\sigma_{yield} = \sigma_o + k_y d^{-1/2}$$

GRAIN SIZE STRENGTHENING: AN EXAMPLE

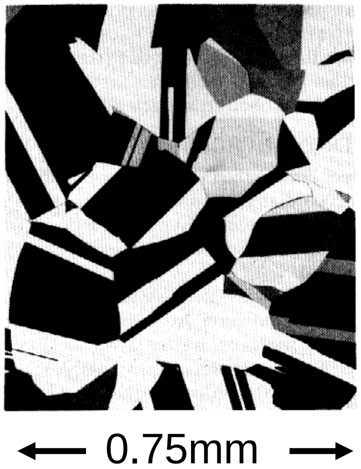
- 70wt%Cu-30wt%Zn brass alloy

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

- 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.)

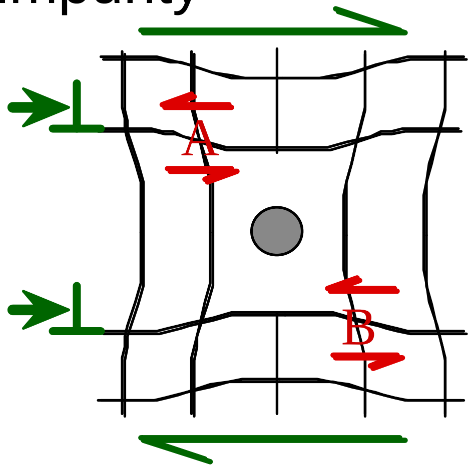


Adapted from Fig. 4.11(c), *Callister 6e.* (Fig. 4.11(c) is courtesy of J.E. Burke, General Electric Co.

SOLID SOLUTION STRENGTHENING

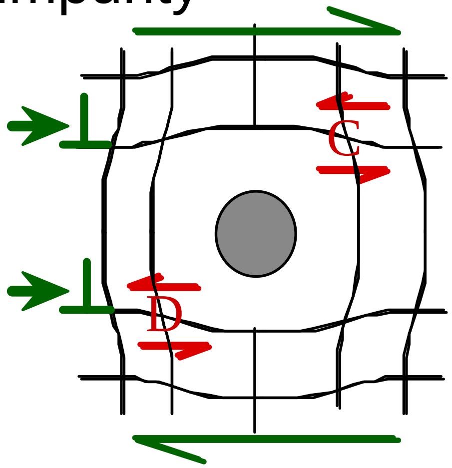
- Impurity atoms distort the lattice & generate stress.
- The stress field of the dislocations interact with the stress field of impurities, and therefore, higher stresses are needed to move the dislocations.

- Smaller substitutional impurity



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

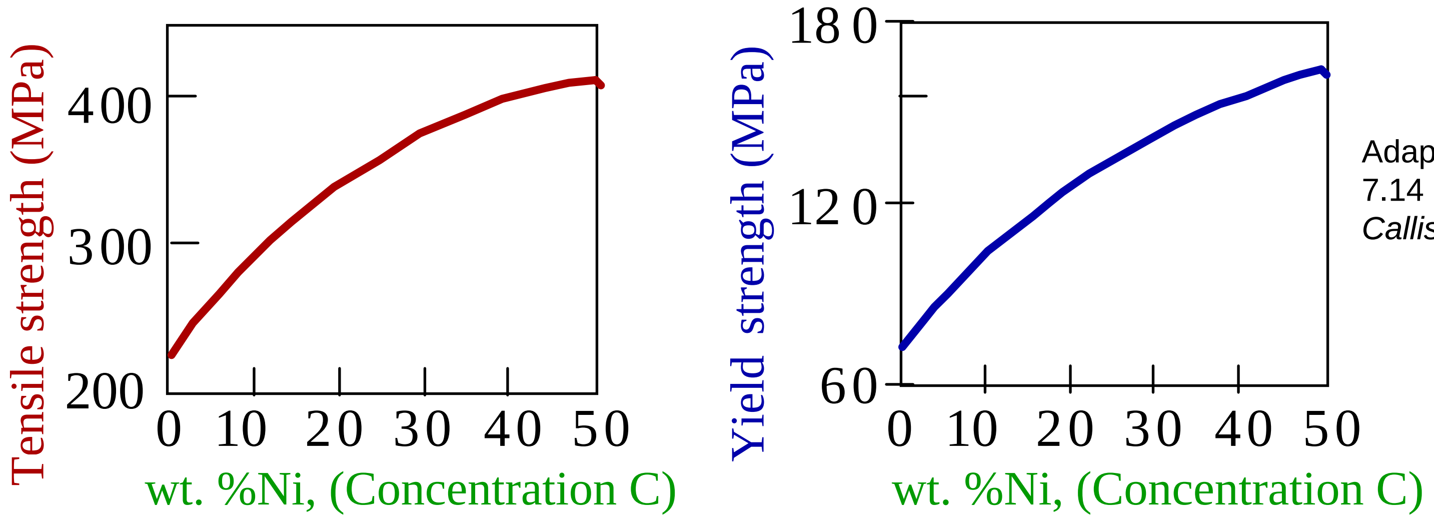
- Larger substitutional impurity



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

EXAMPLE: SOLID SOLUTION STRENGTHENING IN COPPER

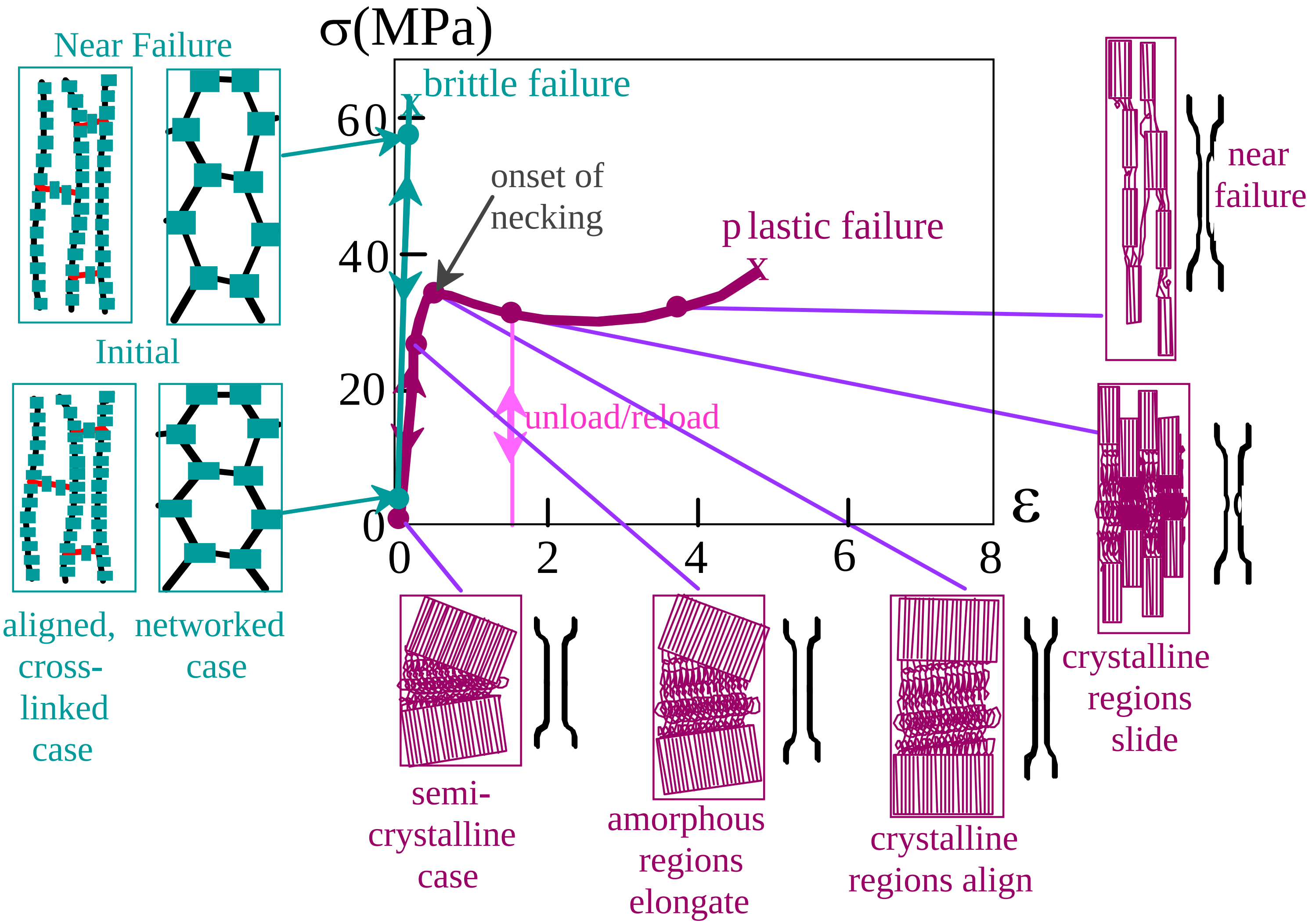
- Tensile strength & yield strength increase with wt% Ni.



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

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

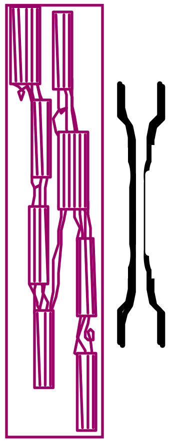
TENSILE RESPONSE: Polymers



Stress-strain curves adapted from Fig. 15.1, *Callister 6e.* Inset figures along plastic response curve (purple) adapted from Fig. 15.12, *Callister 6e*. (Fig. 15.12 is from J.M. Schultz, *Polymer Materials Science*, Prentice-Hall, Inc., 1974, pp. 500-501.)

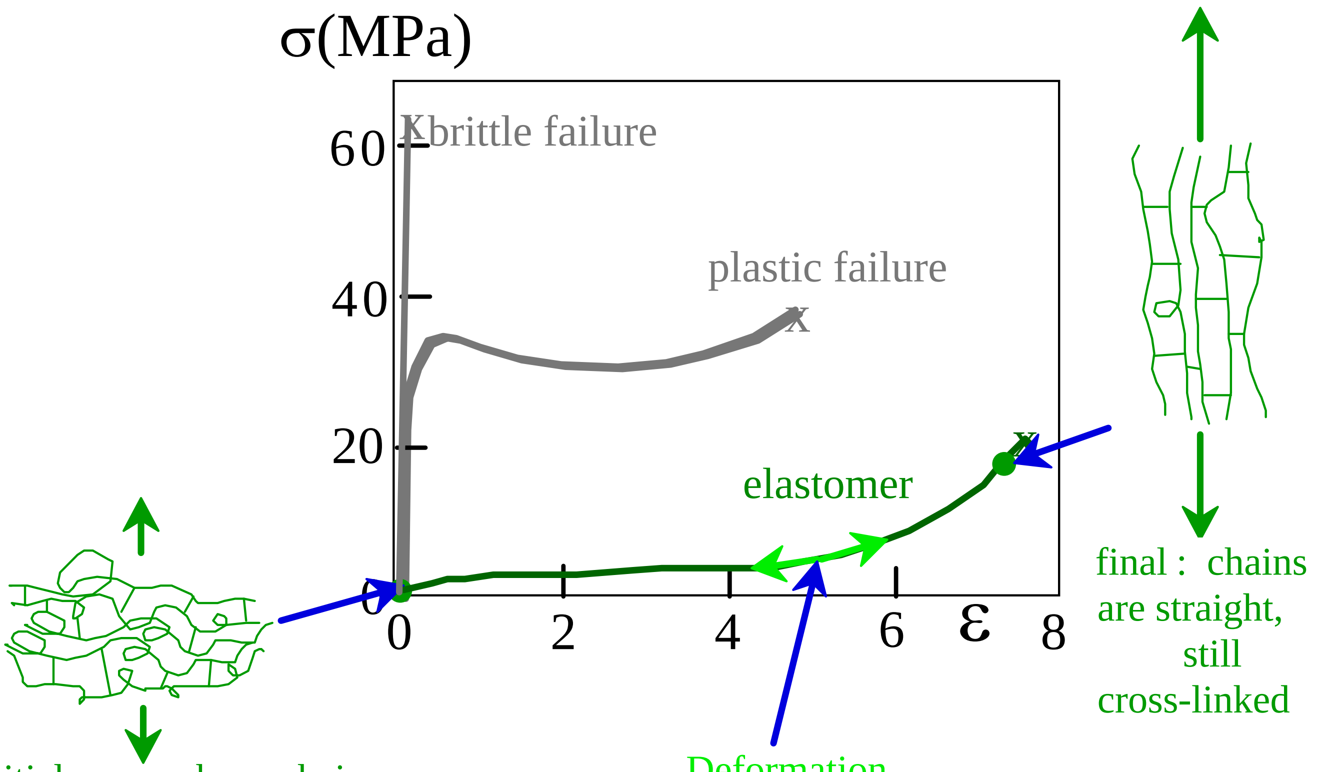
DEFORMATION BY DRAWING: Polymers

- Drawing...
  - --stretches the polymer prior to use
  - --aligns chains to the stretching direction
- Results of drawing:
  - --increases the elastic modulus (E) in the stretching dir.
  - --increases the tensile strength (TS) in the stretching dir.
  - --decreases ductility (%EL)
- Annealing after drawing...
  - --decreases alignment
  - --reverses effects of drawing.
- Compare to cold working in metals!



Adapted from Fig. 15.12, *Callister 6e*. (Fig. 15.12 is from J.M. Schultz, *Polymer Materials Science*, Prentice-Hall, Inc., 1974, pp. 500-501.)

TENSILE RESPONSE: ELASTOMER CASE



initial: amorphous chains are
kinked, heavily cross-linked.

Deformation
is reversible!

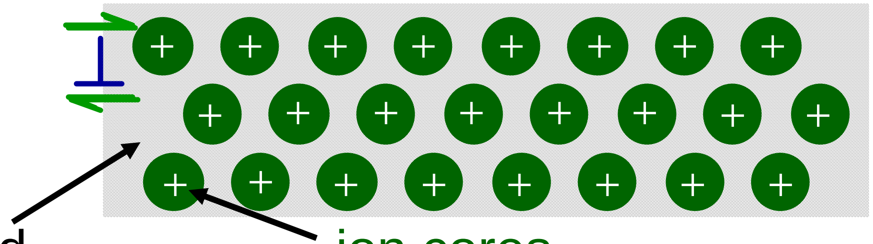
final : chains
are straight,
still
cross-linked

Stress-strain curves adapted from Fig. 15.1, *Callister 6e.* Inset figures along elastomer curve (green) adapted from Fig. 15.14, *Callister 6e.* (Fig. 15.14 is from Z.D. Jastrzebski, *The Nature and Properties of Engineering Materials*, 3rd ed., John Wiley and Sons, 1987.)

- Compare to responses of other polymers:
  - --brittle response (aligned, cross linked & networked case)
  - --plastic response (semi-crystalline case)

DISLOCATIONS & MATERIALS CLASSES

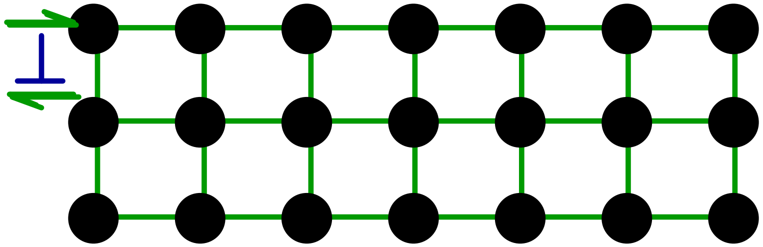
- Metals: Disl. motion easier.
  - -non-directional bonding
  - -close-packed directions for slip.



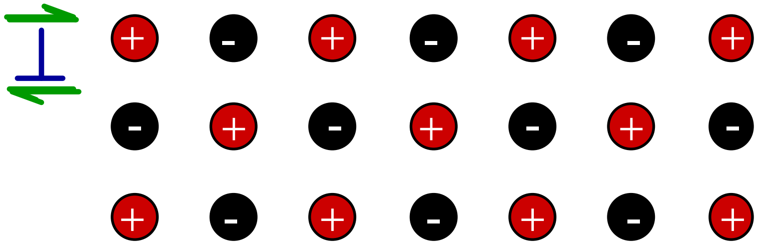
electron cloud

ion cores

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



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



Tensile Behavior of Ceramics

- **Fracture precedes plastic deformation in ceramics, therefore they are brittle.**
- **Porosity plays an important role in mechanical properties!**