

CHAPTER 7: DISLOCATIONS AND STRENGTHENING

ISSUES TO ADDRESS...

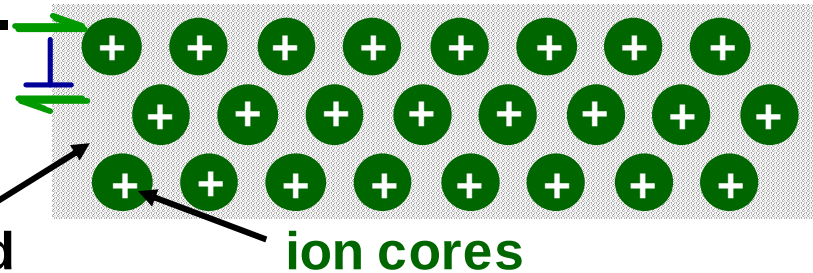
- **Why are dislocations observed primarily in metals and alloys?**
- **How are strength and dislocation motion related?**
- **How do we increase strength?**
- **How can heating change strength and other properties?**

DISLOCATIONS & MATERIALS CLASSES

- **Metals: Disl. motion easier.**

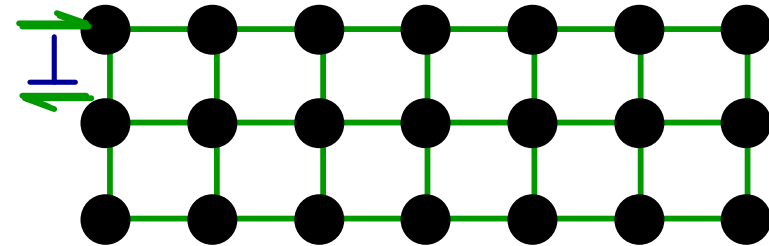
- non-directional bonding
- close-packed directions for slip.

electron cloud



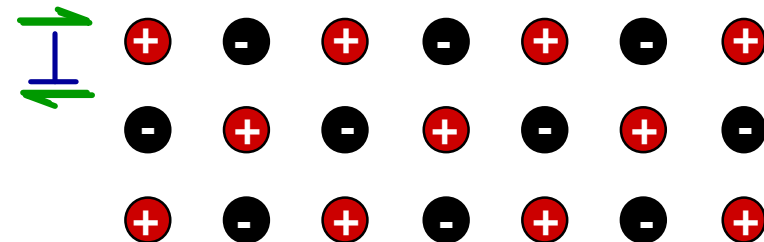
- **Covalent Ceramics**

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



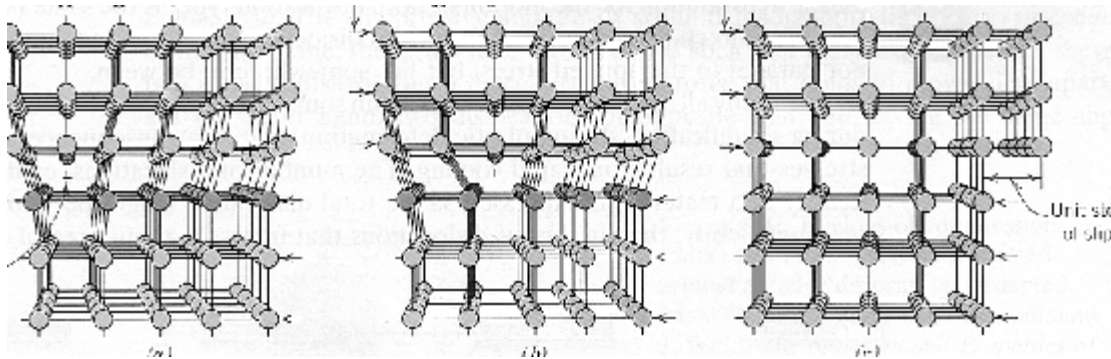
- **Ionic Ceramics (NaCl):**

- Motion hard.
- need to avoid ++ and -- neighbors.



DISLOCATION MOTION

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

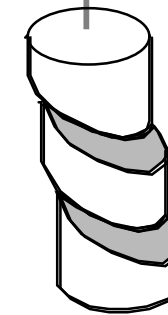


Adapted from Fig. 7.1, *Callister 6e*. (Fig. 7.1 is adapted from A.G. Guy, *Essentials of Materials Science*, McGraw-Hill Book Company, New York, 1976. p. 153.)

- 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*.

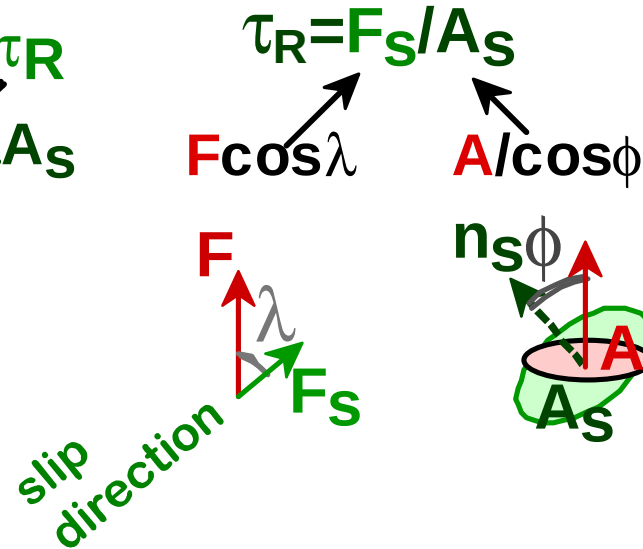
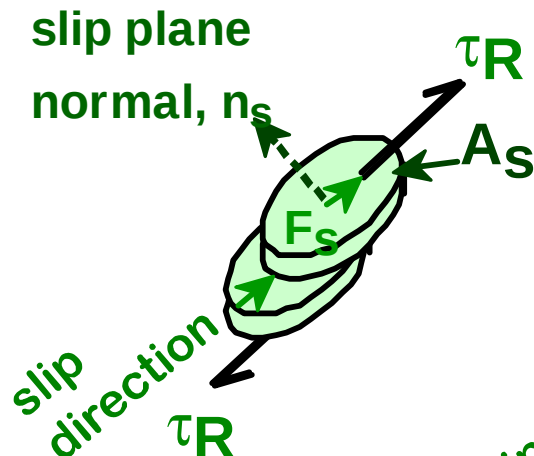
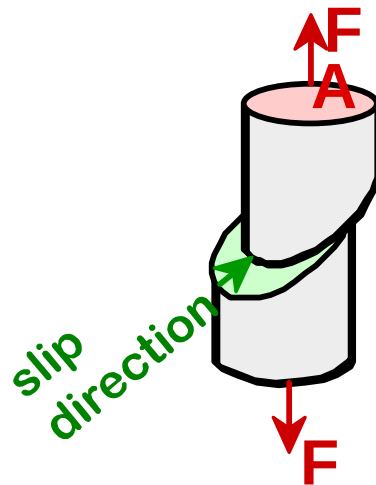
STRESS AND DISLOCATION MOTION

- 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

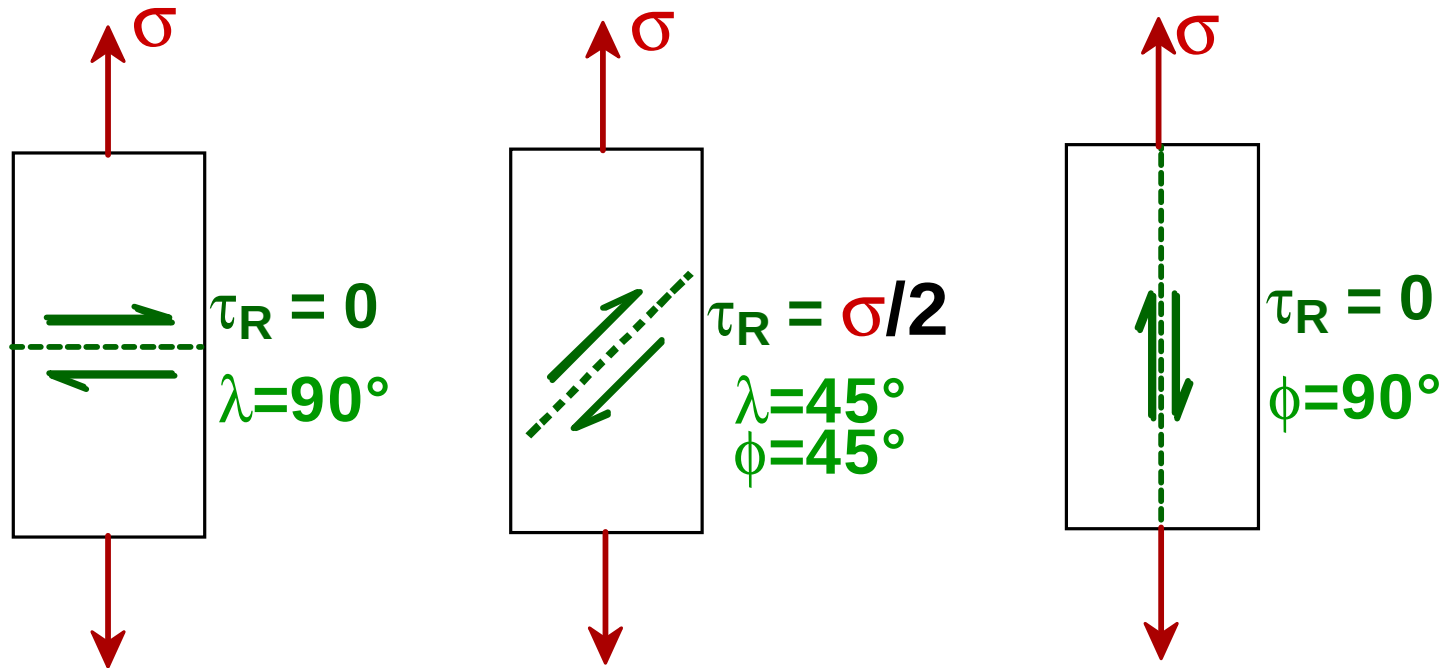


$$\tau_R = \sigma \cos \lambda \cos \phi$$

CRITICAL RESOLVED SHEAR STRESS

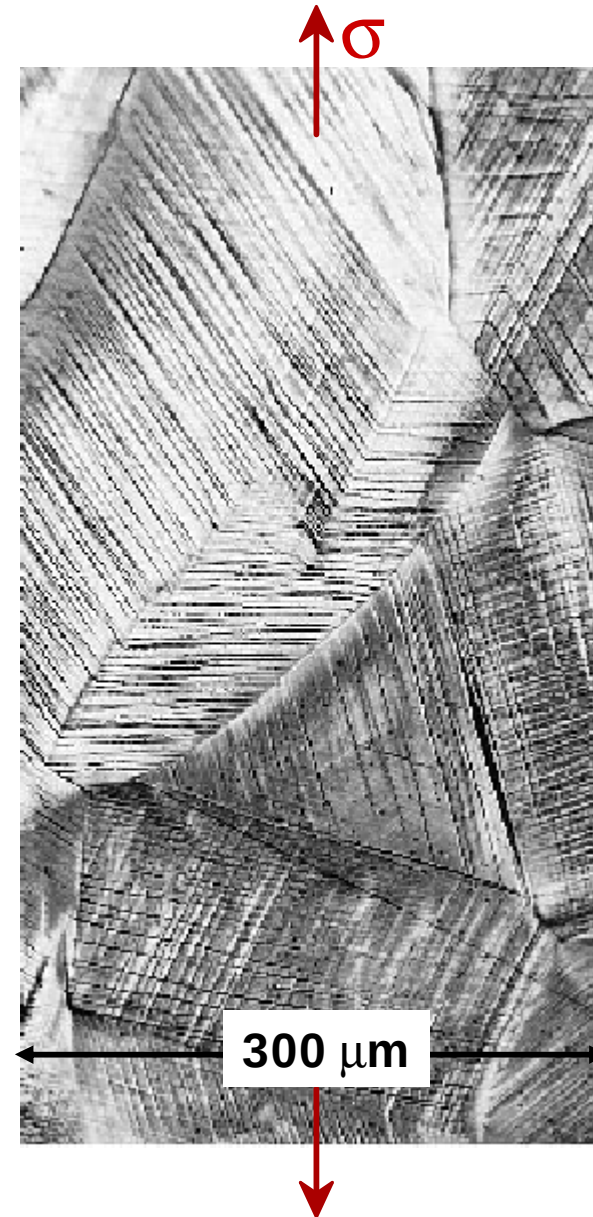
- Condition for dislocation motion: $\tau_R > \tau_{\text{CRSS}}$
 - Crystal orientation can make it easy or hard to move disl.
- $\uparrow$
typically
 10^{-4}G to 10^{-2}G

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



DISL. MOTION 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.

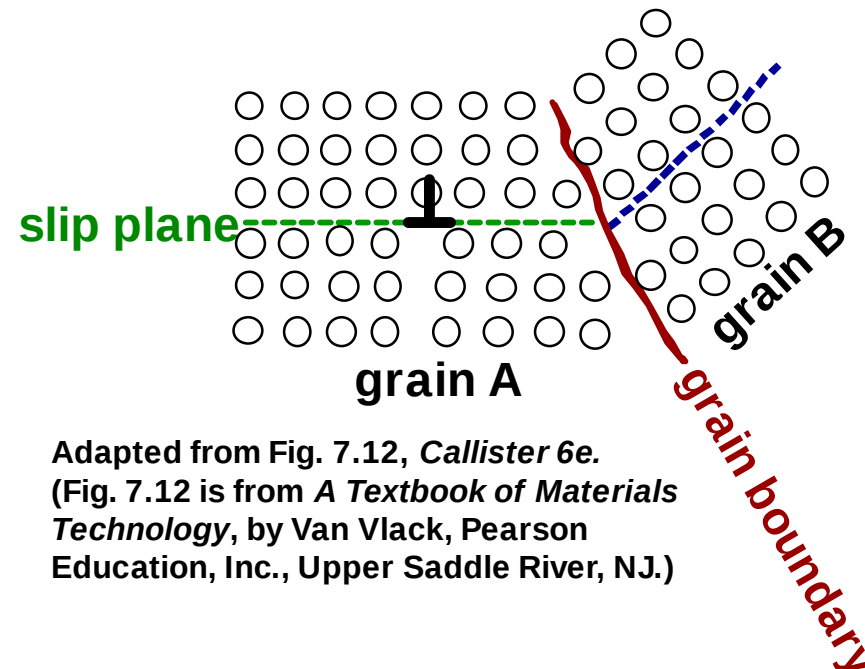


Adapted from Fig. 7.10, *Callister 6e*. (Fig. 7.10 is courtesy of C. Brady, National Bureau of Standards [now the National Institute of Standards and Technology, Gaithersburg, MD].)

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:

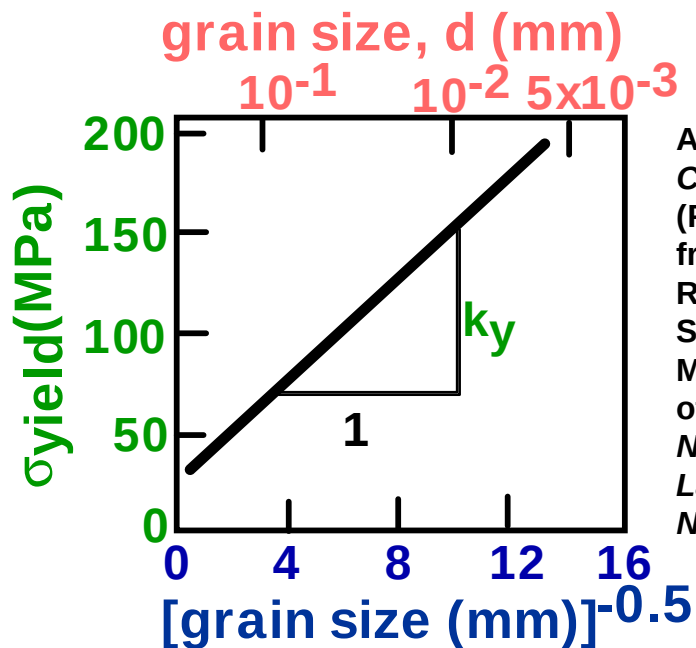
$$\sigma_{\text{yield}} = \sigma_0 + k_y d^{-1/2}$$

GRAIN SIZE STRENGTHENING: AN EXAMPLE

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

$$\sigma_{\text{yield}} = \sigma_0 + k_y d^{-1/2}$$

- 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.)

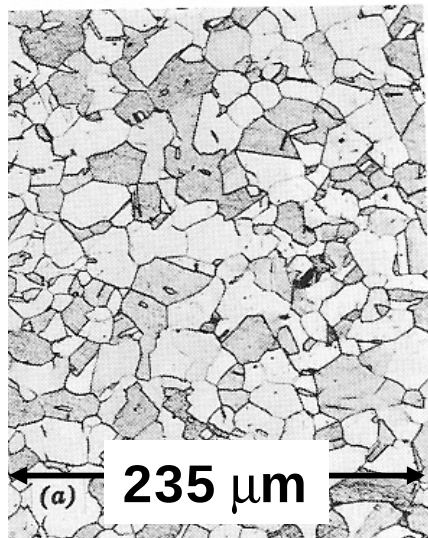


Adapted from Fig. 4.11(c), *Callister 6e*. (Fig. 4.11(c) is courtesy of J.E. Burke, General Electric Co.)

ANISOTROPY IN σ_{yield}

- Can be induced by rolling a polycrystalline metal

-before rolling



-isotropic

since grains are approx. spherical & randomly oriented.

-after rolling



rolling direction

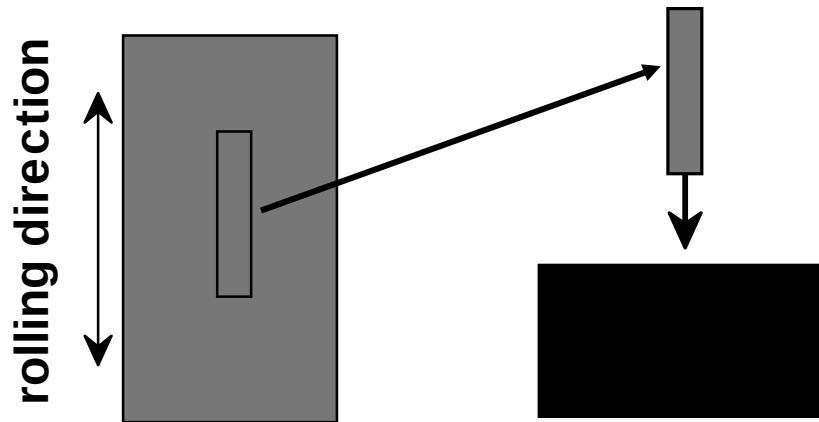
-anisotropic

since rolling affects grain orientation and shape.

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.)

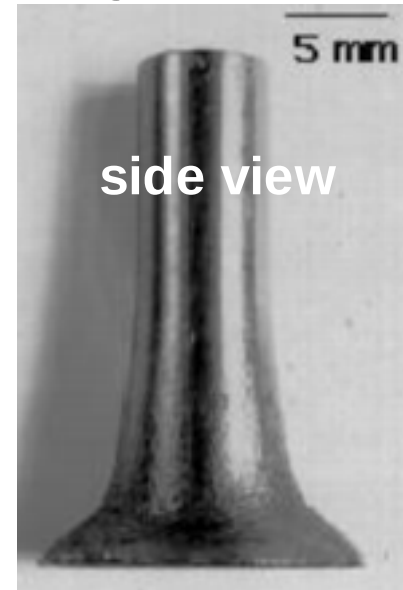
ANISOTROPY IN DEFORMATION

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.

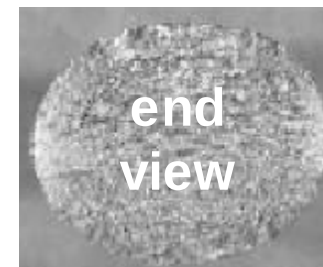
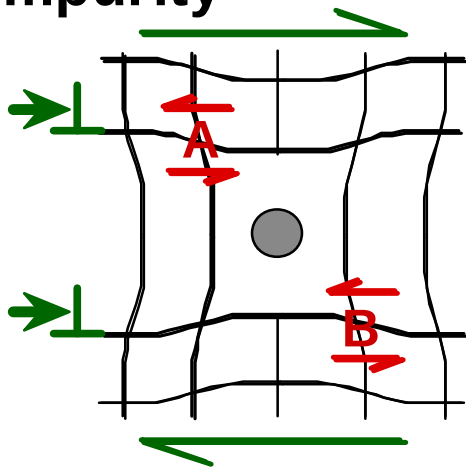


plate thickness direction

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

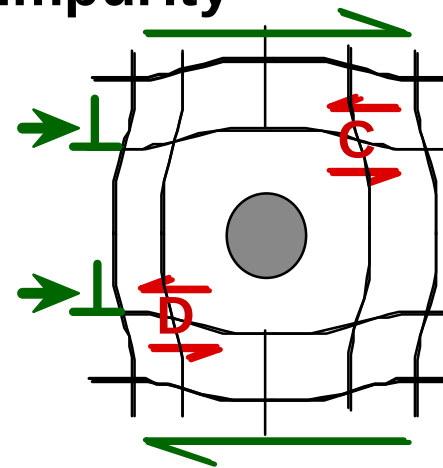
STRENGTHENING STRATEGY 2: SOLID SOLUTIONS

- 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.

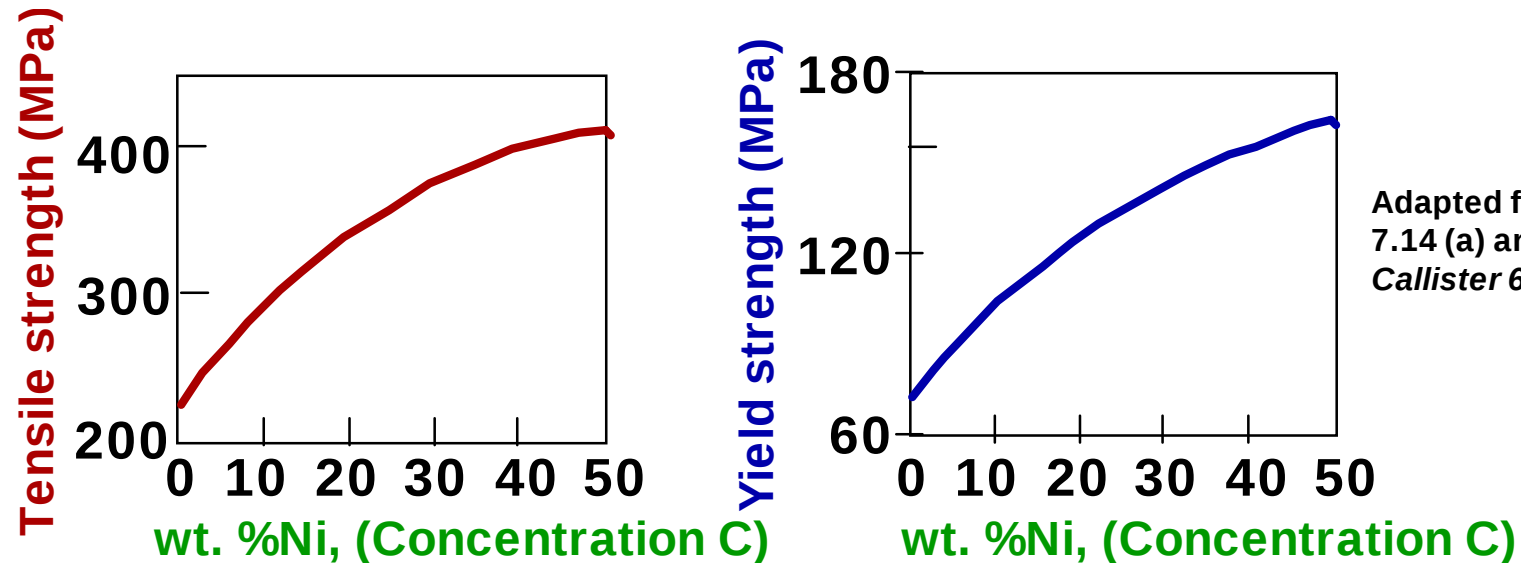
- Larger substitutional impurity



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

EX: SOLID SOLUTION STRENGTHENING IN COPPER

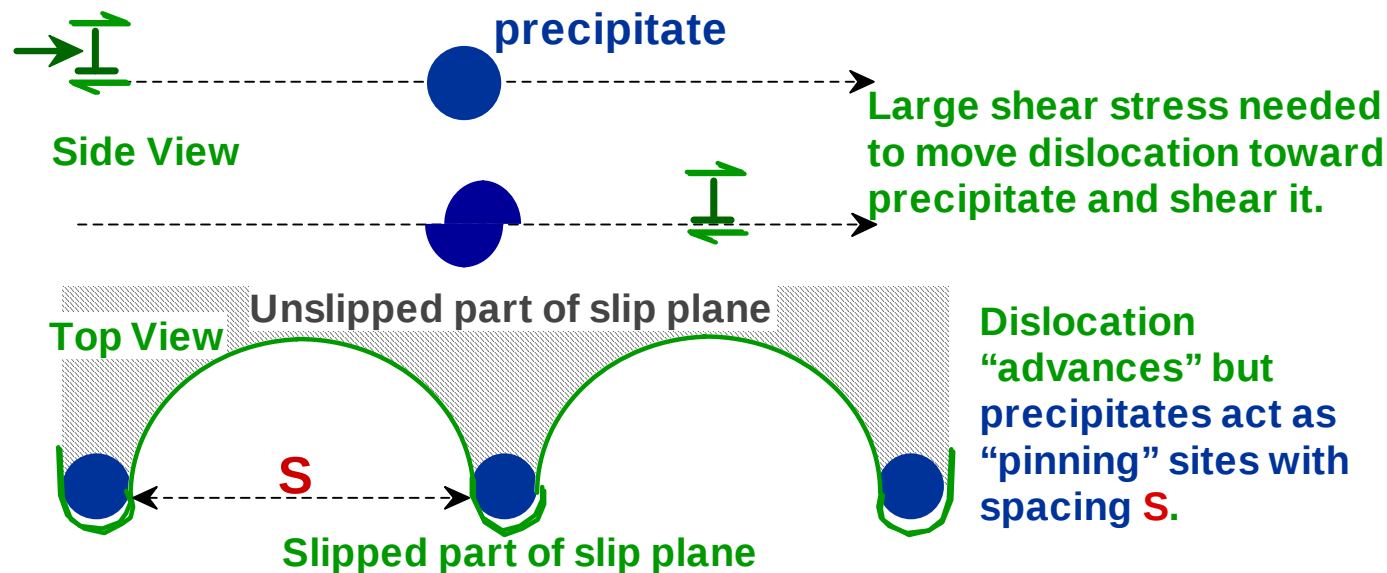
- Tensile strength & yield strength increase w/wt% Ni.



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

STRENGTHENING STRATEGY 3: PRECIPITATION STRENGTHENING

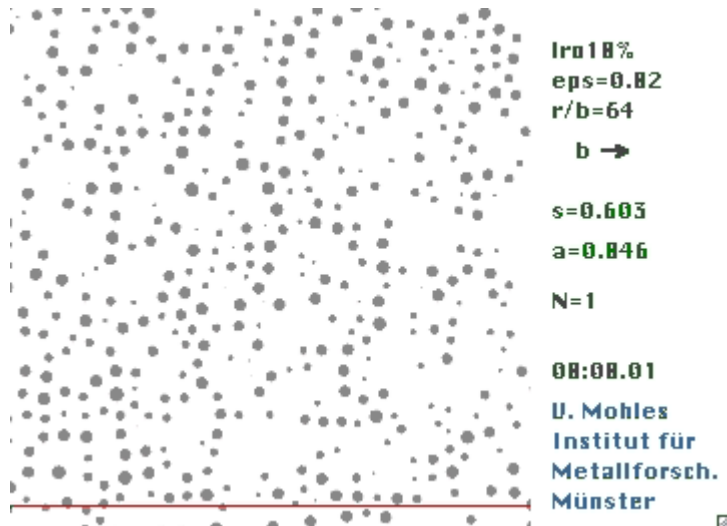
- Hard precipitates are difficult to shear.
Ex: Ceramics in metals (SiC in Iron or Aluminum).



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

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 Universität, Münster, Germany (<http://www.uni-munster.de/physik/MP/mohles/>). Used with permission.

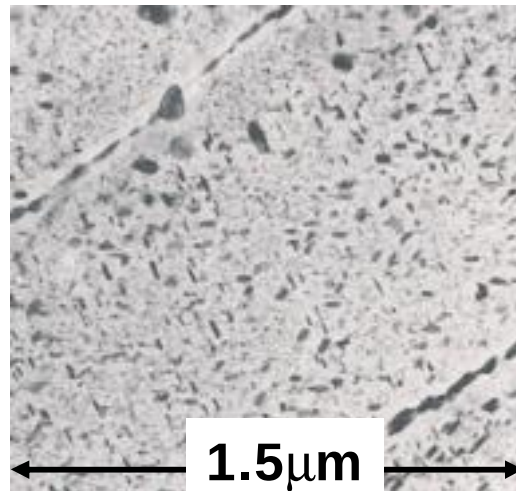
APPLICATION: PRECIPITATION STRENGTHENING

- 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.

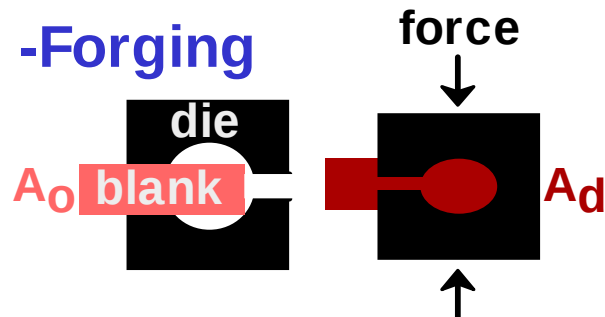


Adapted from Fig. 11.24, *Callister 6e*. (Fig. 11.24 is courtesy of G.H. Narayanan and A.G. Miller, Boeing Commercial Airplane Company.)

STRENGTHENING STRATEGY 4: COLD WORK (%CW)

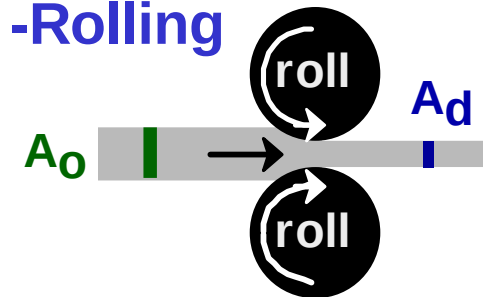
- Room temperature deformation.
- Common forming operations change the cross sectional area:

-Forging

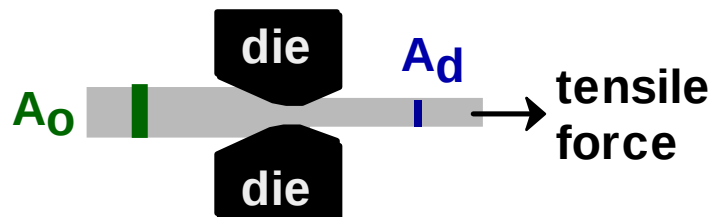


Adapted from Fig. 11.7, Callister 6e.

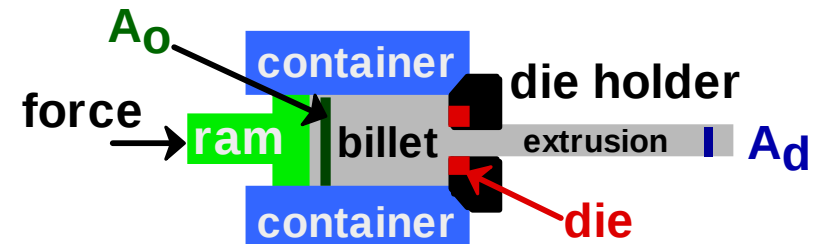
-Rolling



-Drawing



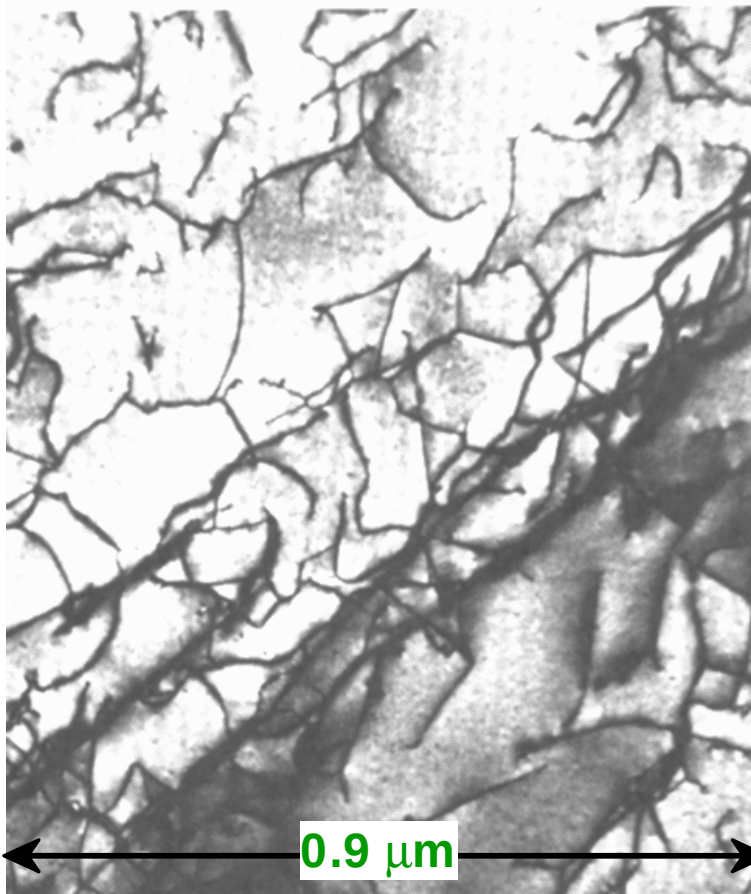
-Extrusion



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

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.)

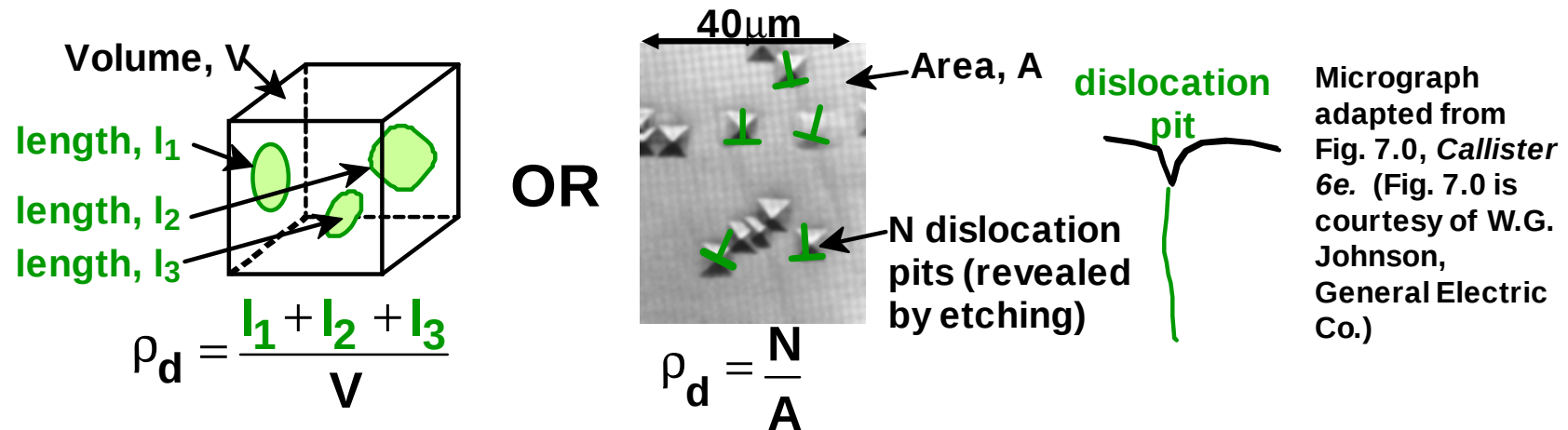
RESULT OF COLD WORK

- Dislocation density (ρ_d) goes up:

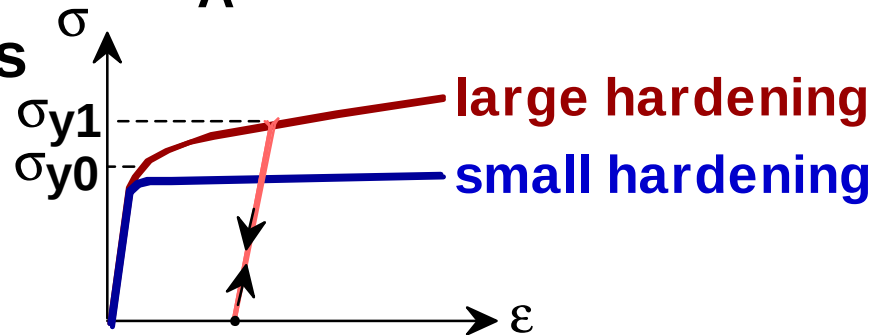
Carefully prepared sample: $\rho_d \sim 10^3 \text{ mm/mm}^3$

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

- Ways of measuring dislocation density:

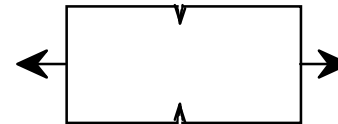
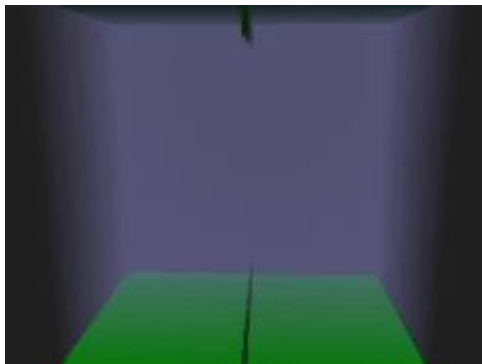


- Yield stress increases as ρ_d increases:



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.

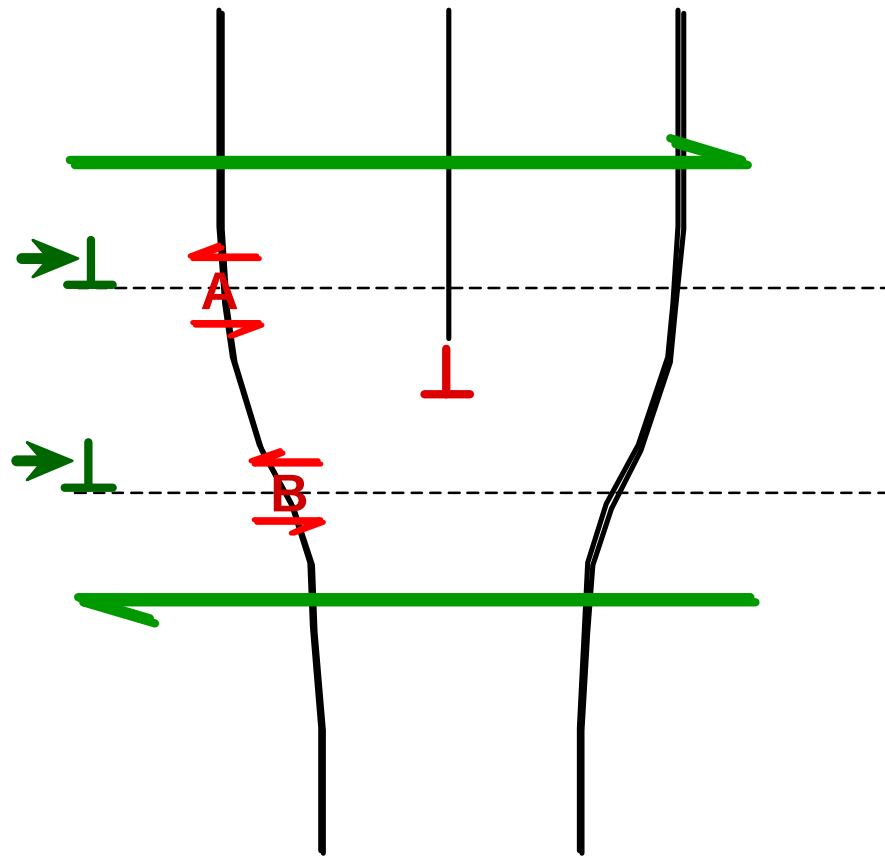


Simulation courtesy of Farid Abraham. Used with permission from International Business Machines Corporation.

DISLOCATION-DISLOCATION TRAPPING

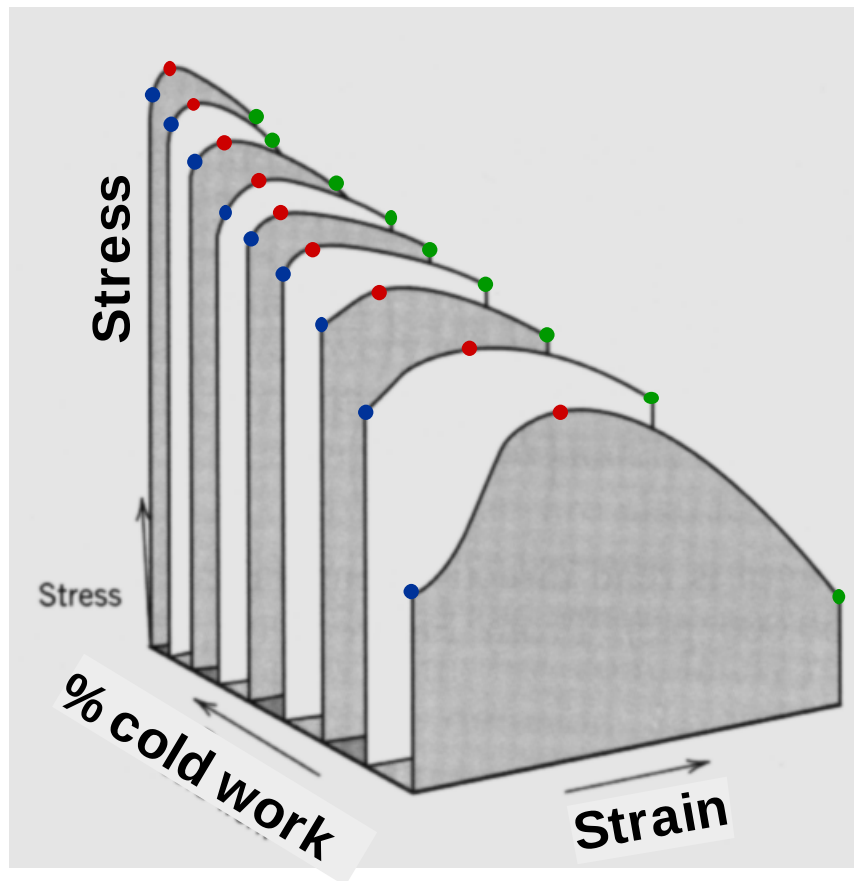
- Dislocation generate stress.
- This traps other dislocations.

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.

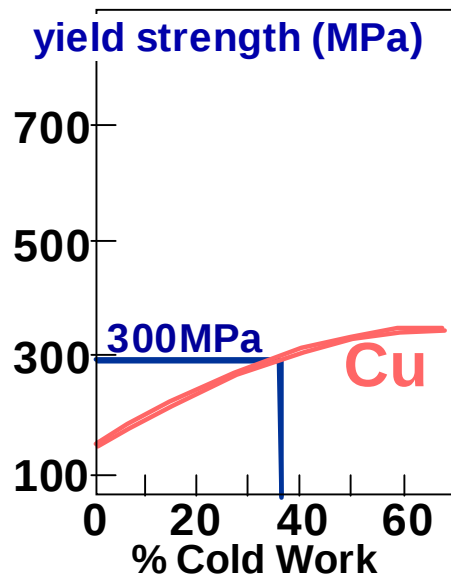
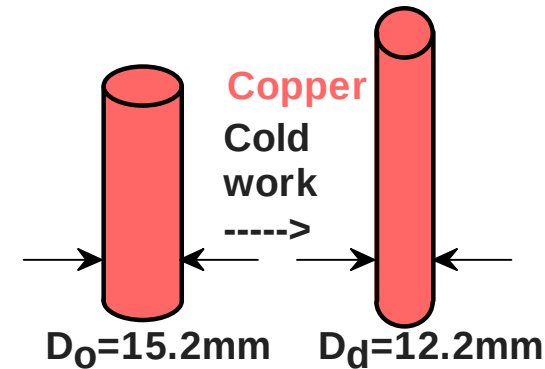


Adapted from Fig. 7.18, *Callister 6e*. (Fig. 7.18 is from *Metals Handbook: Properties and Selection: Iron and Steels*, Vol. 1, 9th ed., B. Bardes (Ed.), American Society for Metals, 1978, p. 221.)

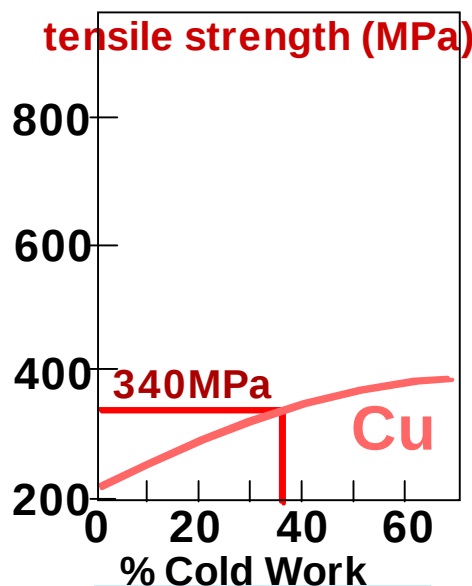
COLD WORK ANALYSIS

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

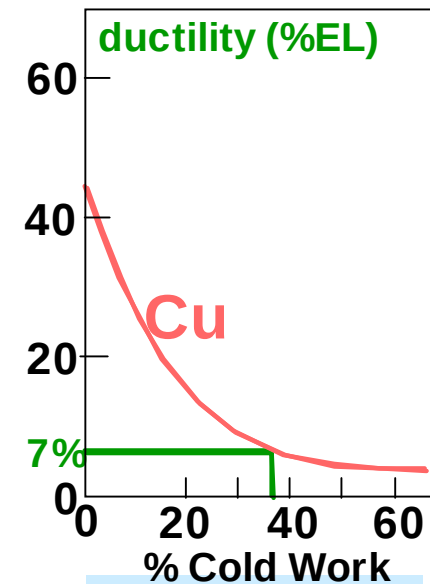
$$\%CW = \frac{\pi r_o^2 - \pi r_d^2}{\pi r_o^2} \times 100 = 35.6\%$$



$\sigma_y = 300\text{MPa}$



TS=340MPa



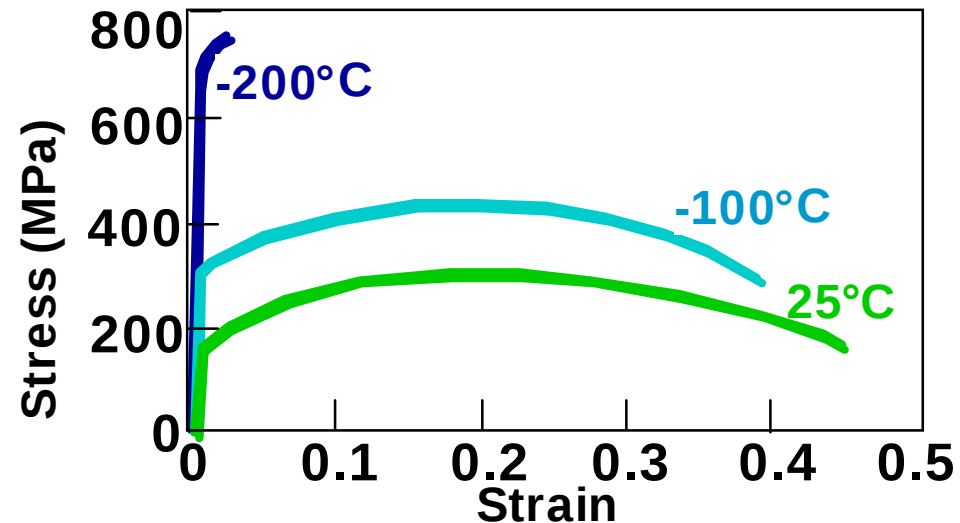
%EL=7%

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.)

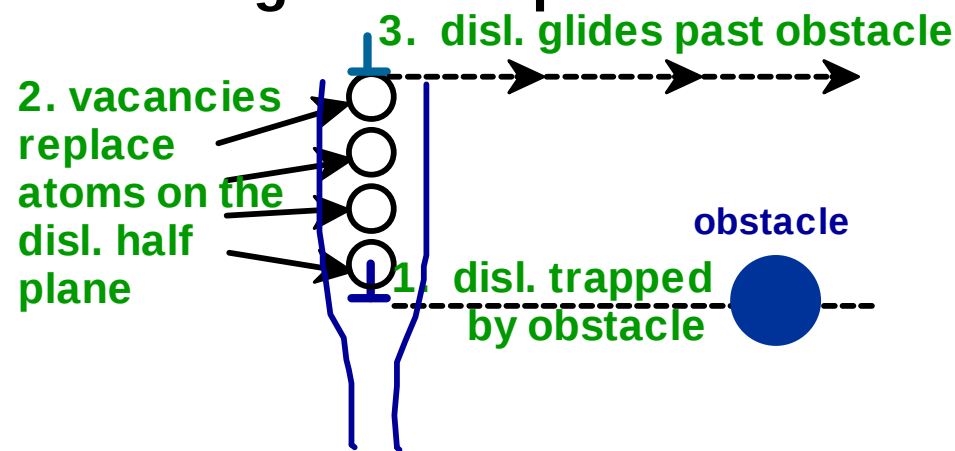
σ - ϵ BEHAVIOR VS TEMPERATURE

- Results for polycrystalline iron:

Adapted from Fig. 6.14,
Callister 6e.

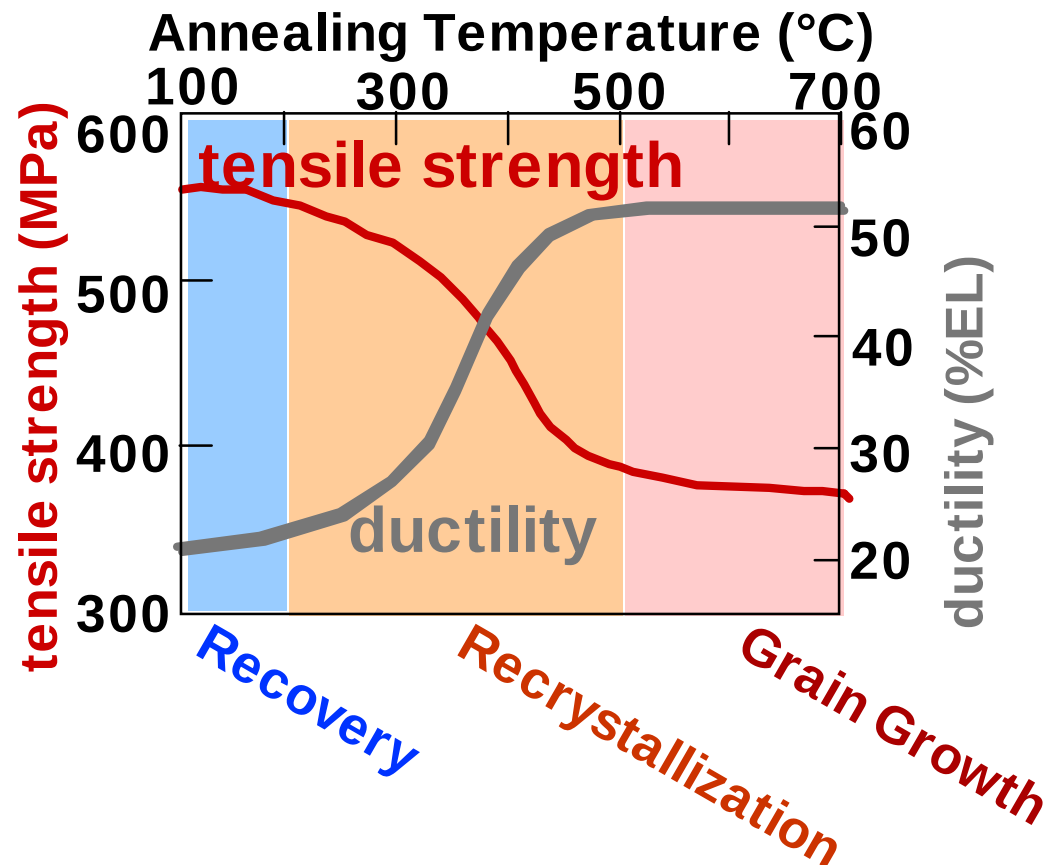


- σ_y and TS *decrease* with increasing test temperature.
- %EL *increases* with increasing test temperature.
- Why? Vacancies help dislocations past obstacles.



EFFECT OF HEATING AFTER %CW

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

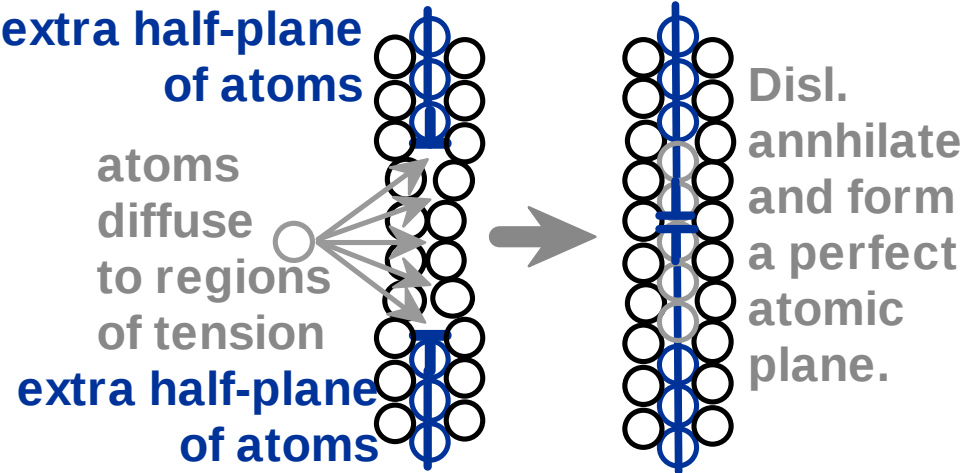


- 3 Annealing stages to discuss...

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**


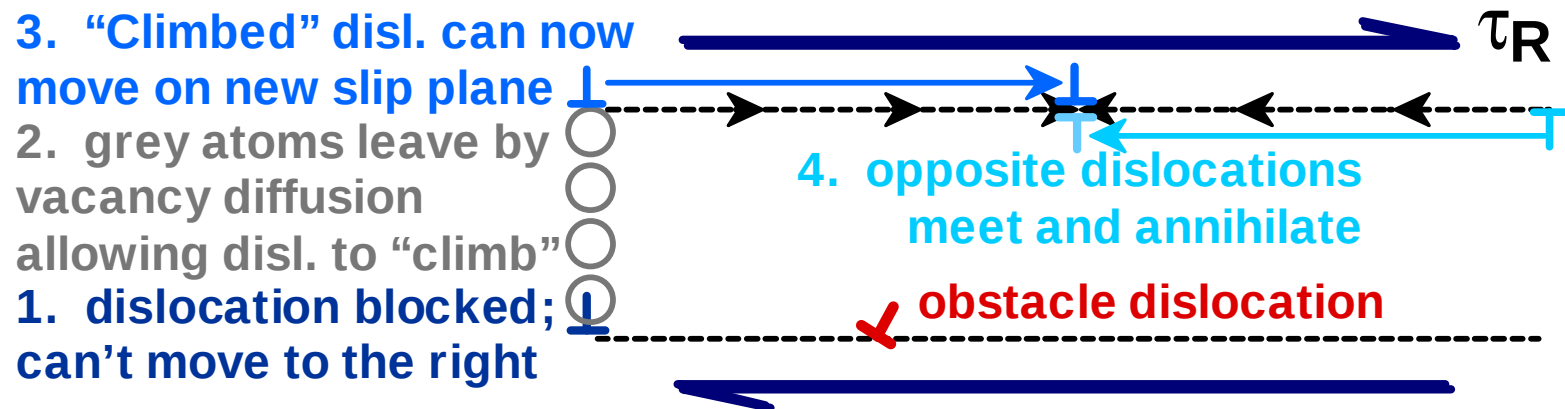
extra half-plane of atoms

atoms diffuse to regions of tension

extra half-plane of atoms

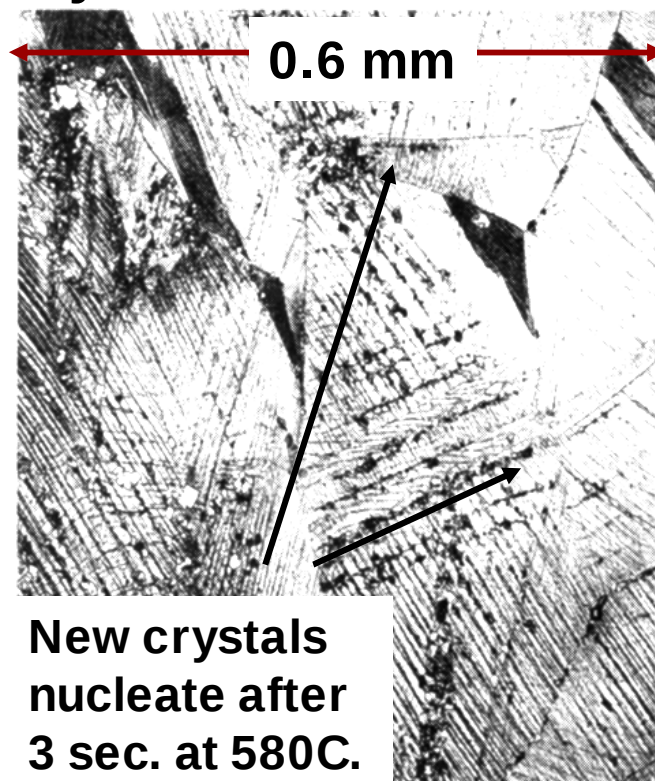
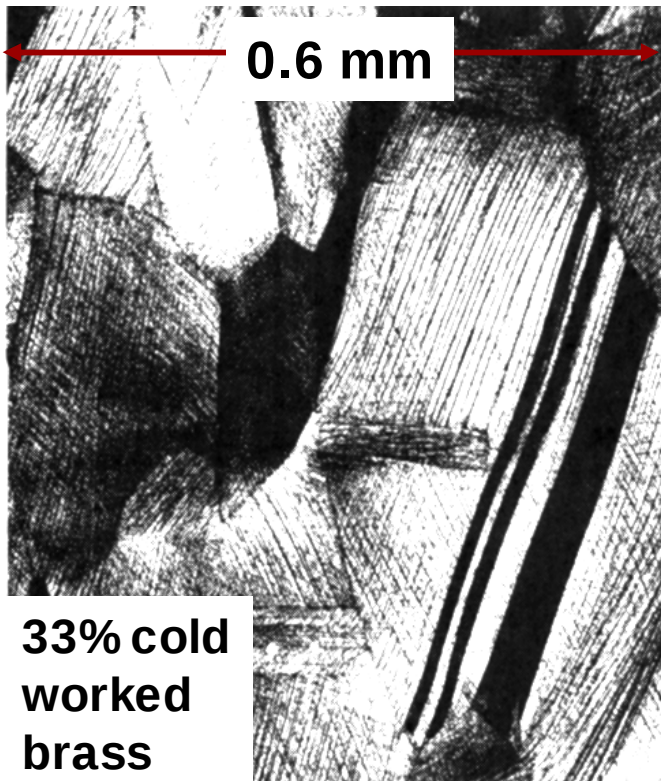
Disl. annihilate and form a perfect atomic plane.

- **Scenario 2**



RECRYSTALLIZATION

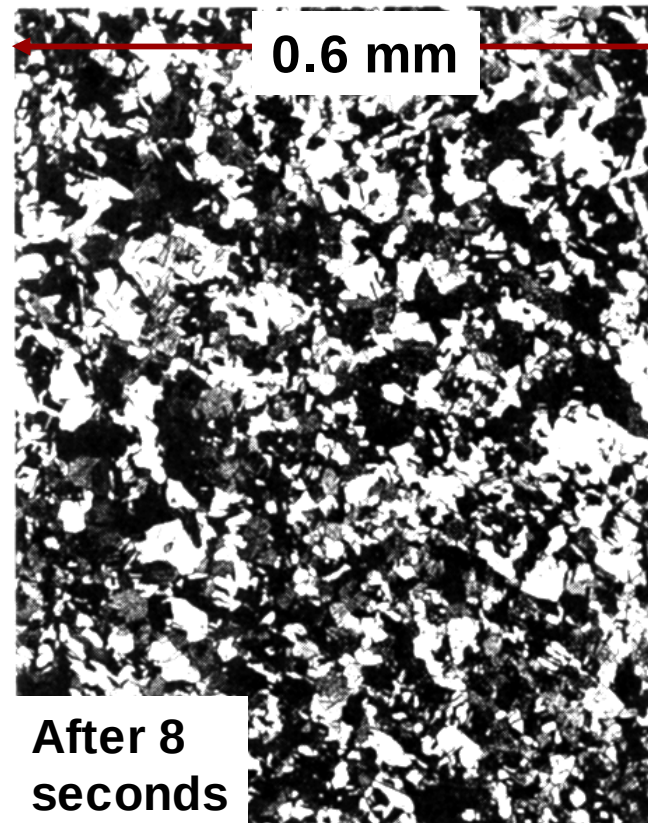
- New crystals are formed that:
 - have a small disl. density
 - are small
 - consume cold-worked crystals.



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

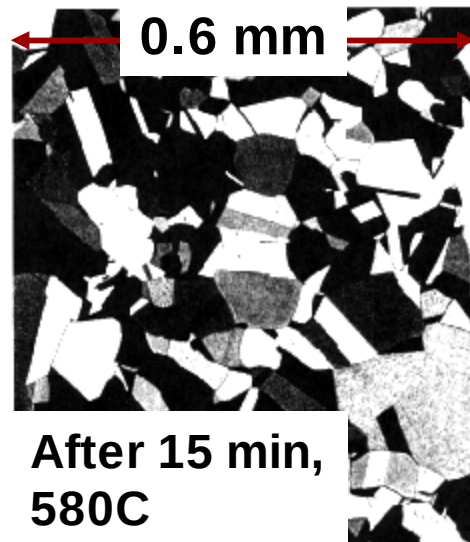
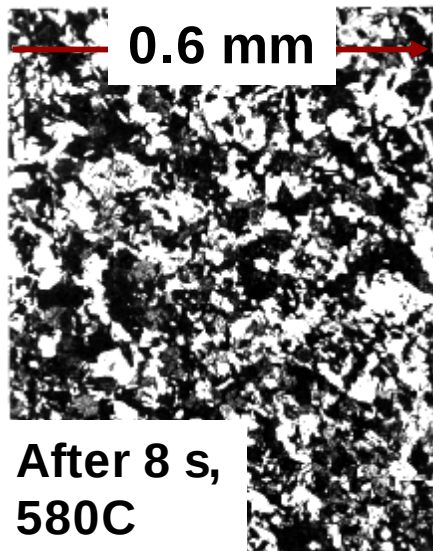
- All cold-worked crystals are consumed.



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:

exponent typ. ~ 2
grain diam.
at time t.

$$d^n - d_0^n = Kt$$

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.