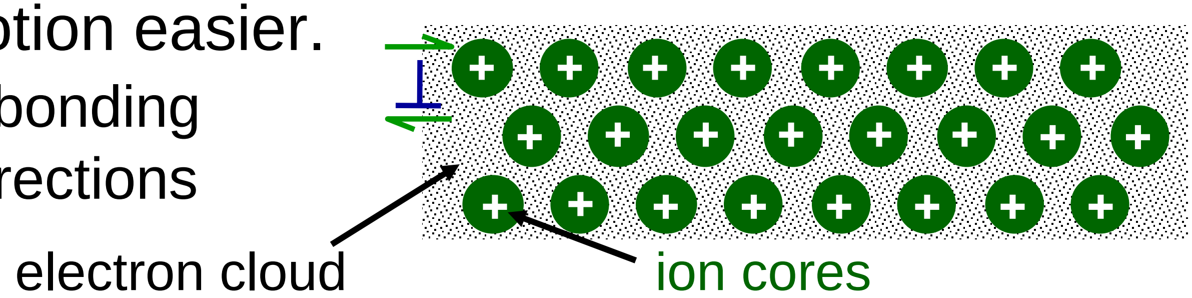
Chapter 7:
Dislocations & Strengthening Mechanisms

ISSUES TO ADDRESS...

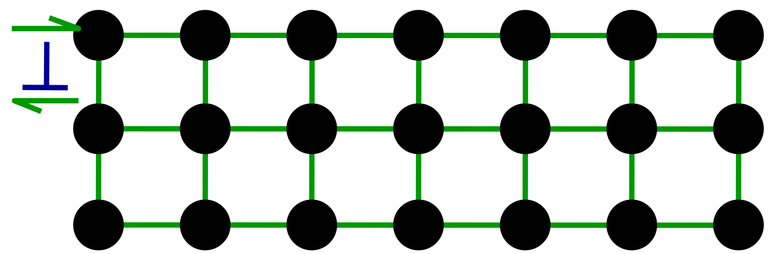
- Why are dislocations observed primarily in metals and alloys?
- How are strength and dislocation motion related?
- How do we increase strength?
- What materials are strengthened for electrical engineering?
- What EE applications require strengthening?

Dislocations & Materials Classes

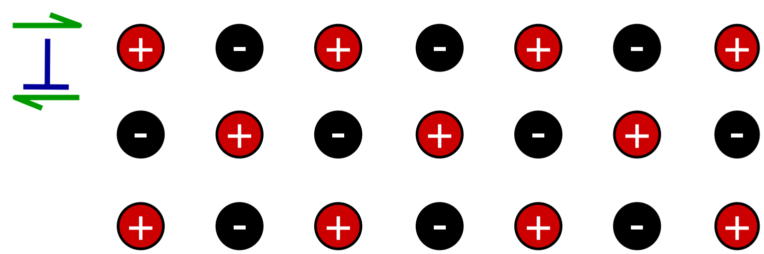
- Metals: Disl. motion easier.
  - -non-directional bonding
  - -close-packed directions for slip.



- Non-metals (covalent bonds) (Si, diamond): Motion hard.
  - -directional (angular) bonding



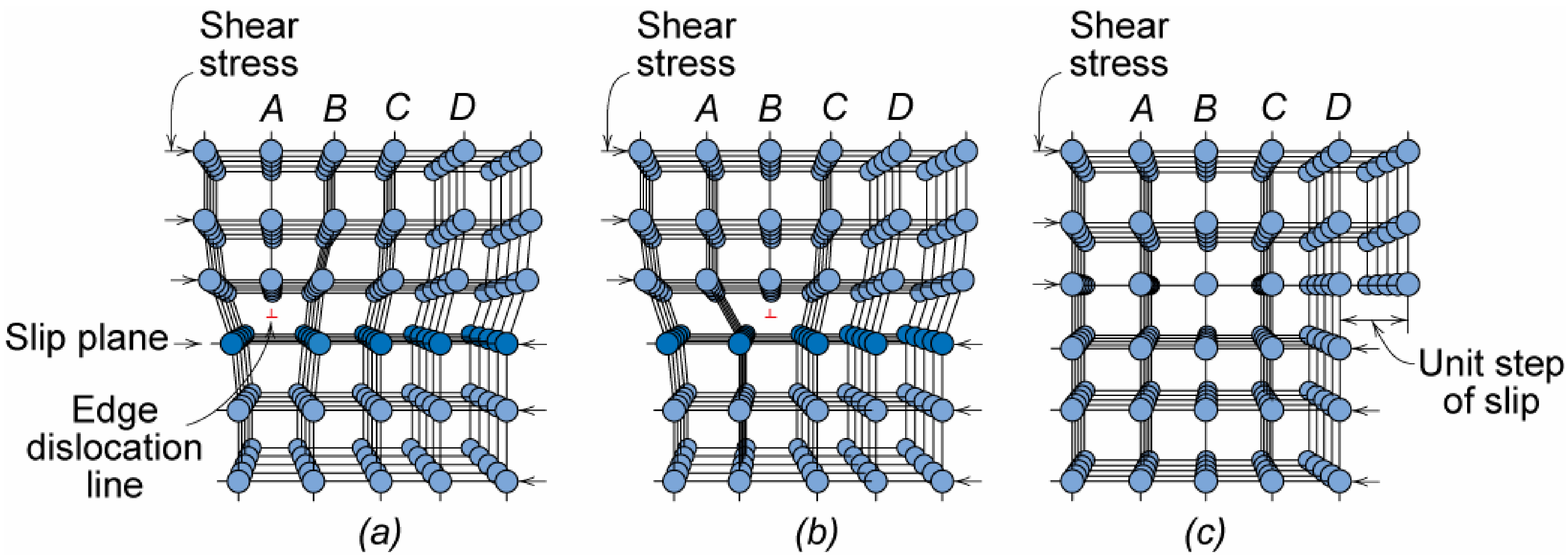
- Ionic Ceramics (NaCl): Motion hard.
  - -need to avoid ++ and - - neighbors.



Dislocation Motion

Dislocations & plastic deformation

- Cubic & hexagonal metals - plastic deformation by plastic shear or slip where one plane of atoms slides over adjacent plane by defect motion (dislocations).



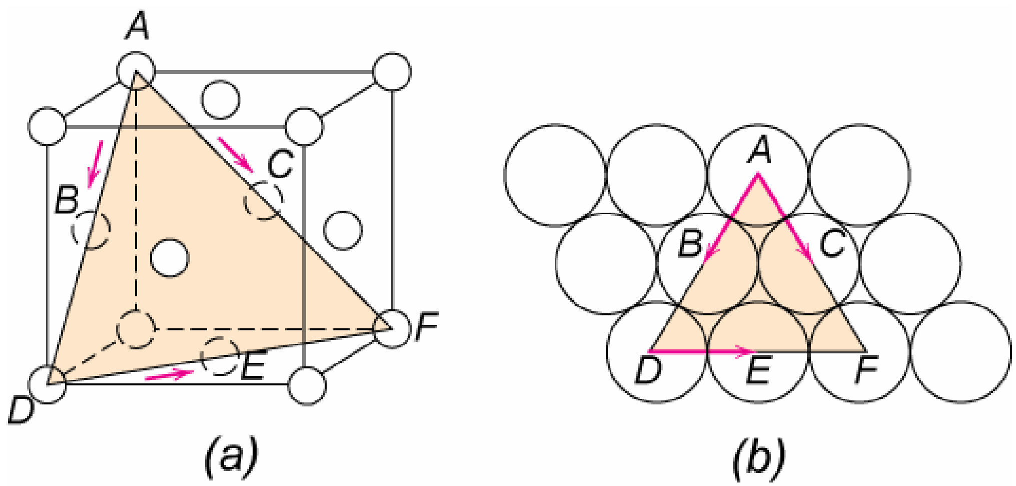
- If dislocations don't move, deformation doesn't occur!

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

Deformation Mechanisms

Slip System

– Slip plane - plane allowing easiest slippage
  - Wide interplanar spacings - highest planar densities
– Slip direction - direction of movement - Highest linear densities



Adapted from Fig. 7.6, *Callister 7e.*

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

=> total of 12 slip systems in FCC

– in BCC & HCP other slip systems occur

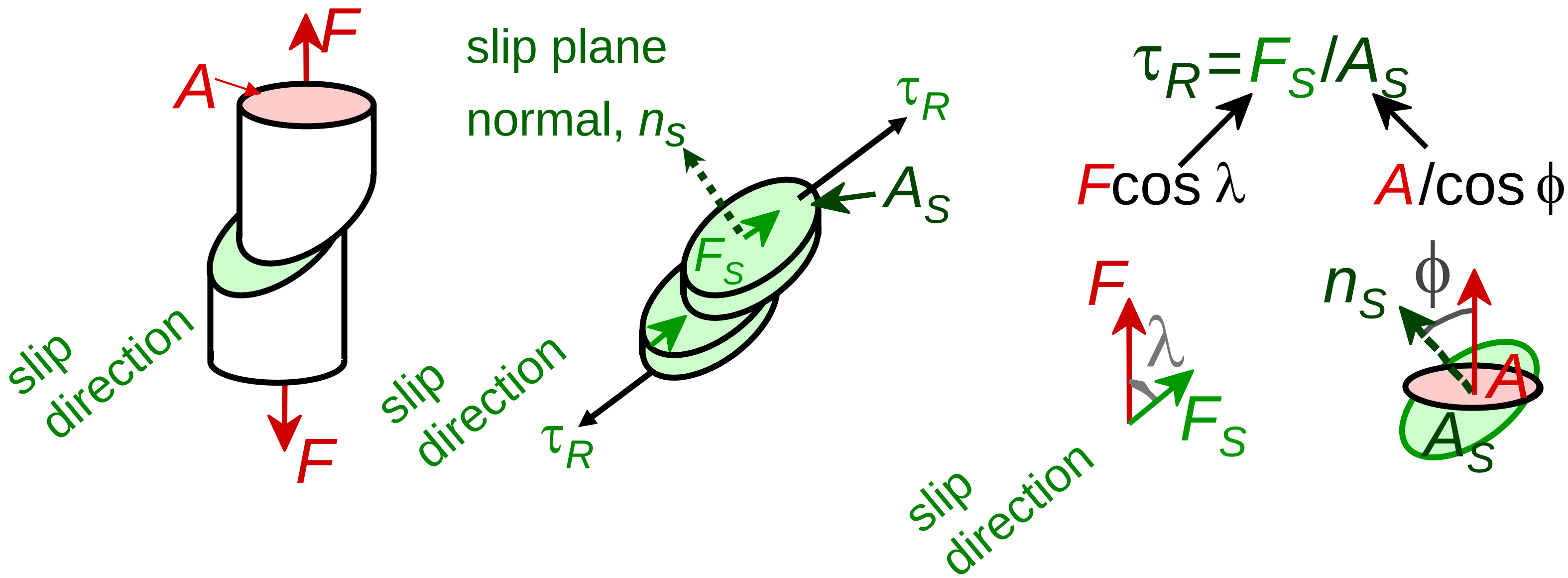
Stress and Dislocation Motion

- Crystals slip due to a resolved shear stress, τ_R.
- Applied tension can produce such a stress.

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

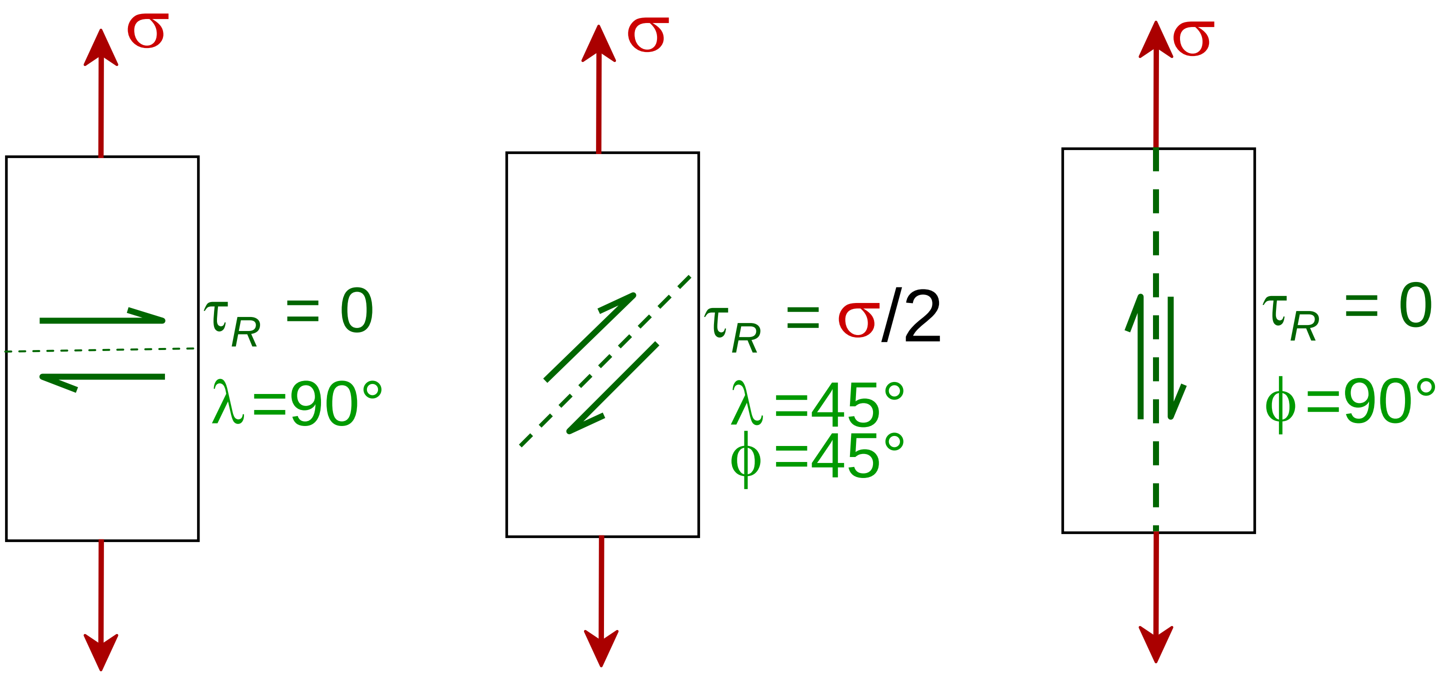
- Condition for dislocation motion: $\tau_R > \tau_{CRSS}$

typically

10^{-4} GPa to 10^{-2} GPa

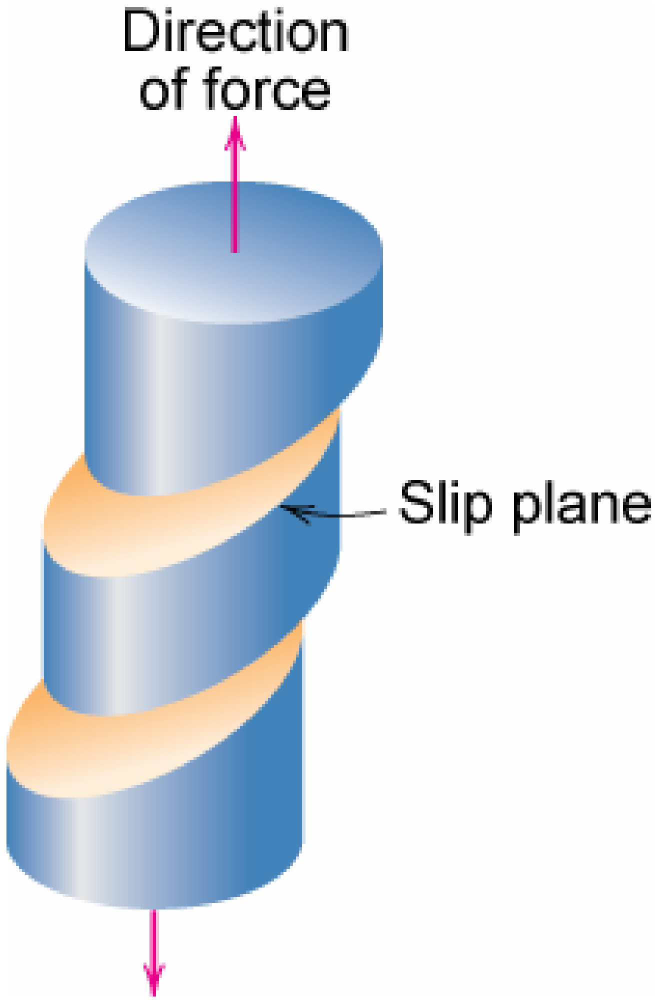
- Crystal orientation can make it easy or hard to move dislocation

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



τ maximum at $\lambda = \phi = 45^o$

Single Crystal Slip



Adapted from Fig. 7.8, *Callister 7e.*

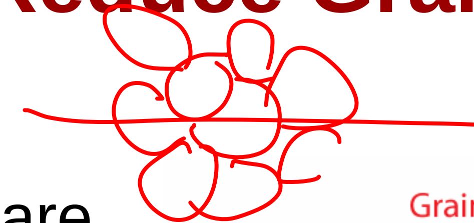
Adapted from Fig. 7.9, *Callister 7e.*

Slip Motion in Polycrystals

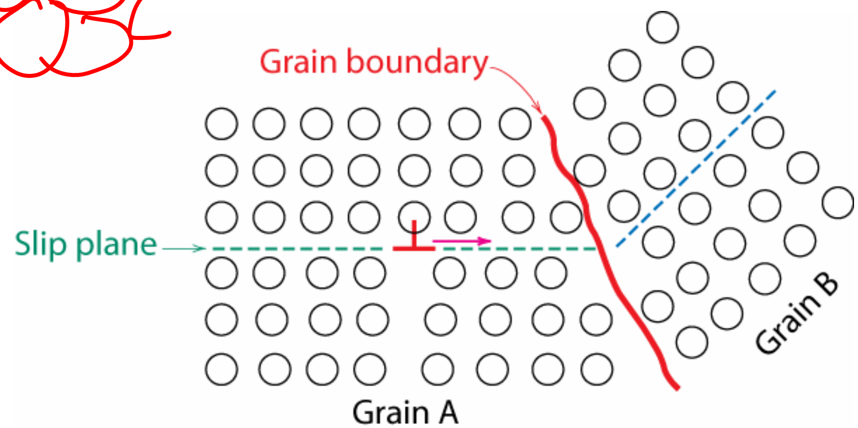
- Stronger - grain boundaries pin deformations
- Slip planes & directions (λ, ϕ) change from one crystal to another.
- τ_R will vary from one crystal to another.
- The crystal with the largest τ_R yields first.
- Other (less favorably oriented) crystals yield later.

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].)

Four 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.)

H-P coefficient

- Hall-Petch Equation:

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

grain size

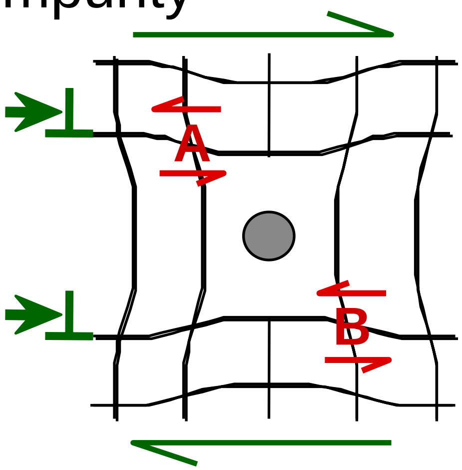
Grain Size in Microelectronics?

- **Sputtered & evaporated metal films often are nanocrystalline**
  - **Stronger than bulk**
  - **Slightly less conductive than bulk**
- **Grain sizes in solder joints range from 100's of nm to a few microns**
  - **No significant strengthening or effect on conductivity**

Four Strategies for Strengthening: #2: Solid Solutions

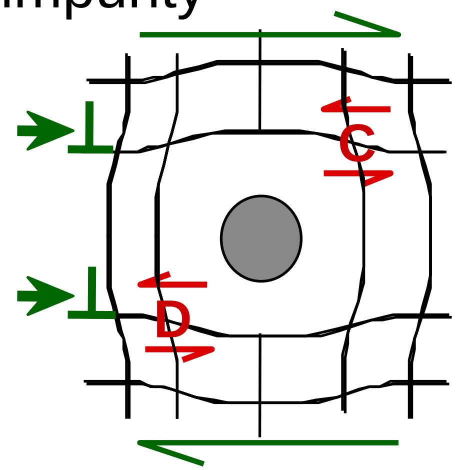
- Impurity atoms distort the lattice & generate stress.
- Stress can produce a barrier to dislocation motion.

- Smaller substitutional impurity



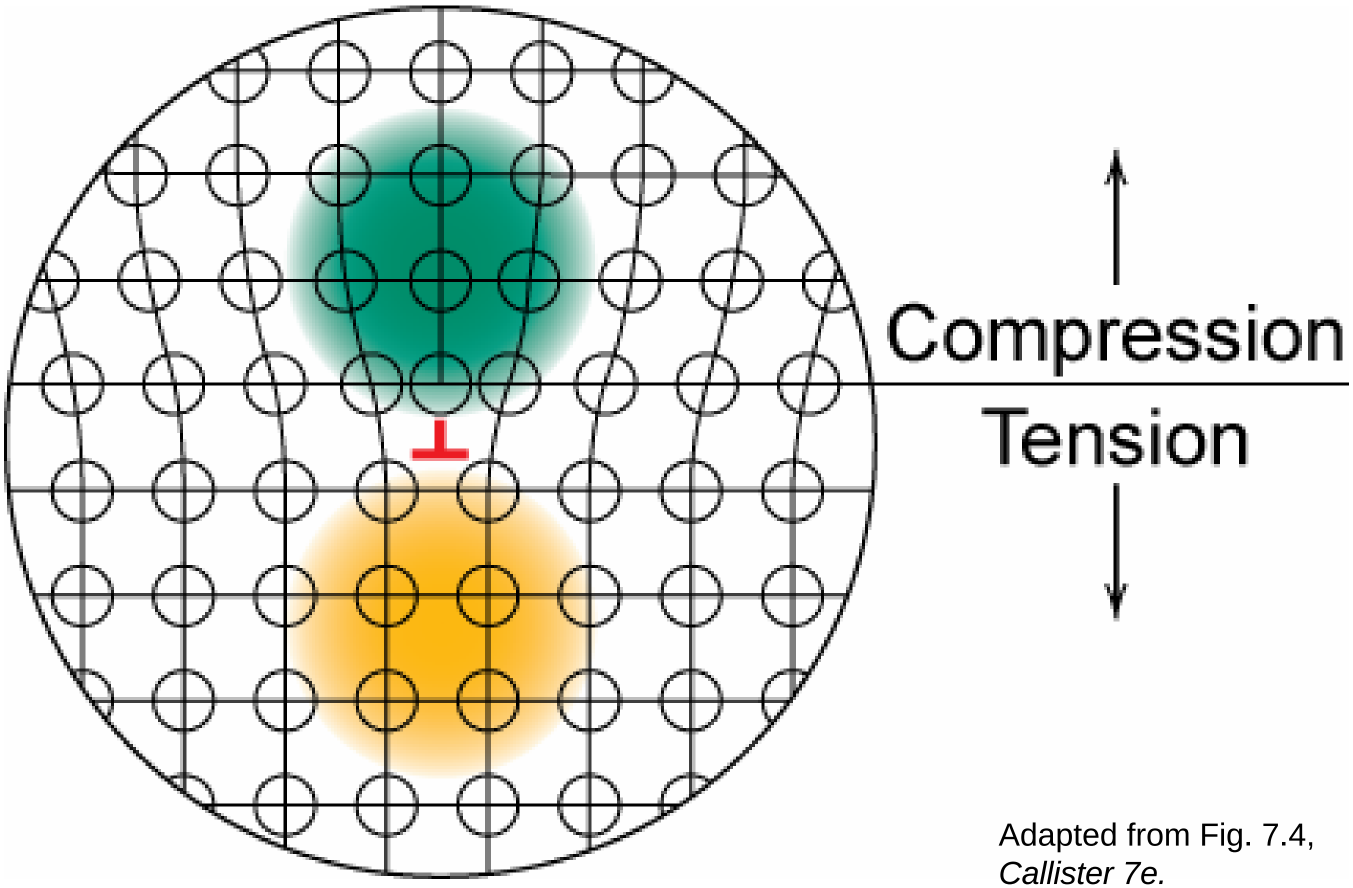
Impurity generates local stress at **A** and **B** that opposes dislocation motion to the right.

- Larger substitutional impurity



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

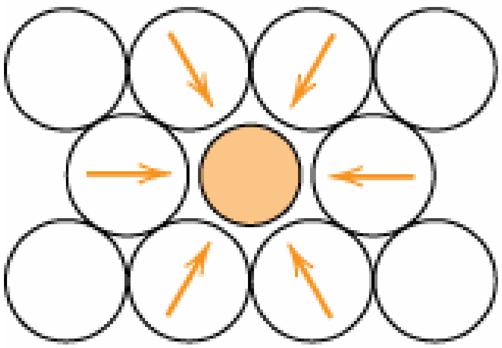
Stress Concentration at Dislocations



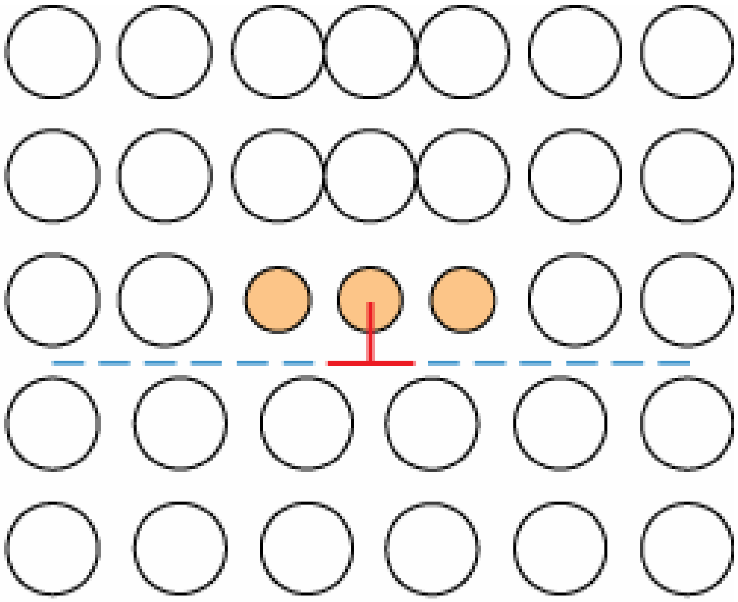
Adapted from Fig. 7.4, *Callister 7e.*

Strengthening by Alloying

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



(a)

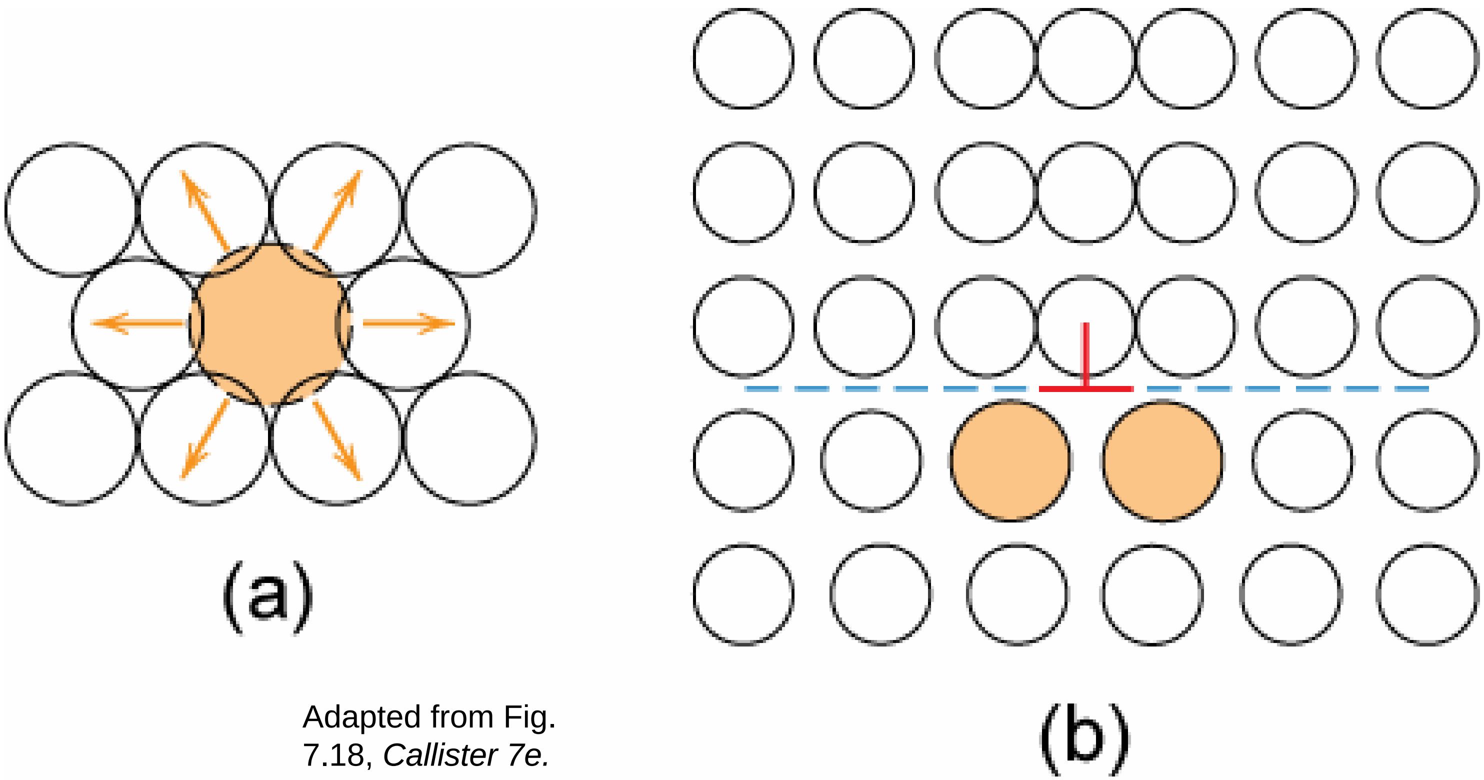


(b)

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

Strengthening by alloying

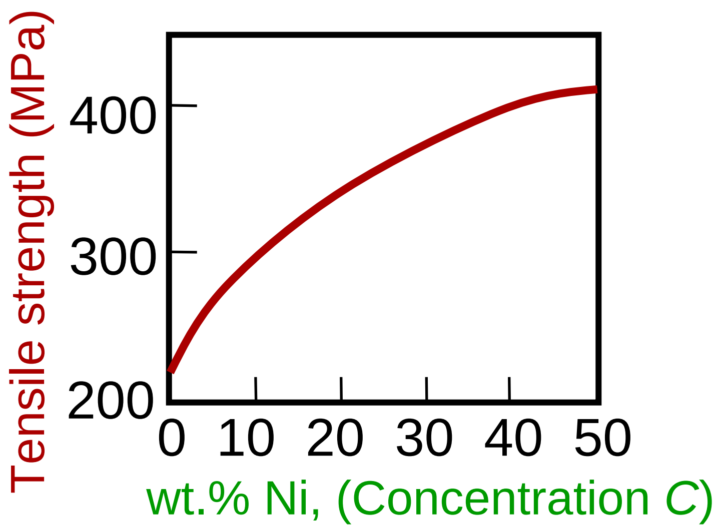
- large impurities concentrate at dislocations on low density side

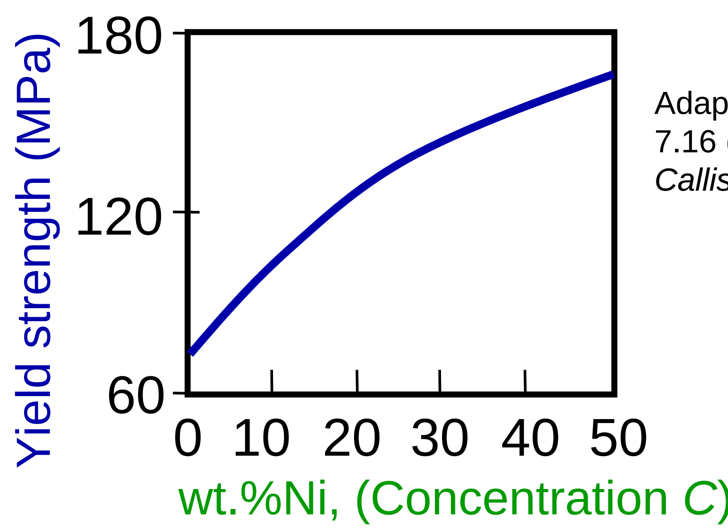


Adapted from Fig. 7.18, *Callister 7e.*

Ex: Solid Solution Strengthening in Copper

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





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

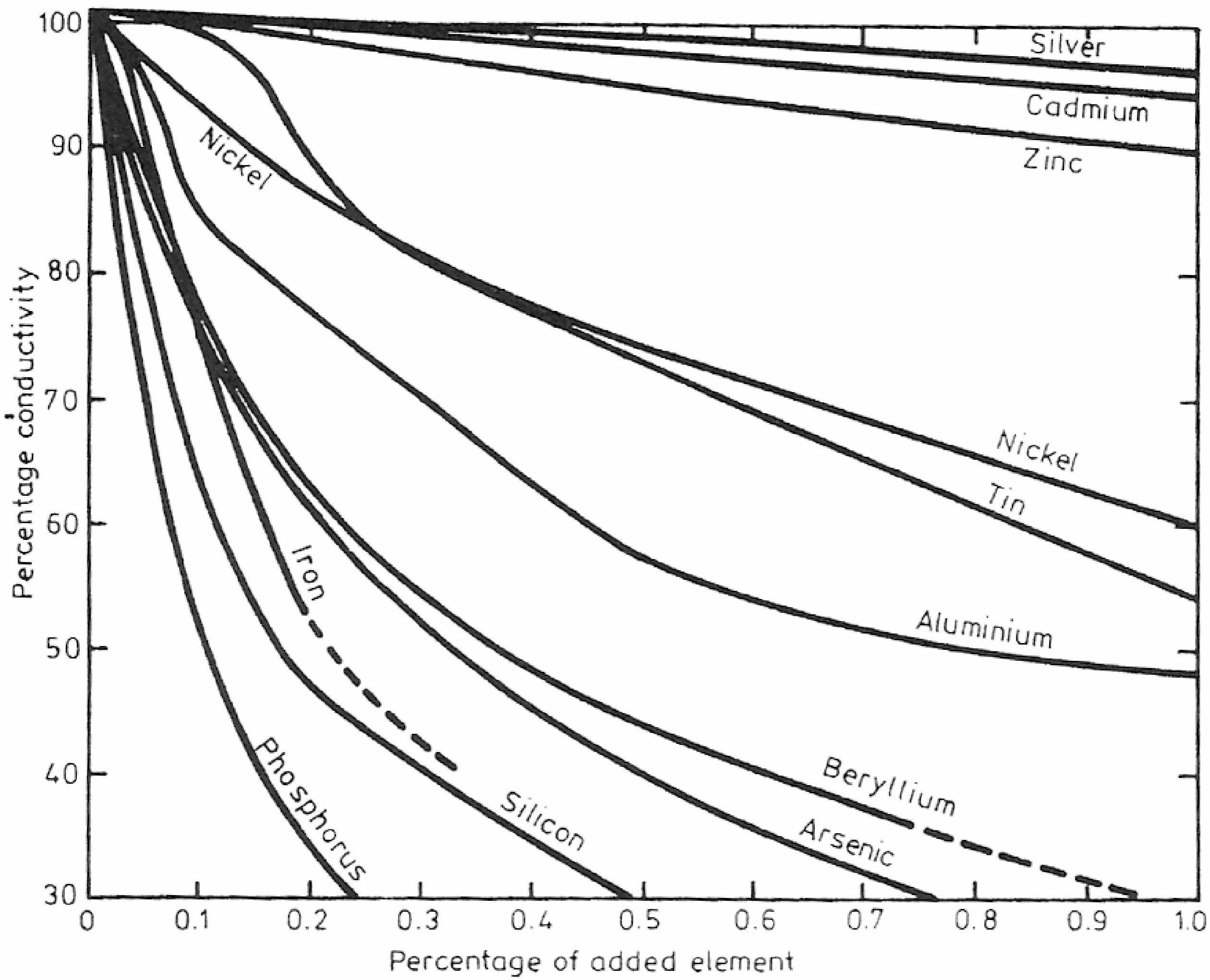
- Empirical relation: $\sigma_y \sim C^{1/2}$

- Alloying increases σ_y and *TS*.

Common Solid Solution Cu Alloys

- Cu-0.08%Ag
  - Commutators
  - Switch gear contacts
- Cu-0.7%Cd
  - Overhead wires for trains
- Cu-30%Zn
  - Cheap electronics
  - Terminals, 3-pin plugs, screw on light bulb

Effect of Solid Solution on Conductivity

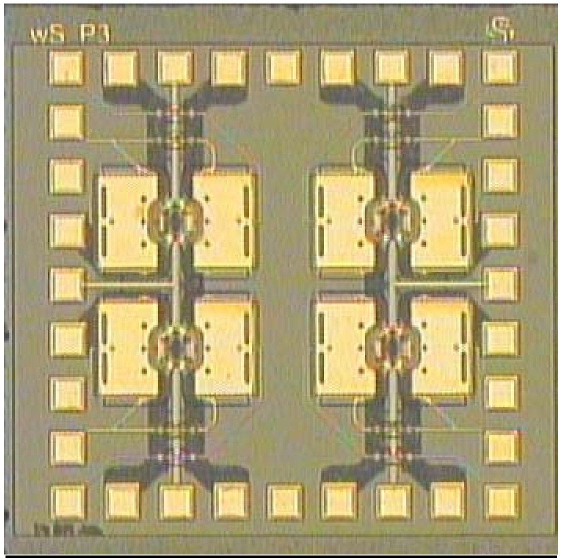


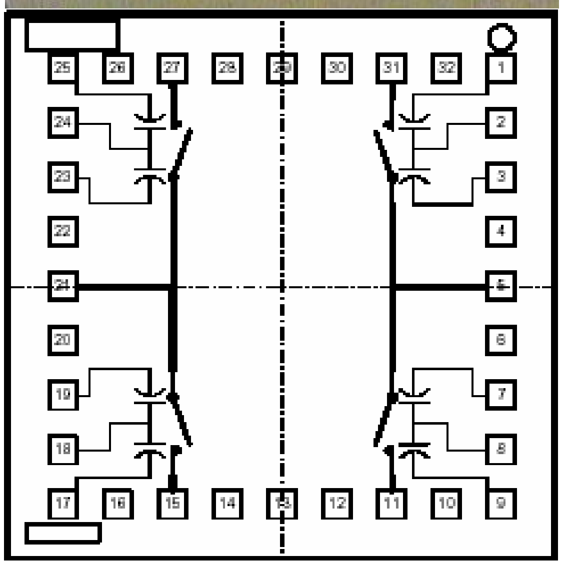
$(\Delta Z)^2$

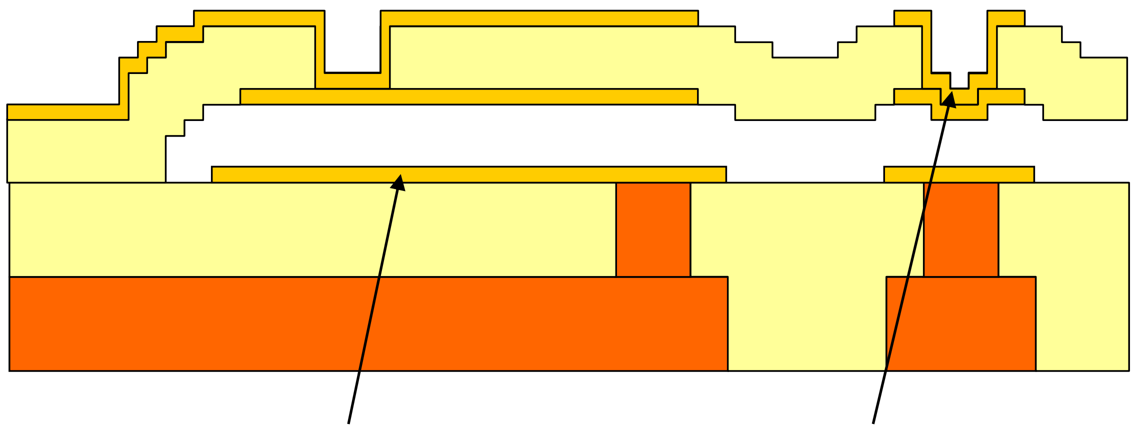
- **Closer valency has less profound effect on reducing conductivity.**

Solid solution alloying

radio frequency ← **RF MEMS** → micro electro mechanical systems







wiSpry

Candidates include…

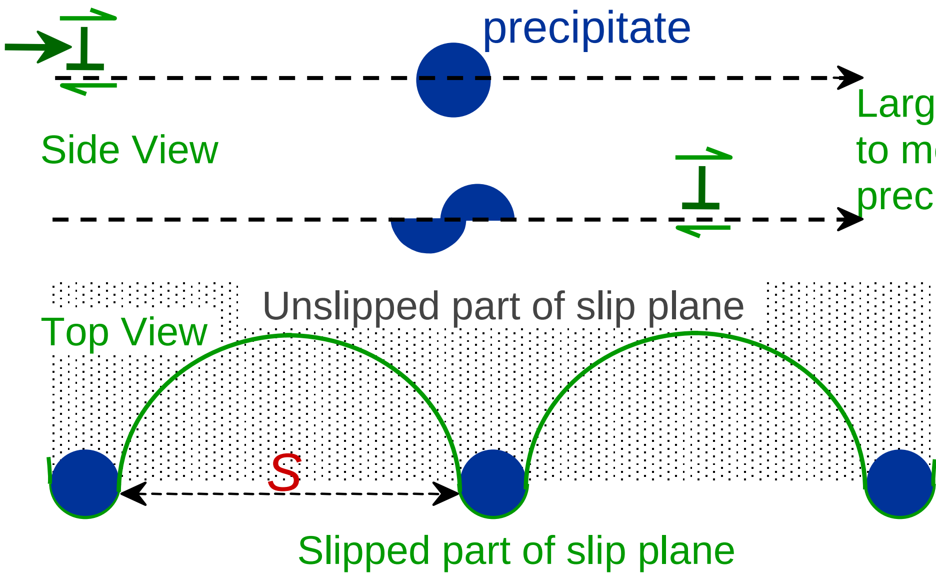
- Au-V, Au-Ni
- Pt-Ir, Pt-Ru
- Many others…
- Requirements would be
  - "Host" metal is noble or near noble
  - Phase diagram with the impurity shows significant solid solution on the host side
  - Another reason to know your Hume-Rothery rules!

Four Strategies for Strengthening: #3: Precipitation Strengthening

Chapter 11.9

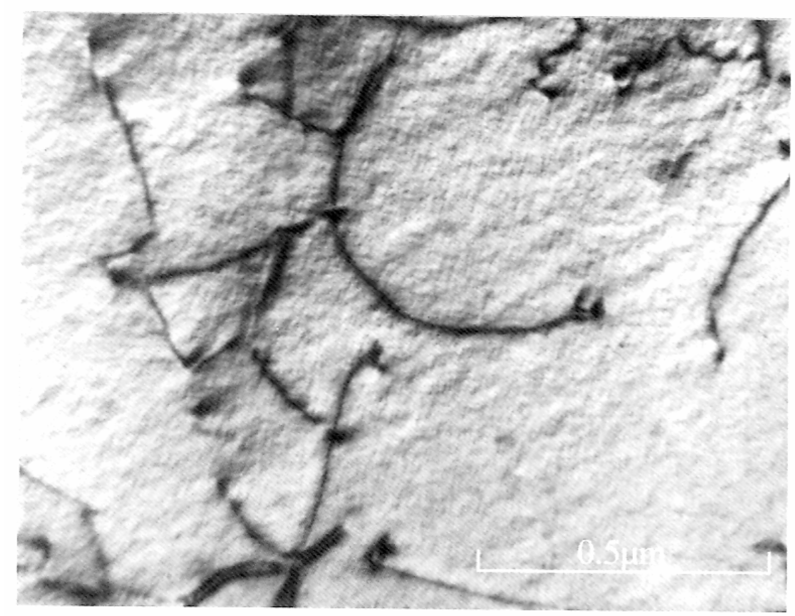
- Hard precipitates are difficult to shear.

  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



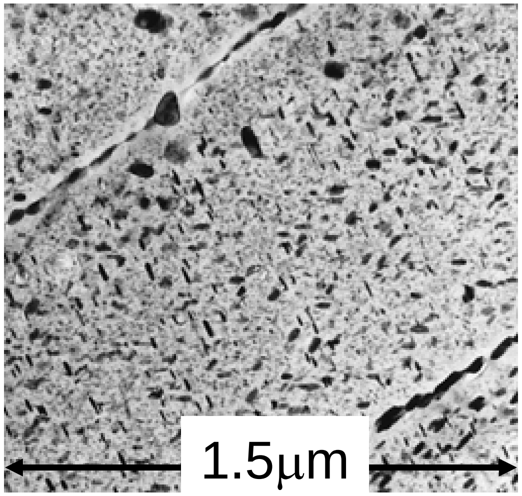
- Result: $\sigma_y \sim \dfrac{1}{S}$

Application:
Precipitation Strengthening (Callister 11.9)

- 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.

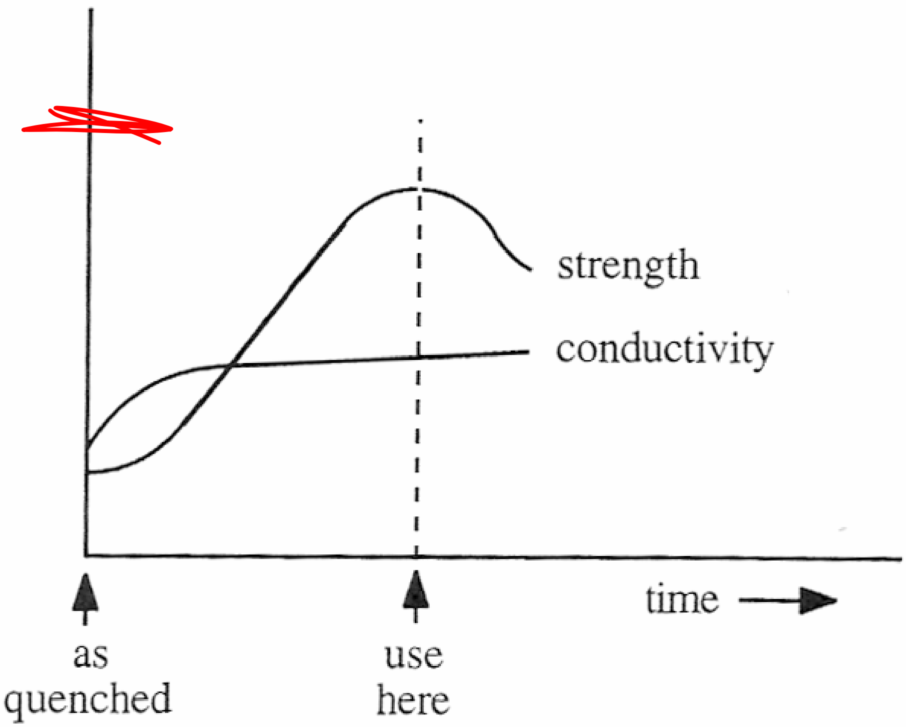


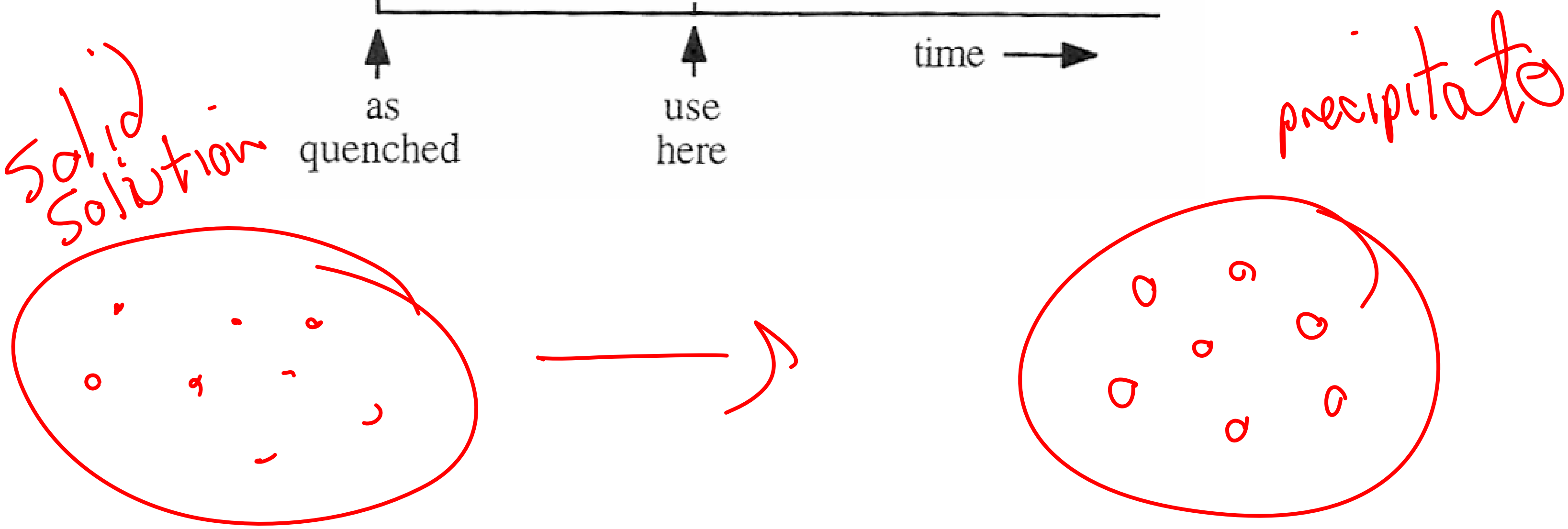
Adapted from Fig. 11.26, *Callister 7e.* (Fig. 11.26 is courtesy of G.H. Narayanan and A.G. Miller, Boeing Commercial Airplane Company.)

Common Precipitate Strengthened Conductors

- **Cu-1%Cr**
  - **Heavy-duty electric motors**
  - **Spot welding electrodes**
- **Cu-0.15%Zr**
  - **Same applications at Cu-Cr**
- **Cu-2%Be-0.5%Co**
  - **Spring contacts**
  - **Welding electrodes**

Effect on Conductivity

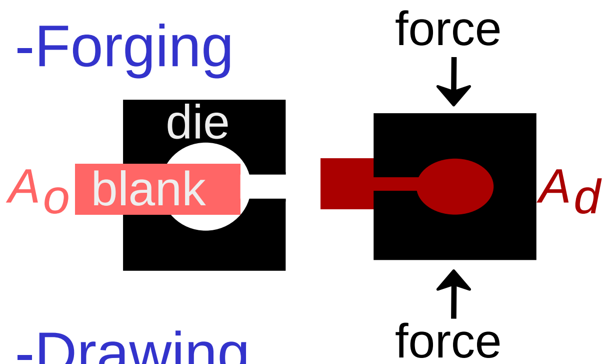




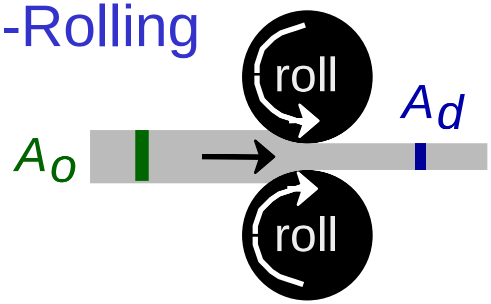
Four Strategies for Strengthening: #4: Cold Work (%*CW*)

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

-Forging

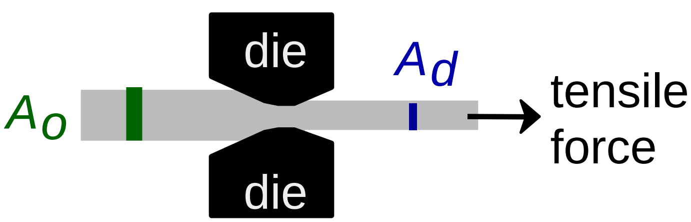


-Rolling

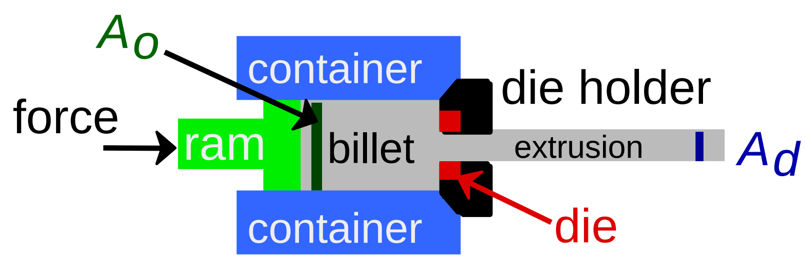


Adapted from Fig. 11.8, *Callister 7e.*

-Drawing



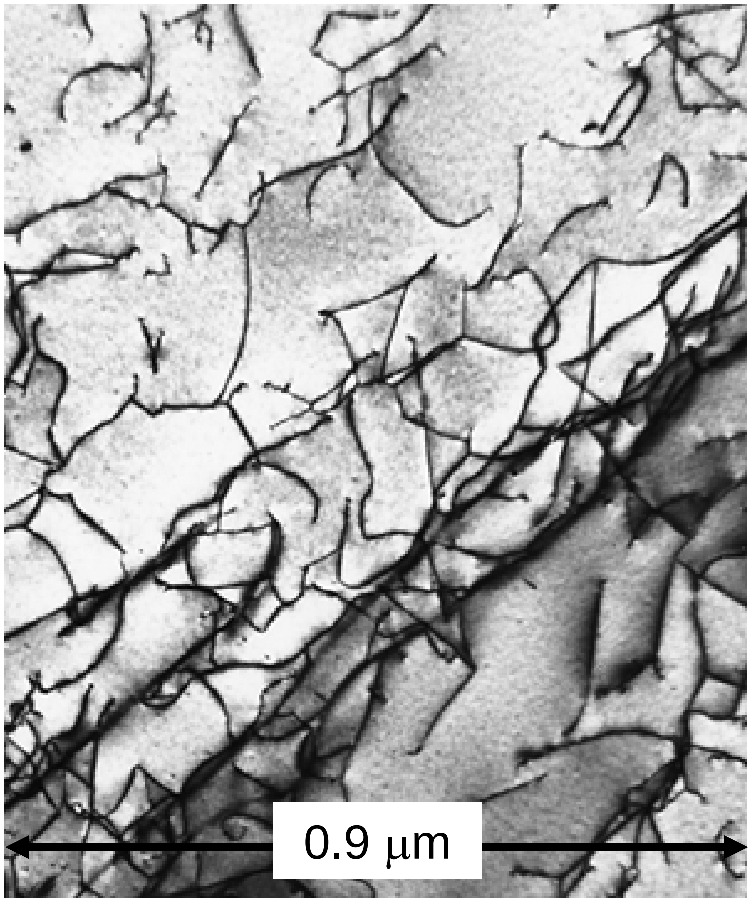
-Extrusion



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

Dislocations During Cold Work

- Ti alloy after cold working:



Adapted from Fig. 4.6, *Callister 7e.*
(Fig. 4.6 is courtesy of M.R. Plichta, Michigan Technological University.)

- Dislocations entangle with one another during cold work.
- Dislocation motion becomes more difficult.

Problem with using cold work for strengthening is that heat will allow for dislocation motion and annihilation. It will undo what the cold work has imposed.

Summary of Ch. 7

- Not important for exams
  - 7.7, 7.11, 7.12, 7.13
- It is important you read Callister (concepts!)
- A few problems will be assigned from this chapter… soon!