Chapter 7:
Dislocations & Strengthening Mechanisms

ISSUES TO ADDRESS...

- How are (yield) strength and dislocation motion related?
- How can (yield) strength of materials (metals) be improved?
- Why does heating alter (yield) strength and other properties?

Theoretical and experimental yield/shear strengths for various Materials

Material	Theoretical Shear Stress		Experimental Shear Stress		⬇
	$G/2\pi$ (GPa)	$G/2\pi$ (10^6 psi)	(MPa)	(psi)	$\tau_{max}/\tau_{exp.}$
Silver	12.6	1.83	0.37	55	$\sim 3 \times 10^4$
Aluminum	11.3	1.64	0.78	115	$\sim 1 \times 10^4$
Copper	19.6	2.84	0.49	70	$\sim 4 \times 10^4$
Nickel	32	4.64	3.2-7.35	465-1,065	$\sim 1 \times 10^4$
Iron	33.9	4.92	27.5	3,990	$\sim 1 \times 10^3$
Molybdenum	54.1	7.85	71.6	10,385	$\sim 8 \times 10^2$
Niobium	16.6	2.41	33.3	4,830	$\sim 5 \times 10^2$
Cadmium	9.9	1.44	0.57	85	$\sim 2 \times 10^4$
Magnesium (basal slip)	7	1.02	39.2	5,685	$\sim 2 \times 10^4$
Magnesium (prism slip)	7	1.02	39.2	5,685	$\sim 2 \times 10^4$
Titanium (prism slip)	16.9	2.45	13.7	1,985	$\sim 1 \times 10^3$
Beryllium (basal slip)	49.3	7.15	1.37	200	$\sim 4 \times 10^4$
Beryllium (prism slip)	49.3	7.15	52	7,540	$\sim 1 \times 10^3$

$\tau_{experimental} << \tau_{max}$; also, $\sigma_{experimental} << \sigma_{max}$

Dr. Mark L. Weaver, University of Alabama
http://bama.ua.edu/~mweaver/courses/MechBeh/N07.pdf

Dislocation

For metals, measured yield strength is much LOWER (by 1000 times or more) than "theoretical strength" – This is explained by presence of dislocations in (metallic) crystalline materials!

Linear Defects (Dislocations)

- Are one-dimensional defects around which atoms are misaligned
- **Edge dislocation:**
  - extra half-plane of atoms inserted in a crystal structure
  - b perpendicular (⊥) to dislocation line
- **Screw dislocation:**
  - spiral planar ramp resulting from shear deformation
  - b parallel (||) to dislocation line

Burger's vector, **b**: measure of lattice distortion

Imperfections in Solids

Edge Dislocation

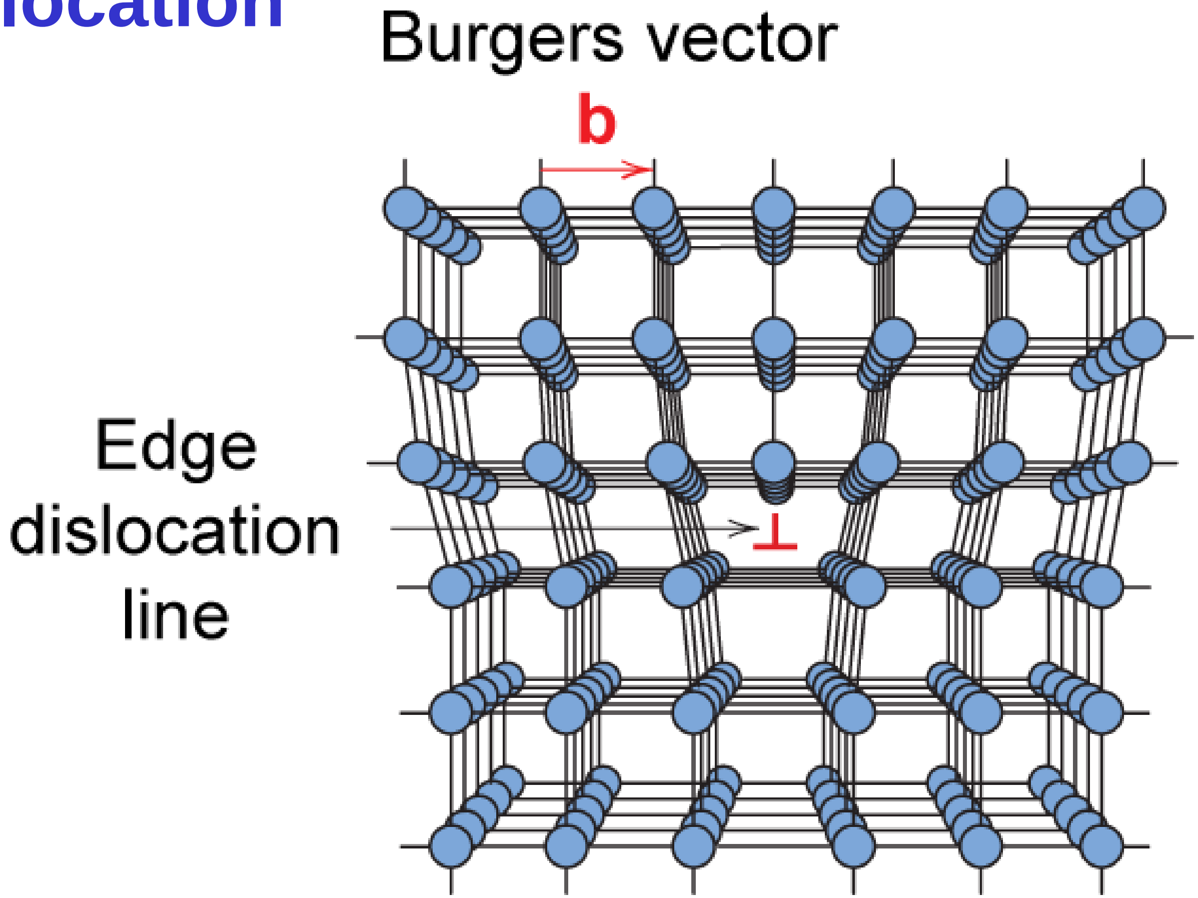
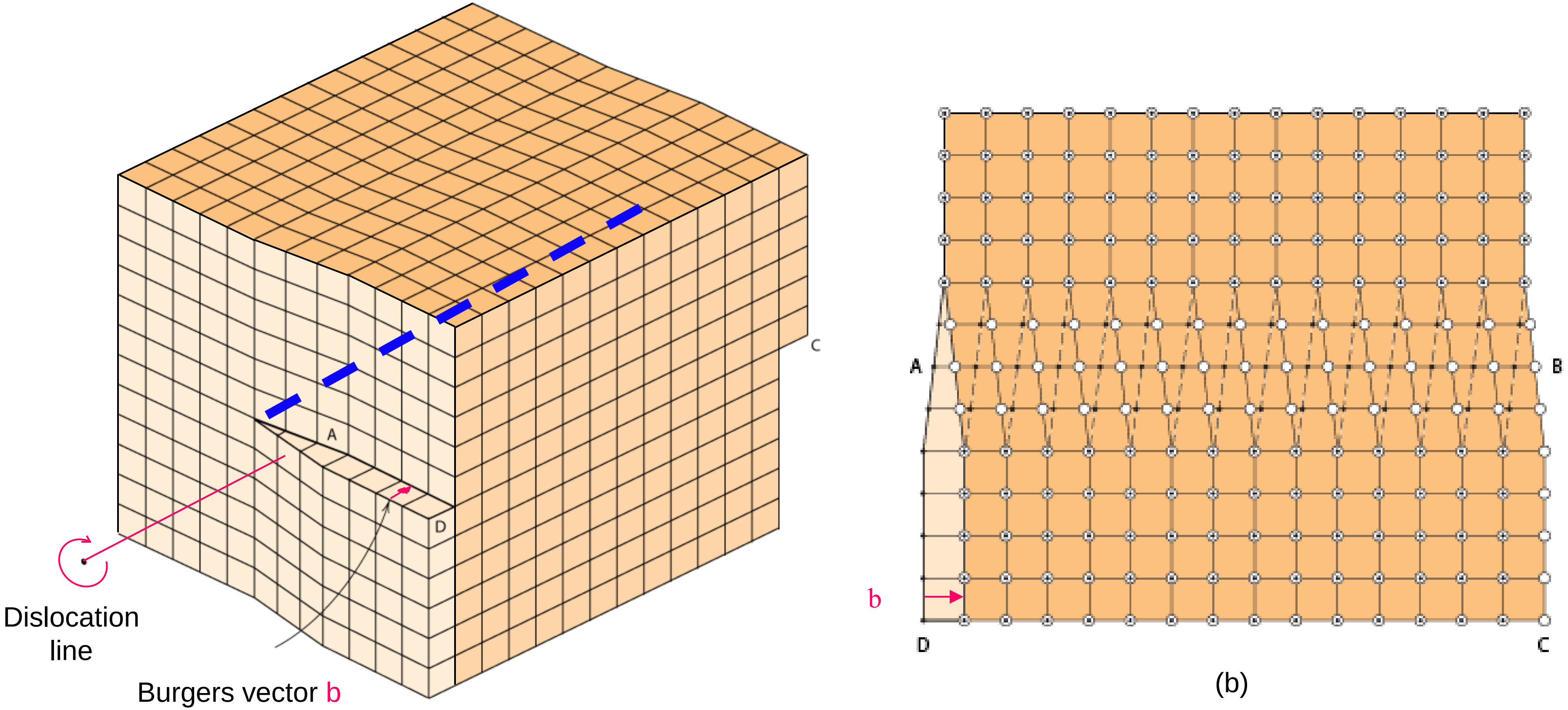


Fig. 4.3, *Callister & Rethwisch 8e.*

Imperfections in Solids

Screw Dislocation



(a)

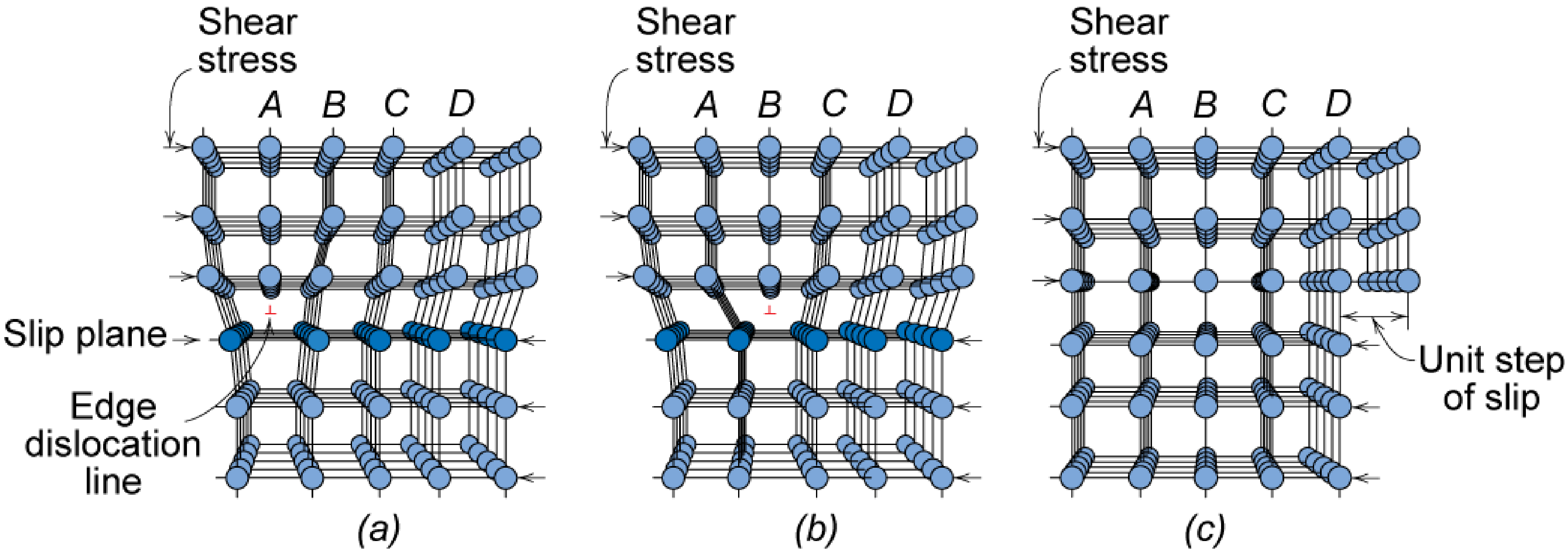
(b)

Adapted from Fig. 4.4, *Callister & Rethwisch 8e.*

Plastic Deformation & Dislocation Motion

Dislocation motion leads to plastic (irreversible) deformation

- Metals - plastic deformation occurs by slip: i.e., a dislocation slides over adjacent plane half-planes of atoms.

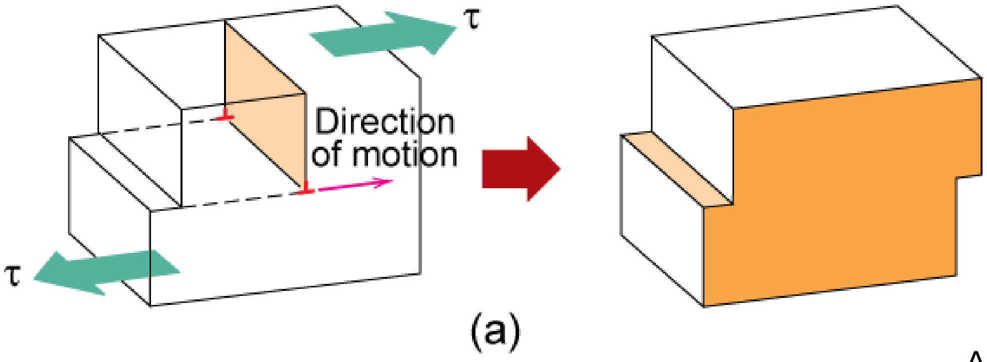


- If dislocations can't move → plastic deformation doesn't occur!

Adapted from Fig. 7.1, *Callister & Rethwisch 8e.*

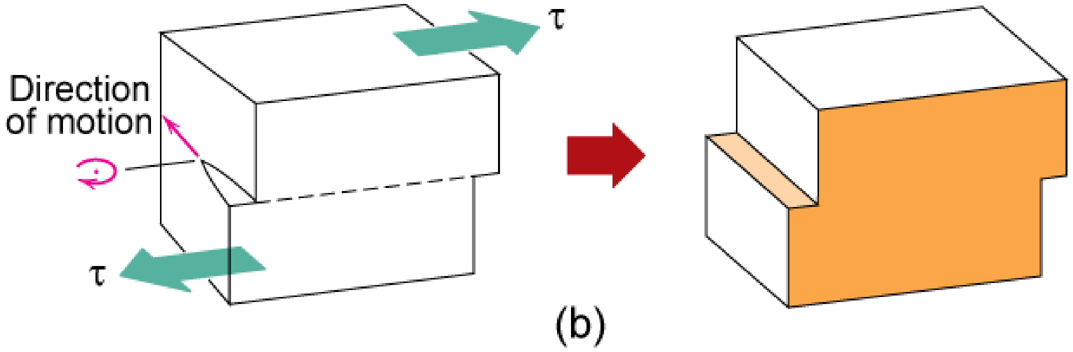
Dislocation Motion & Slip

- A dislocation moves along a slip plane in a slip direction perpendicular to the dislocation line



Edge dislocation

Adapted from Fig. 7.2, *Callister & Rethwisch 8e.*



Screw dislocation

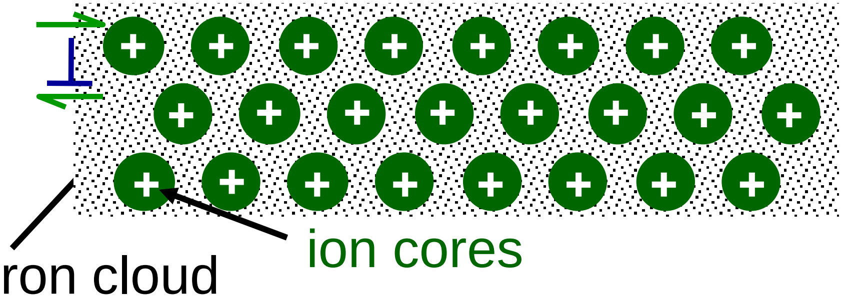
Dislocation Motion & Materials Classes

- Metals (Cu, Al):

  Dislocation motion **easiest**

  - non-directional bonding

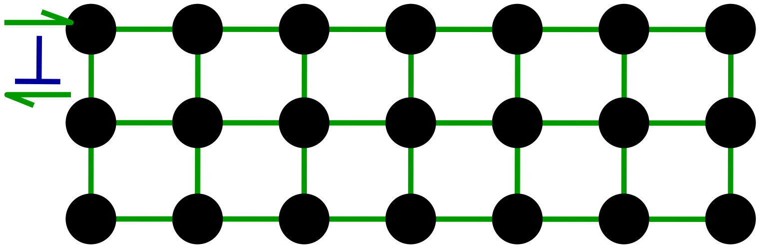
  - close-packed directions for slip



- Covalent Ceramics

  (Si, diamond): Motion **difficult**

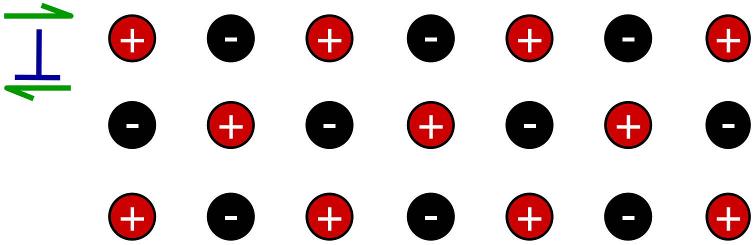
  - directional (angular) bonding



- Ionic Ceramics (NaCl):

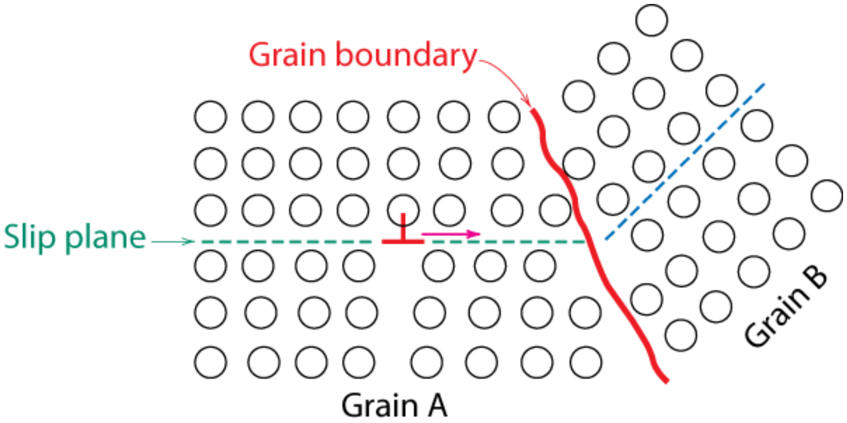
  Motion **difficult**

  - need to overcome nearest neighbors of like sign (- and +)



Four Strategies for Strengthening Metals
1: Reduce Grain Size

- Grain boundaries are barriers to slip (i.e., dislocation motion).
- Barrier "strength" increases with Increasing angle of misorientation.
- **Smaller grain size: more barriers to slip→ Higher (yield) strength**



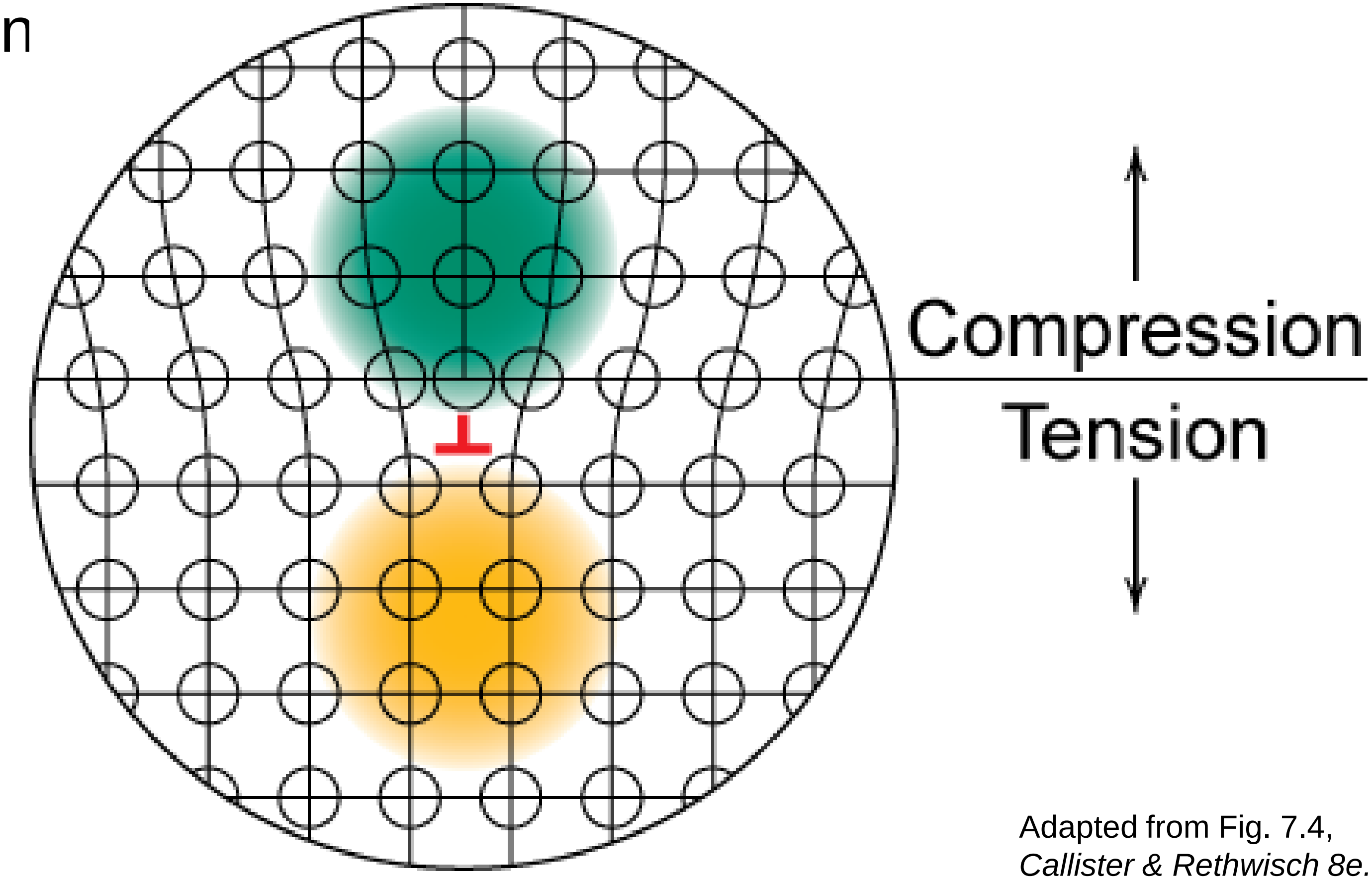
Adapted from Fig. 7.14, *Callister & Rethwisch 8e.* (Fig. 7.14 is from *A Textbook of Materials Technology*, by Van Vlack, Pearson Education, Inc., Upper Saddle River, NJ.)

- Hall-Petch Equation:

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

Four Strategies for Strengthening Metals
2: Form Solid Solutions

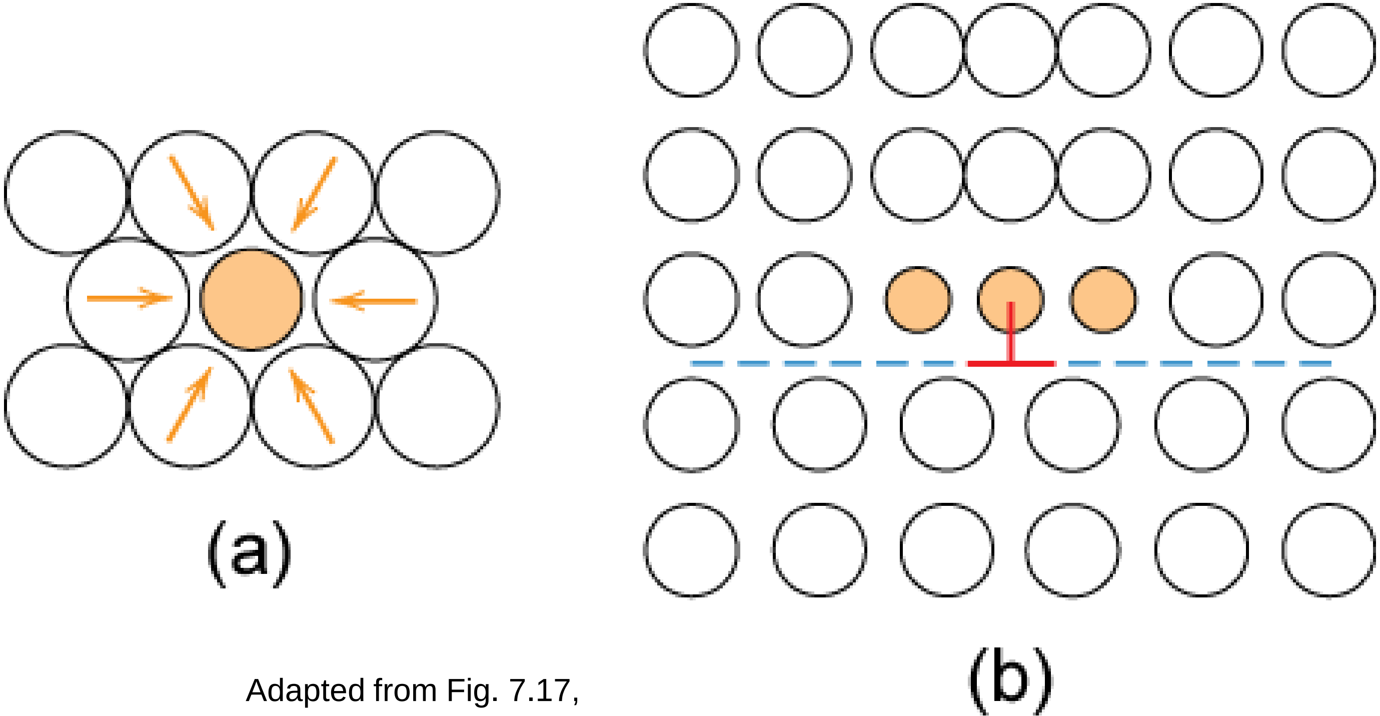
- Impurity atoms distort the lattice & generate lattice strains.
- These strains can act as barriers to slip (or dislocation motion



Adapted from Fig. 7.4,
Callister & Rethwisch 8e.

Strengthening Metals by Solid Solution Alloying (1)

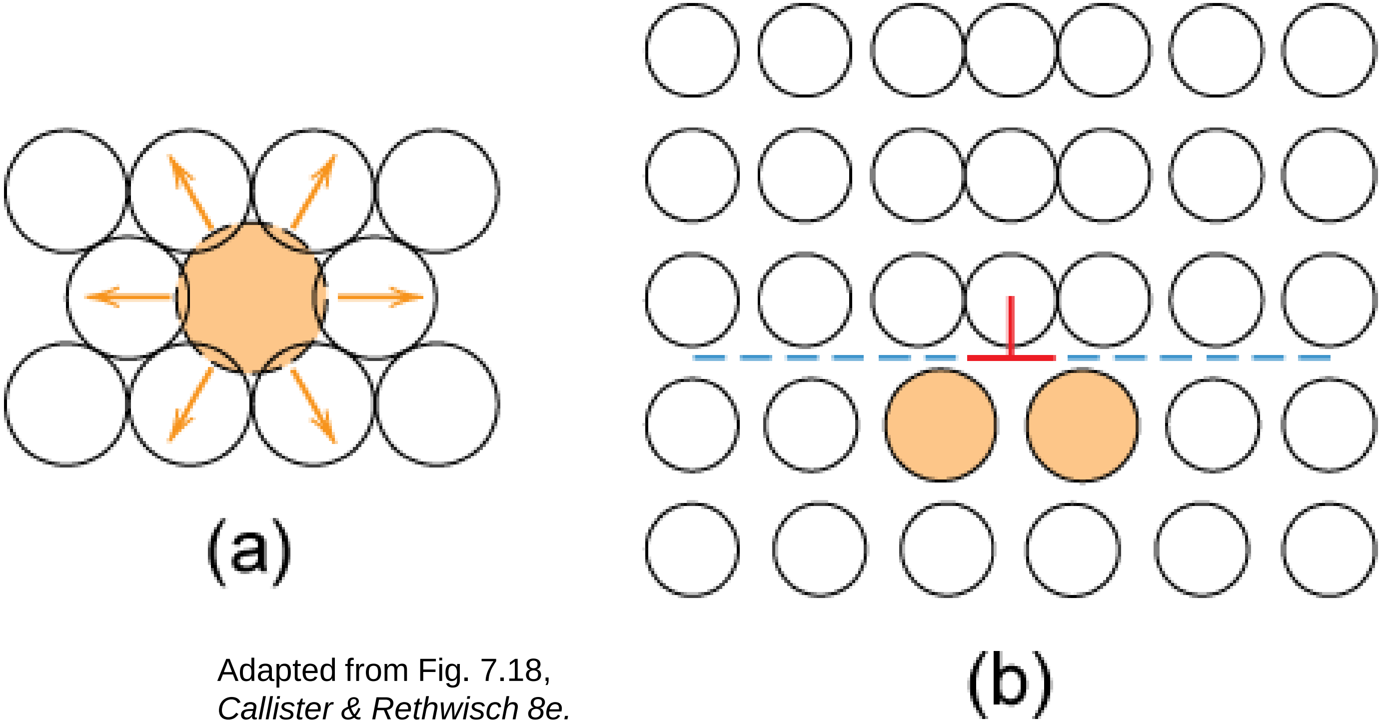
- **Small** impurities tend to concentrate at regions of compressive strains



Adapted from Fig. 7.17,
Callister & Rethwisch 8e.

Strengthening Metals by Solid Solution Alloying (2)

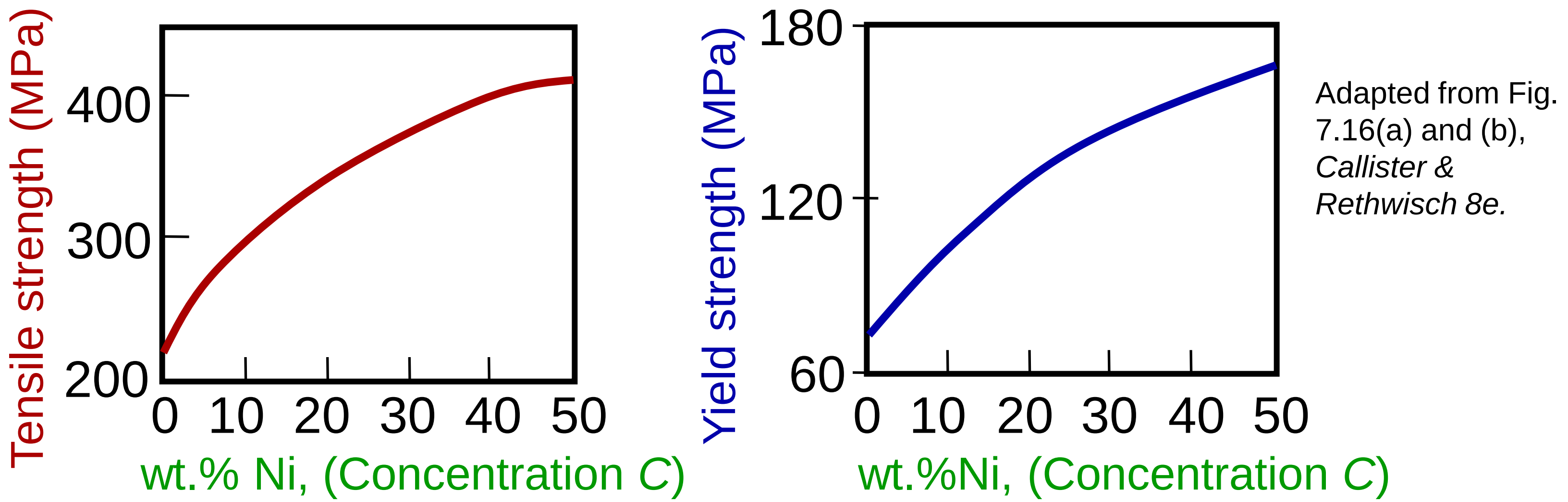
- **Large** impurities tend to concentrate at regions of tensile strains



Adapted from Fig. 7.18,
Callister & Rethwisch 8e.

Ex: Solid Solution Strengthening in Copper

- Tensile strength & yield strength increase with impurity addition (i.e., forming a solid solution instead of pure metal)



Adapted from Fig. 7.16(a) and (b), *Callister & Rethwisch 8e.*

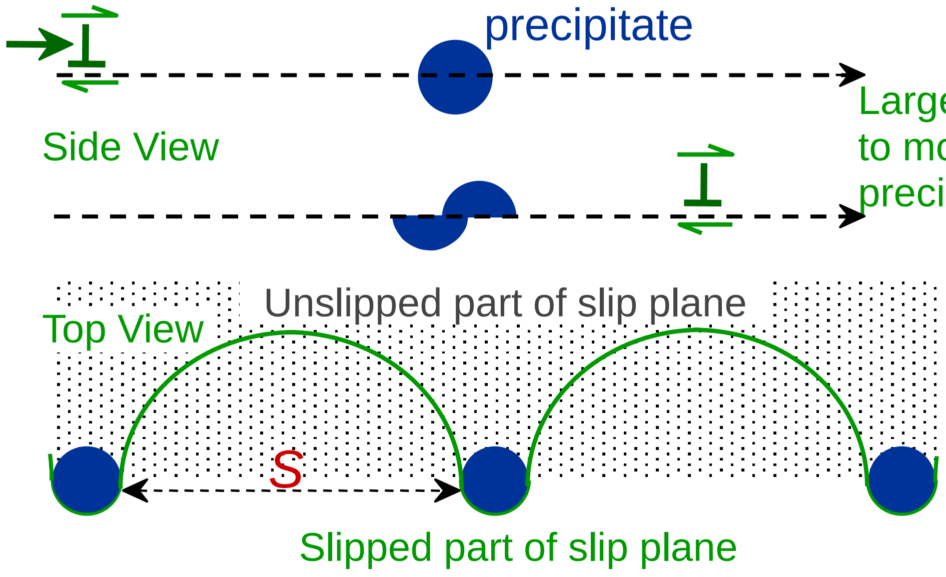
- Empirical relation: $\sigma_y \sim C^{1/2}$

- Adding impurity atoms or alloying increases σ_y and *TS*.
  - Adding Ni to Cu
  - Adding impurity (e.g., Ag, Cu) to gold (Au)

Four Strategies for Strengthening Metals: 3: Precipitation Strengthening

- Hard precipitates are difficult to shear.

  Ex: Ceramic particles 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*.

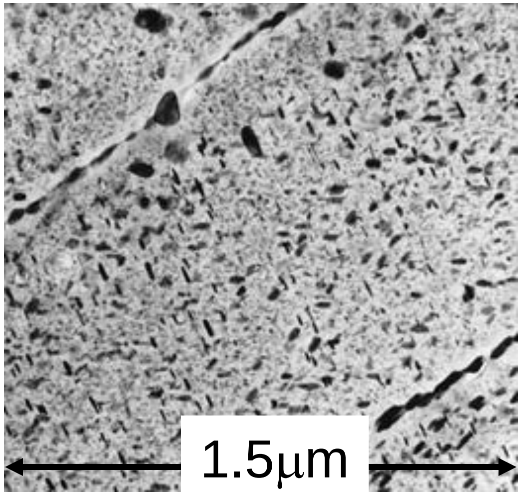
- Result: $\sigma_y \sim \frac{1}{S}$

Application:
Precipitation Strengthening of Aluminum

- Internal wing structure on Boeing 767

Adapted from chapter-opening photograph, Chapter 11, *Callister & Rethwisch 3e.* (courtesy of G.H. Narayanan and A.G. Miller, Boeing Commercial Airplane Company.)

- Aluminum is strengthened with finely dispersed precipitates formed by alloying.



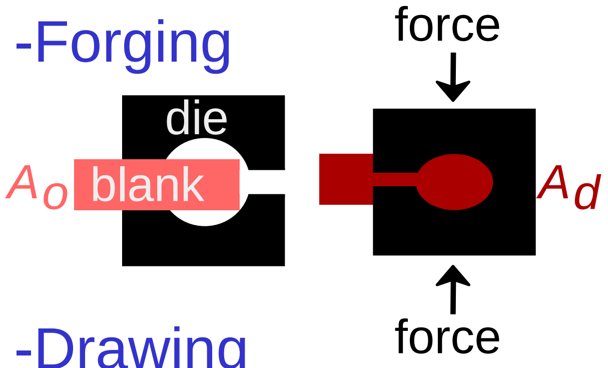
Adapted from Fig. 11.26, *Callister & Rethwisch 8e.* (Fig. 11.26 is courtesy of G.H. Narayanan and A.G. Miller, Boeing Commercial Airplane Company.)

Four Strategies for Strengthening Metals: 4: Cold Work (Strain Hardening)

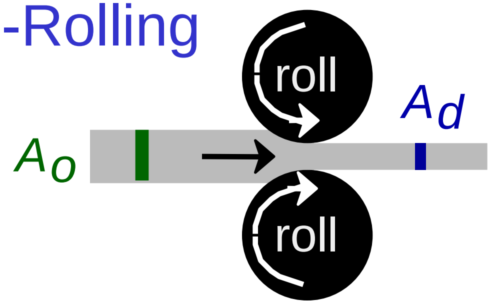
- Deformation at room temperature (for most metals).

Example: forming operations such as reduce the cross-sectional area → Metal appear “stronger” with more cold work (or deformation)

-Forging

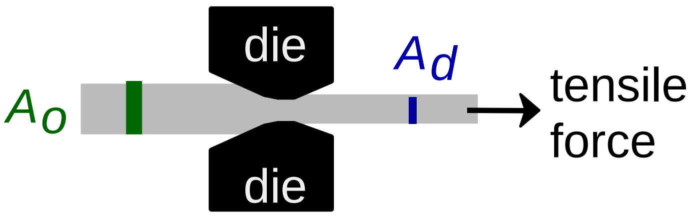


-Rolling

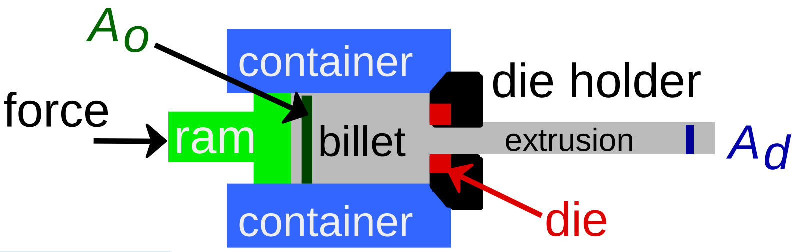


Adapted from Fig. 11.8, *Callister & Rethwisch 8e.*

-Drawing



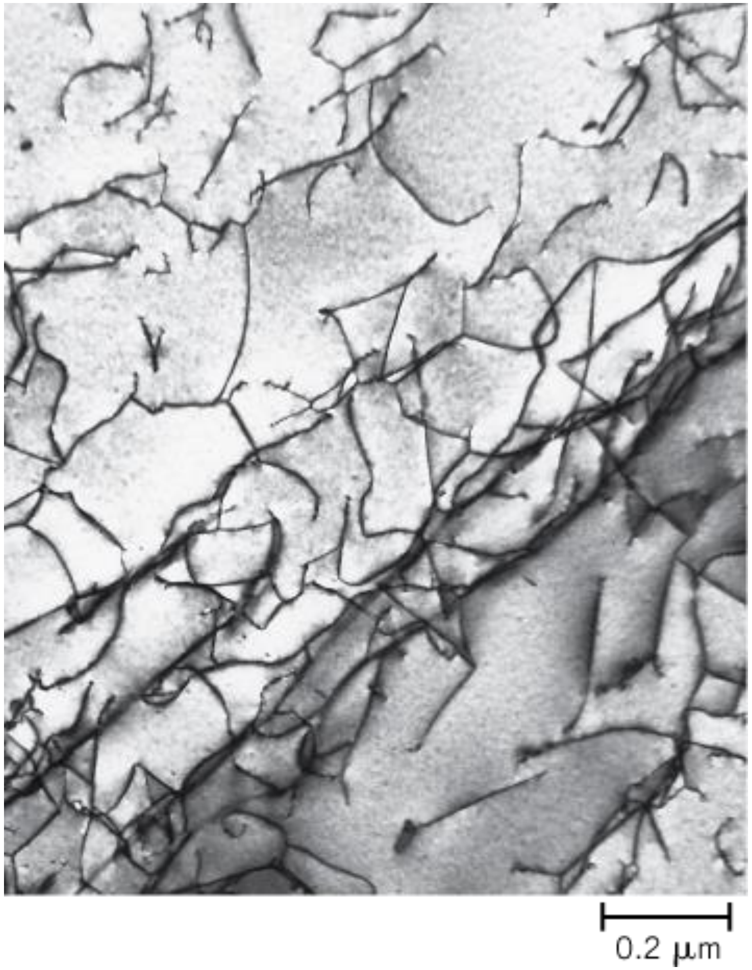
-Extrusion



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

Dislocation Structures Change During Cold Working

- Dislocation structure in Ti after cold working.



More dislocations are created and entangle with one another during **cold work** → Dislocation motion becomes more difficult and materials appear to be stronger

Fig. 4.6, *Callister & Rethwisch 8e.*
(Fig. 4.6 is courtesy of M.R. Plichta, Michigan Technological University.)

Dislocation Density Increases During Cold Working

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

- Carefully grown single crystals

  → $\rho_d \sim 10^3$ mm^{-2}
- Plastically deforming sample increases dislocation density dramatically

  → $\rho_d \sim 10^9\text{-}10^{10}$ mm^{-2}
- Heat treatment reduces dislocation density

  → $\rho_d \sim 10^5\text{-}10^6$ mm^{-2}

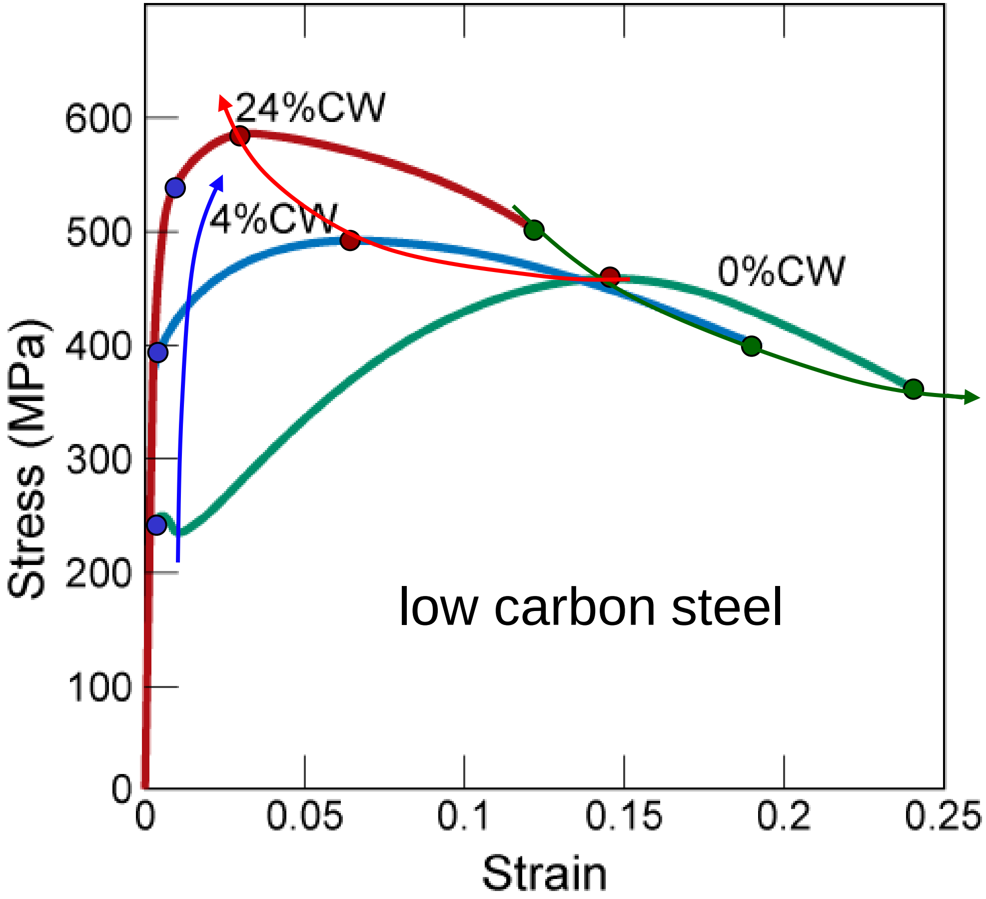
- Yield strength increases as ρ_d increases:

Impact of Cold Work on Metals

As the **amount of cold work (%CW)** is increased

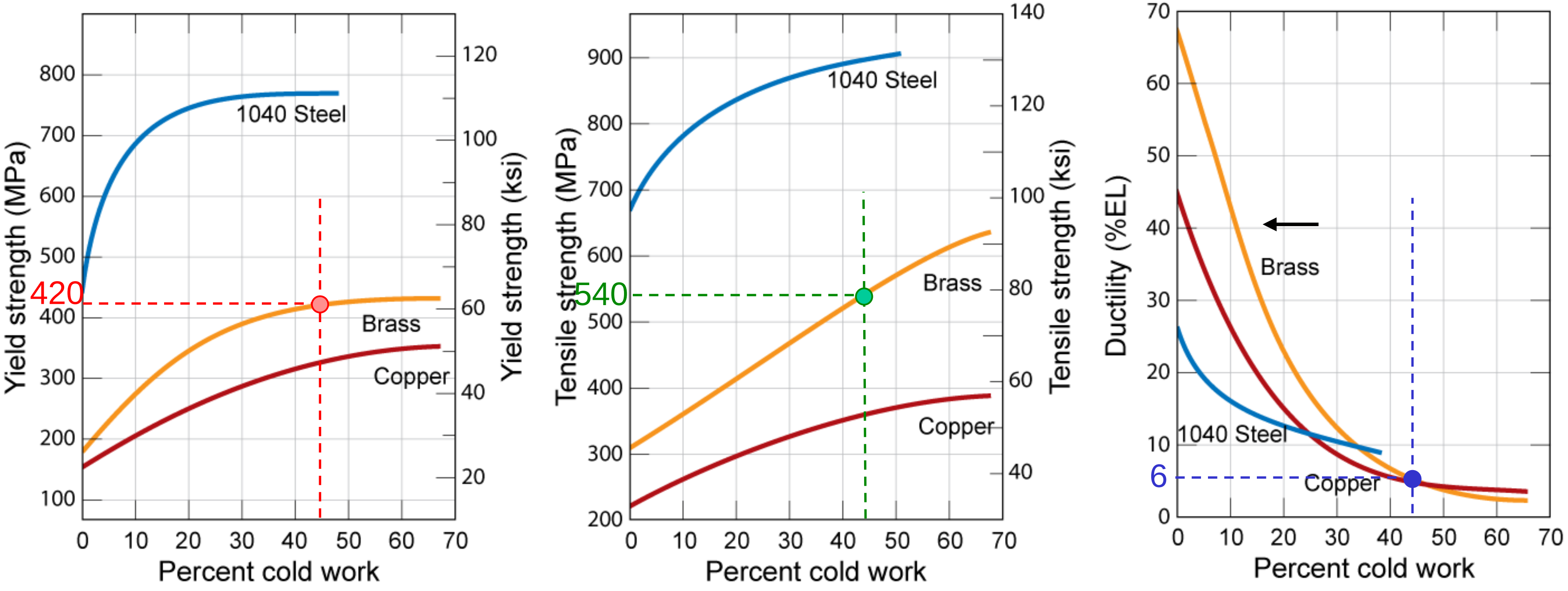
- Modulus (***E***) does NOT change.
- Yield strength (σ_y) increases
- Tensile strength (***TS***) increases
- Ductility (**%*EL* or %*AR***) decreases – more brittle

} "stronger"



Adapted from Fig. 7.20, *Callister & Rethwisch 8e.*

Impact of Cold Working on Mechanical Properties of Metals



(a) *(b)* *(c)*

Adapted from Fig. 7.19, *Callister & Rethwisch 8e.*

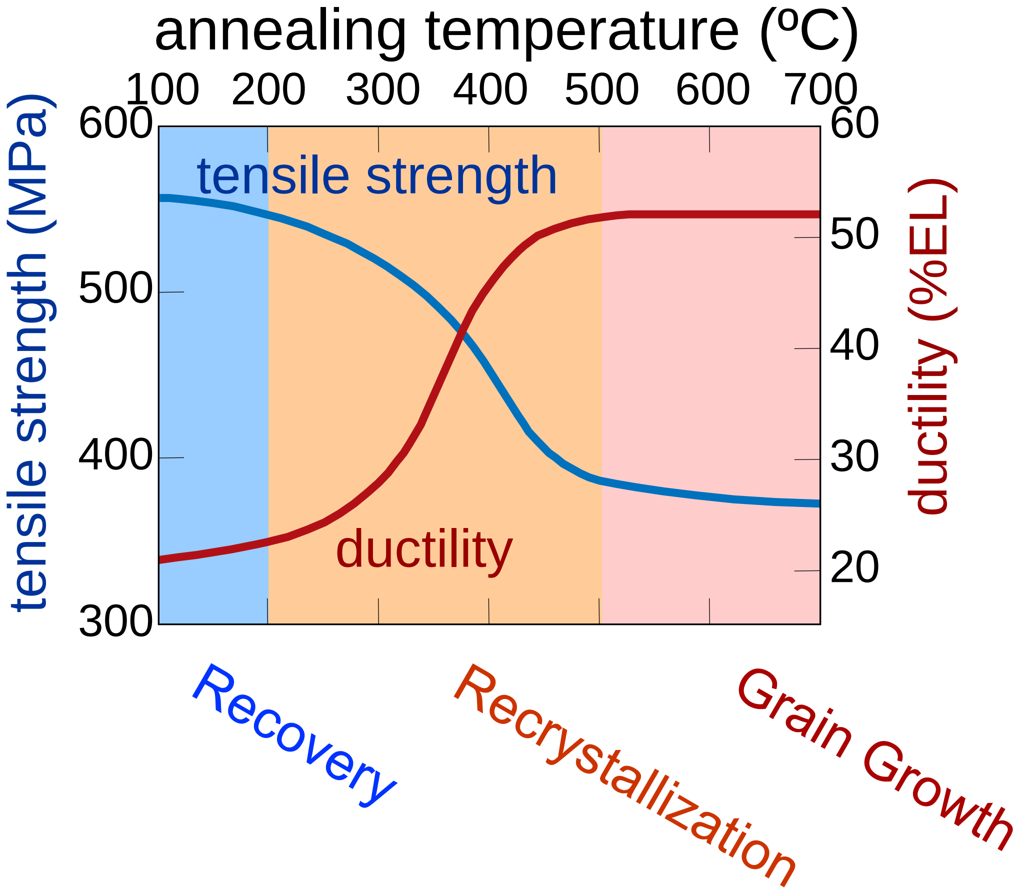
For various metals, as the percent of cold work increases

- The materials become stronger:
  - Yield strength increases
  - Tensile strength increases
- The material become less ductile: total elongation before fracture decreases

Effect of Heat Treating After Cold Working of Metals

- 1 hour treatment at T_{anneal}...

  decreases yield strength and *TS* while increases ductility or %*EL*.
- Effects of cold work (increase in strength and decrease in ductility) are removed after annealing at sufficiently high *T*



Adapted from Fig. 7.22, *Callister & Rethwisch 8e.* (Fig. 7.22 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.)

Summary

- Dislocations are linear defects in materials.
- Plastic deformation (of metals) go by a process called “slip”, which is movement of dislocation.
- Dislocation movement explains the relative low experimental yield strength for materials (especially metals) comparing with theoretically predicted value.
- (Yield and tensile) strength of a material, especially metal is increased by making dislocation motion difficult.
- Strength of metals may be increased by:
  -- decreasing grain size
  -- forming a solid solution (or adding impurity atoms)
  -- forming precipitates
  -- cold working
- For a cold-worked metal that is heat treated or annealed – its ductility would recover while strengths decreases

Homework

- Read chapter 7 and give a statement confirm reading
- Calister 8ed, 7.22, 7.29

Calister 8ed 7.22

Describe in your own words the four strengthening mechanisms i.e., grain size reduction, solid-solution strengthening, precipitation hardening, and work (or strain) hardening.

Calister 8ed 7.29

Two previously undeformed specimens of the same metal are to be plastically deformed by reducing their cross-sectional areas. One has a circular cross section, and the other is rectangular; during deformation the circular cross section is to remain circular, and the rectangular is to remain as such. Their original and deformed dimensions are as follows. Which of these specimens will be the hardest after plastic deformation, and why?

	Circular (diameter, mm)	Rectangular (mm)
Original dimensions	15.2	125 × 175
Deformed dimensions	11.4	75 × 200