ENGG103 – Materials in Design

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Chapter 7:
Deformation & Strengthening Mechanisms

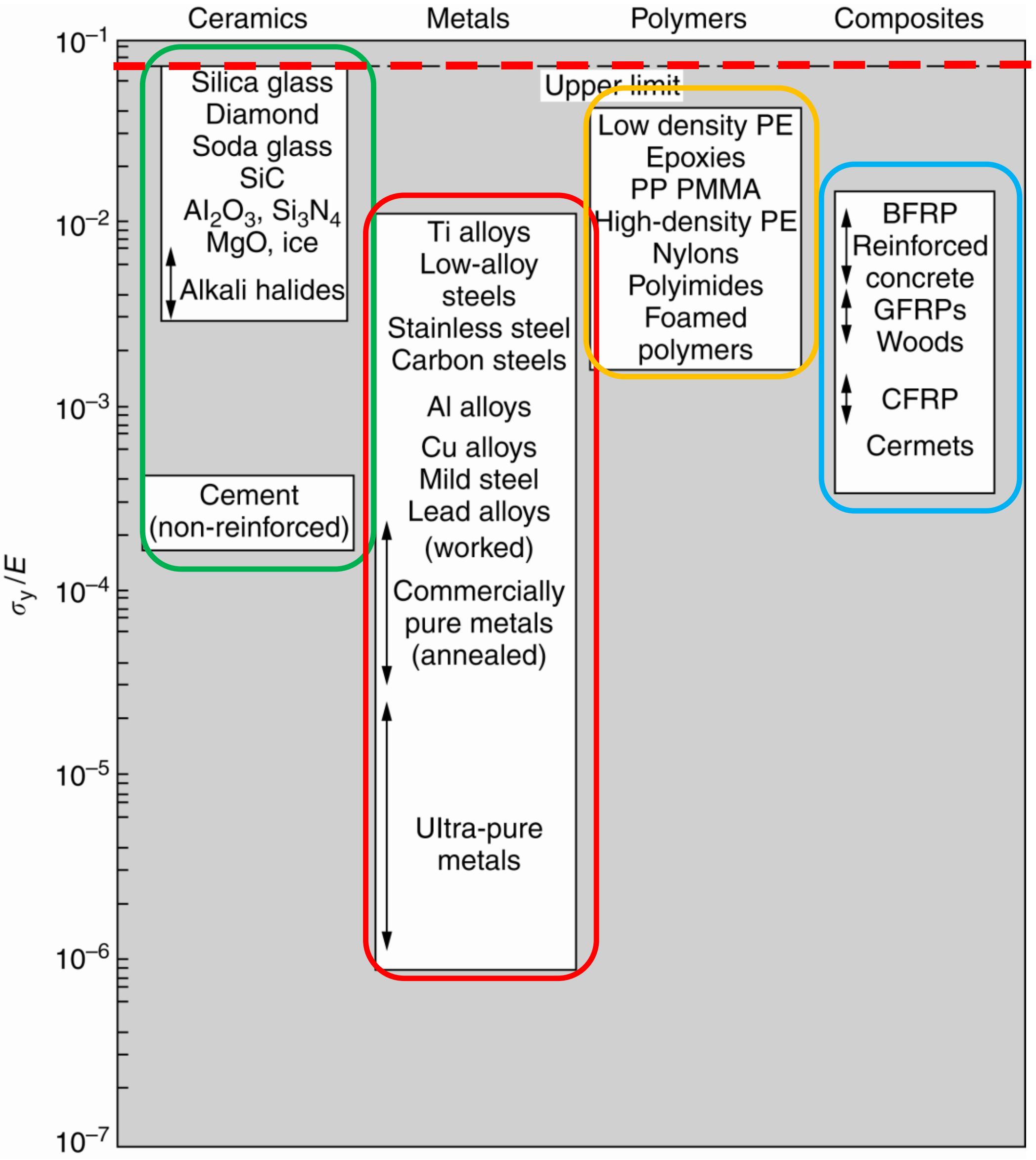
ISSUES TO ADDRESS...

- Why are the number of dislocations present greatest in metals?
- How are strength and dislocation motion related?
- Why does heating alter strength and other properties?

LO1	**Describe the structure, general properties and main applications of metals, polymers, ceramics and composites**
LO4	Describe the relationships that exist between structure, processing and properties of selected materials; and

Ideal Strength

- Real life is not ideal



The ideal strength of a material is the force required to break interatomic bonds in a perfect <u>defect free</u> crystal

Metals, have yield strengths far below the levels predicted by our calculation—as much as a factor of 10^5 less.
Even many ceramics yield at stresses that are a factor of 10 below their ideal strength. **Why is this?**

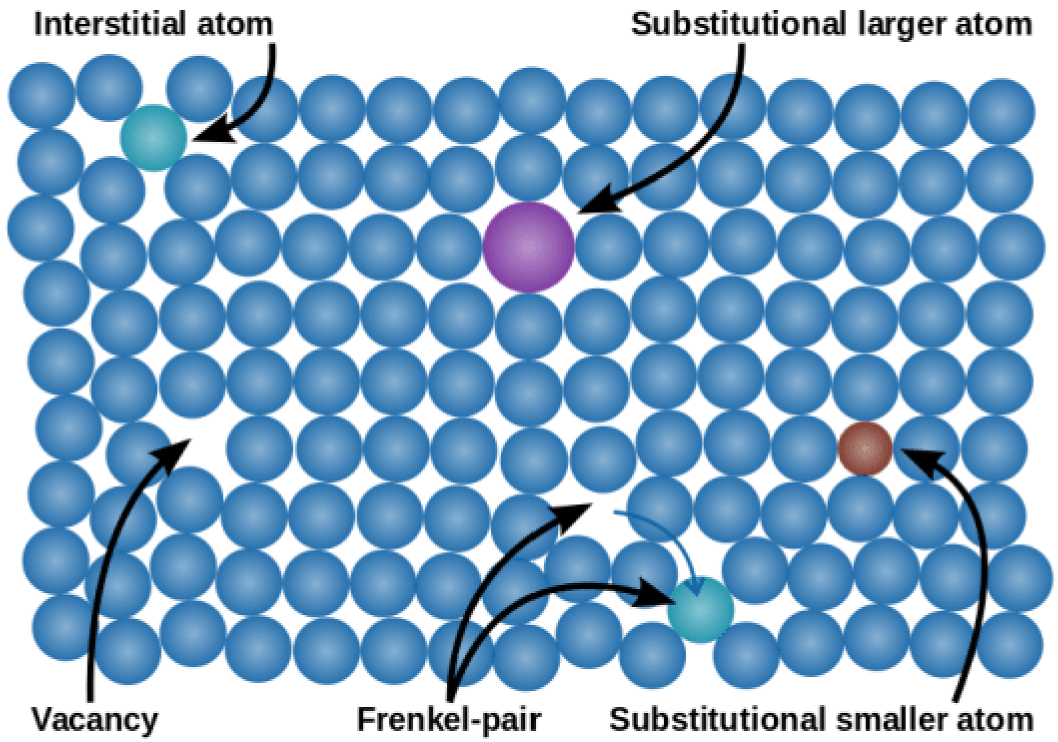
The theoretical yield strength can be estimated by considering the process of yield at the atomic level. In a perfect crystal, shearing results in the displacement of an entire plane of atoms by one interatomic separation distance, b, relative to the plane below.

Defects in Metallic Crystals

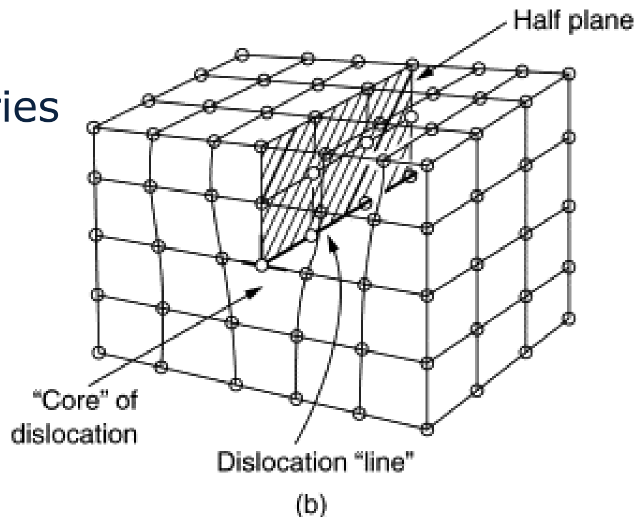
Perfect crystal is an assembly of atoms packed together in a regularly repeating pattern

Metallic crystals are **not perfect**.

- Point defects:
  - Vacancies
  - Self interstitials
  - Solute atoms
- Line defects:
  - Dislocations
- Area defects:
  - Surfaces
  - Grain boundaries



https://www.differencebetween.com/difference-between-metal-excess-defect-and-metal-deficiency-defect/



Dislocation Motion

Dislocation motion & plastic deformation

- Metals - plastic deformation occurs by slip – an edge dislocation (extra half-plane of atoms) slides over adjacent plane half-planes of atoms.

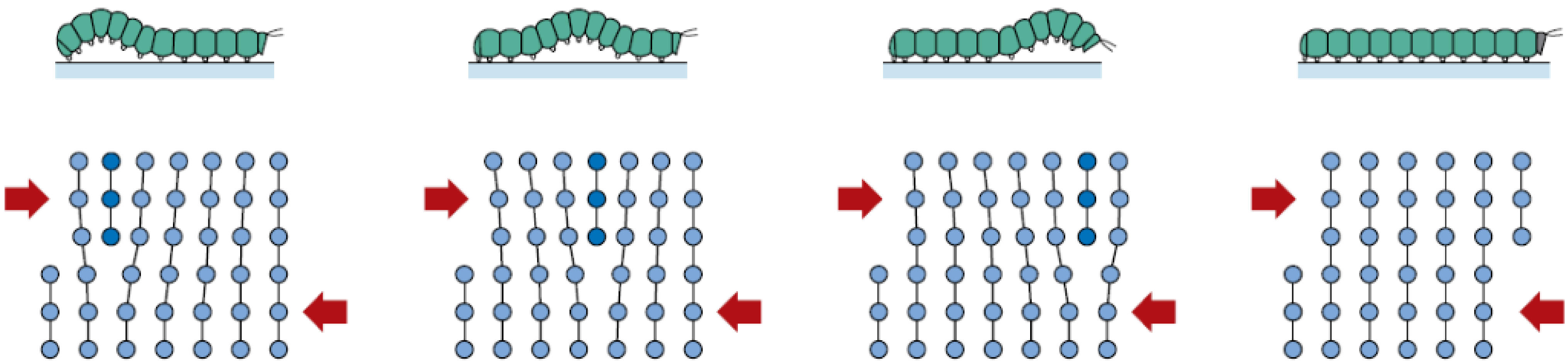


Figure 7.3 The analogy between caterpillar and dislocation motion.

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

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

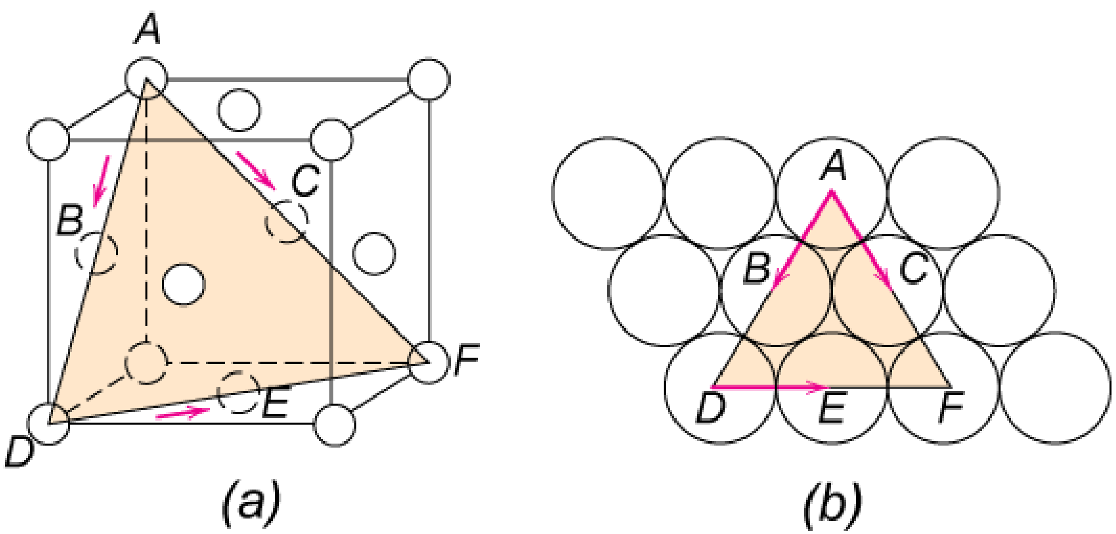
Dislocation

- The dislocations move along the densest planes of atoms in a material, because the stress needed to move the dislocation increases with the spacing between the planes.
- FCC and BCC metals have many dense planes, so dislocations move relatively easy and these materials have high ductility.
- Metals are strengthened by making it more difficult for dislocations to move.
- This may involve the introduction of obstacles, such as interstitial atoms or grain boundaries, to “pin” the dislocations.
- Also, as a material plastically deforms, more dislocations are produced and they will get into each others way and impede movement. This is why strain or work hardening occurs.

Deformation Mechanisms

Slip System (not examined)

- Slip plane - plane on which easiest slippage occurs
  - Highest planar densities (and large interplanar spacings)
- Slip directions - directions of movement
  - Highest linear densities



Adapted from Fig. 7.6, *Callister & Rethwisch 8e.*

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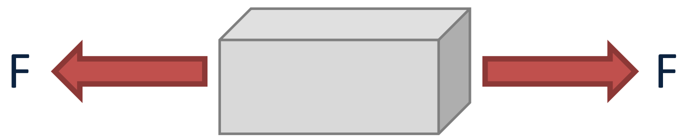
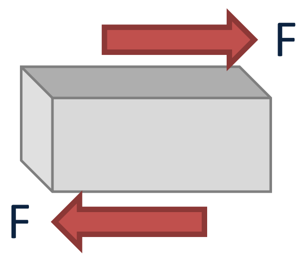
Normal vs Shear Stress

- Stress is force per unit area $\sigma = \frac{F}{A}$
- Normal stress, **σ**, is the stress perpendicular to a plane or surface.
  - Due to components of force acting perpendicular (normal) to the plane.

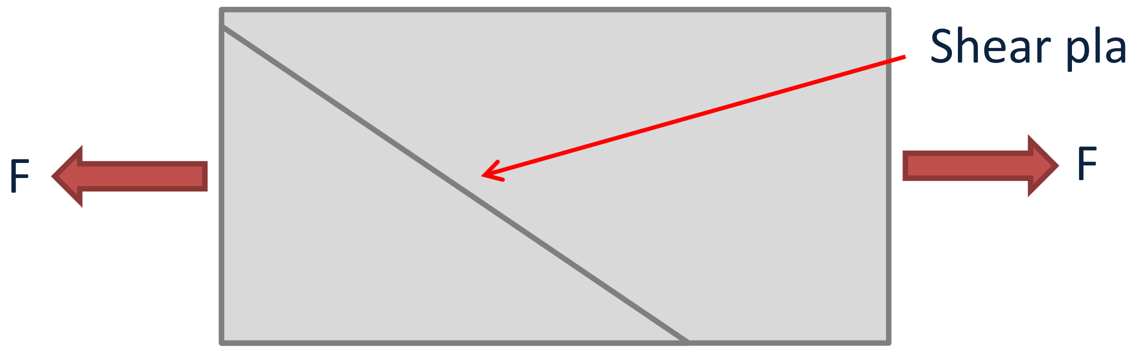


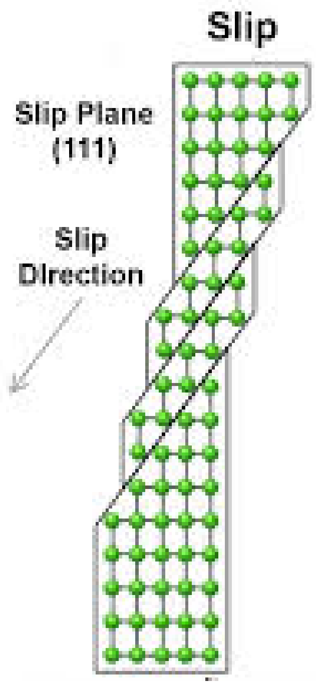
- Shear stress, **τ**, is the stress parallel to a plane/surface.
  - Due to components of force acting parallel to the plane.



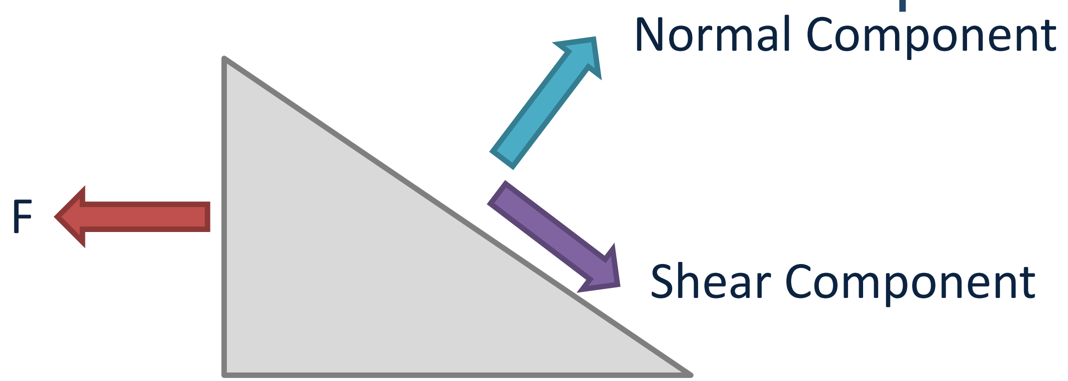
Dislocation Movement

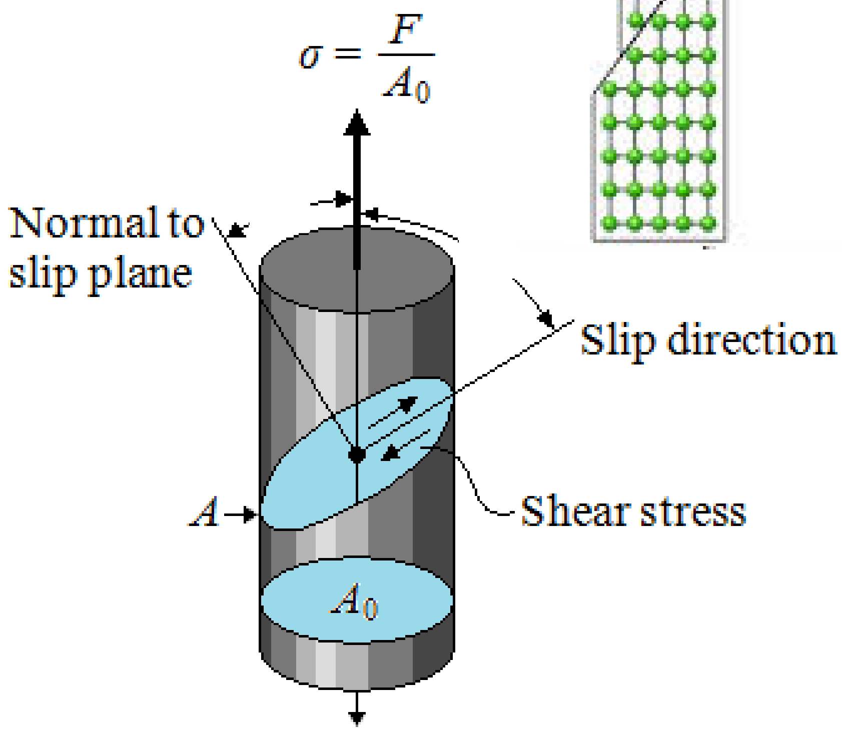
- Dislocations move under the influence of a ***shear*** stress.





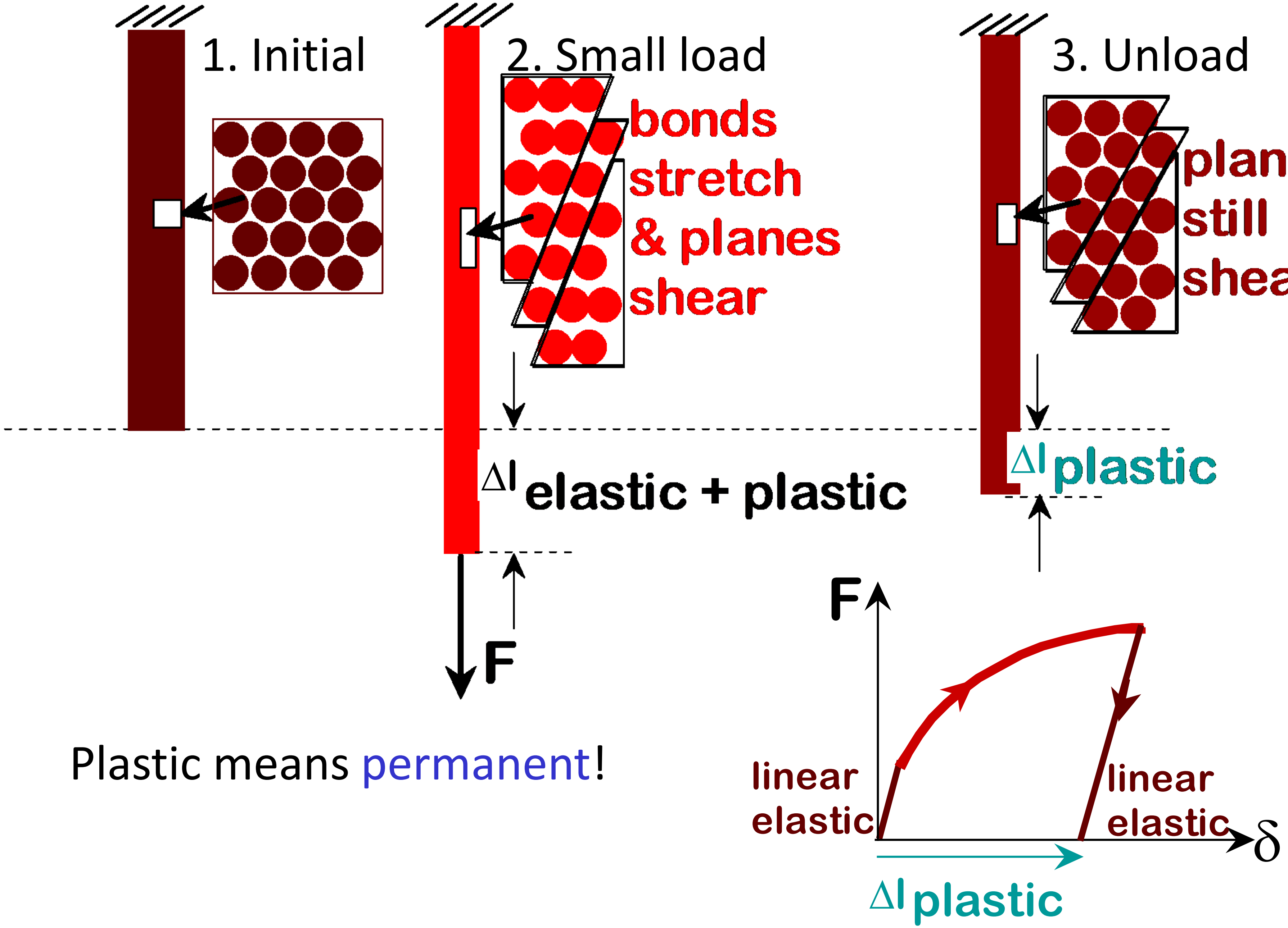
- Consider an inclined plane





Source: www.engineeringarchives.com/les_matsci_schmidslaw.html

Dislocation Movement



Plastic means permanent!

Metal and Alloys Strengthening

Important points

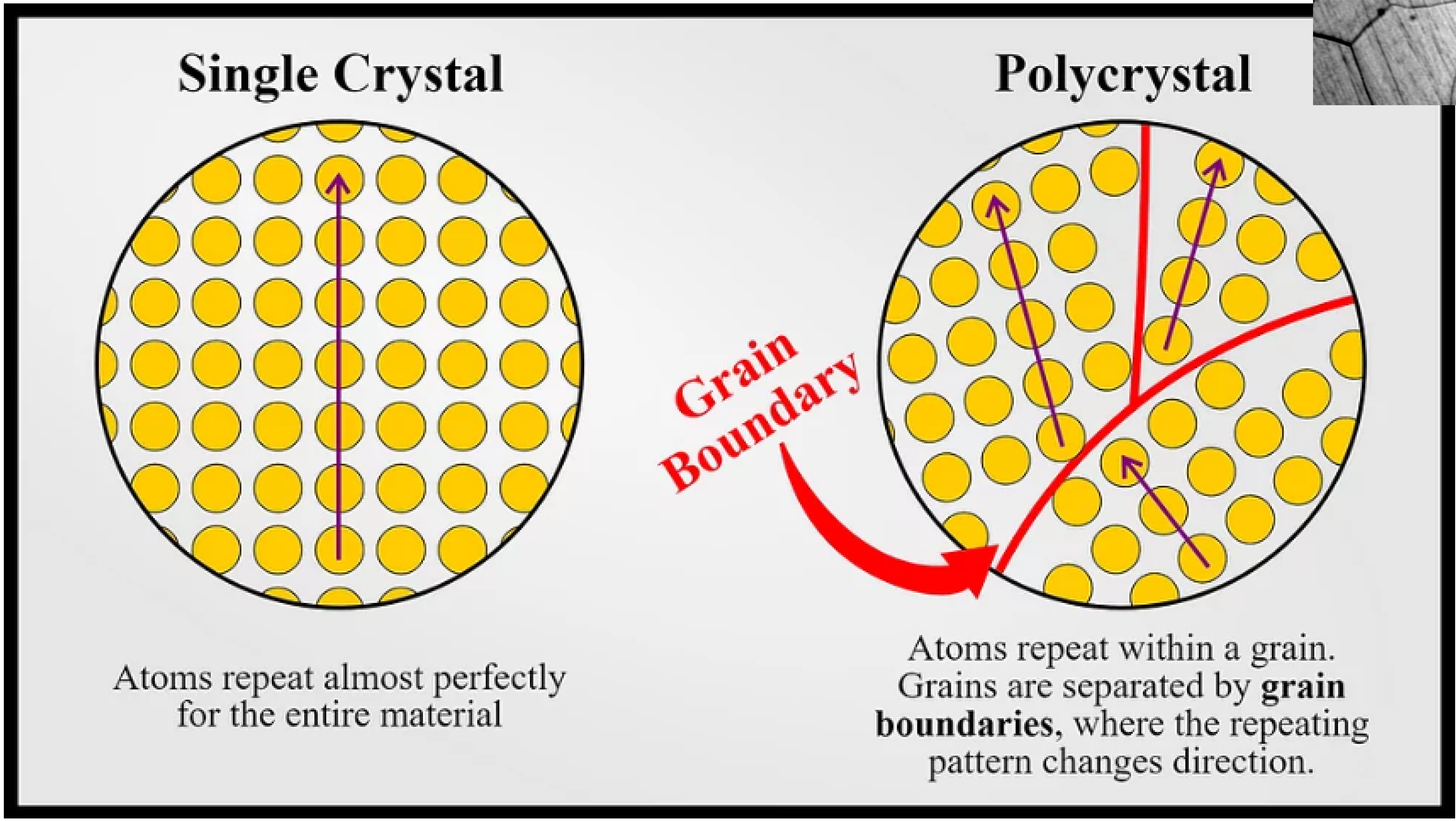
- The ability of a metal to plastically deform depends on the ability of the dislocation to move.
- Restricting of hindering dislocation motion renders a material harder and stronger.

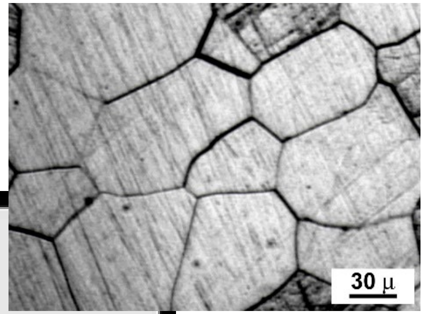
Strengthening Mechanisms

1. Grain Size Reduction
2. Solid-Solution Strengthening
3. Precipitation Hardening (Age Hardening)
4. Strain Hardening - (cold work)

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.

https://www.ilearnengineering.com/mechanical/how-does-the-grain-size-affect-the-strength-of-a-material

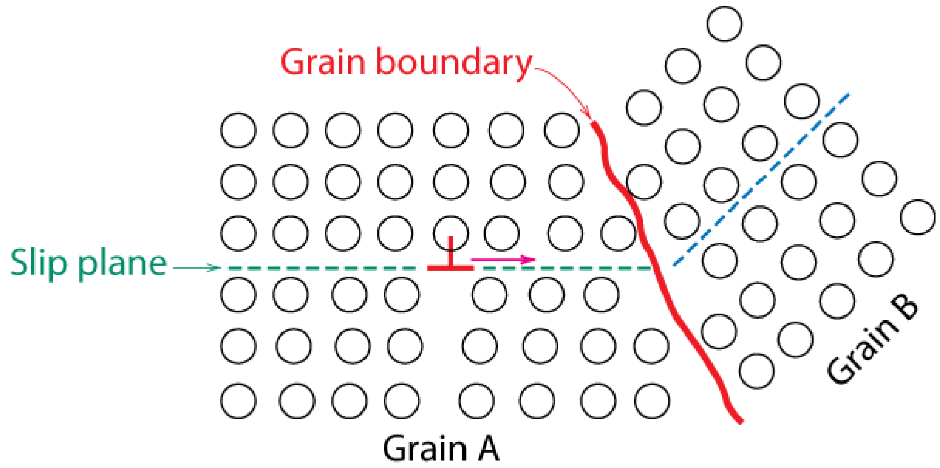
The relationship between yield stress and grain size is described mathematically by the following equation

- Hall-Petch Equation:

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

The Hall–Petch relationship tells us that we could achieve strength in materials that is as high as their own theoretical strength by reducing grain size.

- By changing grain size, one can influence the number of dislocations piled up at the grain boundary and 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

$$\sigma_y = \sigma_0 + k_y d^{-0.5}$$

Resistance of lattice to dislocation movement

σ_y = *yield strength (MPa)*
σ_0 = *intrinsic strength of lattice (MPa)*
k_y = *strengthening constant (MPa.m$^{0.5}$)*
d = *grain size (m$^{-0.5}$)*

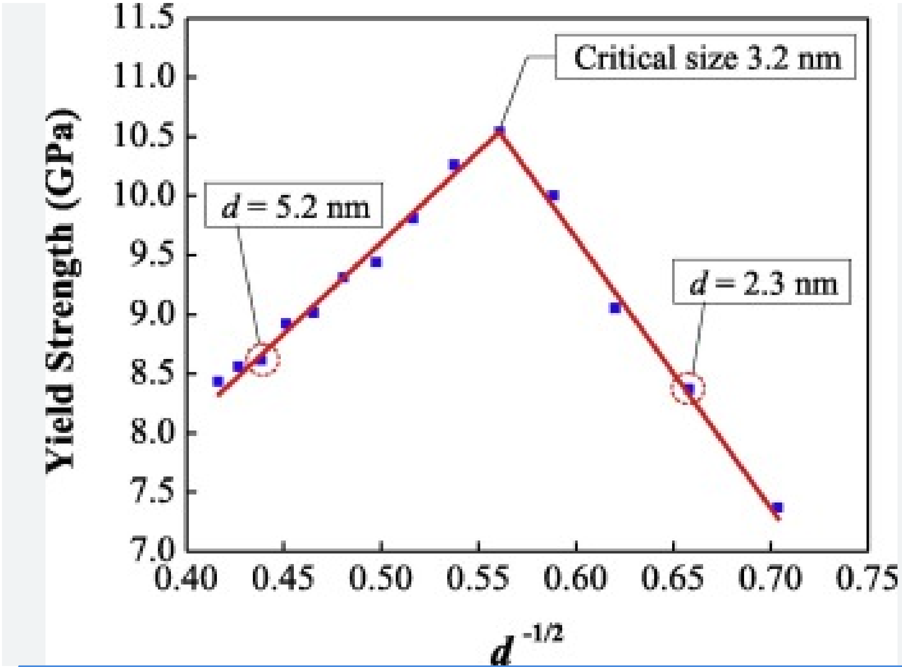
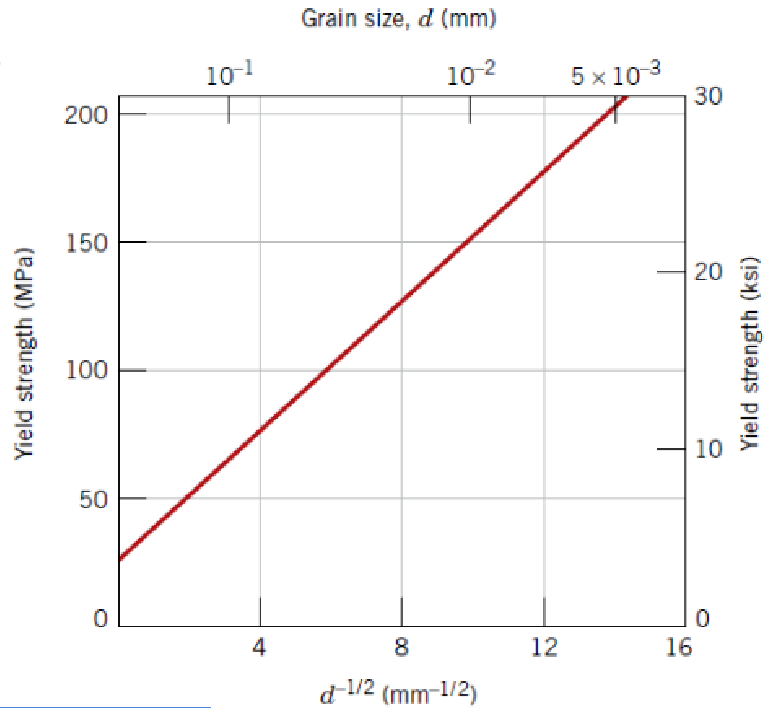


Figure 7.15 The influence of grain size on the yield strength of a 70 Cu–30 Zn brass alloy. Note that the grain diameter increases from right to left and is not linear. (Adapted from H. Suzuki, "The Relation between the Structure and Mechanical Properties of Metals," Vol. II, *National Physical Laboratory, Symposium No. 15*, 1963, p. 524.)



When the average grain size, *d*, was greater than 3.2 nm (i.e., $d^{-1/2}$ was less than 0.56), the yield strength σ_y of Titanium Nitride (TiN) (hard ceramic coating) increased with a decrease in *d*. This result conforms to the classical Hall–Petch

https://www.sciencedirect.com/science/article/abs/pii/S0927025617306183

Strengthening Mechanisms
Exam Example

The yield strength (σ_y) of the AZ31 magnesium alloy is 52 MPa for an average grain size (d) of 104 µm. Reducing grain size to 4 µm increases the yield strength to 253 MPa. Assuming that grain boundary refinement is the only significant strengthening mechanism at play:

a) Determine the intrinsic strength (σ_0) and grain refinement constant (k_y) of the magnesium alloy.

b) Calculate the expected yield strength of AZ31 for an average grain size of 40 µm.

Hall-Petch Equation $\sigma_y = \sigma_0 + k_y d^{-0.5}$

σ_y = *yield strength (MPa)*

σ_0 = *intrinsic strength of lattice (MPa)*

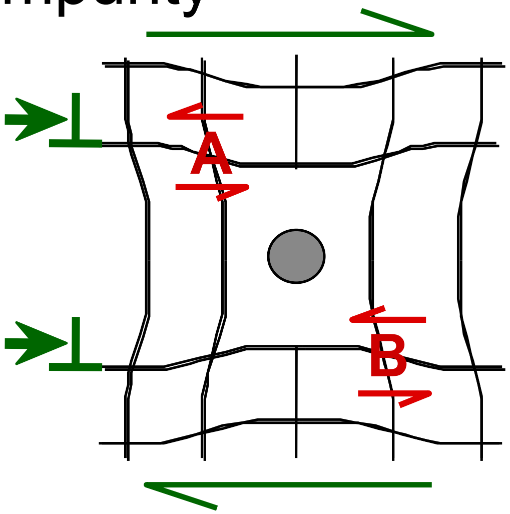
k_y = *strengthening constant (MPa.m$^{0.5}$)*

d = *grain size (m$^{-0.5}$)*

Four Strategies for Strengthening:
2: Form Solid Solutions

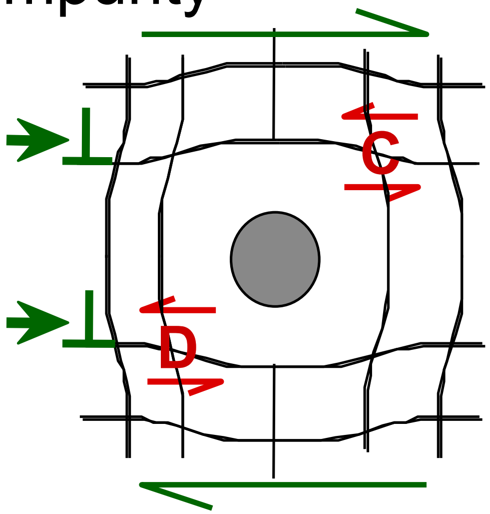
- Impurity atoms distort the lattice & generate lattice strains.
- These strains can act as barriers to dislocation motion.

- Smaller substitutional impurity



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

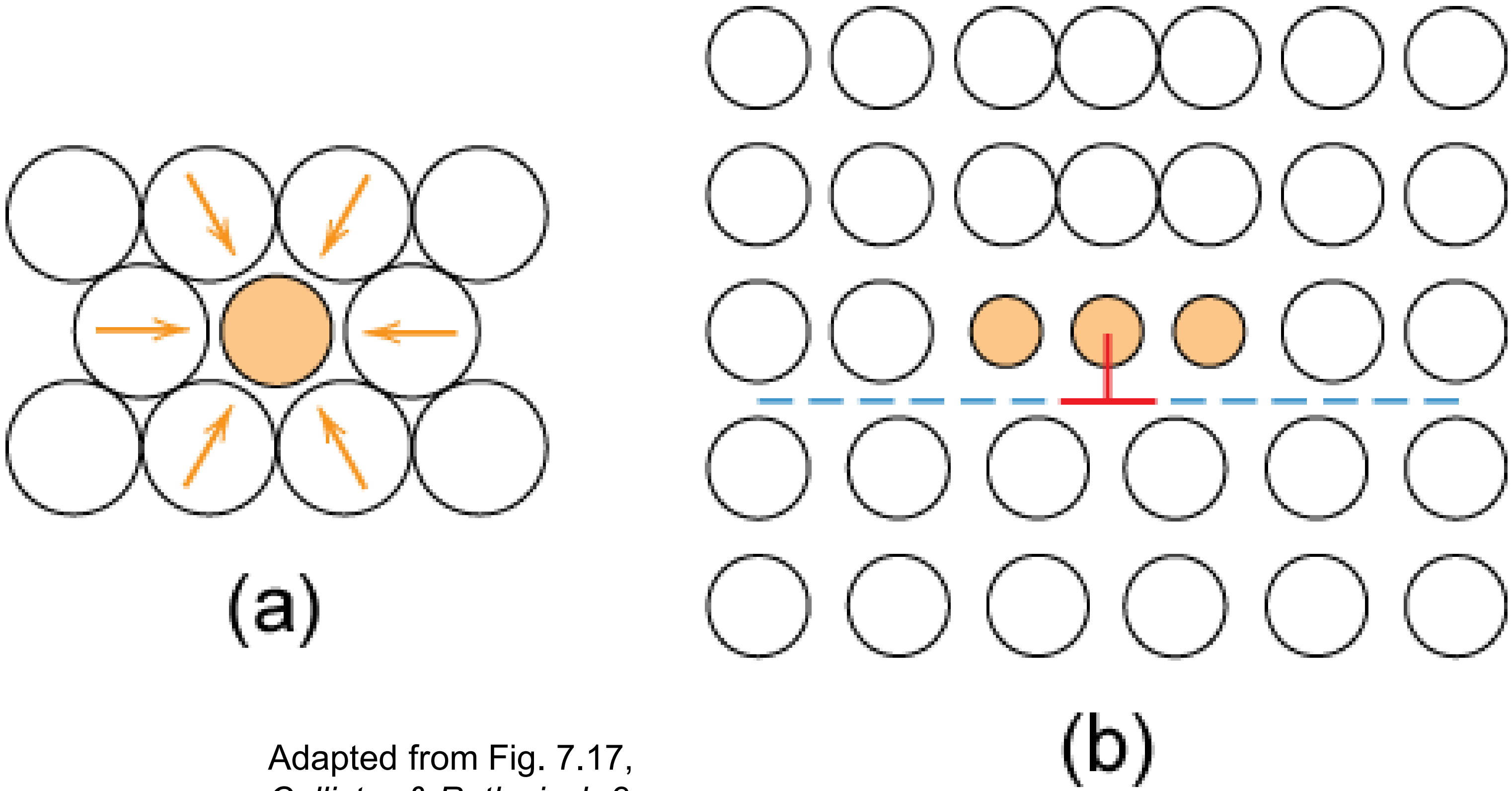
- Larger substitutional impurity



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

Strengthening by Solid Solution Alloying

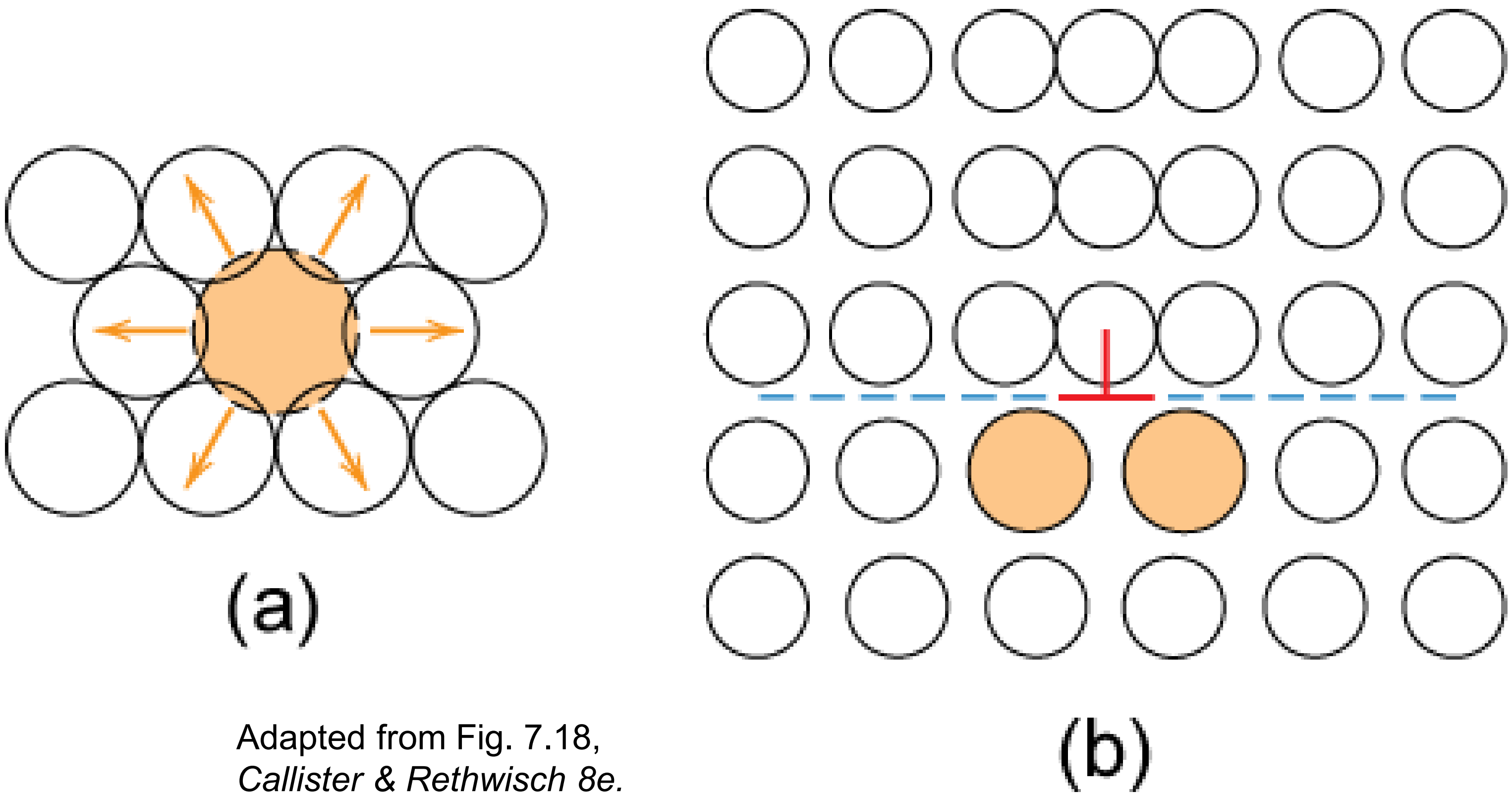
- Small impurities tend to concentrate at dislocations (regions of compressive strains) - partial cancellation of dislocation compressive strains and impurity atom tensile strains
- Reduce mobility of dislocations and increase strength



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

Strengthening by Solid Solution Alloying

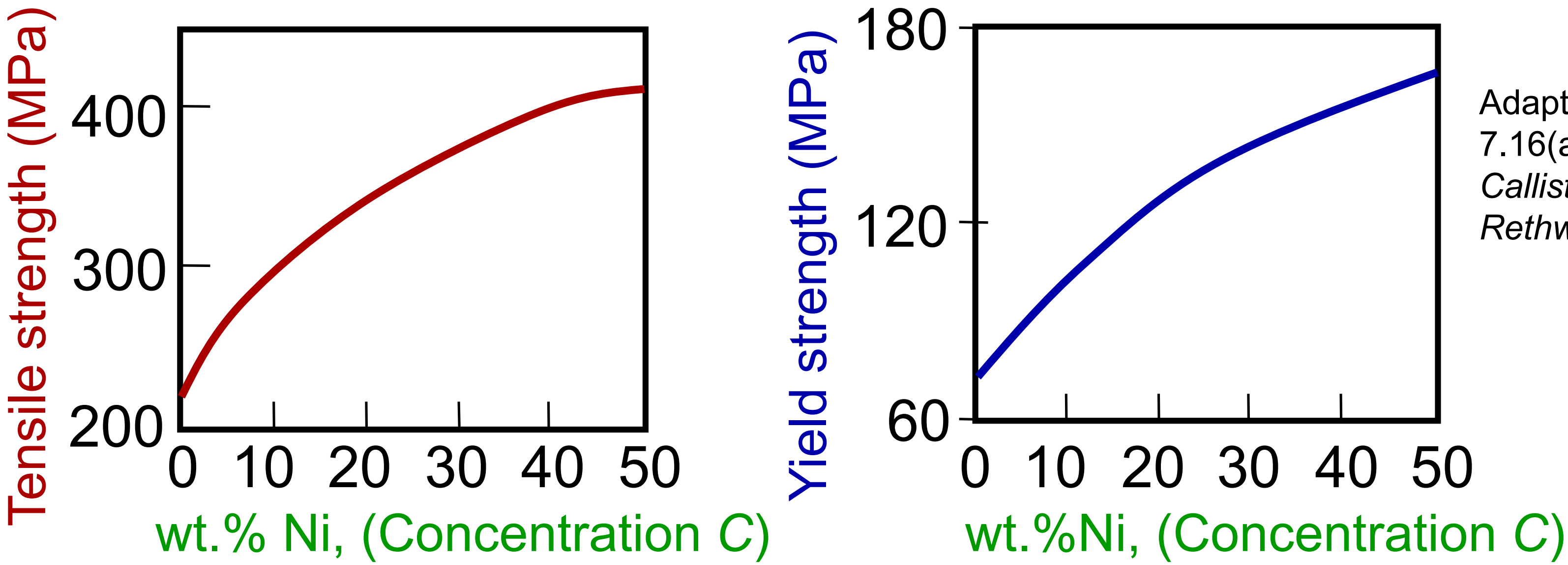
- Large impurities tend to concentrate at dislocations (regions of tensile strains)



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

Ex: Solid Solution Strengthening in Copper

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



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

- Alloying increases σ_y and *TS*.

Four Strategies for Strengthening: 3: Precipitation Strengthening

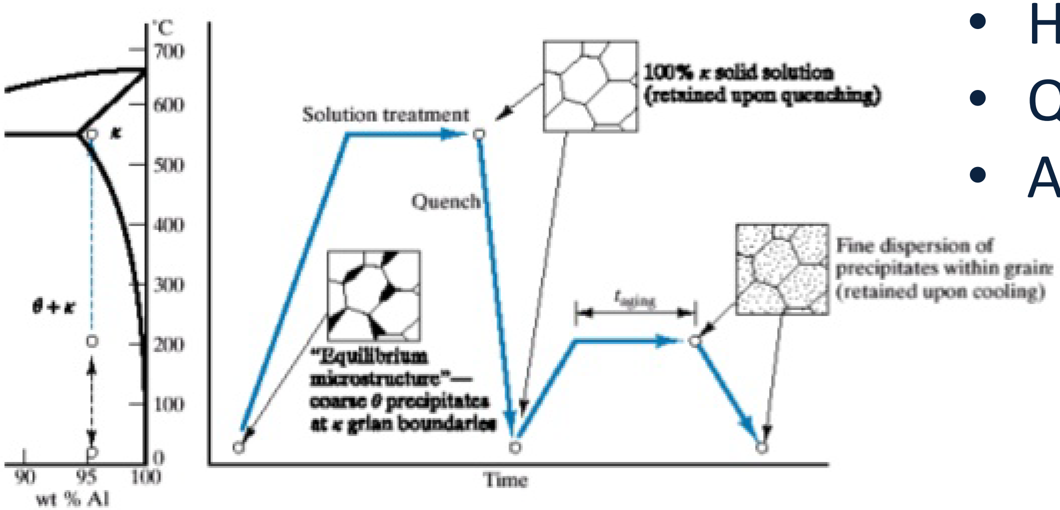
Precipitation hardening (Age hardening):
heat treatment technique used to increase the yield strength of malleable materials, including most structural alloys of aluminium, magnesium, nickel, titanium, and some steels and stainless steels.

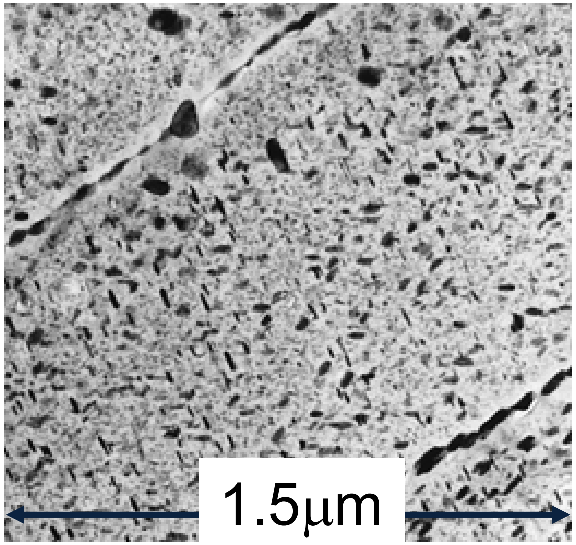
- Aluminum is strengthened with precipitates formed by alloying.

Steps in Precipitation Hardening

3 Steps

- Heat & solution treat
- Quench
- Age hardened

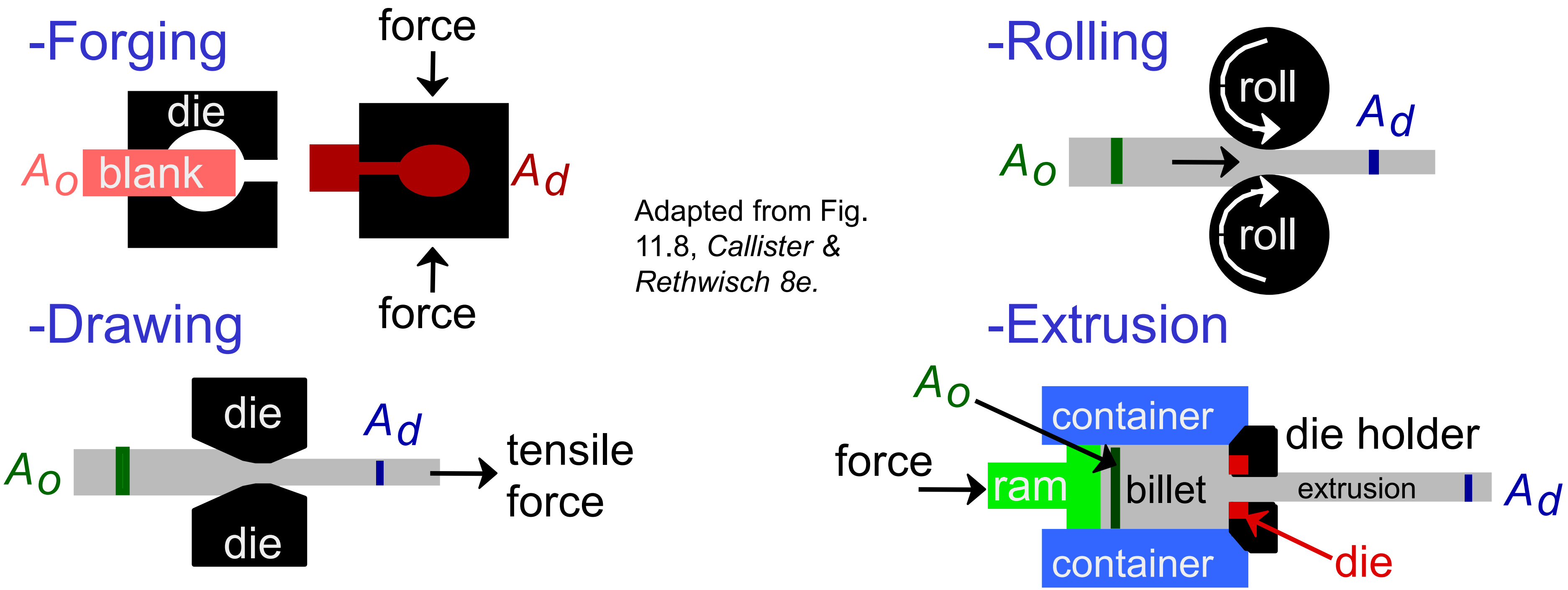




Adapted from Fig. 11.26, *Callister & Rethwisch 8e.* (Fig. 11.26 is courtesy of G.H. Narayanan and A.G. Miller, Boeing Commercial Airplane Company.)

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

- Deformation at room temperature (for most metals).
- Common forming operations reduce the cross-sectional area:



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

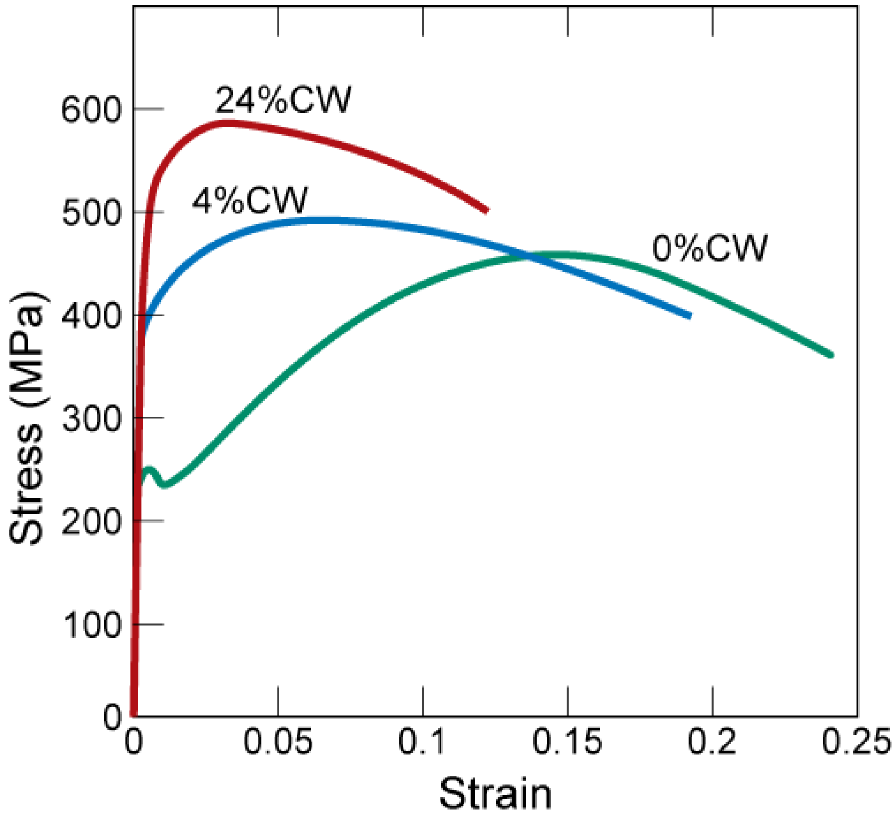
https://www.youtube.com/watch?v=J_7QmbcORak

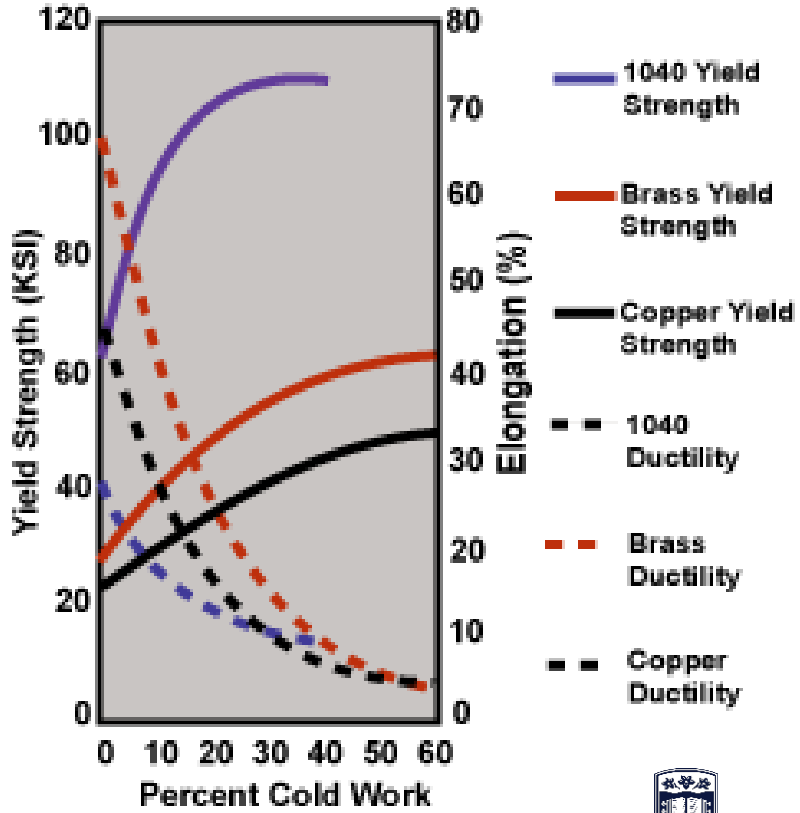
$$\%CW = \frac{A_o - A_d}{A_o} \times 100$$

Work hardening

- As cold work is increased:
  - **Yield strength** increases.
  - **Tensile strength** increases.
  - **Ductility** decreases.

Strain hardening (also called work-hardening or cold-working) is the process of making a metal harder and stronger through plastic deformation.





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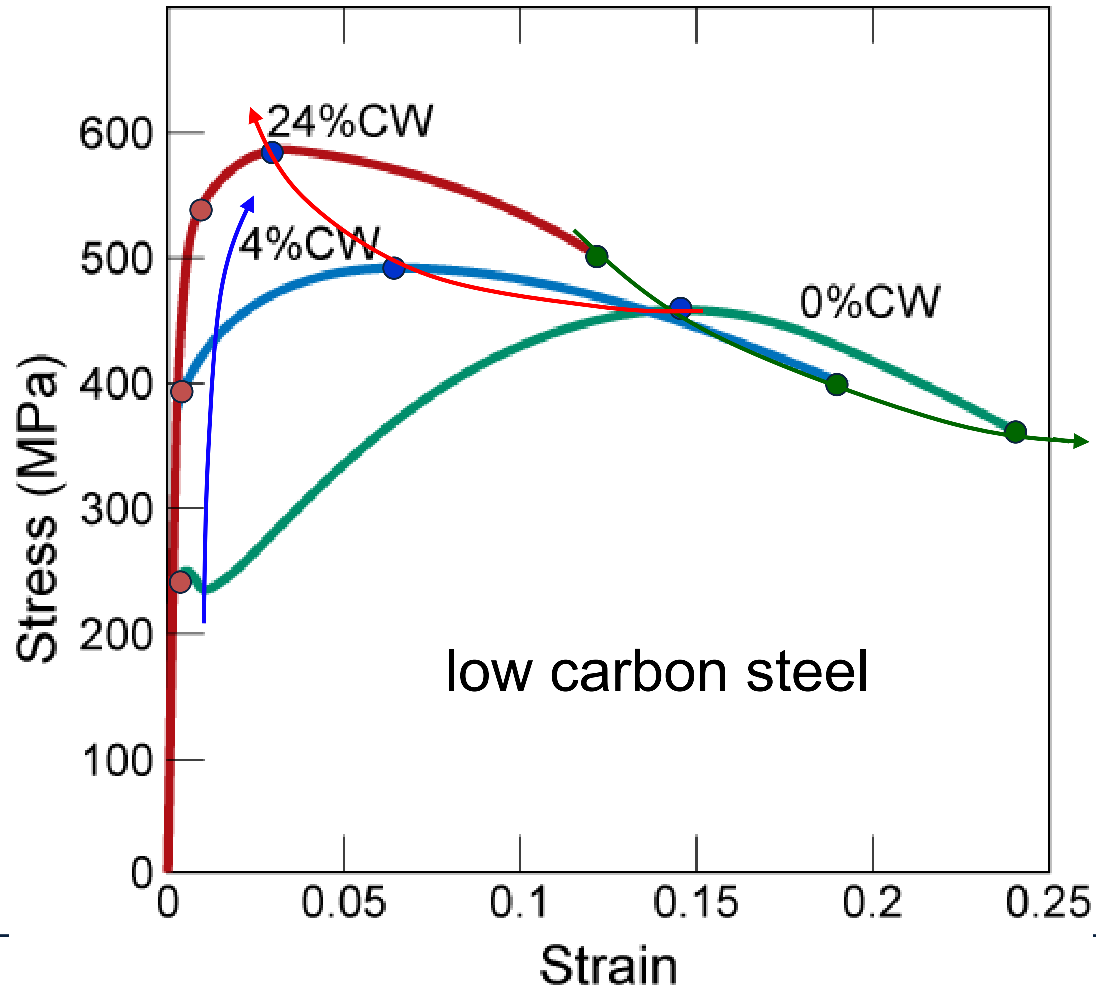
Impact of Cold Work

As cold work is increased

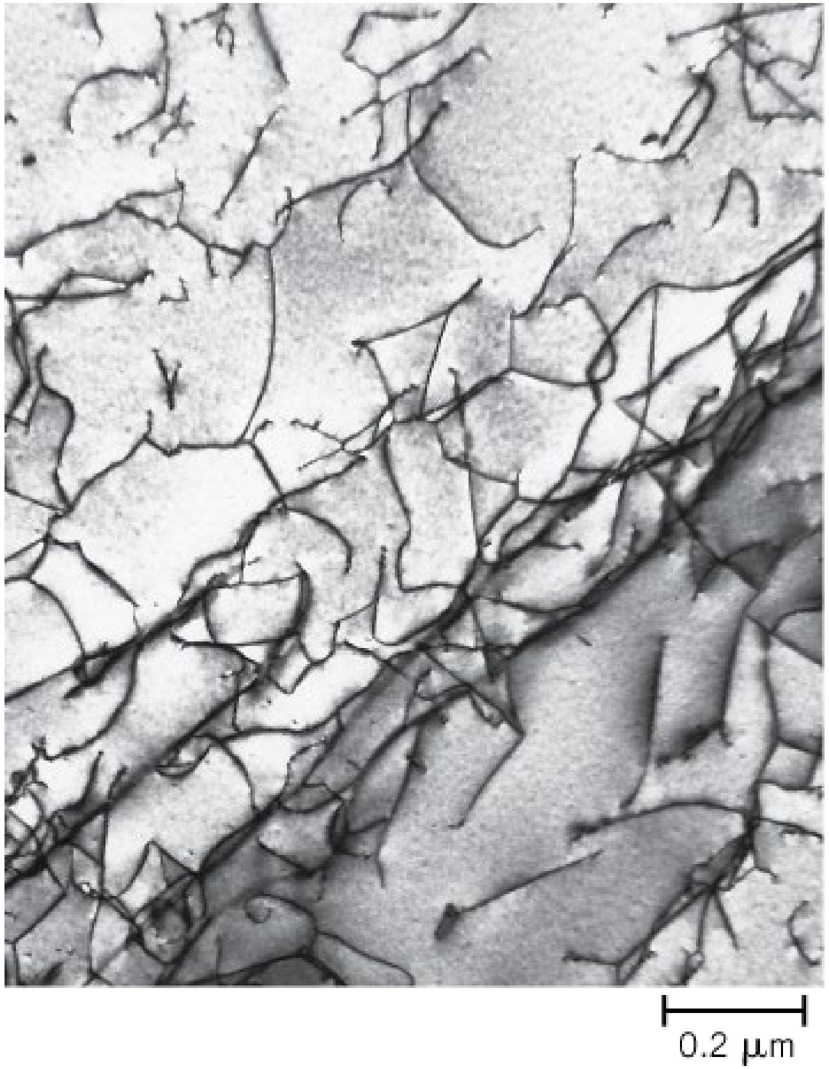
- Yield strength (σ_y) increases.
- Tensile strength (*TS*) increases.
- Ductility (*%EL* or *%AR*) decreases.



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

Dislocation Structures Change During Cold Working

- Dislocation structure in Titanium after cold working.



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

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

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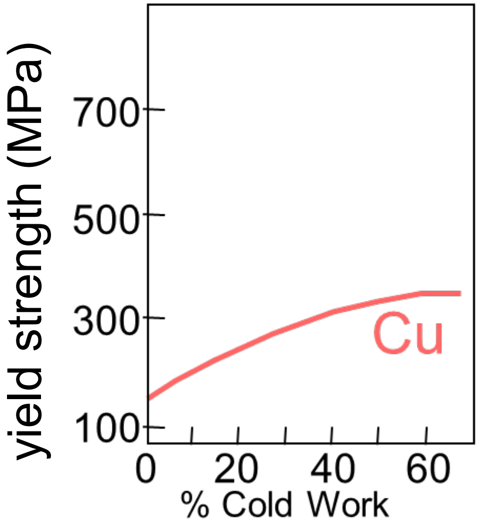
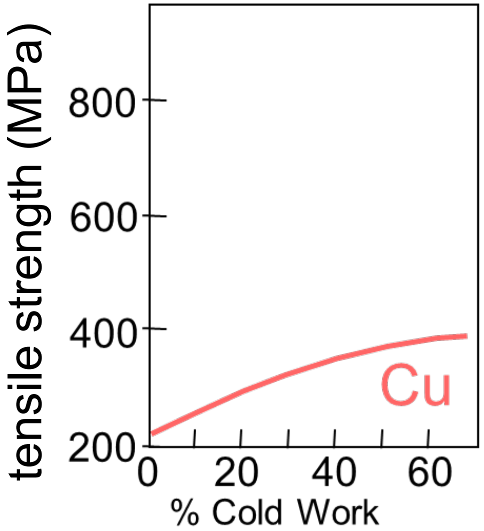
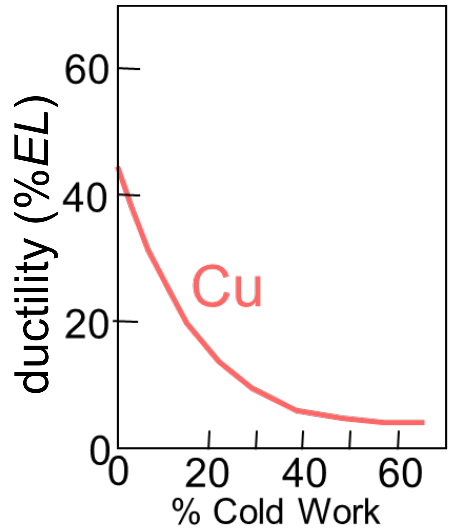
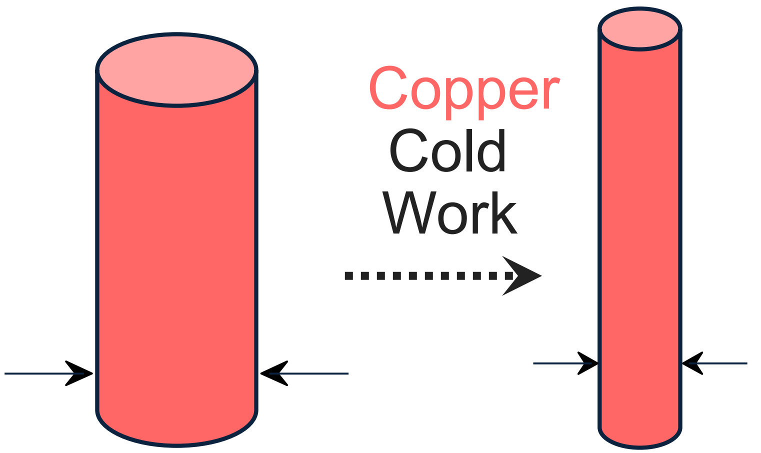
Mechanical Property Alterations Due to Cold Working

- What are the values of yield strength, tensile strength & ductility after cold working Cu?







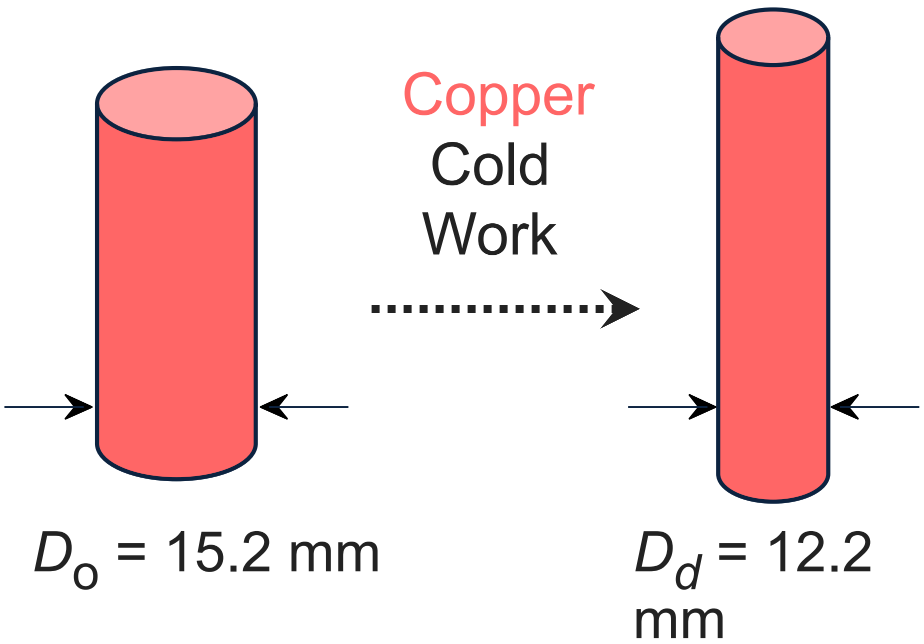


D_o = 15.2 mm D_d = 12.2 mm

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

Mechanical Property Alterations Due to Cold Working

- What are the values of yield strength, tensile strength & ductility after cold working Cu?



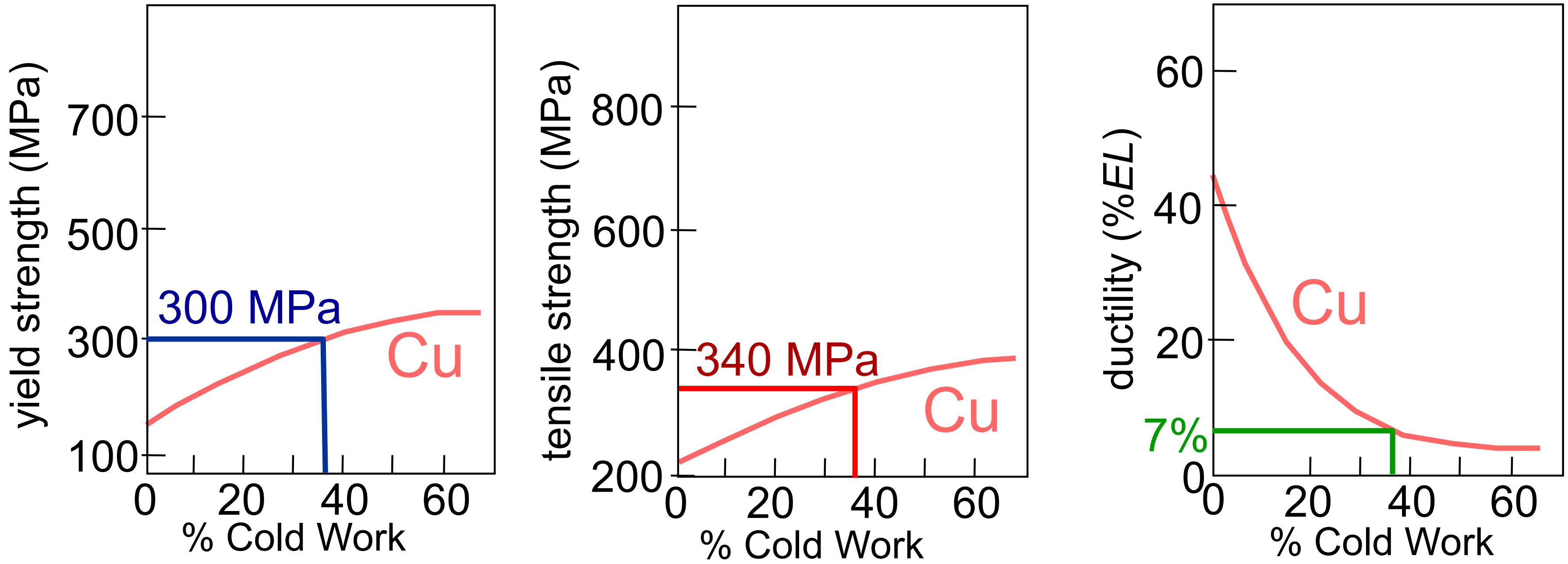
$$\%CW = \frac{\frac{\pi D_o^2}{4} - \frac{\pi D_d^2}{4}}{\frac{\pi D_o^2}{4}} \times 100$$

$$= \frac{D_o^2 - D_d^2}{D_o^2} \times 100$$

$$\%CW = \frac{(15.2\,\text{mm})^2 - (12.2\,\text{mm})^2}{(15.2\,\text{mm})^2} \times 100 = 35.6\%$$

Mechanical Property Alterations Due to Cold Working

- What are the values of yield strength, tensile strength & ductility for Cu for %CW = 35.6%?



σ_y = 300 MPa

TS = 340 MPa

%*EL* = 7%

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

Cold Working and Annealing

- Since cold working or strain hardening results from increased dislocation density we can assume that any treatment to rearrange or annihilate dislocations would begin to undo the effects of cold working.

- Annealing is a heat treatment used to eliminate some or all of the effects of cold working.

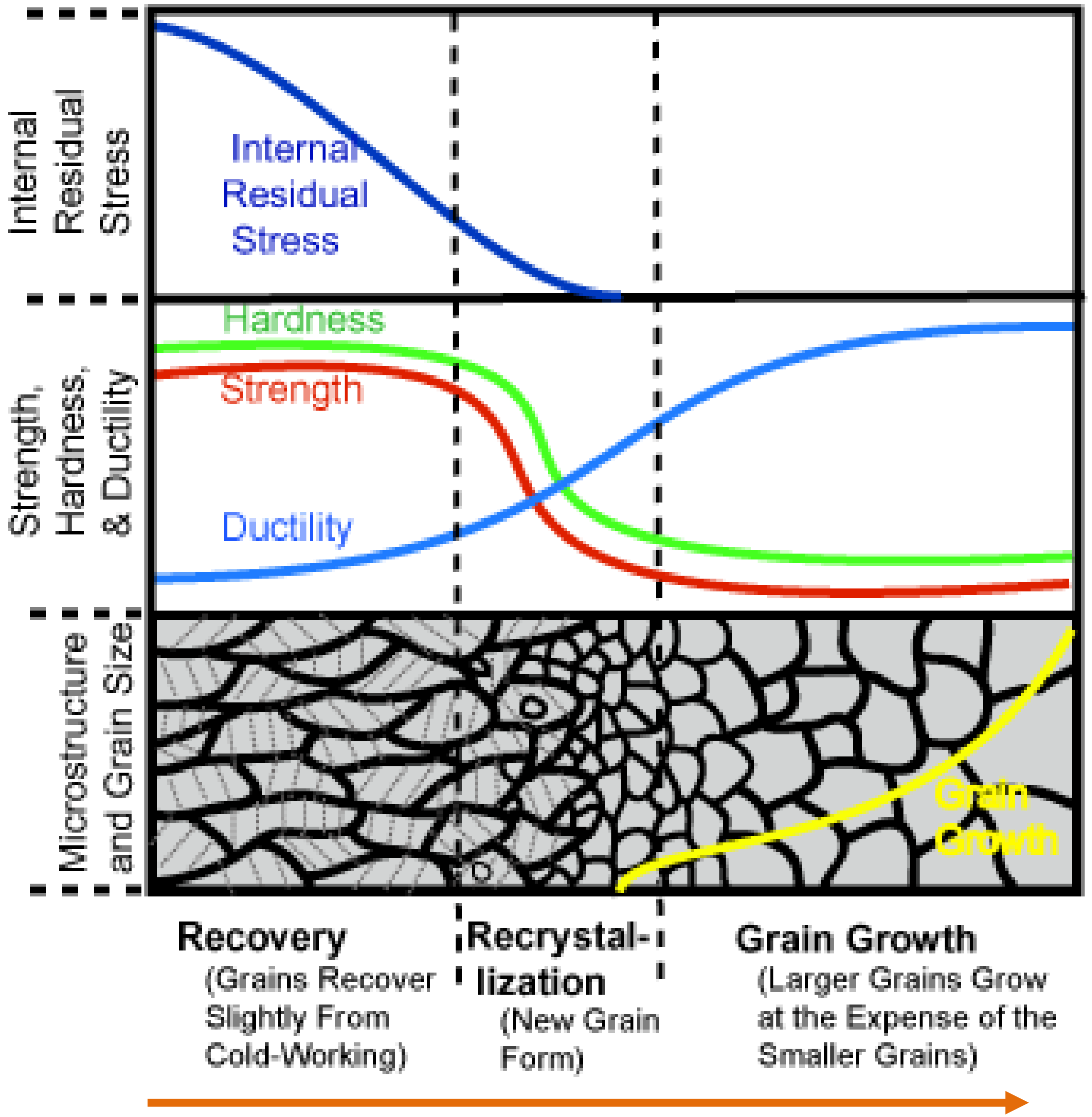
- After annealing, additional cold work could be done, since the ductility is restored; by combining repeated cycles of cold working and annealing, large total deformations may be achieved.

Heat treatment

Heat treatment can be used to remove the effects of strain hardening. Three things can occur during heat treatment:

1. Recovery
2. Recrystallization
3. Grain growth

https://www.youtube.com/watch?v=xmuiMdSaGHk



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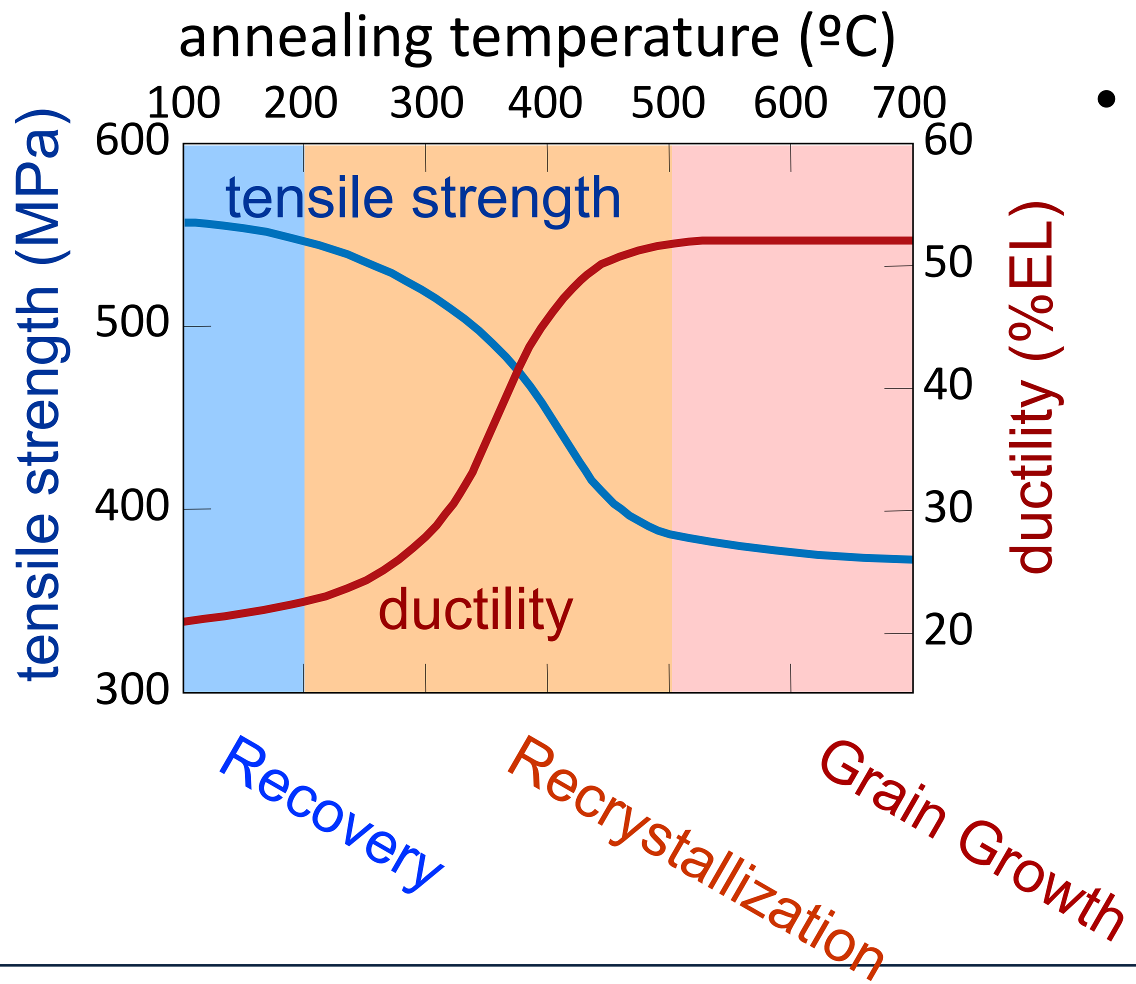
Effect of Heat Treating After Cold Working

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



- Three Annealing stages:
  1. Recovery
  2. Recrystallization
  3. Grain Growth

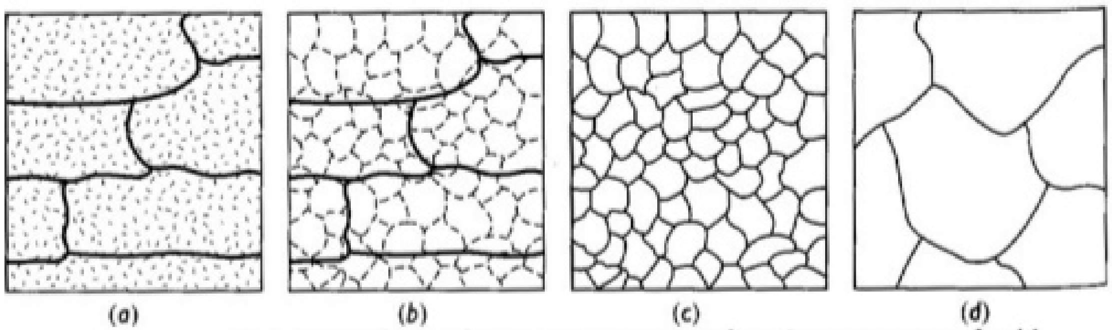
Adapted from Fig. 7.22, *Callister & Rethwisch 8e.* (Fig. 7.22 is adapted from G. Sachs and K.R. van Horn, *Practical Metallurgy, Applied Metallurgy, and the Industrial Processing of Ferrous and Nonferrous Metals and Alloys*, American Society for Metals, 1940, p. 139.)

Annealing

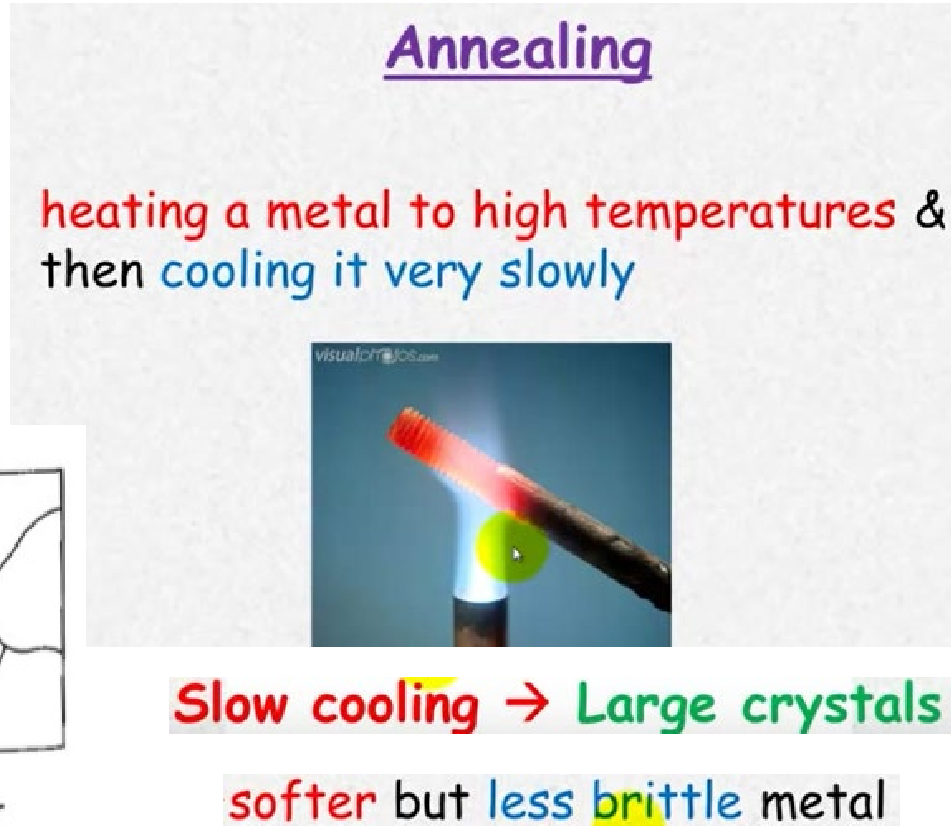
Reversing Cold working : Heat Treatment Annealing

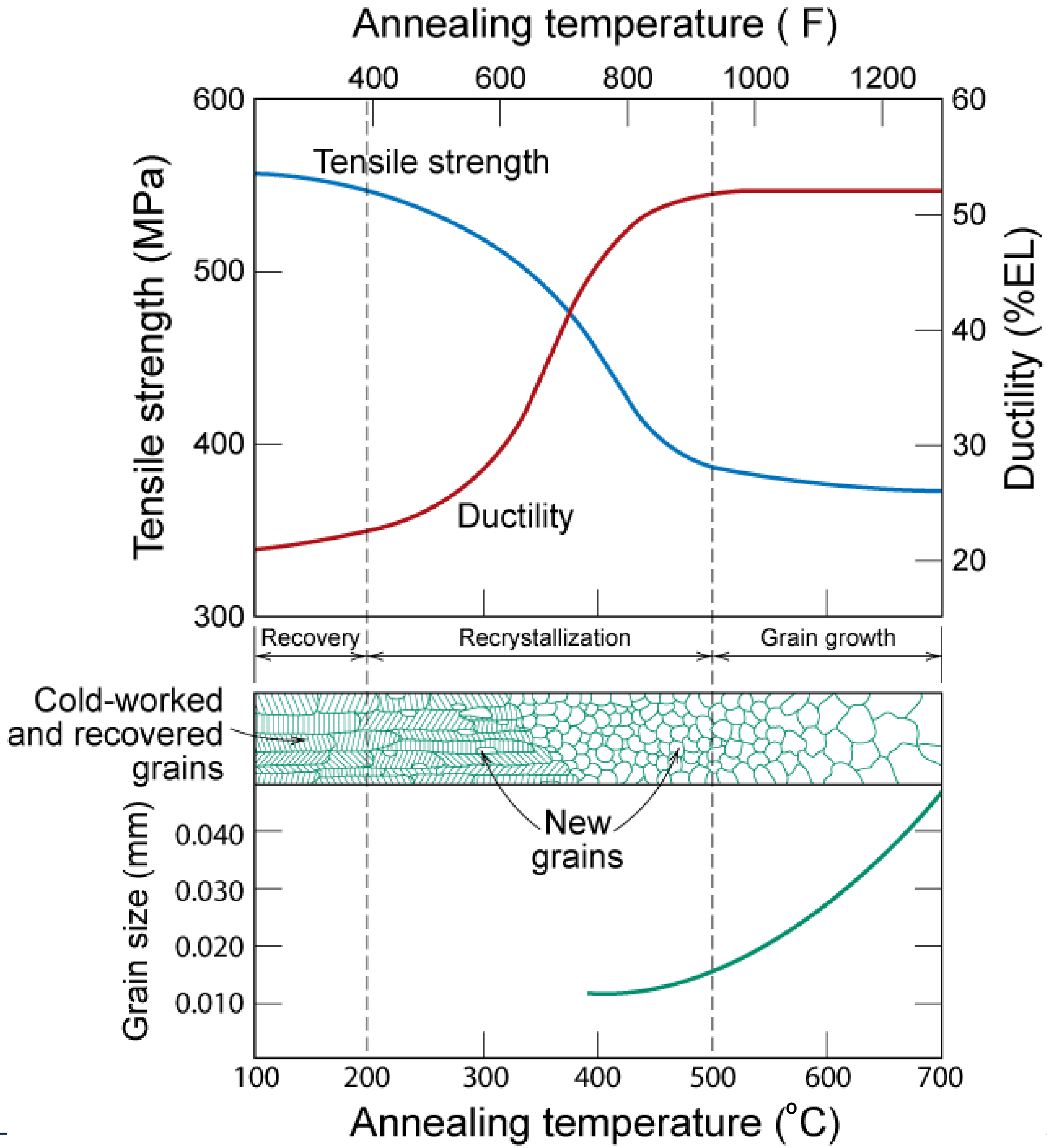
- Recover or re-gain ductility by heating metal above recrystallization temperature for enough time and then cooling

- Annealing :
    - Crystal grains grow
    - Dislocations move



The effect of annealing temperature on the microstructure of cold-worked metals: (a) cold worked, (b) after recovery, (c) after recrystallization, and (d) after grain growth.

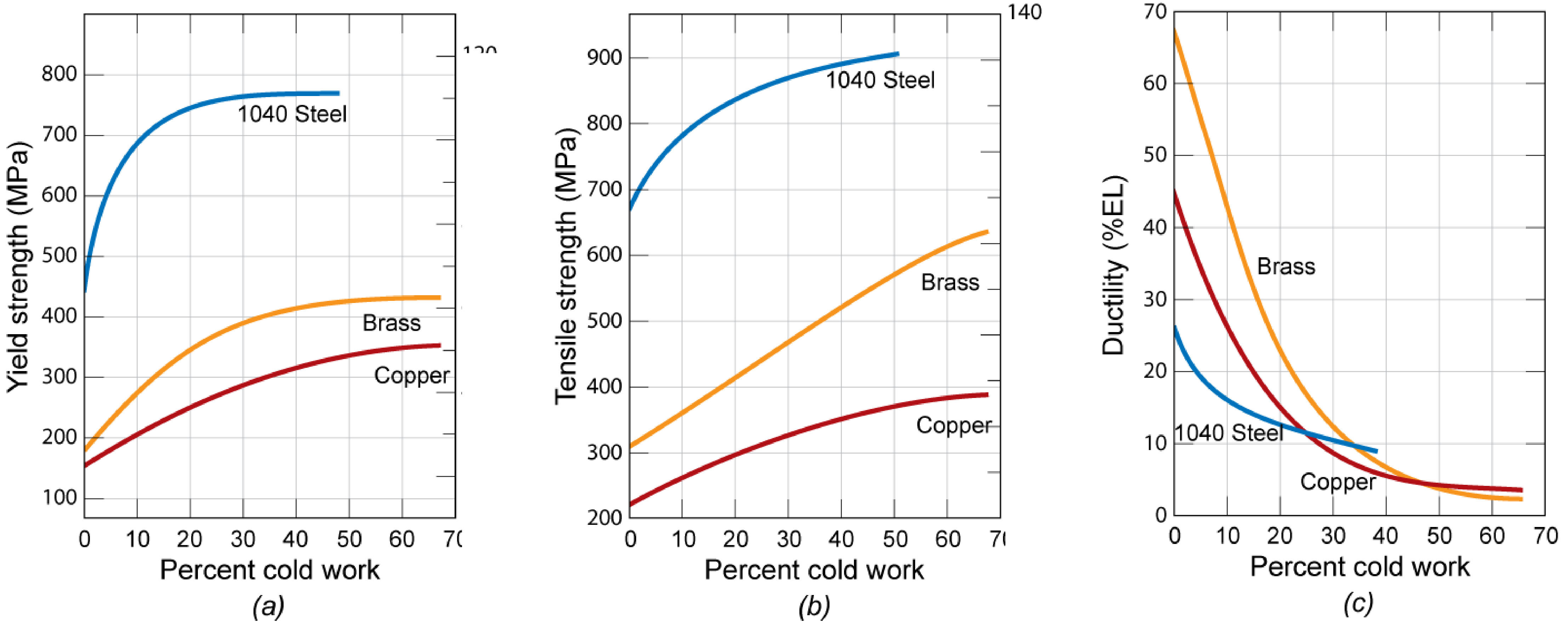




Adapted from Fig. 7.22, *Callister & Rethwisch 8e.*

Strengthening Mechanisms

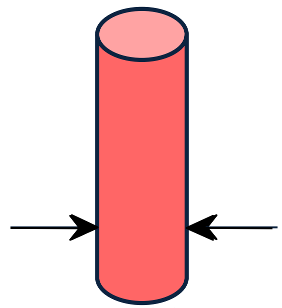
Exam Example



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

Diameter Reduction Procedure - Problem

A cylindrical rod of brass originally 10 mm in diameter is to be cold worked by drawing.



The circular cross section will be maintained during deformation.

A cold-worked tensile strength in excess of 380 MPa and a ductility of at least 15 %*EL* are desired.

Furthermore, the final diameter must be 7.5mm.

Explain how this may be accomplished.

Stop and check videos on moodle

Lecture 3: Stop and Check videos

Grain Size Influences Properties

- Metals having small grains – relatively strong and tough at low temperatures
- Metals having large grains – good creep resistance at relatively high temperatures

Summary

- Dislocations are observed primarily in metals and alloys.
- Strength is increased by making dislocation motion difficult.
- Strength of metals may be increased by:
  -- decreasing grain size
  -- solid solution strengthening
  -- precipitate hardening
  -- cold working
- A cold-worked metal that is heat treated may experience recovery, recrystallization, and grain growth – its properties will be altered.