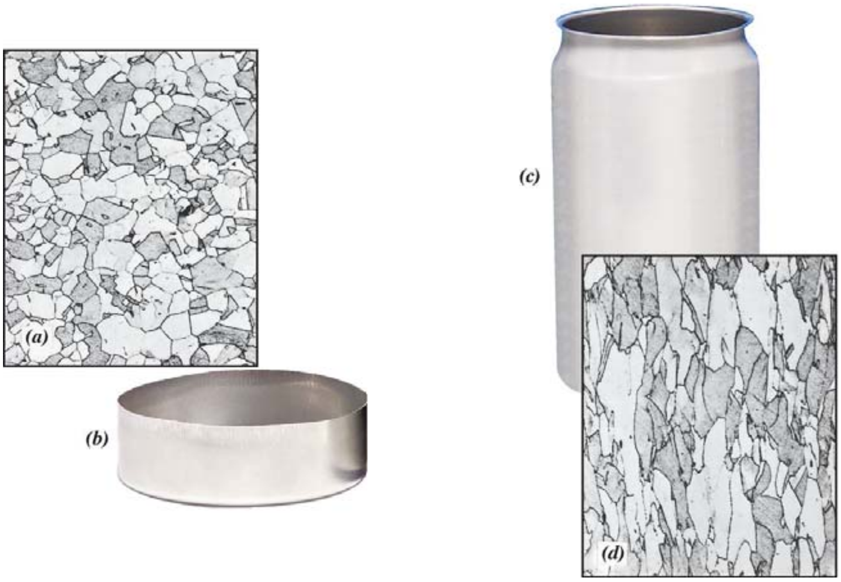
Chapter 9: Dislocations & Strengthening Mechanisms

- **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?



9.2 Basic Concepts

- **Plastic deformation corresponds to the motion of large numbers of dislocations.**
- **Dislocation motion is easier in metals rather than in ceramics.**
  - non-directional bonding
  - close-packed directions for slip
- **In metals, plastic deformation occurs by slip – an edge dislocation (extra half-plane of atoms) slides over adjacent plane half-planes of atoms.**

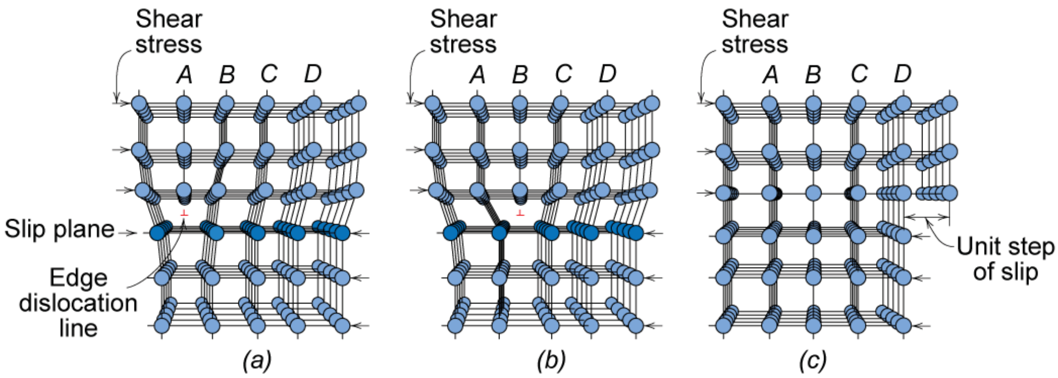


Fig. 9.1, *Callister & Rethwisch 9e.* (Adapted from A. G. Guy, Essentials of Materials Science, McGraw-Hill Book Company, New York, 1976, p. 153.)

9.2 Basic Concepts

- **A dislocation moves along a slip plane in a slip direction perpendicular to the dislocation line.**
- **The slip direction is the same as the Burgers vector direction.**

Edge dislocation Screw dislocation

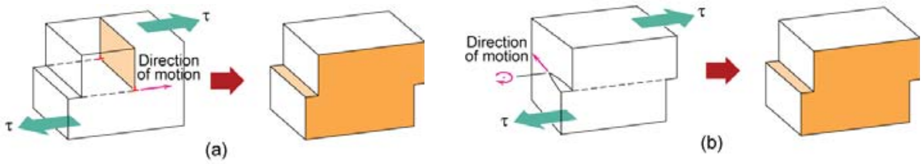
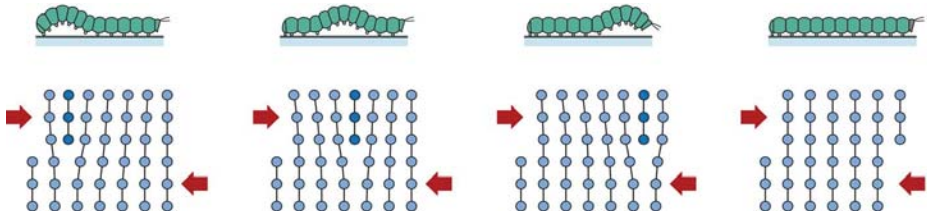


Fig. 9.2, *Callister & Rethwisch 9e.*



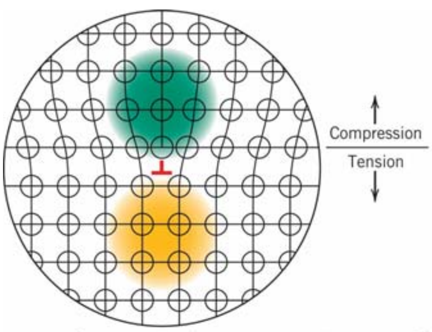
The analogy between caterpillar and dislocation motion (Fig. 9.3, *Callister & Rethwisch 9e.)*

- **Dislocation density**
  - The total dislocation length per unit volume
  - The number of dislocations that intersect a unit area

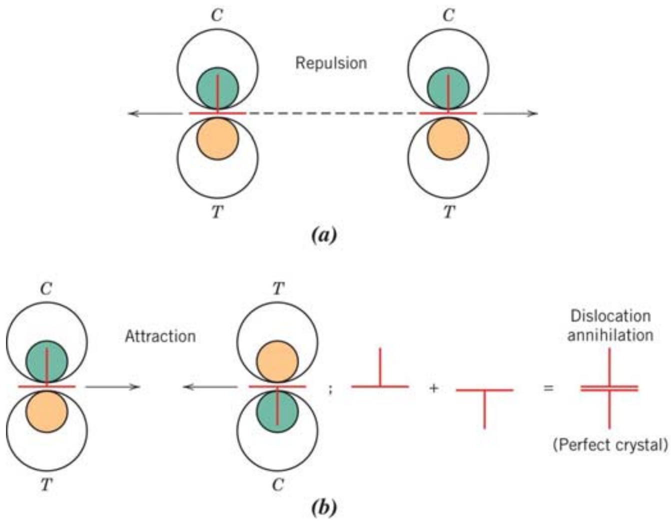
Solidified metals: 10^{3} mm^{-2}
Heavily deformed metals: 10^{9} - 10^{10} mm^{-2}
Heat-treated metals: 10^{5} - 10^{6} mm^{-2}

9.3 Characteristics of Dislocations

- **When metals are plastically deformed, some fraction of the deformation energy (approximately 5%) is retained internally; the remainder is dissipated as heat.**
- **The main portion of the stored energy is the strain energy associated with dislocations.**



Regions of compression (green) and tension (yellow) located around an edge dislocation. (Fig. 9.4, *Callister & Rethwisch 9e.)*



Energetic interaction of two edge dislocations (Fig. 9.5, *Callister & Rethwisch 9e.)*

9.4 Slip Systems

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

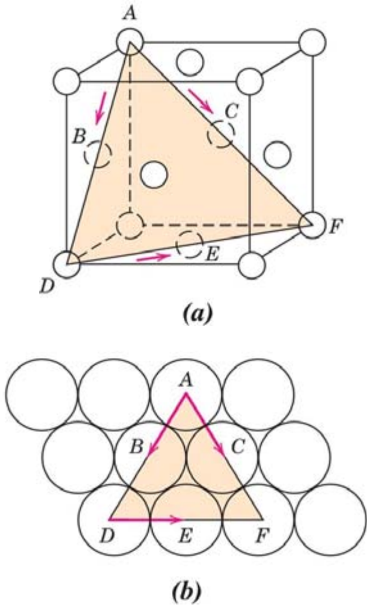


Fig. 9.6, *Callister & Rethwisch 9e.*

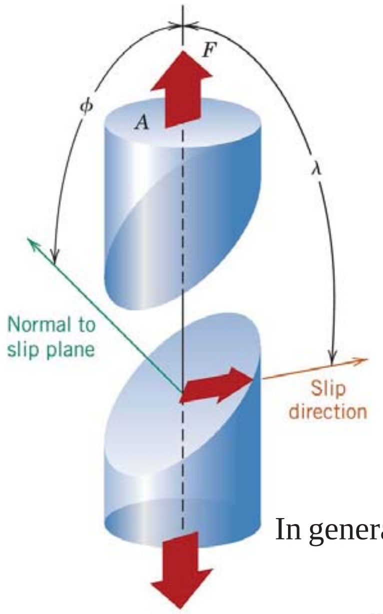
Table 9.1 Slip systems for FCC, BCC, and HCP metals, *Callister & Rethwisch 9e.*

Metals	*Slip Plane*	*Slip Direction*	*Number of Slip Systems*
	Face-Centered Cubic		
Cu, Al, Ni, Ag, Au	{111}	⟨110⟩	12
	Body-Centered Cubic		
α-Fe, W, Mo	{110}	⟨111⟩	12
α-Fe,W	{211}	⟨111⟩	12
α-Fe, K	{321}	⟨111⟩	24
	Hexagonal Close-Packed		
Cd, Zn, Mg, Ti, Be	{0001}	$\langle 11\bar{2}0\rangle$	3
Ti, Mg, Zr	$\{10\bar{1}0\}$	$\langle 11\bar{2}0\rangle$	3
Ti, Mg	$\{10\bar{1}1\}$	$\langle 11\bar{2}0\rangle$	6

- **Burgers vector, b: unit slip distance in sip direction**
  - **b**(FCC) = (a/2)<110>, **b**(BCC) = (a/2)<111>, **b**(HCP) = (a/3)<1120>

9.5 Slip in Single Crystals

- **Resolved shear stress, τ_R**
  - Depends not only on the applied stress but also on the orientation of both the slip plane and direction within that plane.

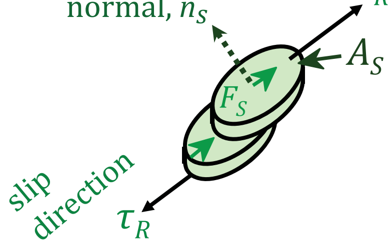


In general, $\lambda + \varphi \neq 90^\circ$

Fig. 9.7, *Callister & Rethwisch 9e.*

Resolved shear stress:

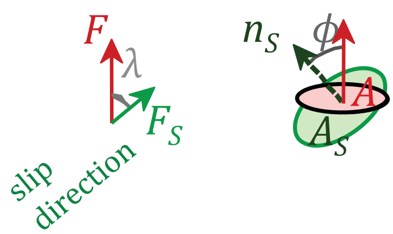
$$\tau_R = F_S / A_S$$



Relation between σ and τ_R

$$\tau_R = F_S / A_S$$

$F \cos \lambda$ $\quad$ $A / \cos \phi$

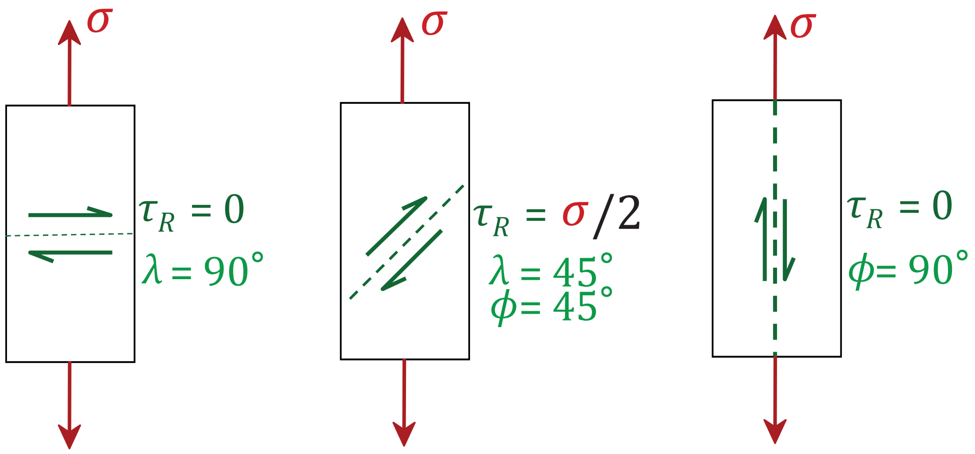


$$\tau_R = \sigma \cos \lambda \cos \varphi$$

Critical Resolved Shear Stress (Peierls Stress)

- **Condition for dislocation motion:** $\tau_R > \tau_{CRSS}$
  - Critical resolved shear stress (Peierls stress, material property)= the minimum resolved shear stress required to initiate slip (Typically 100 kPa to 10 MPa)
  - Ease of dislocation motion depends on crystallographic orientation

$$\tau_R = \sigma \cos\lambda \cos\varphi$$



$\therefore \tau$ maximum at $\lambda = \phi = 45°$

Single Crystal Slip

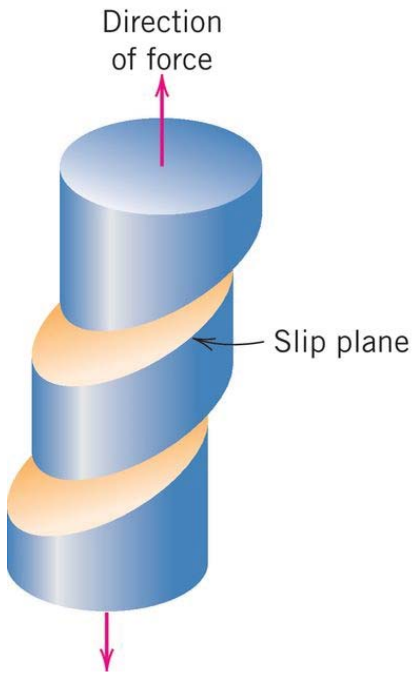
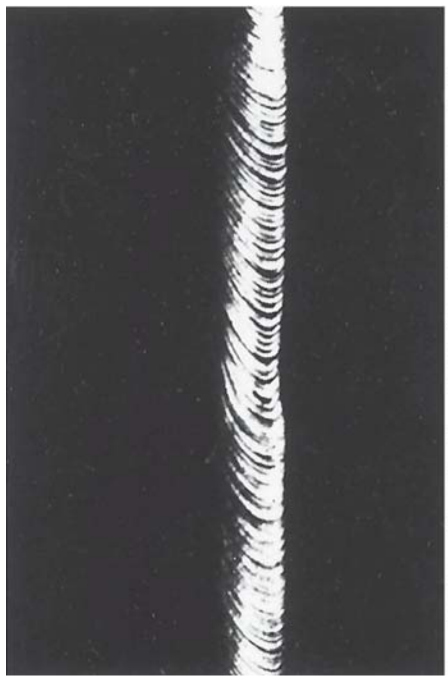


Fig. 9.8, *Callister & Rethwisch 9e.*



From C. F. Elam, The Distortion of Metal Crystals, Oxford University Press, London, 1935.

Fig. 9.9, *Callister & Rethwisch 9e.*

9.6 Plastic Deformation of Polycrystalline Materials

- Polycrystals stronger than single crystals–grain boundaries are barriers to dislocation motion.
- Slip planes & directions (λ, ϕ) change from one grain to another.
- τ_R will vary from one grain to another.
- The grain with the largest τ_R yields first.
- Other (less favorably oriented) grains yield later.
- Geometric constraints are imposed on the grains during deformation.

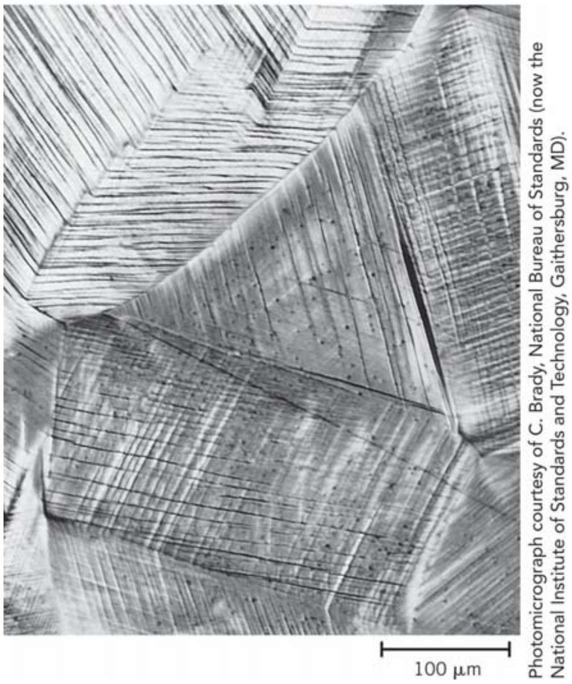


Fig. 9.10, *Callister & Rethwisch 9e.*

Anisotropy in Yield Strength

- **Anisotropy in yield stress can be induced by rolling a polycrystalline metal**

- before rolling - after rolling

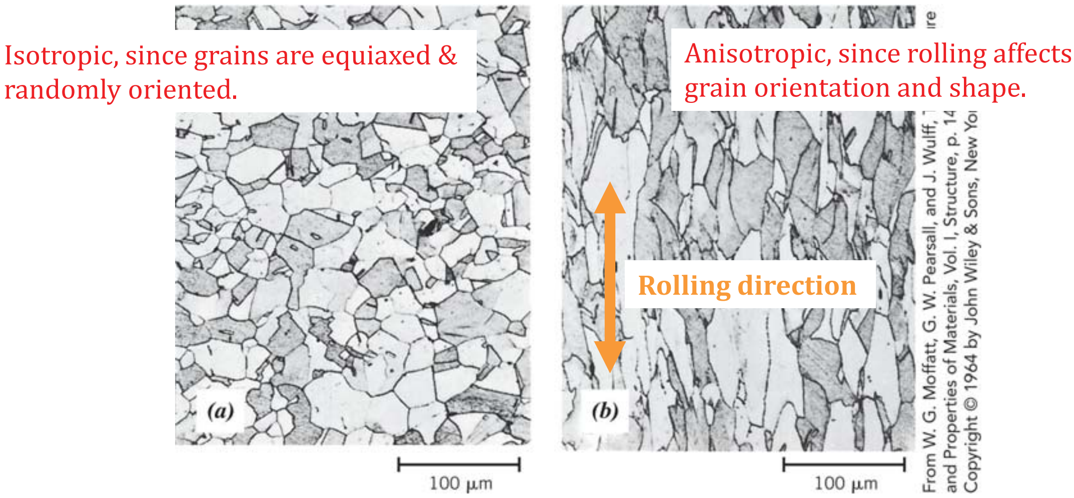
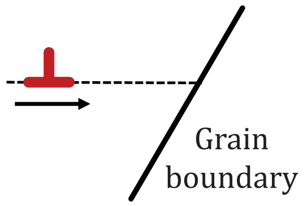


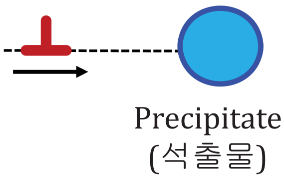
Fig. 9.11 Alteration of the grain structure of a polycrystalline metal as a result of plastic deformation. (a) Before deformation the grains are equiaxed. (b) The deformation has produced elongated grains, *Callister & Rethwisch 9e.*

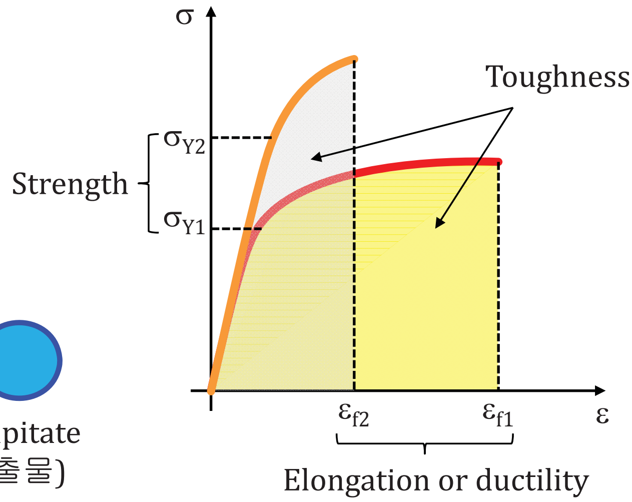
Mechanisms of Strengthening in Metals

- **Strength vs. Ductility and Toughness**
  - Ductility is sacrificed when an alloy is strengthened.
  - The ability of a metal to deform plastically depends on the ability of dislocations to move.
  - Restricting or hindering dislocation motion renders a material harder and stronger.

- **Four Strategies for Strengthening:**
  - Grain size reduction
  - Solid solution alloying
  - Precipitation strengthening
  - Strain hardening







9.8 Strengthening by Grain Size Reduction

- **Grain boundary (GB) acts as a barrier to dislocation motion.**
  - Adjacent grains normally have different orientations.
  - The atomic disorder within a GB region results in a discontinuity of slip planes.
  - Barrier "strength" increases with increasing angle of misorientation.
  - Smaller grain size: more barriers to slip.
  - Dislocations tend to “pile up” at GBs.

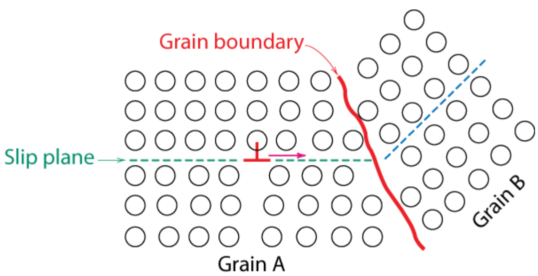
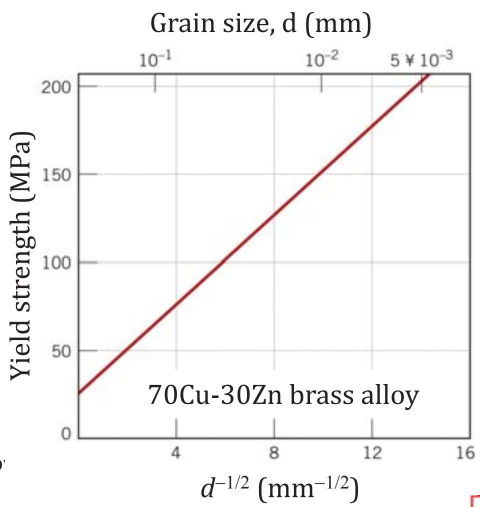


Fig. 9.14 The motion of a dislocation as it encounters a GB, illustrating ho the GB acts as a barrier to continued slip. Slip planes are discontinuous and change directions across the GB. *Callister & Rethwisch 9e.*

- **Hall-Petch Equation:**

$$\sigma_Y = \sigma_0 + k_Y d^{-1/2}$$

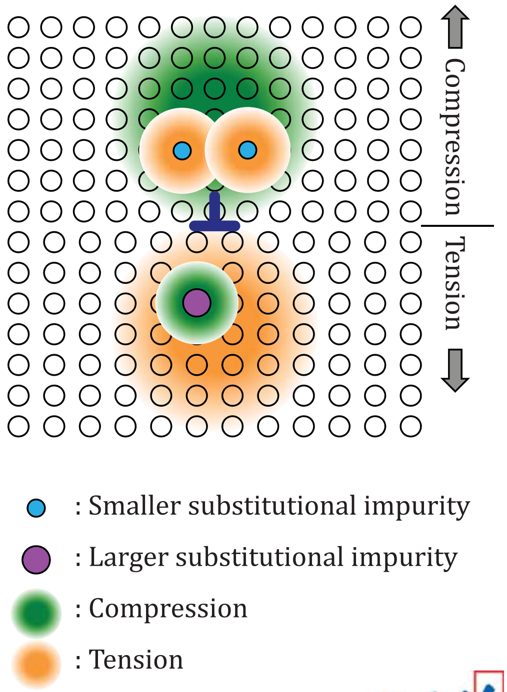
  - *d*: average grain diameter
  - σ_0 and k_Y: material constant



9.9 Solid-Solution Strengthening

- **Alloys are stronger than pure metals because impurity atoms that go into solid solution typically impose lattice strains on the surrounding host atoms.**
  - Impurity atoms distort the lattice & generate lattice strains.
  - These strains can act as barriers to dislocation motion.
- **Small impurities tend to concentrate at regions of compressive strains near dislocations.**
  - Partial cancellation of dislocation compressive strains and impurity atom tensile strains
  - Reduce mobility of dislocations and increase strength
- **Large impurities tend to concentrate at regions of tensile strains near dislocations.**

Lattice strains around a dislocation



Example: Solid Solution Strengthening in Copper

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

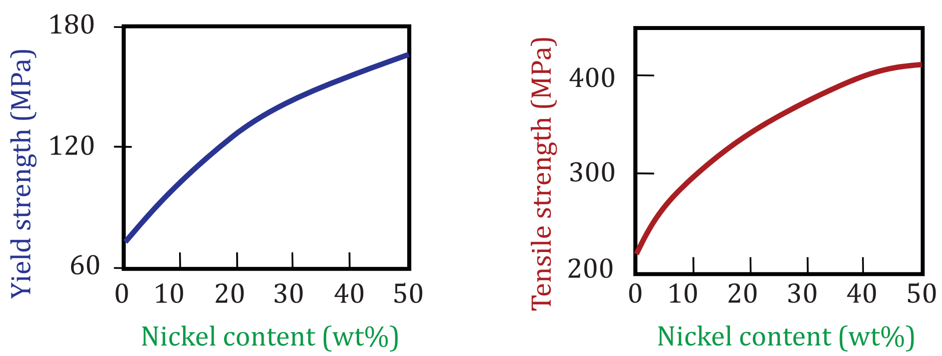
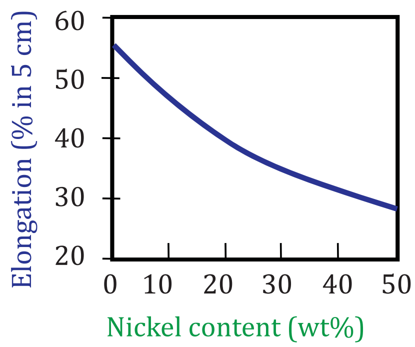


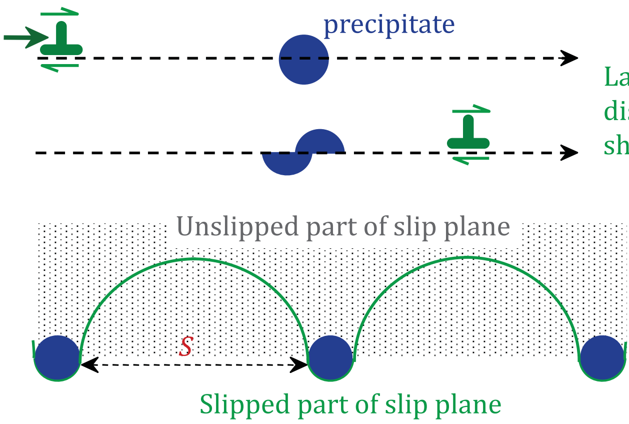
Fig. 9.16, *Callister & Rethwisch 9e.*

- Empirical relation: $\sigma_Y \sim C^{1/2}$
- Alloying increases yield strength and tensile strength.



Precipitation Strengthening

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



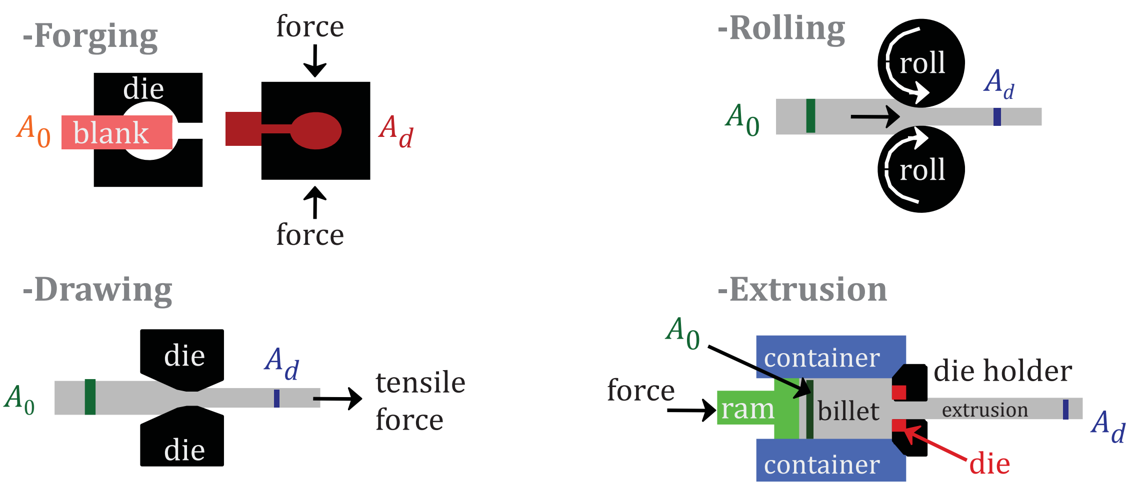
Large shear stress needed to move dislocation toward precipitate and shear it.

Dislocation "advances" but precipitates act as "pinning" sites with spacing S.

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

9.10 Strain Hardening

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



- Percent cold work: $\%CW = \dfrac{A_0 - A_d}{A_0} \times 100$

Adapted from Fig. 17.2, *Callister & Rethwisch 9e.*

Effect of Cold Working

- **Dislocation structures change during cold working**
  - Dislocations entangle with one another during cold work.
  - Dislocation motion becomes more difficult.

Dislocation structure in Ti after cold working

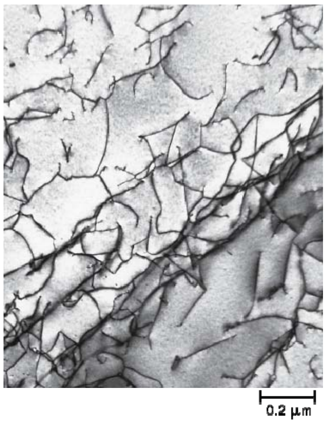


Fig. 6.12, *Callister & Rethwisch 9e.*

- **Dislocation density increases during cold working**
  - Dislocation density

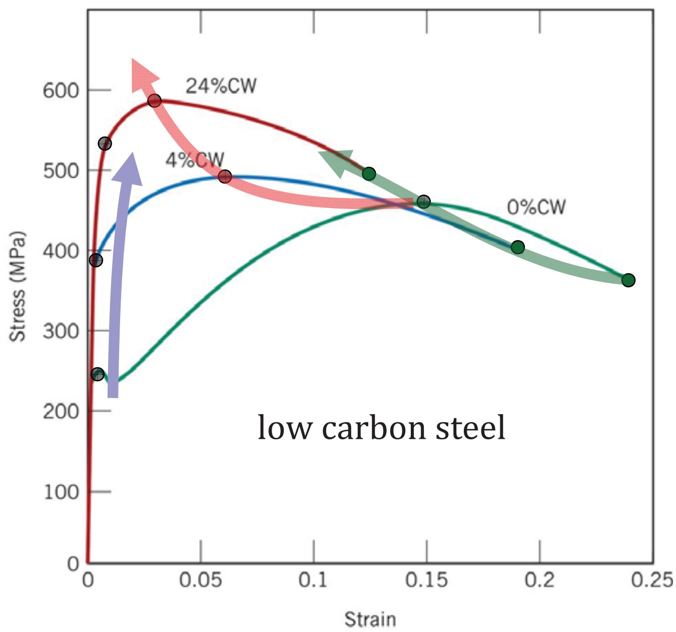
$$= \frac{\text{total dislocation length}}{\text{unit volume}}$$

  - Carefully grown single crystals: about 10^3 mm^{-2}
  - Deforming sample increases density: 10^9-10^{10} mm^{-2}
  - Heat treatment reduces density: 10^5-10^6 mm^{-2}
  - Yield stress increases as ρ_d increases.

Impact of Cold Work

As cold work is increased

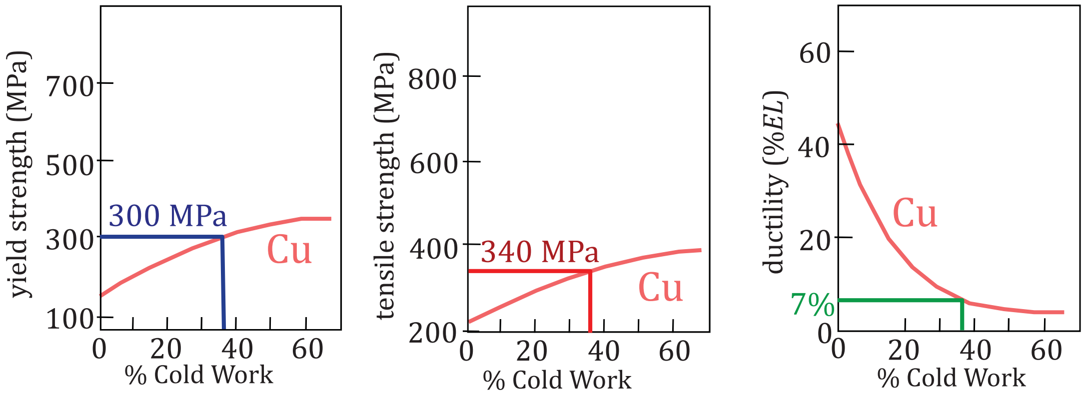
- Yield strength (σ_y) increases.
- Tensile strength (TS) increases.
- Ductility ($\%EL$ or $\%AR$) decreases.



Adapted from Fig. 9.20, *Callister & Rethwisch 9e.*

Mechanical Property Alterations Due to Cold Work

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

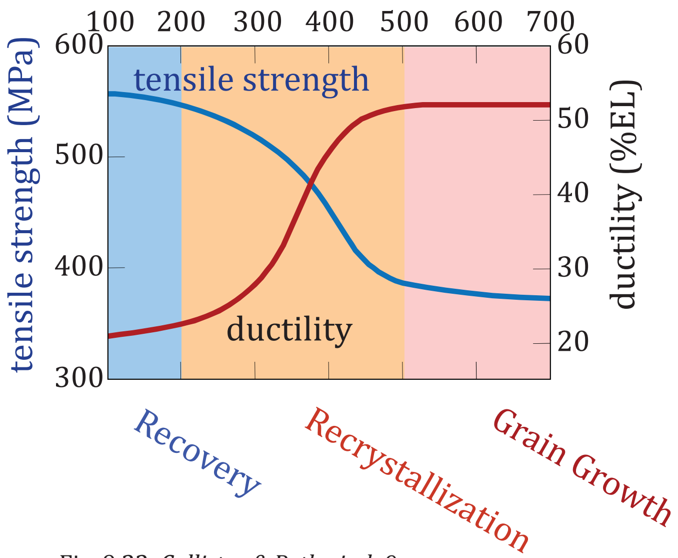


σ_y = 300 MPa | *TS* = 340 MPa | *%EL* = 7%

Fig. 9.19, *Callister & Rethwisch 9e.* [Adapted from *Metals Handbook: Properties and Selection: Irons and Steels*, Vol. 1, 9th edition, B. Bardes (Editor), 1978; and *Metals Handbook: Properties and Selection: Nonferrous Alloys and Pure Metals*, Vol. 2, 9th edition, H. Baker (Managing Editor), 1979. Reproduced by permission of ASM International, Materials Park, OH.]

Effect of Heat Treating After Cold Working

- One hour treatment at annealing temperature decreases TS and increases %EL.
- Effects of cold work are nullified!



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

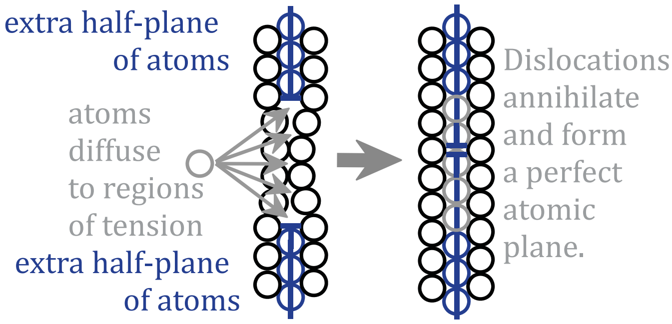
Fig. 9.22, *Callister & Rethwisch 9e.*

9.11 Recovery

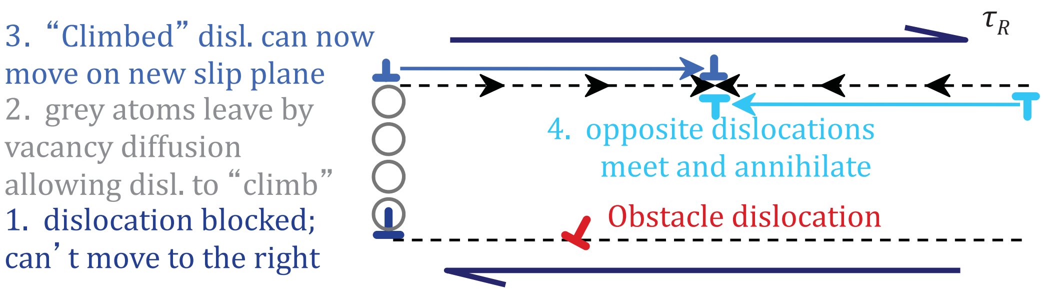
- Reduction of dislocation density by annihilation.

  - Scenario 1

    Results from diffusion



  - Scenario 2



9.12 Recrystallization

- **New grains are formed that:**
  - have low dislocation densities
  - are small in size
  - consume and replace parent cold-worked grains.

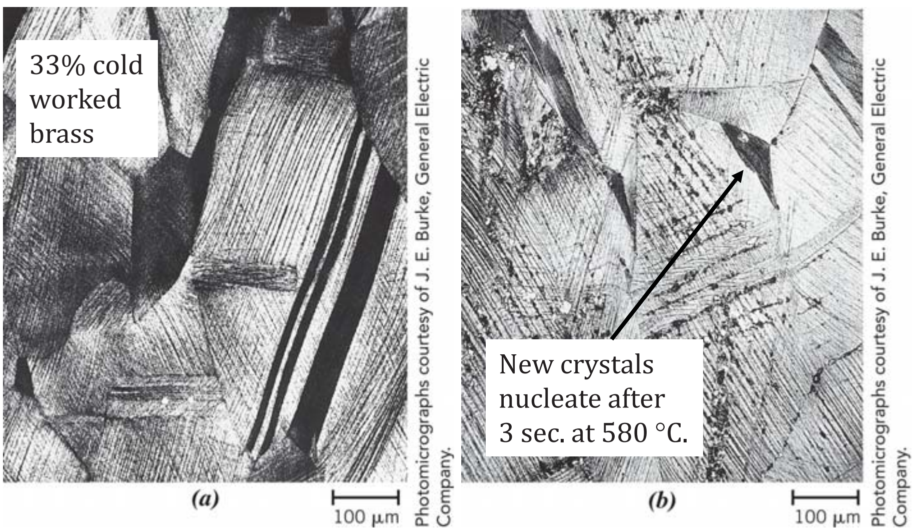


Fig. 9.21 Photomicrographs showing several stages of the recrystallization and grain growth of brass. (a) Cold-worked (33%CW) grain structure. (b) Initial stage of recrystallization after heating for 3 s at 580 °C; the very small grains are those that have recrystallized., *Callister & Rethwisch 9e.*

As Recrystallization Continues…

- All cold-worked grains are eventually consumed/replaced.

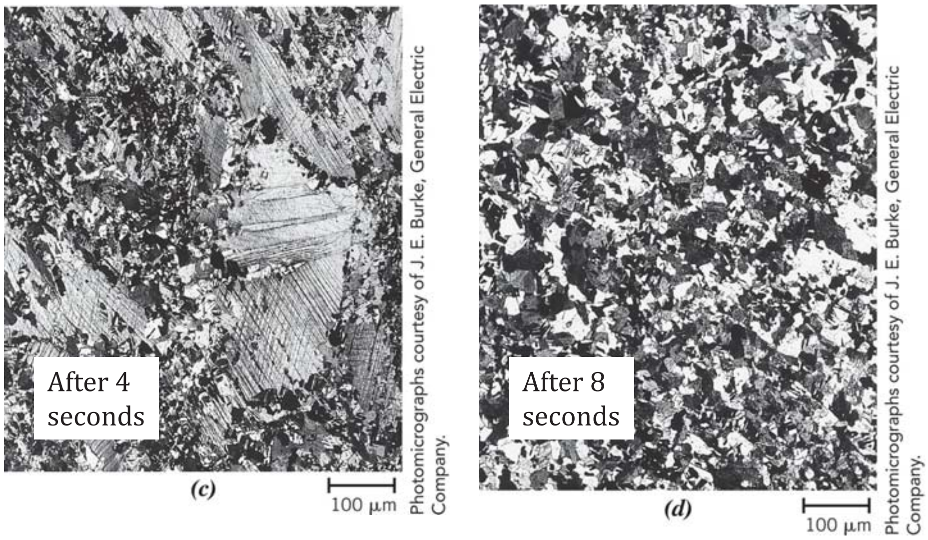
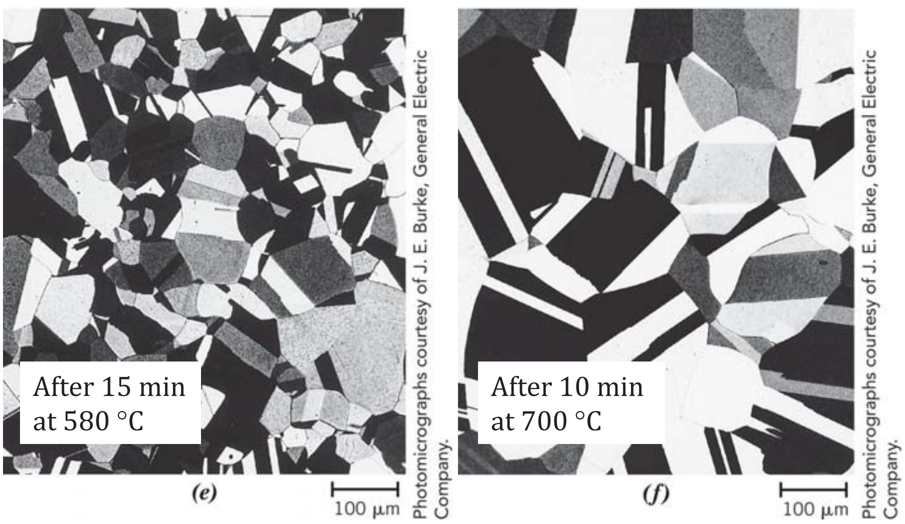


Fig. 9.21 Photomicrographs showing several stages of the recrystallization and grain growth of brass. (c) Partial replacement of cold-worked grains by recrystallized once (4 s at 580 °C). (d) Complete recrystallization (8 s at 580 °C)., *Callister & Rethwisch 9e.*

Grain Growth

- At longer times, average grain size increases.
  - Small grains shrink (and ultimately disappear).
  - Large grains continue to grow.



Empirical Relation:

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

- *d*: grain diameter at time t
- *n*: exponent (typically ~2)
- *K*: coefficient dependent on material and T
- *t*: elapsed time

Fig. 9.21 Photomicrographs showing several stages of the recrystallization and grain growth of brass. (e) Grain growth after 15 min at 580 °C. (d) Grain growth after 10 min at 700 °C., *Callister & Rethwisch 9e.*

Recrystallization Temperature

- Recrystallization temperature (T_R) = temperature at which recrystallization just reaches completion in 1 h.
  0.3Tm < TR < 0.6Tm
- For a specific metal/alloy, T_R depends on %CW: T_R decreases with increasing %CW.
- Purity of metal: T_R decreases with increasing purity.

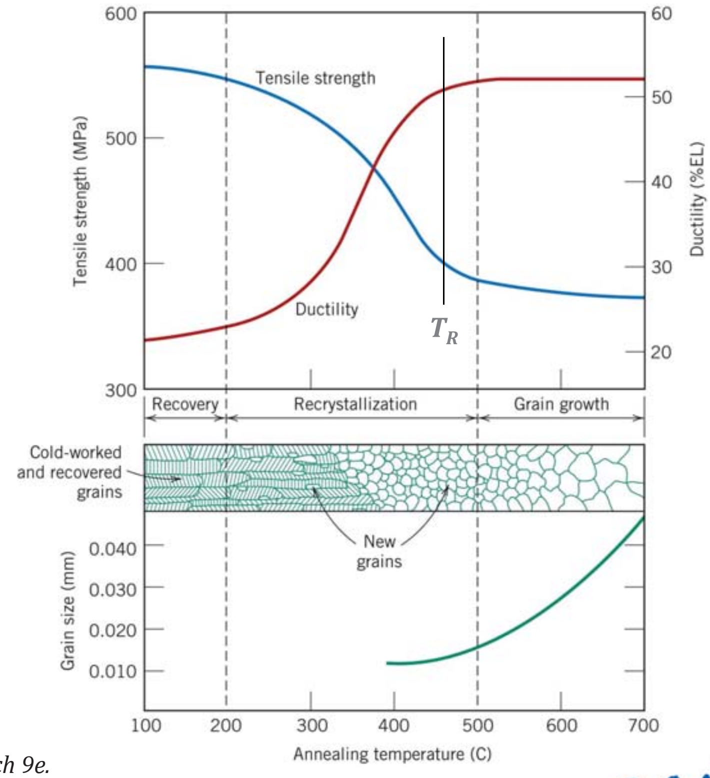
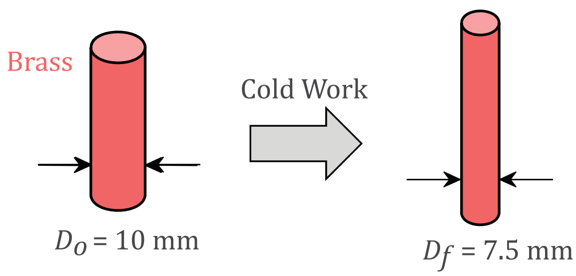


Fig. 9.22, *Callister & Rethwisch 9e.*

Problem: Diameter Reduction Procedure

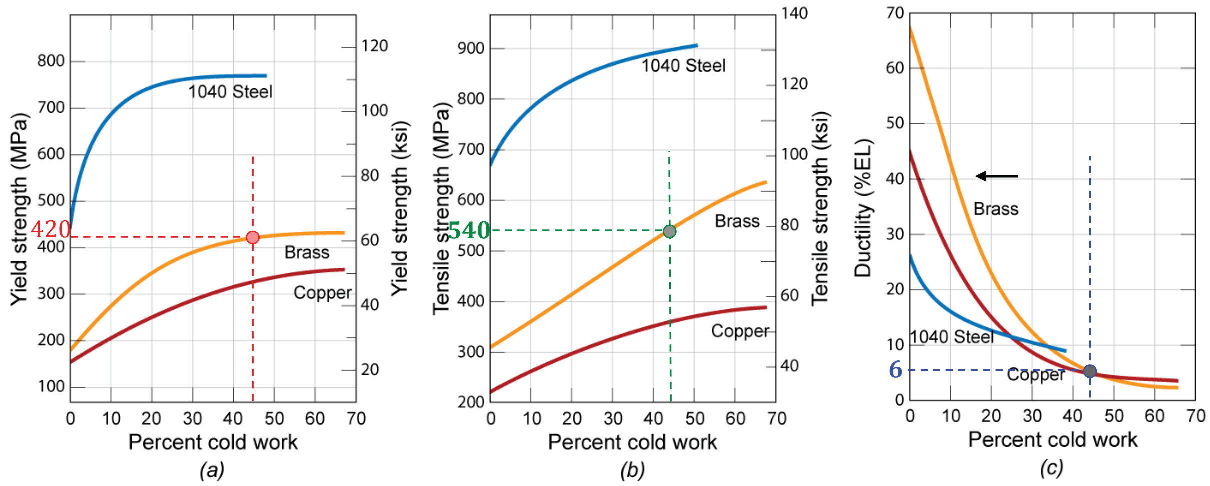
- Problem: A cylindrical rod of brass originally 10 mm in diameter is to be cold worked by drawing. The circular cross section will be maintained during deformation. A cold-worked tensile strength in excess of 380 MPa and a ductility of at least 15 %*EL* are desired. Furthermore, the final diameter must be 7.5 mm. Explain how this may be accomplished.
- Solution: What are the consequences of directly drawing to the final diameter?



$$\%CW = \left(\frac{A_o - A_f}{A_o}\right) x\,100 = \left(1 - \frac{A_f}{A_o}\right) x\,100$$

$$= \left(1 - \frac{\pi D_f^2/4}{\pi D_o^2/4}\right) x\,100 = \left(1 - \left(\frac{7.5}{10}\right)^2\right) x\,100 = 43.8\%$$

Diameter Reduction Procedure (Continued)

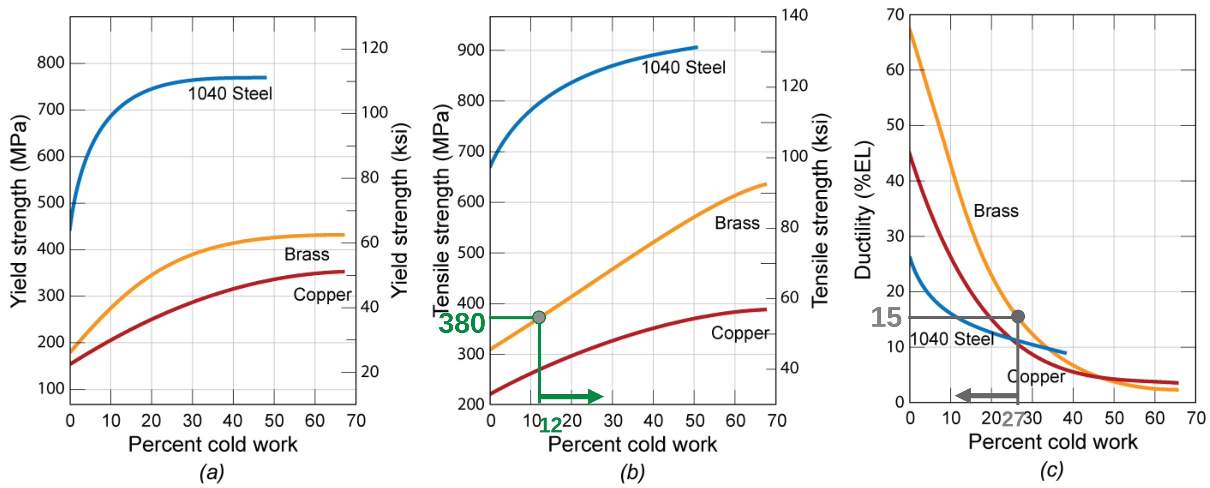


- For %CW = 43.8%
  - σ_y = 420 MPa
  - *TS* = 540 MPa > 380 MPa
  - %*EL* = 6 < 15

Fig. 9.19, *Callister & Rethwisch 9e.*
[Adapted from *Metals Handbook: Properties and Selection: Irons and Steels*, Vol. 1, 9th edition, B. Bardes (Editor), 1978; and *Metals Handbook: Properties and Selection: Nonferrous Alloys and Pure Metals*, Vol. 2, 9th edition, H. Baker (Managing Editor), 1979. Reproduced by permission of ASM International, Materials Park, OH.]

- This doesn't satisfy criteria… what other options are possible?

Diameter Reduction Procedure (Continued)



For *TS* > 380 MPa → > 12 %CW

For %*EL* > 15 → < 27 %CW

Fig. 9.19, *Callister & Rethwisch 9e.*
[Adapted from *Metals Handbook: Properties and Selection: Irons and Steels*, Vol. 1, 9th edition, B. Bardes (Editor), 1978; and *Metals Handbook: Properties and Selection: Nonferrous Alloys and Pure Metals*, Vol. 2, 9th edition, H. Baker (Managing Editor), 1979. Reproduced by permission of ASM International, Materials Park, OH.]

∴ Our working range is limited to 12 < %CW < 27

Diameter Reduction Procedure (Continued)

- Cold work, then anneal, then cold work again!
- For objective we need a cold work of 12 < %CW < 27: We'll use 20 %CW.
- Diameter after the first cold work stage (but before the second cold work stage) is calculated as follows:

$$\%\text{CW} = \left(1 - \frac{D_{f2}^2}{D_{02}^2}\right) x100 \Rightarrow 1 - \frac{D_{f2}^2}{D_{02}^2} = \frac{\%\text{CW}}{100} \Rightarrow \frac{D_{f2}}{D_{02}} = \left(1 - \frac{\%\text{CW}}{100}\right)^{0.5} \Rightarrow D_{02} = \frac{D_{f2}}{\left(1 - \frac{\%\text{CW}}{100}\right)^{0.5}}$$

$$\text{Intermediate diameter} = D_{f1} = D_{02} = 7.5\,\text{mm} \Big/ \left(1 - \frac{20}{100}\right)^{0.5} = 8.39\,\text{mm}$$

- Diameter Reduction Procedure – Summary
  - Stage 1: Cold work – reduce diameter from 10 mm to 8.39 mm
  - Stage 2: Heat treat (allow recrystallization)
  - Stage 3: Cold work – reduce diameter from 8.39 mm to 7.5 mm

$$\%\text{CW}_2 = \left(1 - \left(\frac{7.5}{8.49}\right)^2\right) \times 100 = 20 \Rightarrow \text{(Fig 7.19)}$$

$$\sigma_Y = 340\,\text{MPa} \quad TS = 400\,\text{MPa} \quad \%EL = 24$$

  - Therefore, all criteria are satisfied.

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
- Cold Working vs. Hot Working
  - Cold working → deformation below T_R
  - Hot working → deformation above T_R
- A cold-worked metal that is heat treated may experience recovery, recrystallization, and grain growth – its properties will be altered.
- 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
- Three annealing stages: Recovery, Recrystallization, and Grain Growth.