Chapter 9:

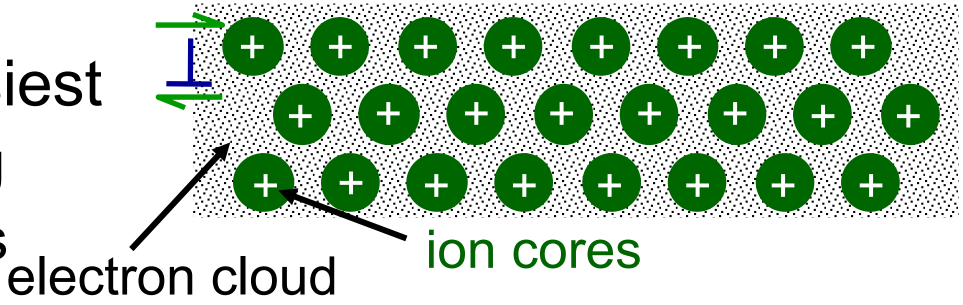
Dislocations & Strengthening Mechanisms

ISSUES TO ADDRESS...

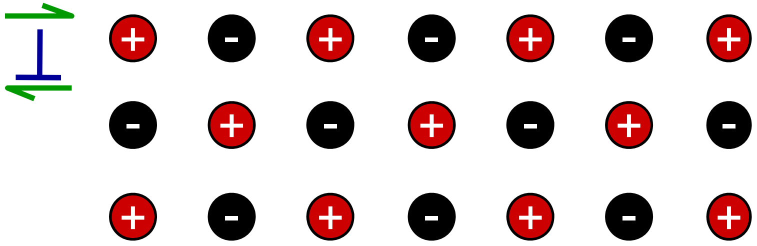
- Why are the number of dislocations present greatest in metals?
- How are strength and dislocation motion related?
- Why does heating alter strength and other properties?

Dislocations & Materials Classes

- Metals (Cu, Al):
  Dislocation motion easiest
  - non-directional bonding
  - close-packed directions for slip



- Ionic Ceramics (NaCl):
  Motion difficult
  - need to avoid nearest neighbors of like sign (- and +)



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.

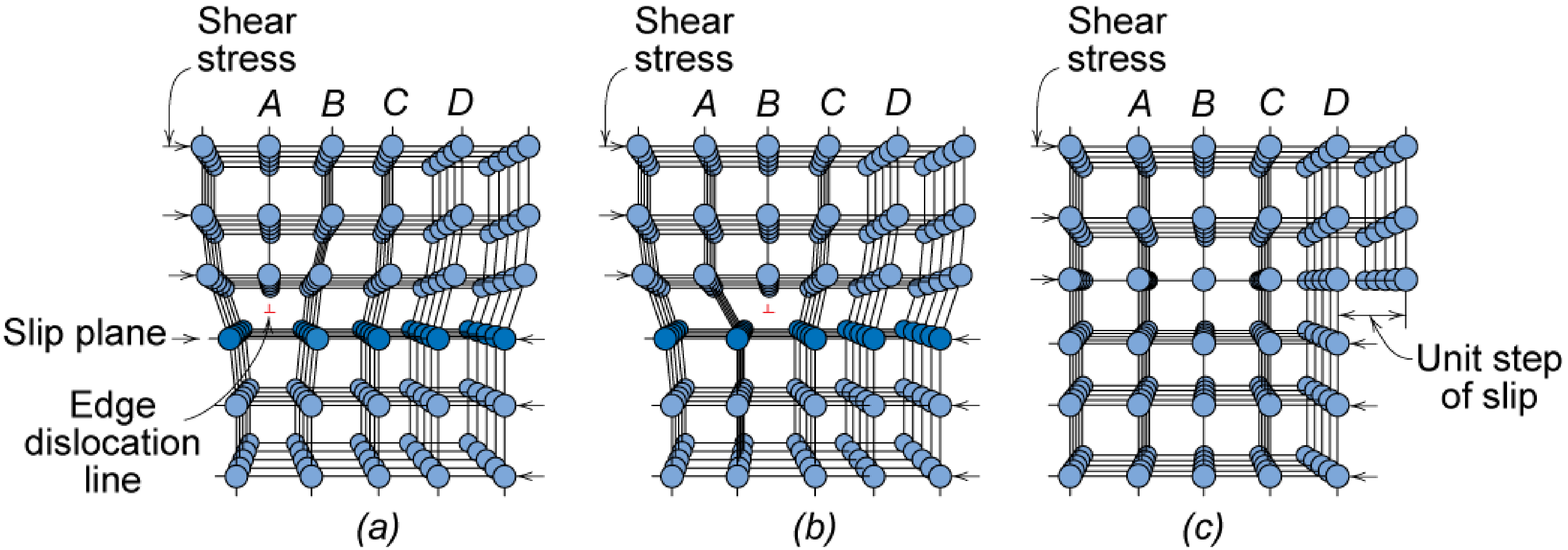
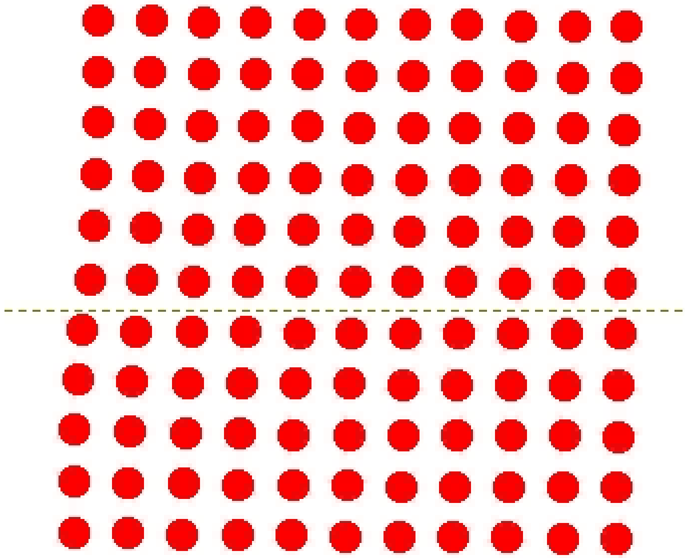


Fig. 9.1, *Callister & Rethwisch 9e.* (Adapted from A. G. Guy, Essentials of Materials Science, McGraw-Hill Book Company, New York, 1976, p. 153.)

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

Motion of Edge Dislocation

- Dislocation motion requires the successive bumping of a half plane of atoms (from left to right here).
- Bonds across the slipping planes are broken and remade in succession.

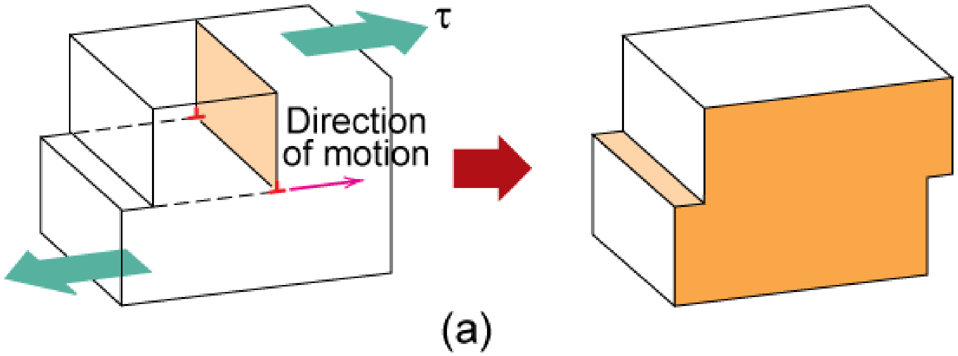


Atomic view of edge dislocation motion from left to right as a crystal is sheared.

(Courtesy P.M. Anderson)

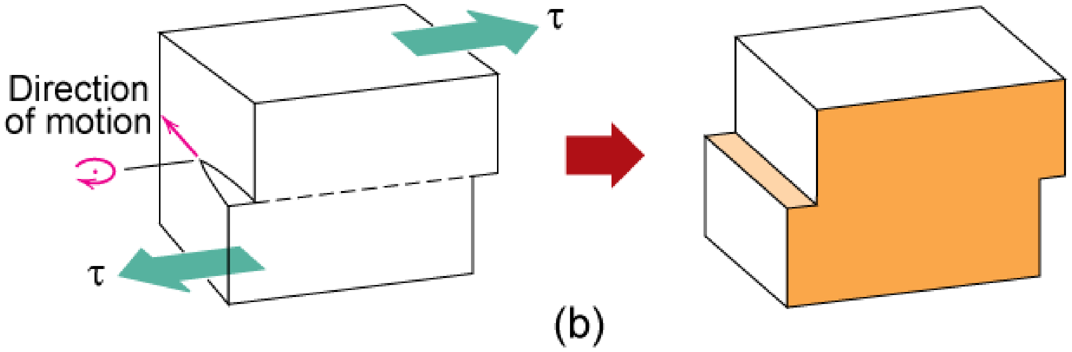
Dislocation Motion

- 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



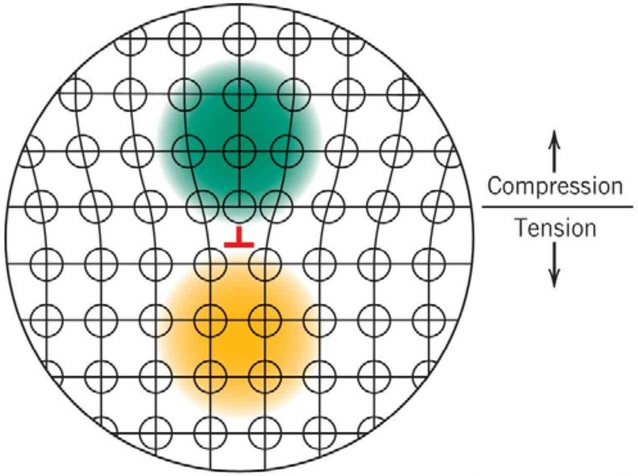
Edge dislocation

Fig. 9.2, *Callister & Rethwisch 9e.*
(Adapted from H. W. Hayden, W. G. Moffatt, and J. Wulff, The Structure and Properties of Materials, Vol. III, Mechanical Behavior, p. 70. Copyright © 1965 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)

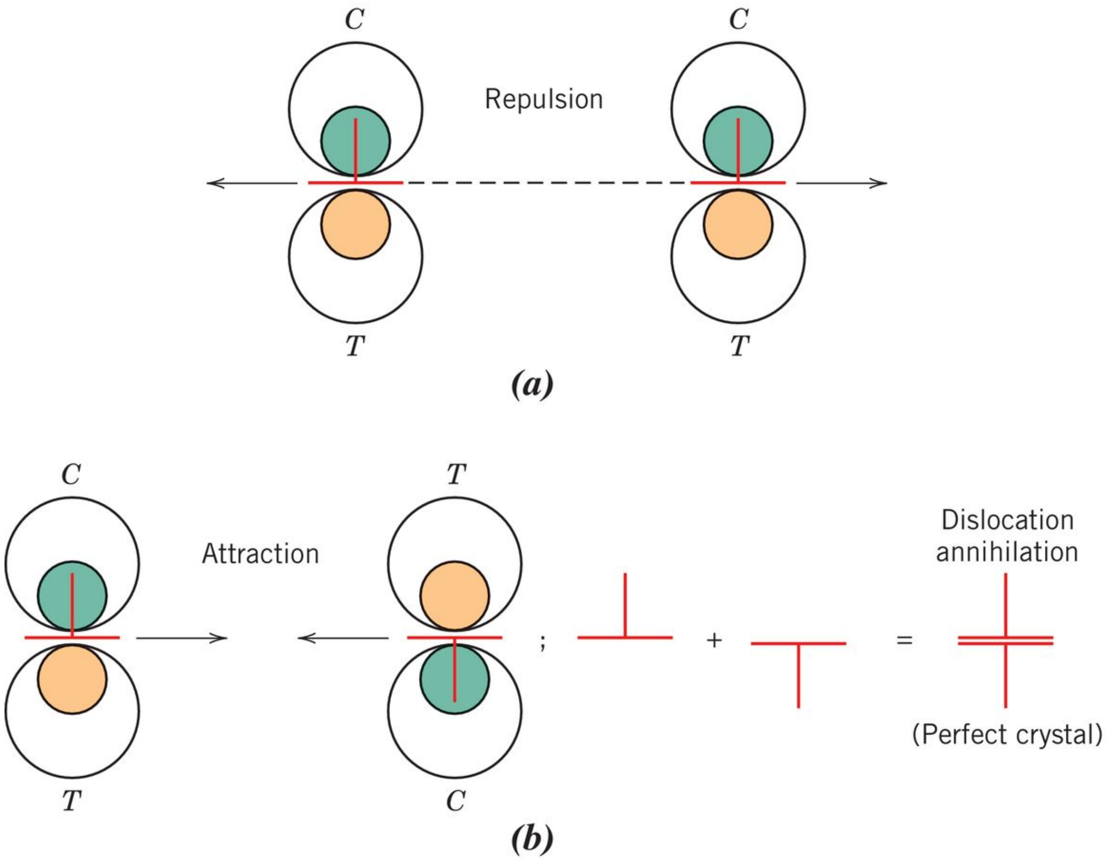


Screw dislocation

Characteristics of Dislocation



Adapted from W. G. Moffatt, G. W. Pearsall, and J. Wulff, The Structure and Properties of Materials, Vol. I, Structure, p. 85. Copyright © 1964 by John Wiley & Sons, New York.



Adapted from H. W. Hayden, W. G. Moffatt, and J. Wulff, The Structure and Properties of Materials, Vol. III, Mechanical Behavior, p. 75. Copyright © 1965 by John Wiley & Sons, New York.

Deformation Mechanisms

Slip System

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

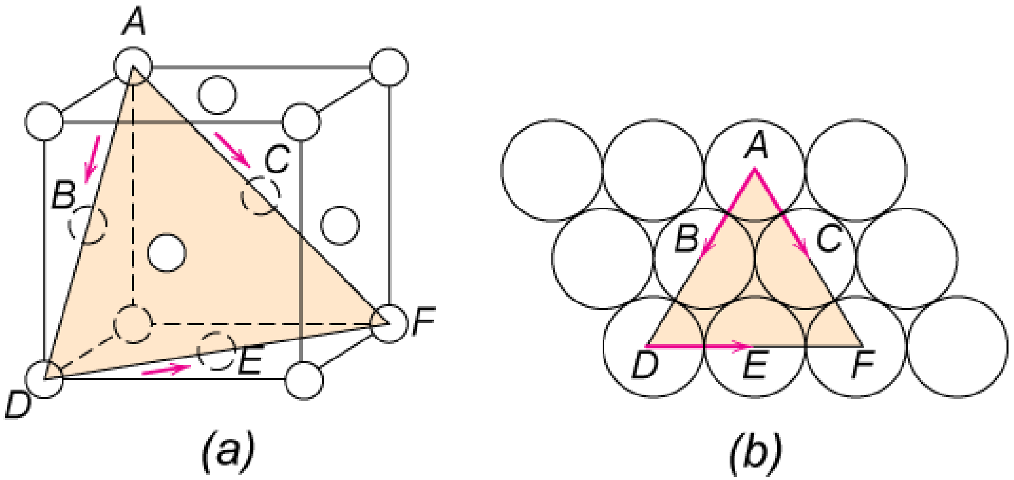


Fig. 9.6, *Callister & Rethwisch 9e.*

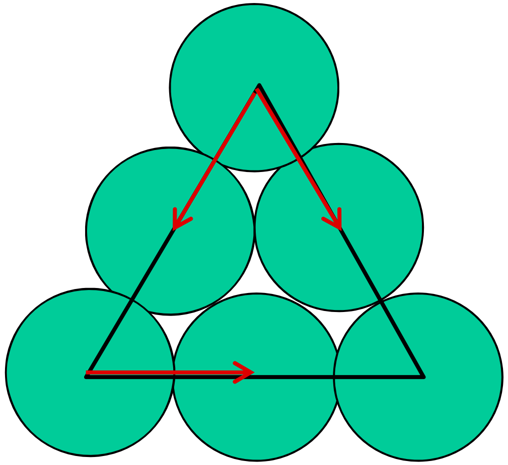
- FCC Slip occurs on {111} planes (close-packed) in <110> directions (close-packed)

  => total of 12 slip systems in FCC
- For BCC & HCP there are other slip systems.

Burger’s vector, ***b***

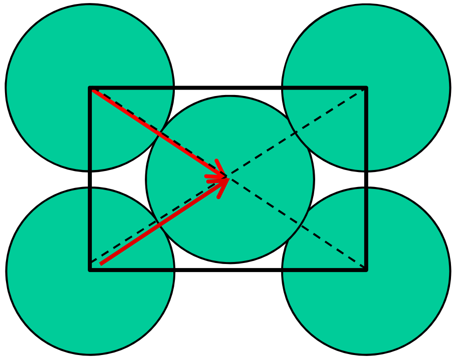
$\boldsymbol{b}\,(FCC) = \frac{a}{2}\langle 110\rangle$

{111} planes in <110>



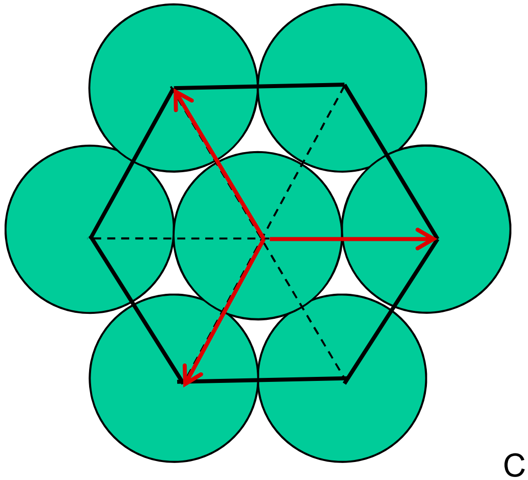
$\boldsymbol{b}\,(BCC) = \frac{a}{2}\langle 111\rangle$

{110} planes in <111>



$\boldsymbol{b}\,(HCP) = \frac{a}{2}\langle 11\bar{2}0\rangle$

{0001} planes in $\langle 11\bar{2}0\rangle$



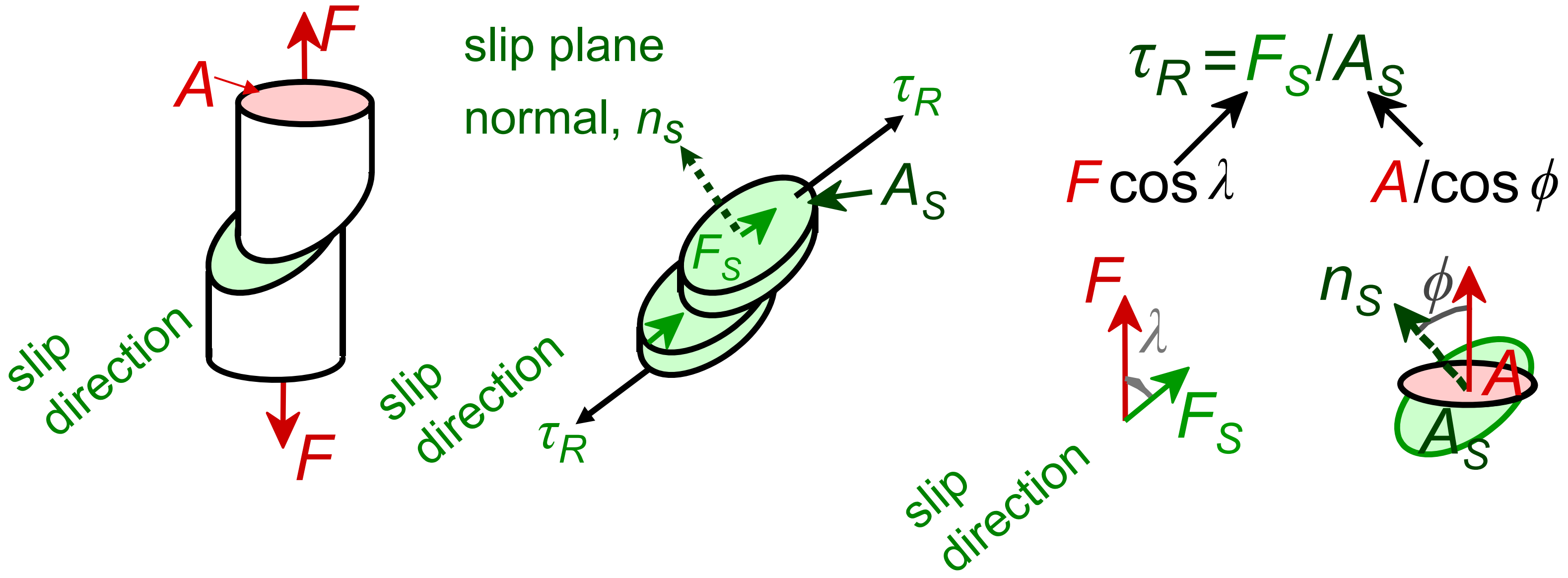
Stress and Dislocation Motion

- Resolved shear stress, τ_R
  - – results from applied tensile stresses

Applied tensile stress: $\sigma = F/A$

Resolved shear stress: $\tau_R = F_S/A_S$

Relation between σ and τ_R



$$\boxed{\tau_R = \sigma\cos\lambda\cos\phi}$$

Critical Resolved Shear Stress

- Condition for dislocation motion:

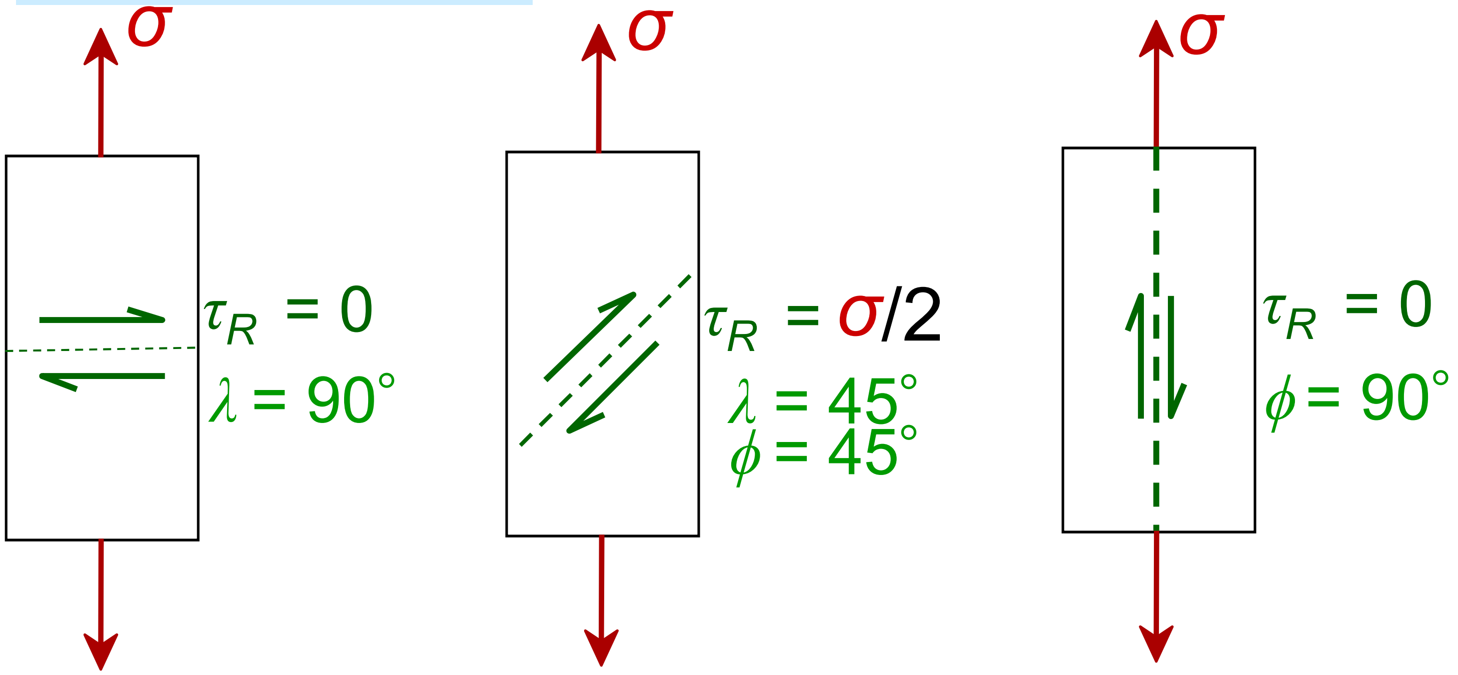
$$\tau_R > \tau_{CRSS}$$

typically

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

- Ease of dislocation motion depends on crystallographic orientation

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



τ maximum at $\lambda = \phi = 45°$

Single Crystal Slip

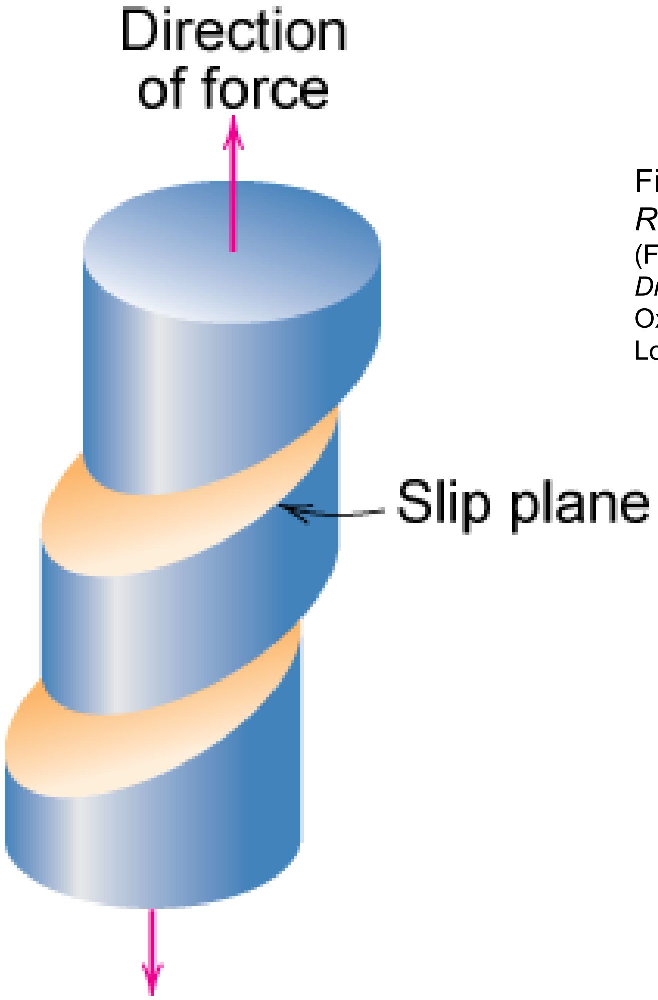
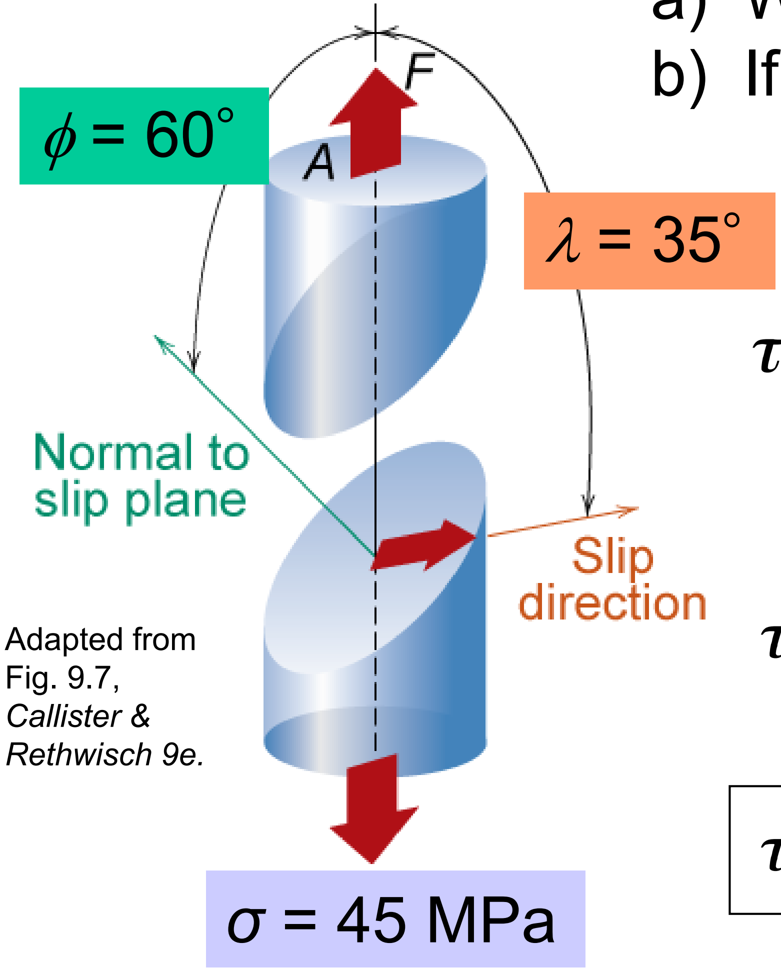


Fig. 9.8, *Callister & Rethwisch 9e.*

Fig. 9.9, *Callister & Rethwisch 9e.*
(From C. F. Elam, *The Distortion of Metal Crystals*, Oxford University Press, London, 1935.)

Ex: Deformation of single crystal



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

a) Will the single crystal yield?
b) If not, what stress is needed?

$$\tau_{crss} = 20.7 \text{ MPa}$$

$$\tau = \sigma \cos\lambda \cos\phi$$

$$\sigma = 45 \text{ MPa}$$

$$\tau = (45 \text{ MPa})(\cos 35°)(\cos 60°)$$
$$= (45 \text{ MPa})(0.41)$$

$$\boxed{\tau = 18.4 \text{ MPa} < \tau_{crss} = 20.7 \text{ MPa}}$$

So the applied stress of 45 MPa will not cause the crystal to yield.

Ex: Deformation of single crystal

What stress *is* necessary (i.e., what is the yield stress, σ_y)?

$$\tau_{\text{crss}} = 20.7\ MPa = \sigma_y \cos\lambda \cos\phi = \sigma_y (0.41)$$

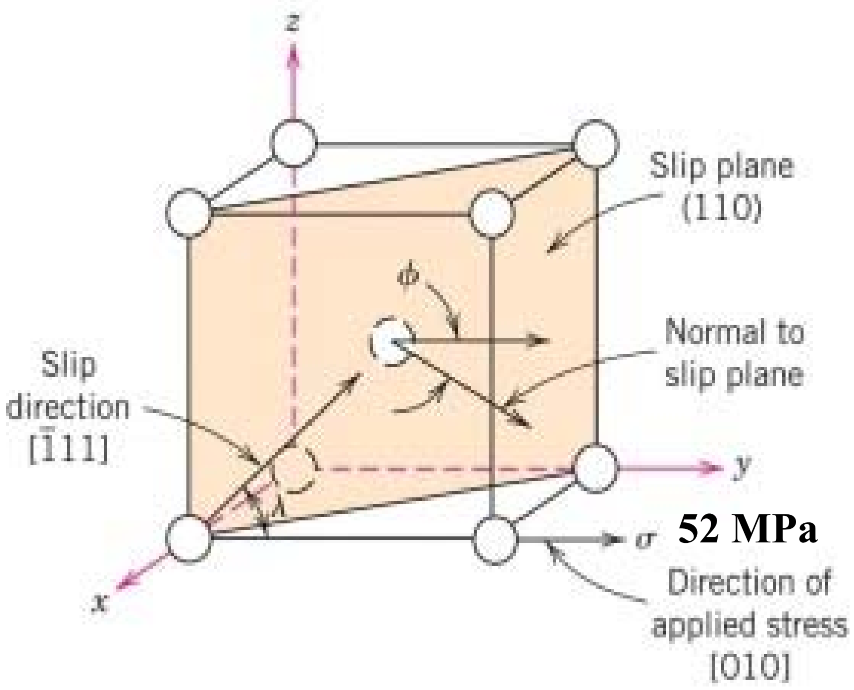
$$\therefore \sigma_y = \frac{\tau_{crss}}{\cos\lambda \cos\varphi} = \frac{20.7\ MPa}{0.41} = \underline{\underline{50.5\ MPa}}$$

So for deformation to occur the applied stress must be greater than or equal to the yield stress

$$\boxed{\sigma \geq \sigma_y = 50.5\ \text{MPa}}$$

Ex: Deformation of single crystal (BCC Iron)

Stress is applied along a [010] direction.
(a) Compute τ_R along a (110) plane and in a $[\bar{1}11]$ direction when a tensile stress of 52 MPa is applied.



Remember $\boldsymbol{a} \cdot \boldsymbol{b} = |\boldsymbol{a}||\boldsymbol{b}| \cos\theta$

The angle between $[u_1v_1w_1]$ and $[u_2v_2w_2]$

$$\theta = cos^{-1}\left[\frac{u_1u_2 + v_1v_2 + w_1w_2}{\sqrt{(u_1{}^2 + v_1{}^2 + w_1{}^2)(u_2{}^2 + v_2{}^2 + w_2{}^2)}}\right]$$

For Ø, $[u_1v_1w_1] = [110]$ and $[u_2v_2w_2] = [010]$

$$\emptyset = cos^{-1}\left[\frac{(1)(0) + (1)(1) + (0)(0)}{\sqrt{[(1)^2 + (1)^2 + (0)^2]\,[(0)^2 + (1)^2 + (0)^2)}}\right]$$

$$= cos^{-1}\left(\frac{1}{\sqrt{2}}\right) = 45^o$$

For λ, $[u_1v_1w_1] = [\bar{1}11]$ and $[u_2v_2w_2] = [010]$

$$\lambda \;\; = cos^{-1}\left[\frac{(-1)(0)+(1)(1)+(1)(0)}{\sqrt{[(-1)^2+(1)^2+(1)^2]\,[(0)^2+(1)^2+(0)^2)}}\right]$$

$$= cos^{-1}\left(\frac{1}{\sqrt{3}}\right) = 54.7^o$$

$$\tau_R = \sigma \cos\emptyset \cos\lambda = (52 \text{ MPa})\ (\cos 45^\circ)(\cos 54.7^\circ)$$
$$= 21.3 \text{ MPa}$$

(b) If slip occurs on a (110) plane and in a $[\bar{1}11]$ direction, and the critical resolved shear stress is 30 MPa, calculate the magnitude of the applied tensile stress necessary to initiate yielding.

The yield strength σ_y may be computed

$$\sigma_y = \frac{\tau_{crss}}{\cos\lambda \cos\varphi} = \frac{30 \text{ MPa}}{(\cos 45^\circ)\ (\cos 54.7^\circ)}$$

$$= 73.4 \text{ MPa}$$

Slip Motion in Polycrystals

- 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.

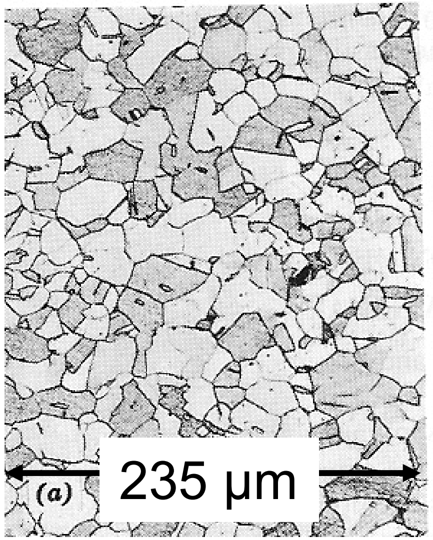
- Other (less favorably oriented) grains yield later.

Adapted from Fig. 9.10, *Callister & Rethwisch 9e.* (Photomicrograph courtesy of C. Brady, National Bureau of Standards [now the National Institute of Standards and Technology, Gaithersburg, MD].)

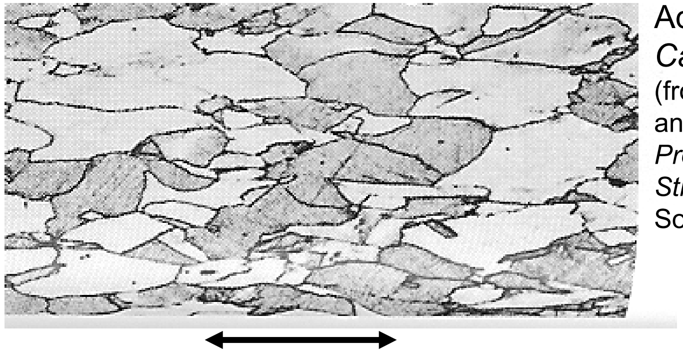
Anisotropy in σ_y

- Can be induced by rolling a polycrystalline metal

- before rolling



- after rolling



rolling direction

Adapted from Fig. 9.11, *Callister & Rethwisch 9e.* (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.)

- isotropic

since grains are equiaxed & randomly oriented.

- anisotropic

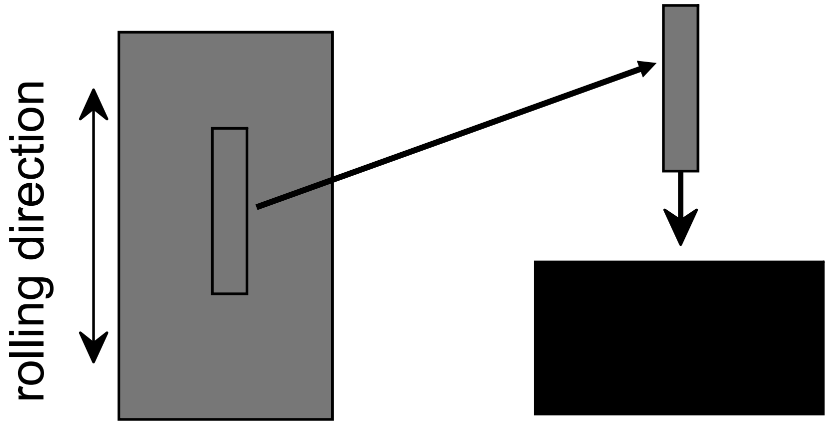
since rolling affects grain orientation and shape.

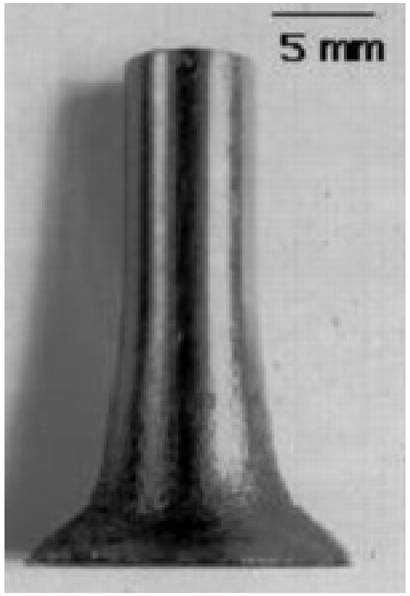
Anisotropy in Deformation

1. Cylinder of tantalum machined from a rolled plate:

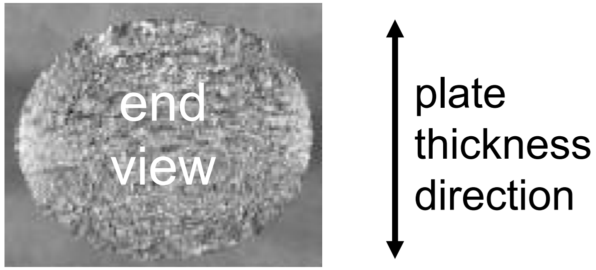
2. Fire cylinder at a target.

3. Deformed cylinder





Photos courtesy of G.T. Gray III, Los Alamos National Labs. Used with permission.



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

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.

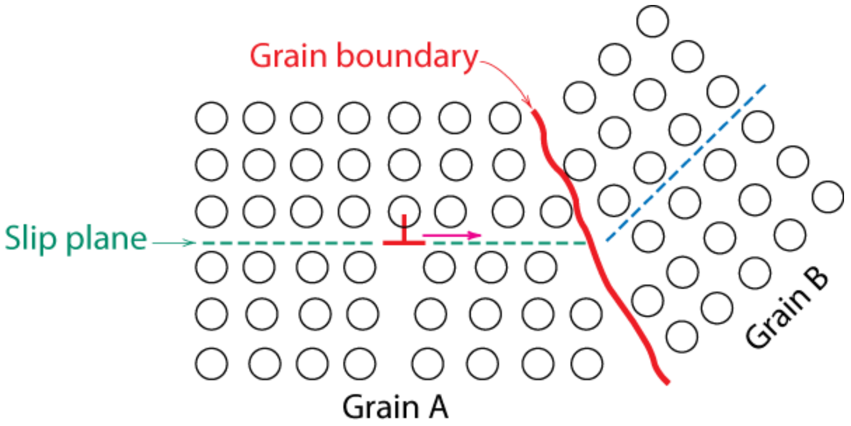


Fig. 9.14, *Callister & Rethwisch 9e.*
(From L. H. Van Vlack, *A Textbook of Materials Technology*, Addison-Wesley Publishing Co., 1973. Reproduced with the permission of the Estate of Lawrence H. Van Vlack.)

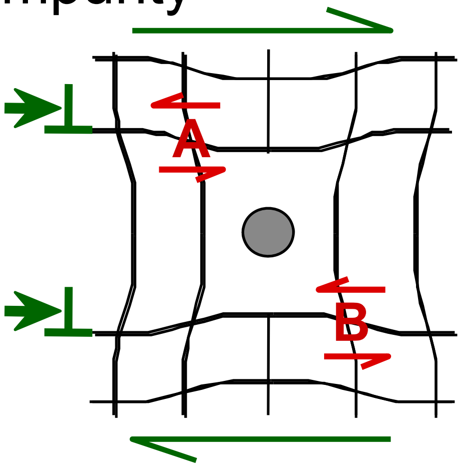
- Hall-Petch Equation:

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

Four Strategies for Strengthening:
2: Form Solid Solutions

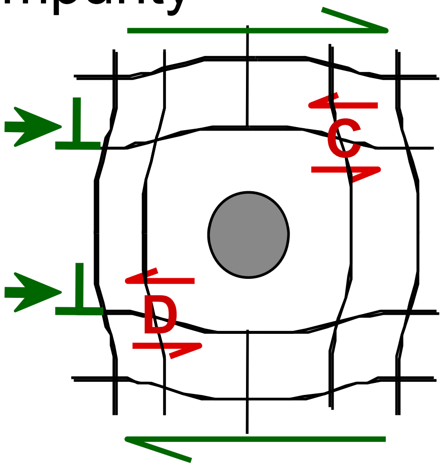
- Impurity atoms distort the lattice & generate lattice strains.
- These strains can act as barriers to dislocation motion.

- 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.

Lattice Strains Around Dislocations

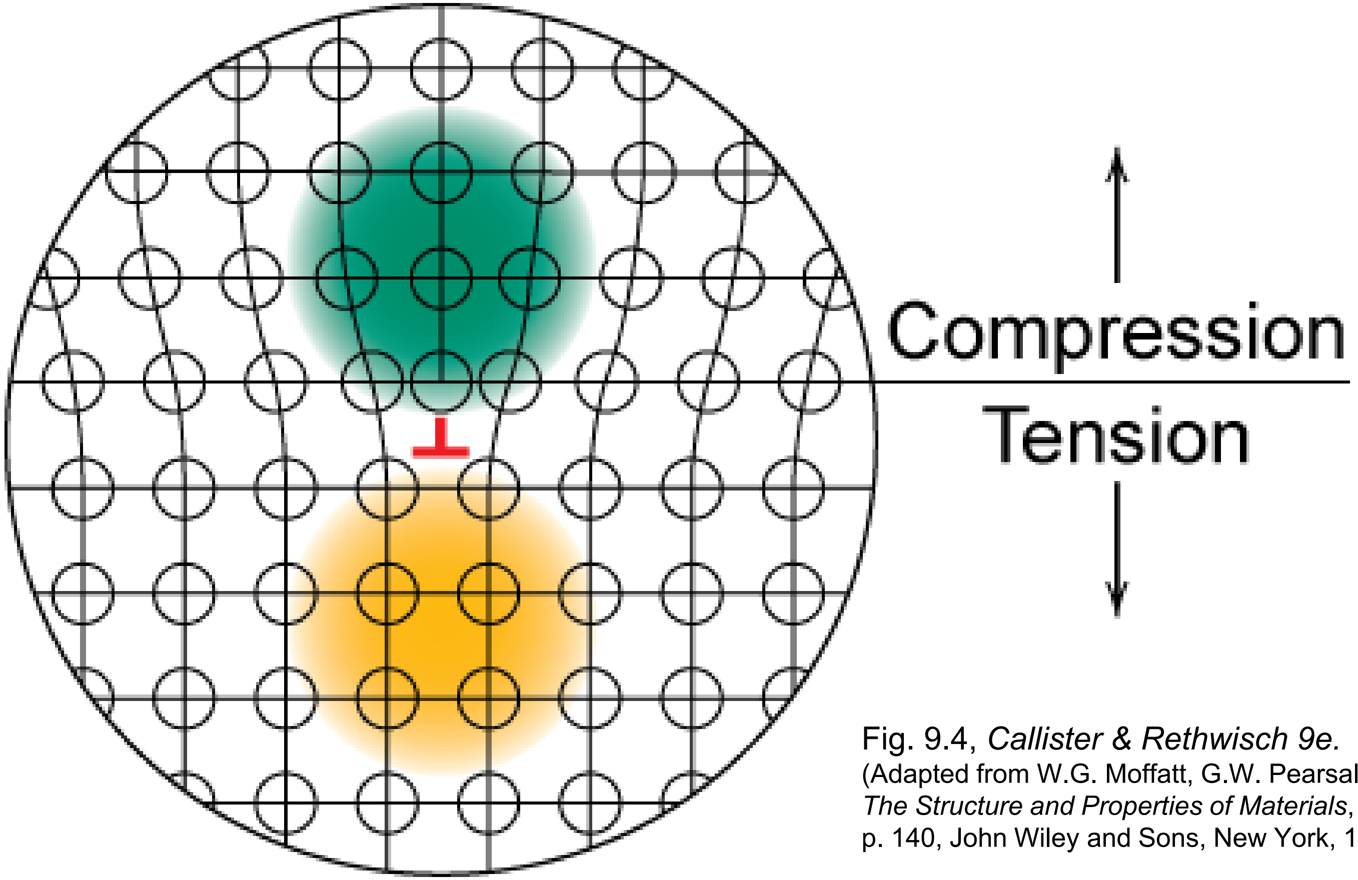


Fig. 9.4, *Callister & Rethwisch 9e.*
(Adapted from W.G. Moffatt, G.W. Pearsall, and J. Wulff, *The Structure and Properties of Materials*, Vol. I, *Structure*, p. 140, John Wiley and Sons, New York, 1964.)

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

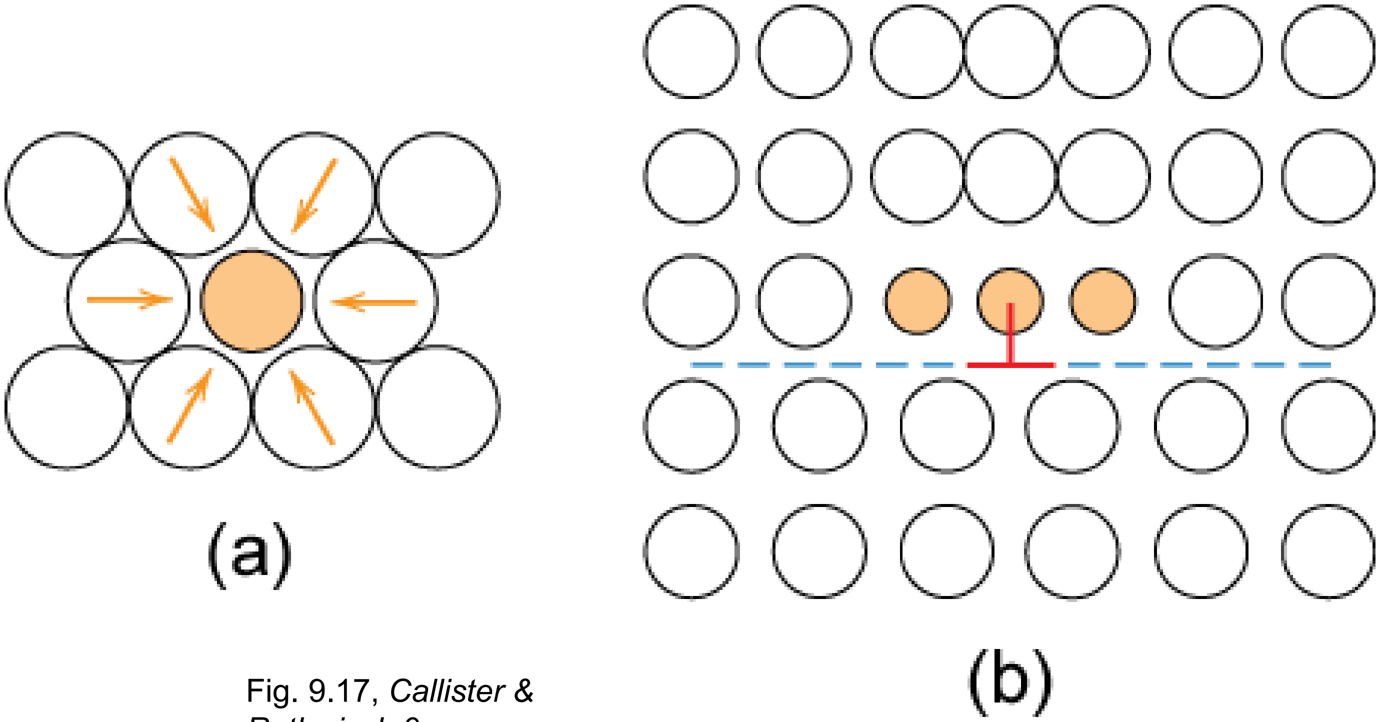


Fig. 9.17, *Callister & Rethwisch 9e.*

Strengthening by Solid Solution Alloying

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

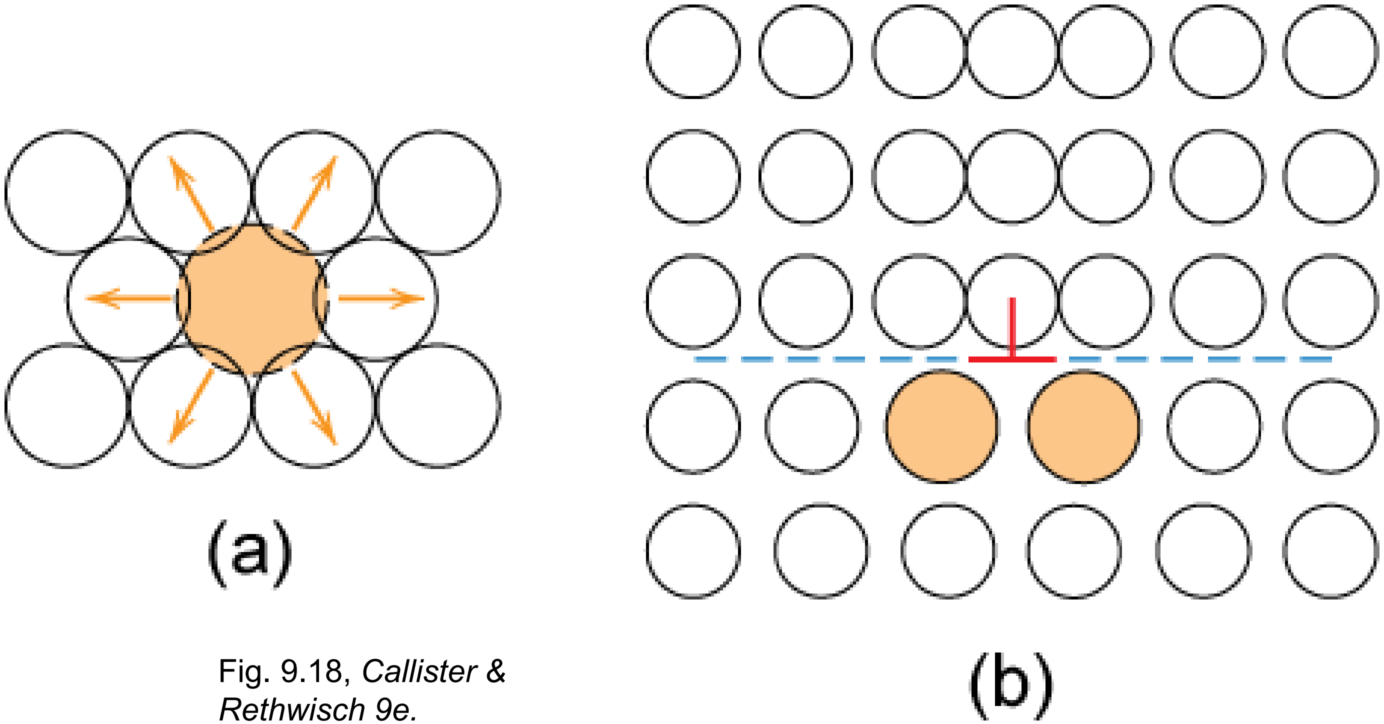
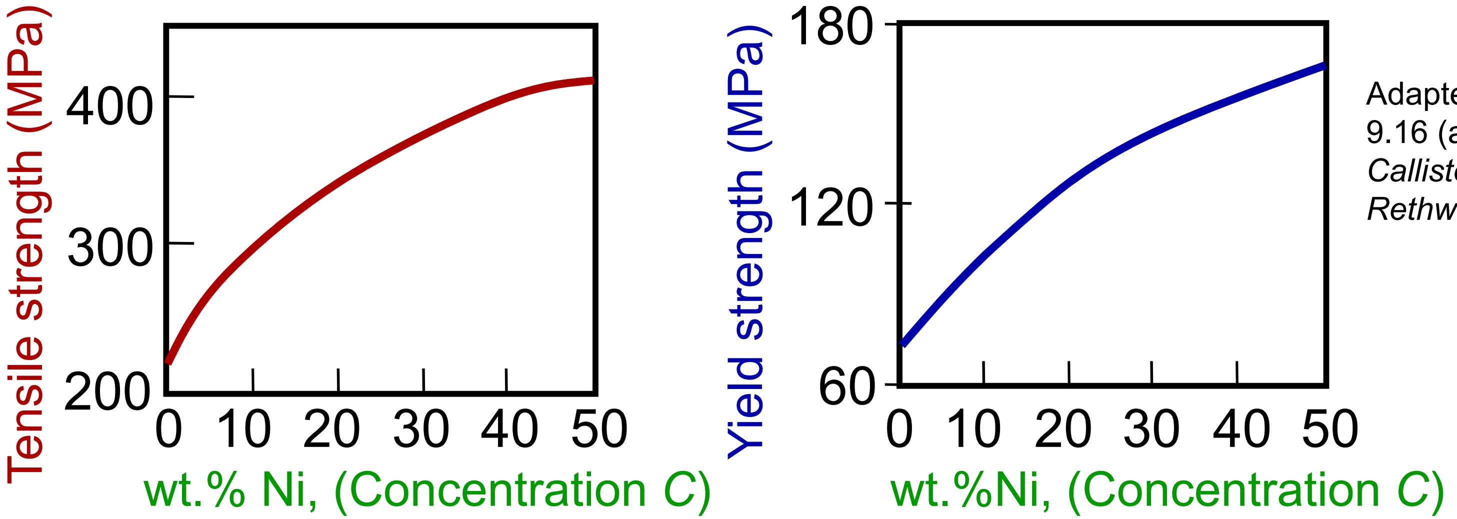


Fig. 9.18, *Callister & Rethwisch 9e.*

Ex: Solid Solution Strengthening in Copper

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



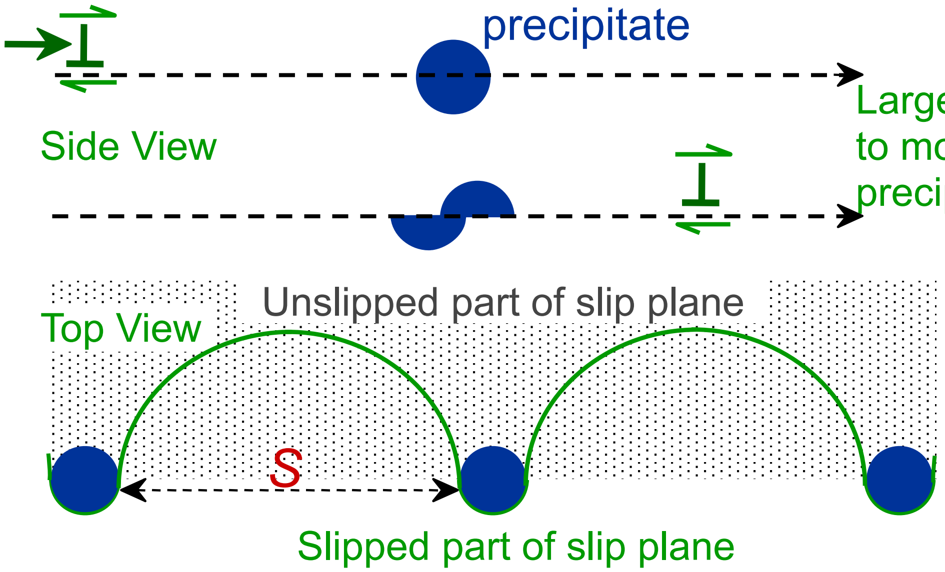
Adapted from Fig. 9.16 (a) and (b), *Callister & Rethwisch 9e.*

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

Four Strategies for Strengthening: 3: 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.

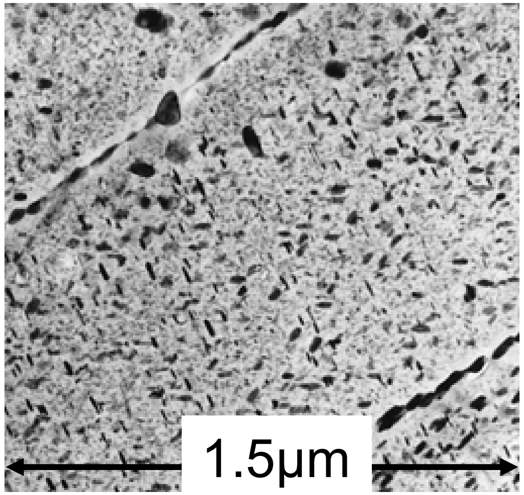
- Result: $\sigma_y \sim \frac{1}{S}$

Application: Precipitation Strengthening

- Internal wing structure on Boeing 767

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 precipitates formed by alloying.

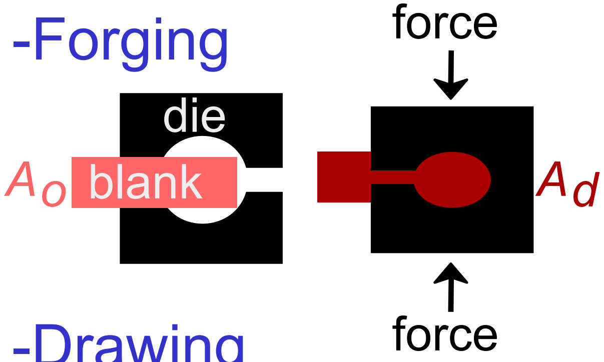


Adapted from Fig. 17.20, *Callister & Rethwisch 9e.*
(Courtesy of G.H. Narayanan and A.G. Miller, Boeing Commercial Airplane Company.)

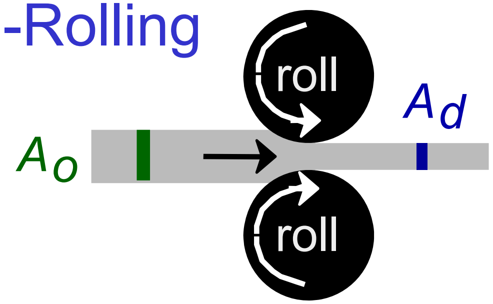
Four Strategies for Strengthening: 4: Cold Work (Strain Hardening)

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

-Forging

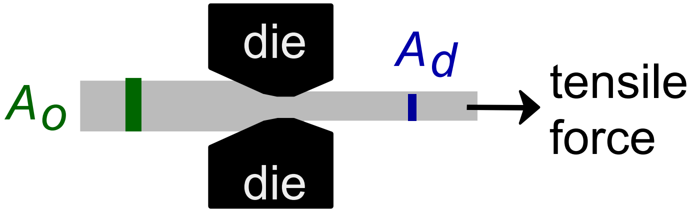


-Rolling

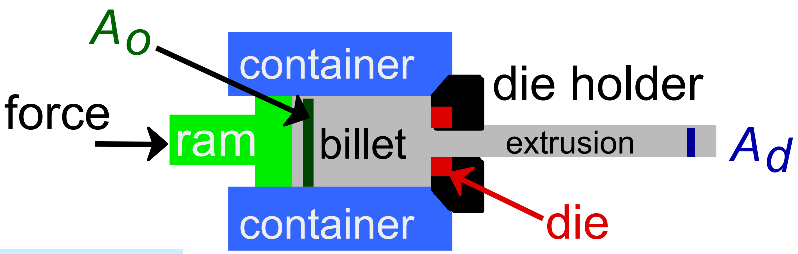


Adapted from Fig. 17.2, *Callister & Rethwisch 9e.*

-Drawing



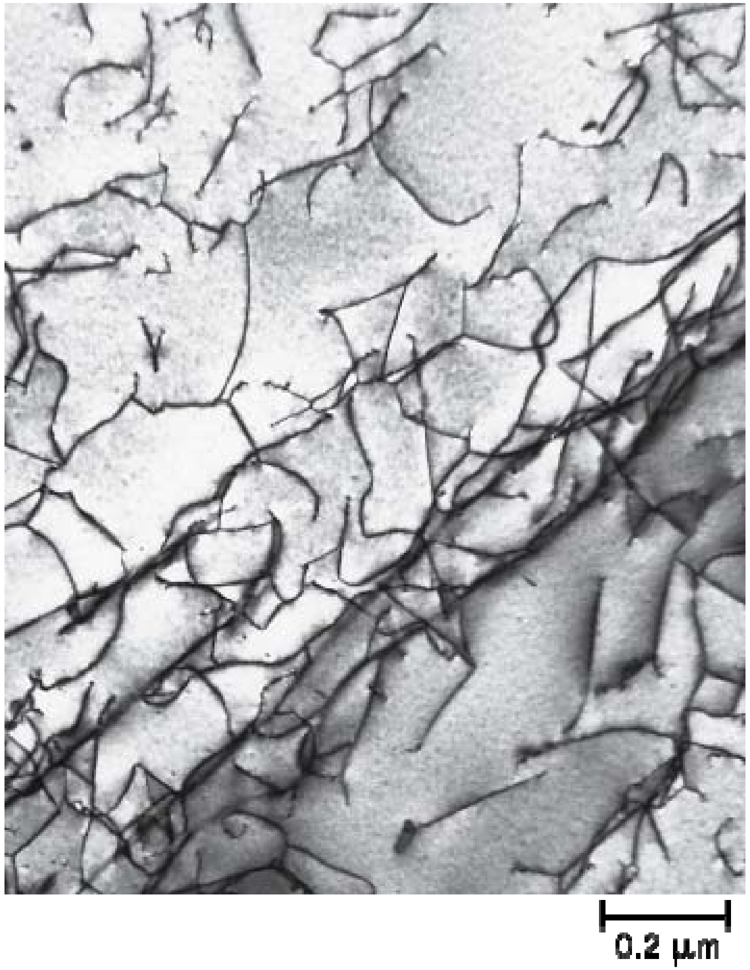
-Extrusion



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

Dislocation Structures Change During Cold Working

- Dislocation structure in Ti after cold working.



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

Fig. 6.12, *Callister & Rethwisch 9e.*
(Courtesy of M.R. Plichta, Michigan Technological University.)

Dislocation Density Increases During Cold Working

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

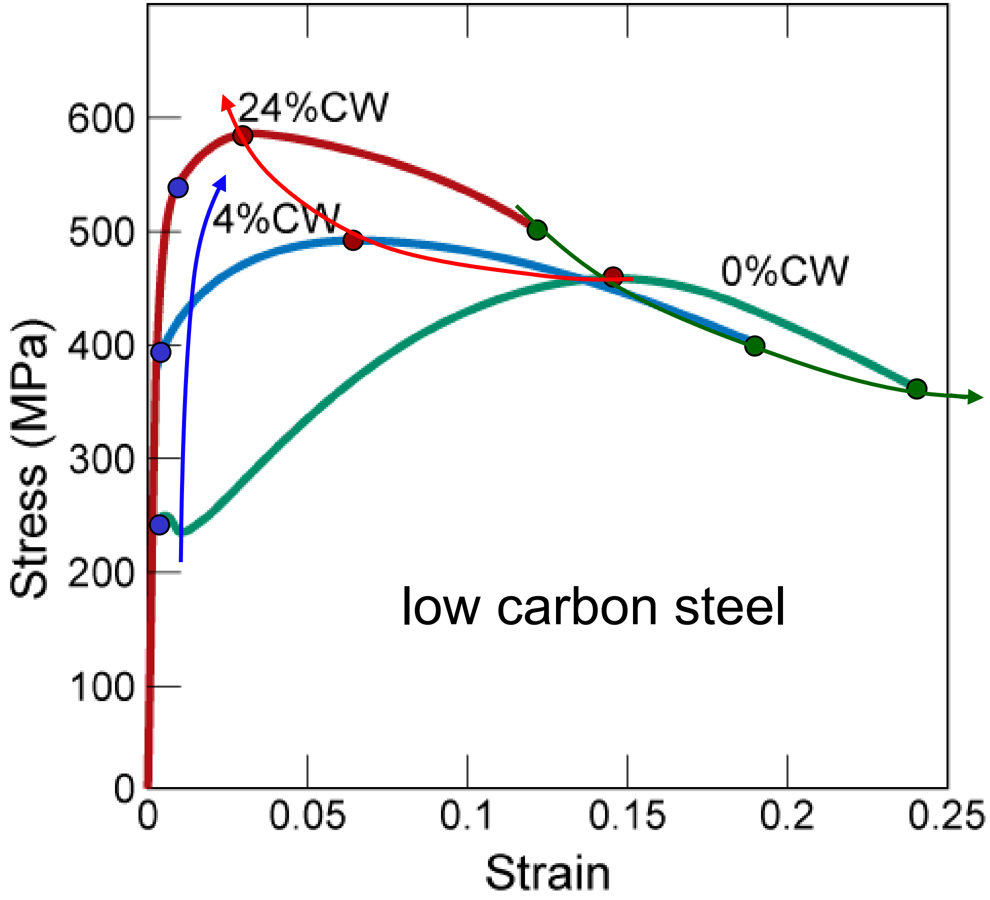
- Carefully grown single crystals
  - → ca. 10^{3} mm^{-2}
- Deforming sample increases density
  - → 10^{9}-10^{10} mm^{-2}
- Heat treatment reduces density
  - → 10^{5}-10^{6} mm^{-2}

- Yield stress increases as ρ_d increases:

Impact of Cold Work

As cold work is increased

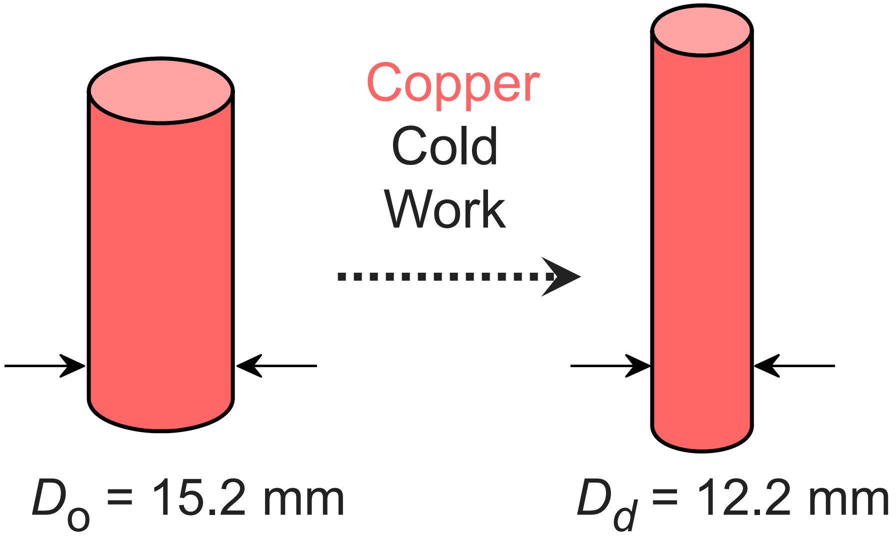
- Yield strength (σ_y) increases.
- Tensile strength (*TS*) increases.
- Ductility (%*EL* or %*AR*) decreases.



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

Mechanical Property Alterations Due to Cold Working

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



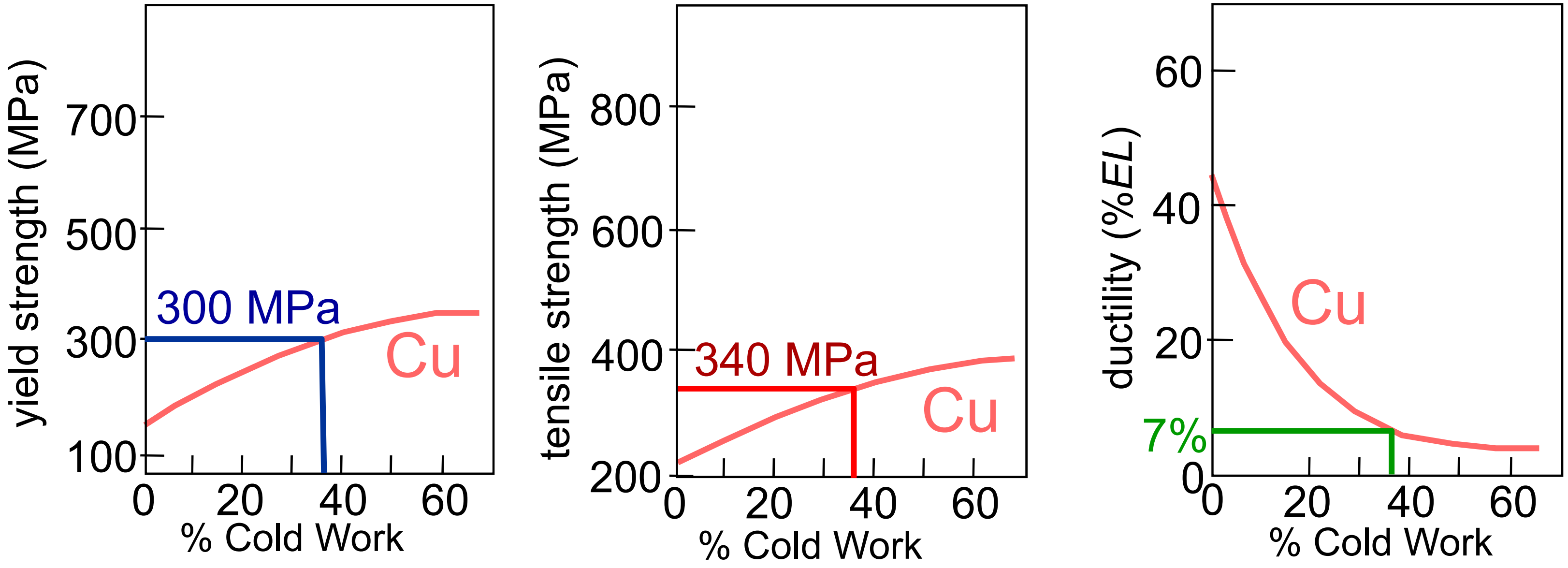
$$\%CW = \frac{\frac{\pi D_o^2}{4} - \frac{\pi D_d^2}{4}}{\frac{\pi D_o^2}{4}} \text{ x } 100$$

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

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

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

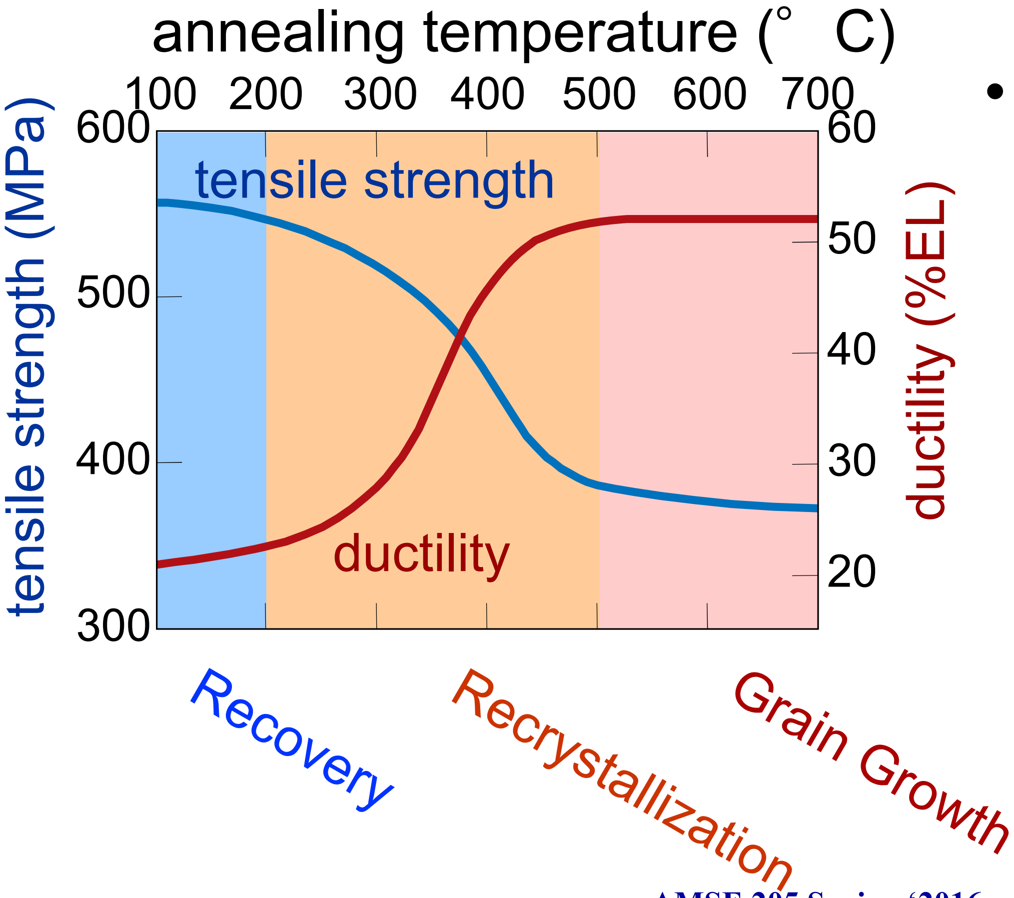
TS = 340 MPa

%*EL* = 7%

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

- 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

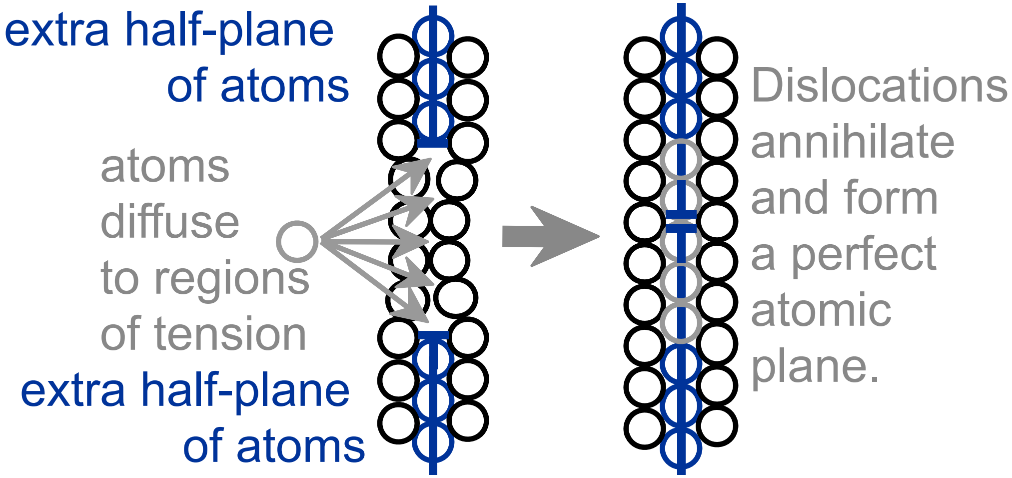
Fig. 9.22, *Callister & Rethwisch 9e.*
(Adapted from G. Sachs and K. R. Van Horn, *Practical Metallurgy, Applied Metallurgy and the Industrial Processing of Ferrous and Nonferrous Metals and Alloys*, 1940. Reproduced by permission of ASM International, Materials Park, OH.)

Three Stages During Heat Treatment:
1. Recovery

Reduction of dislocation density by annihilation.

- Scenario 1

  Results from diffusion



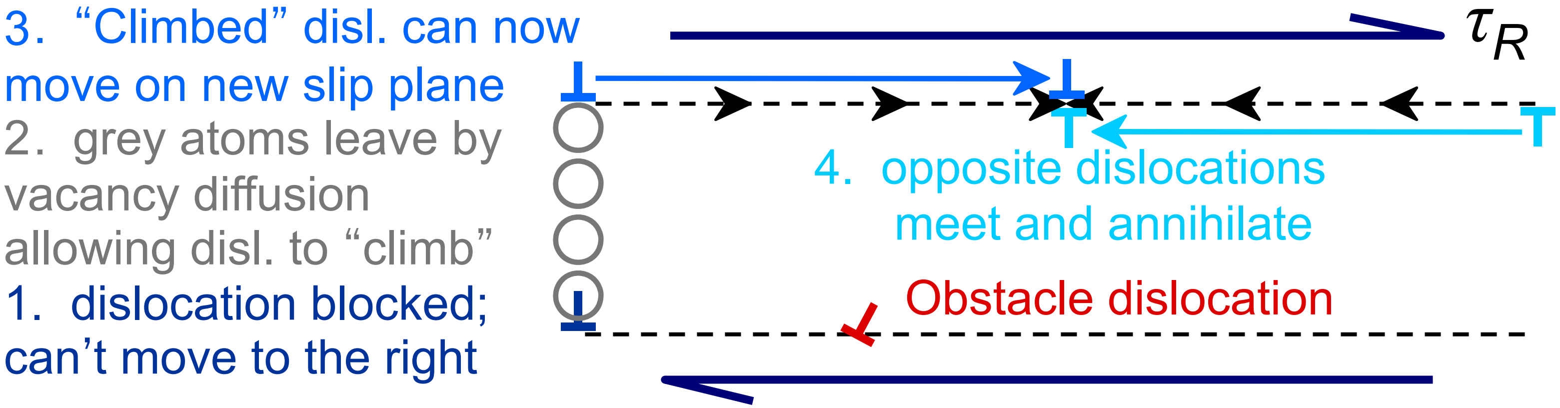
extra half-plane of atoms

atoms diffuse to regions of tension

extra half-plane of atoms

Dislocations annihilate and form a perfect atomic plane.

- Scenario 2



3. "Climbed" disl. can now move on new slip plane

2. grey atoms leave by vacancy diffusion allowing disl. to "climb"

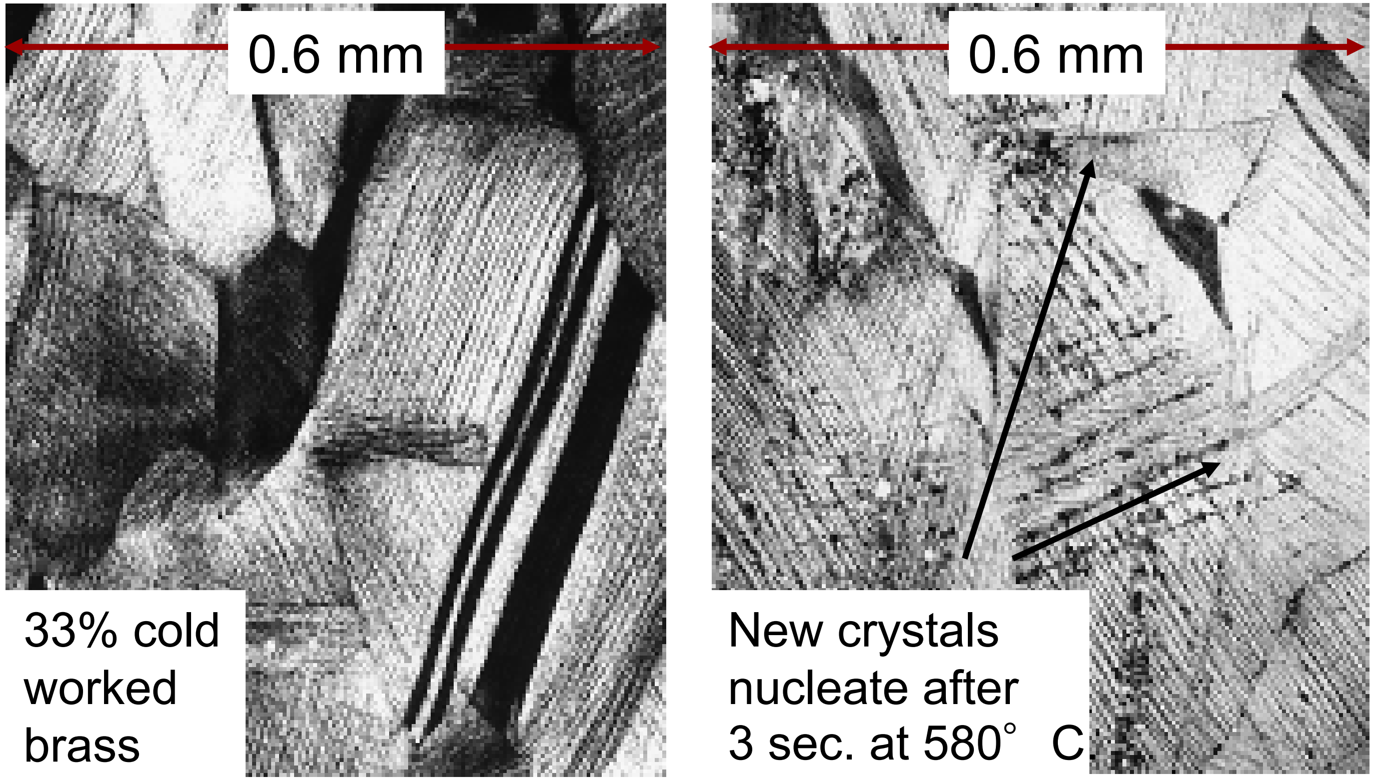
1. dislocation blocked; can't move to the right

4. opposite dislocations meet and annihilate

Obstacle dislocation

Three Stages During Heat Treatment:
2. Recrystallization

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



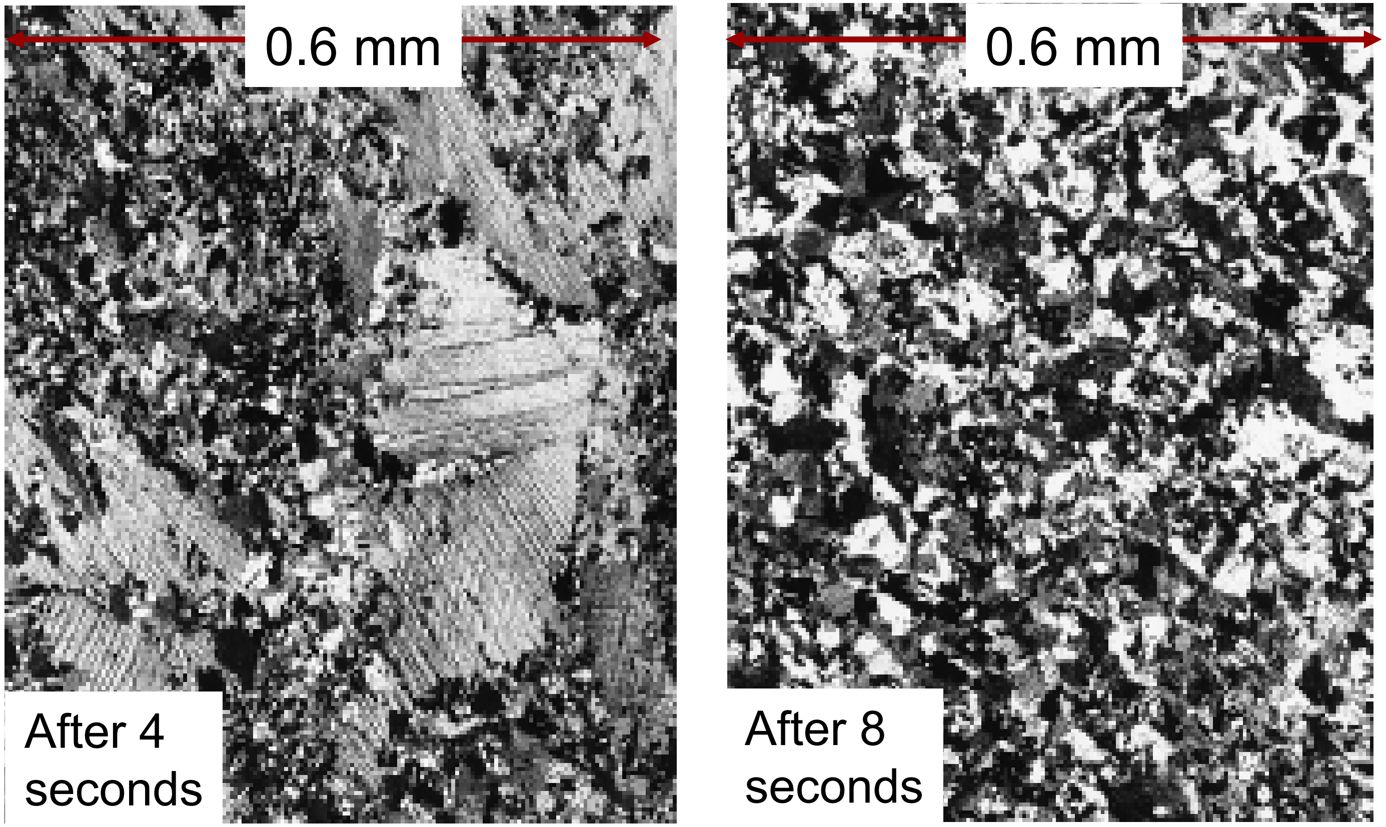
33% cold worked brass

New crystals nucleate after 3 sec. at 580° C

Adapted from Fig. 9.21 (a),(b), *Callister & Rethwisch 9e.* (Photomicrographs courtesy of J.E. Burke, General Electric Company.)

As Recrystallization Continues…

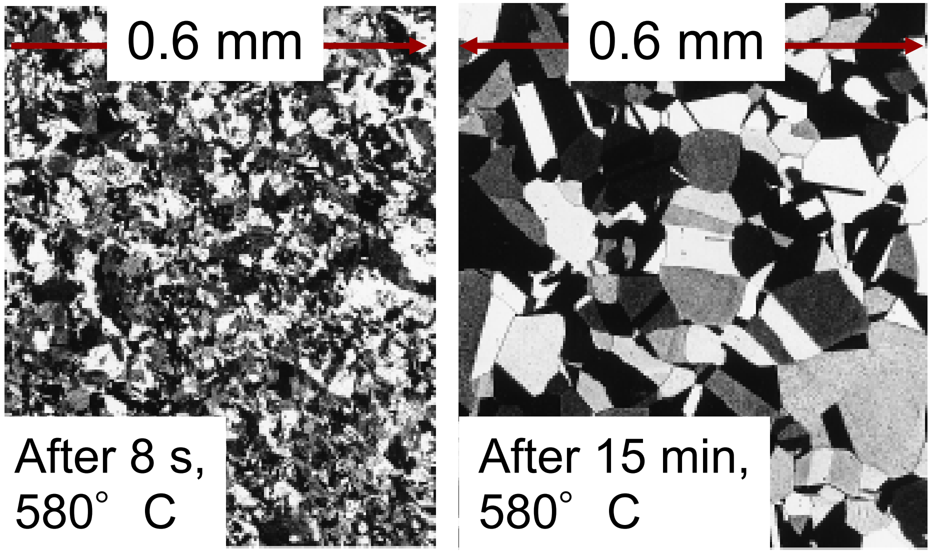
- All cold-worked grains are eventually consumed/replaced.



Adapted from Fig. 9.21 (c),(d), *Callister & Rethwisch 9e.* (Photomicrographs courtesy of J.E. Burke, General Electric Company.)

Three Stages During Heat Treatment:
3. Grain Growth

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



Adapted from Fig. 11.21 (d),(e), *Callister & Rethwisch 9e.* (Photomicrographs courtesy of J.E. Burke, General Electric Company.)

- Empirical Relation:

exponent typ. ~ 2

grain diam. at time t.

coefficient dependent on material and *T*.

elapsed time

$$d^n - d_o^n = Kt$$

- Empirical Relation:

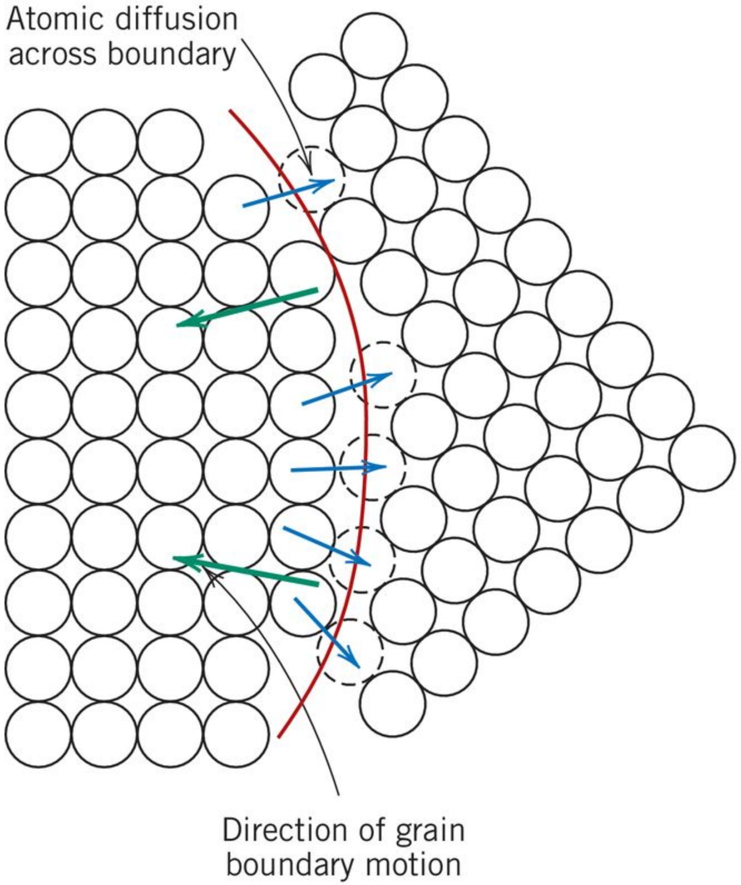
exponent typ. ~ 2

grain diam.
at time t.

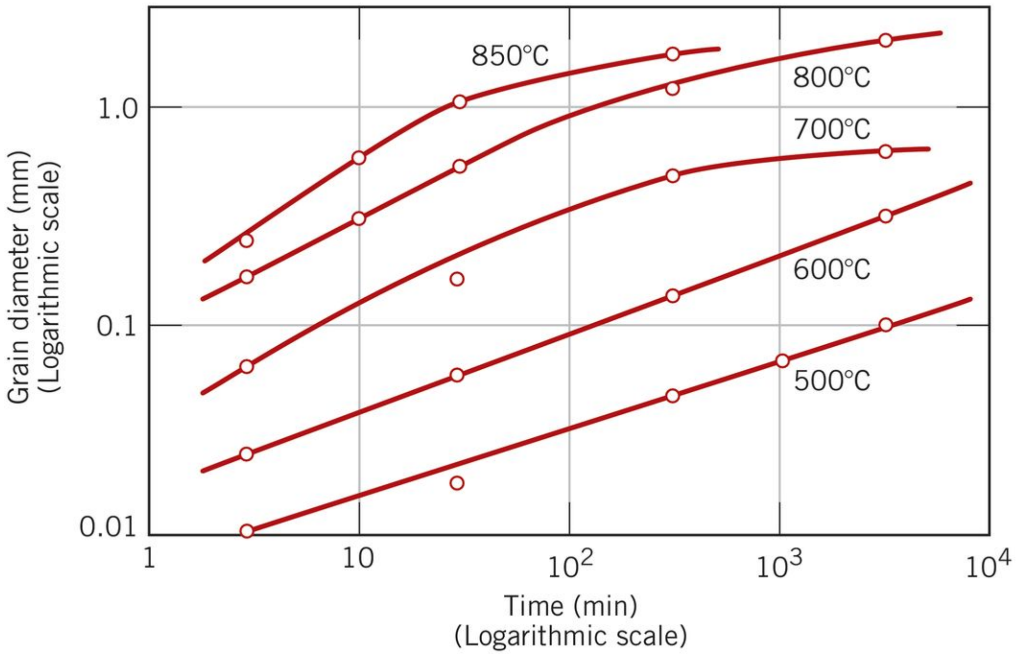
$$d^n - d_o^n = Kt$$

coefficient dependent on material and *T*.

elapsed time



Adapted from L. H. Van Vlack, Elements of Materials Science and Engineering, 6th edition. © 1989 by Addison-Wesley Publishing Company, Inc.



From J. E. Burke, "Some Factors Affecting the Rate of Grain Growth in Metals." Reprinted with permission from Metallurgical Transactions, Vol. 180, 1949, a publication of The Metallurgical Society of AIME, Warrendale, Pennsylvania.

Ex: Grain Growth

A metal having a grain diameter of $8.2\text{x}10^{-3}$ mm is heated to 500 °C for 12.5 min, the grain diameter increases to $2.7\text{x}10^{-2}$ mm. Compute the grain diameter when a specimen of the original material is heated at 500 °C for 100 min.
Assume the grain diameter exponent n has a value of 2.

$$d^2 - {d_o}^2 = Kt$$

$d_o = 8.2\text{x}10^{-3}$ mm, $d = 2.7\text{x}10^{-2}$ mm, $t = 12.5$ min

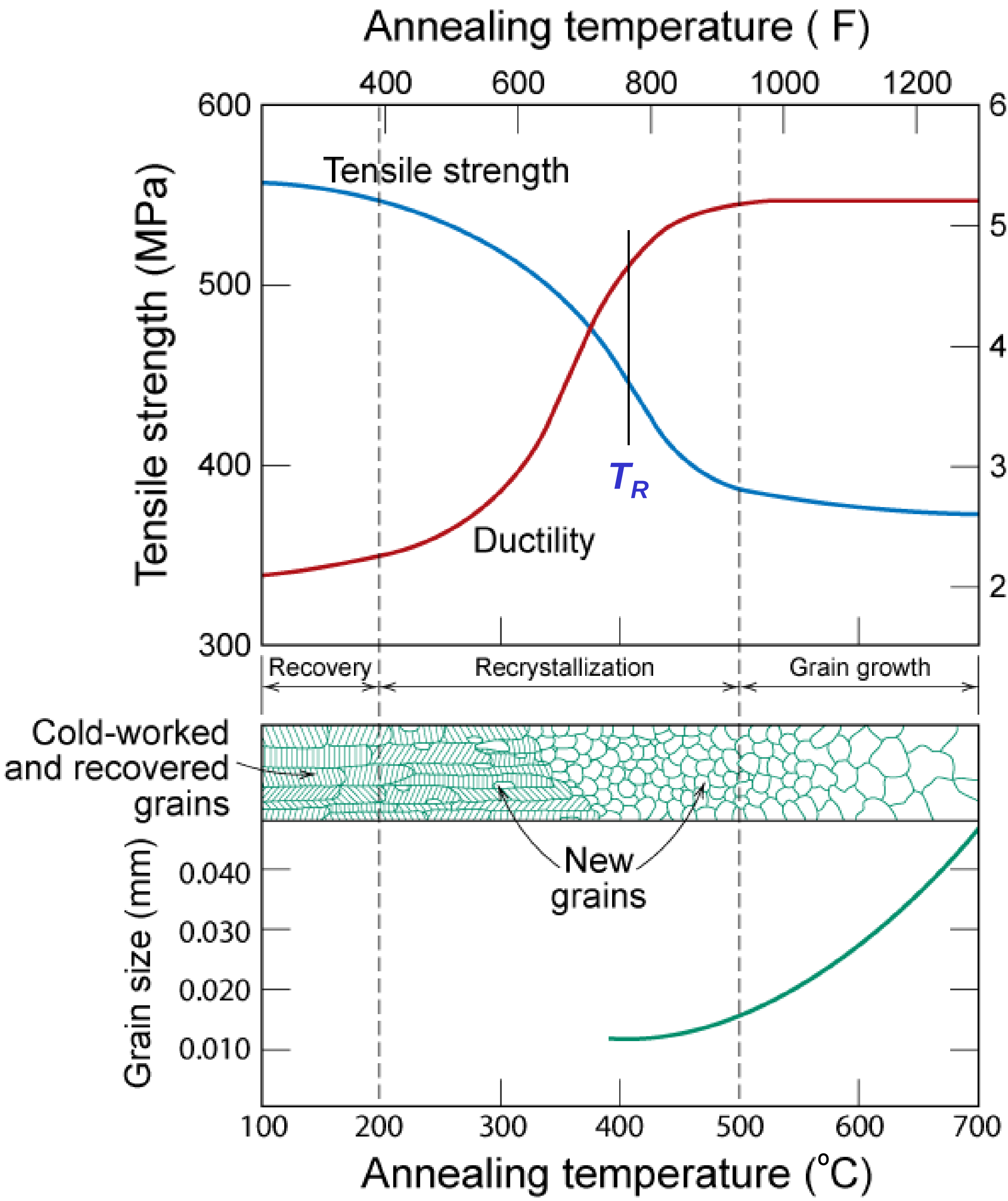
$$K = \frac{d^2 - {d_o}^2}{t} = \frac{(2.7 \times 10^{-2}\ mm)^2 - (8.2 \times 10^{-3}\ mm)^2}{12.5\ min}$$

$$= 5.29 \text{ x } 10^{-5}\ \text{mm}^2/\text{min}$$

$$d = \sqrt{{d_o}^2 + Kt}$$

$$= \sqrt{(8.2x10^{-3}mm)^2 + (5.29x10^{-5}\ mm^2/\text{ min})\ (100\ min)}$$

$$= 0.0732\ \text{mm}$$



T_R = recrystallization temperature

Fig. 9.22, *Callister & Rethwisch 9e.*
(Adapted from G. Sachs and K. R. Van Horn, *Practical Metallurgy, Applied Metallurgy and the Industrial Processing of Ferrous and Nonferrous Metals and Alloys*, 1940. Reproduced by permission of ASM International, Materials Park, OH.)

Recrystallization Temperature

T_R = recrystallization temperature = temperature at which recrystallization just reaches completion in 1 h.

$$0.3T_m < T_R < 0.6T_m$$

For a specific metal/alloy, T_R depends on:

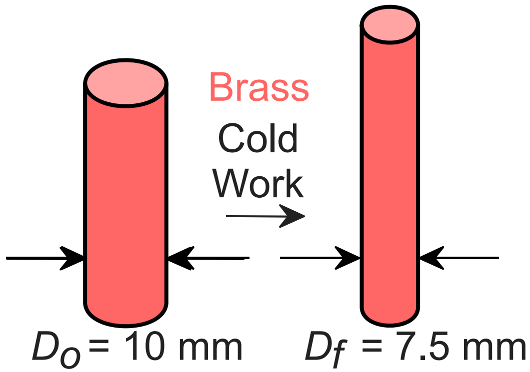
- %CW -- T_R decreases with increasing %CW
- Purity of metal -- T_R decreases with increasing purity

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.

Diameter Reduction Procedure - 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 – Solution (Cont.)

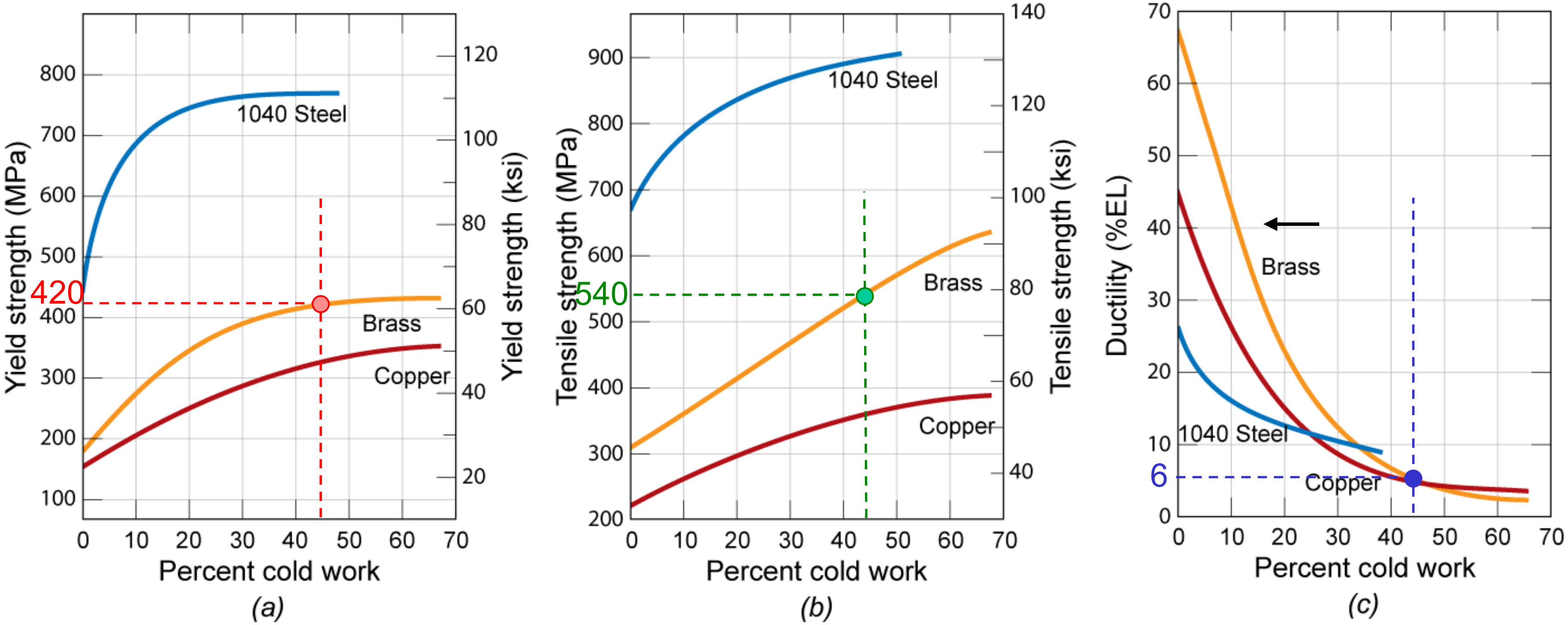
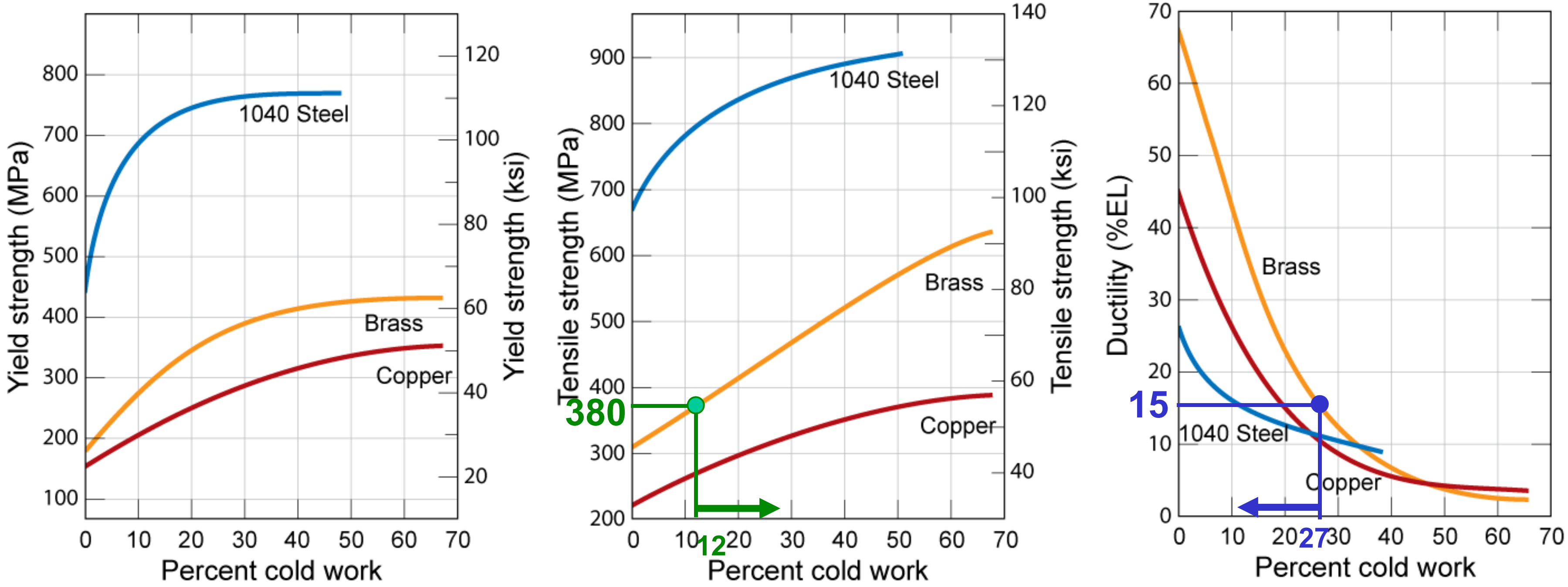


Fig. 9.19, *Callister & Rethwisch 9e.*
[Adapted from *Metals Handbook: Properties and Selection: Irons and Steels*, Vol. 1, 9th edition, B. Bardes (Editor), 1978; and *Metals Handbook: Properties and Selection: Nonferrous Alloys and Pure Metals*, Vol. 2, 9th edition, H. Baker (Managing Editor), 1979.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

- For %CW = 43.8%
  - σ_y = 420 MPa
  - *TS* = 540 MPa > 380 MPa
  - %*EL* = 6 < 15
- This doesn't satisfy criteria… what other options are possible?

Diameter Reduction Procedure – Solution (cont.)



(a) (b) (c)

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.]

For *TS* > 380 MPa ➡ > 12 %CW

For %*EL* > 15 ➡ < 27 %CW

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

Diameter Reduction Procedure – Solution (cont.)

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 first cold work stage (but before 2nd cold work stage) is calculated as follows:

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

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

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

Diameter Reduction Procedure – Summary

Stage 1: Cold work – reduce diameter from 10 mm to 8.39 mm

$$\%CW_1 = \left(1 - \left(\frac{8.39\text{ mm}}{10\text{ mm}}\right)^2\right) x\ 100 = 29.6$$

Stage 2: Heat treat (allow recrystallization)

Stage 3: Cold work – reduce diameter from 8.39 mm to 7.5 mm

$$\%CW_2 = \left(1 - \left(\frac{7.5}{8.39}\right)^2\right) x\ 100 = 20$$

Fig 7.19 $\Rightarrow$

$$\sigma_y = 340\text{ MPa}$$
$$TS = 400\text{ MPa}$$
$$\%EL = 24$$

Therefore, all criteria satisfied

Cold Working vs. Hot Working

- Hot working → deformation above T_R
- Cold working → deformation below T_R

Grain Size Influences Properties

- Metals having small grains – relatively strong and tough at low temperatures

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

- Metals having large grains – good creep resistance at relatively high temperatures

$$\dot{\varepsilon} = A\,\sigma^n\,d^{-m}\exp\left(-\frac{Q}{RT}\right)$$

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.