**2019 Fall**

# Introduction to Materials Science and Engineering

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**Eun Soo Park**

**Office: 33-313**
**Telephone: 880-7221**
**Email: espark@snu.ac.kr**
**Office hours: by appointment**

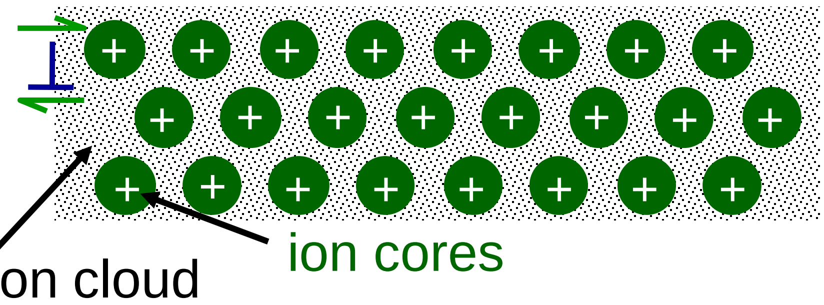
# I. Dislocation motion in different material classes

- **Metals (Cu, Al):**

  Dislocation motion easiest

  - non-directional bonding

  - close-packed directions
    for slip

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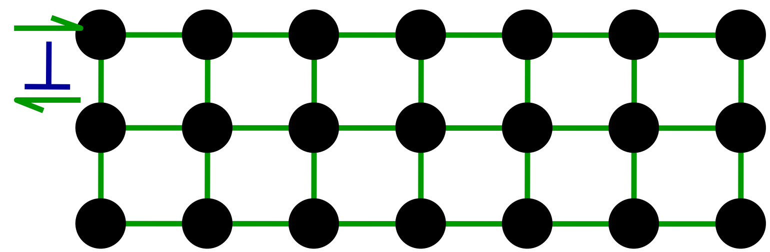
- Covalent Ceramics

  (Si, diamond): Motion difficult

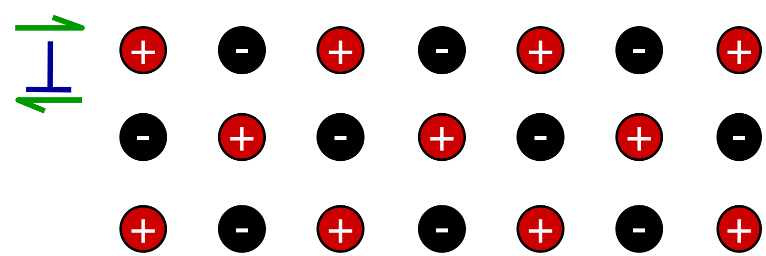
  - directional (angular) bonding



- Ionic Ceramics (NaCl):

  Motion difficult

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



## II. Slip occurs in close-packed directions on highest-density planes

The **slip system (=Slip plane + Slip direction)** depends on the **crystal structure** of the metal and is such that **the atomic distortion** that accompanies the motion of a dislocation is **a minimum**.

e.g. FCC Slip occurs on

{111} planes (close-packed) in <110> directions (close-packed)

→ total of 12 slip systems in FCC

**Table 9.1**
Slip Systems for Face-Centered Cubic, Body-Centered Cubic, and Hexagonal Close-Packed Metals

| *Metals* | *Slip Plane* | *Slip Direction* | *Number of Slip Systems* |
|---|---|---|---|
| | **Face-Centered Cubic** | | |
| Cu, Al, Ni, Ag, Au | 4 $\{111\}$ | 3 $\langle 110\rangle$ | 12 |
| | **Body-Centered Cubic** | | |
| $\alpha$-Fe, W, Mo | $\{110\}$ | $\langle 111\rangle$ | 12 |
| $\alpha$-Fe, W | $\{211\}$ | $\langle 111\rangle$ | 12 |
| $\alpha$-Fe, K | $\{321\}$ | $\langle 111\rangle$ | 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 |

Quite ductile

Quite brittle

**Burgers vector b _** b(FCC) =a/2<110> , b(BCC)=a/2<111>, b(HCP)=a/3<1120>

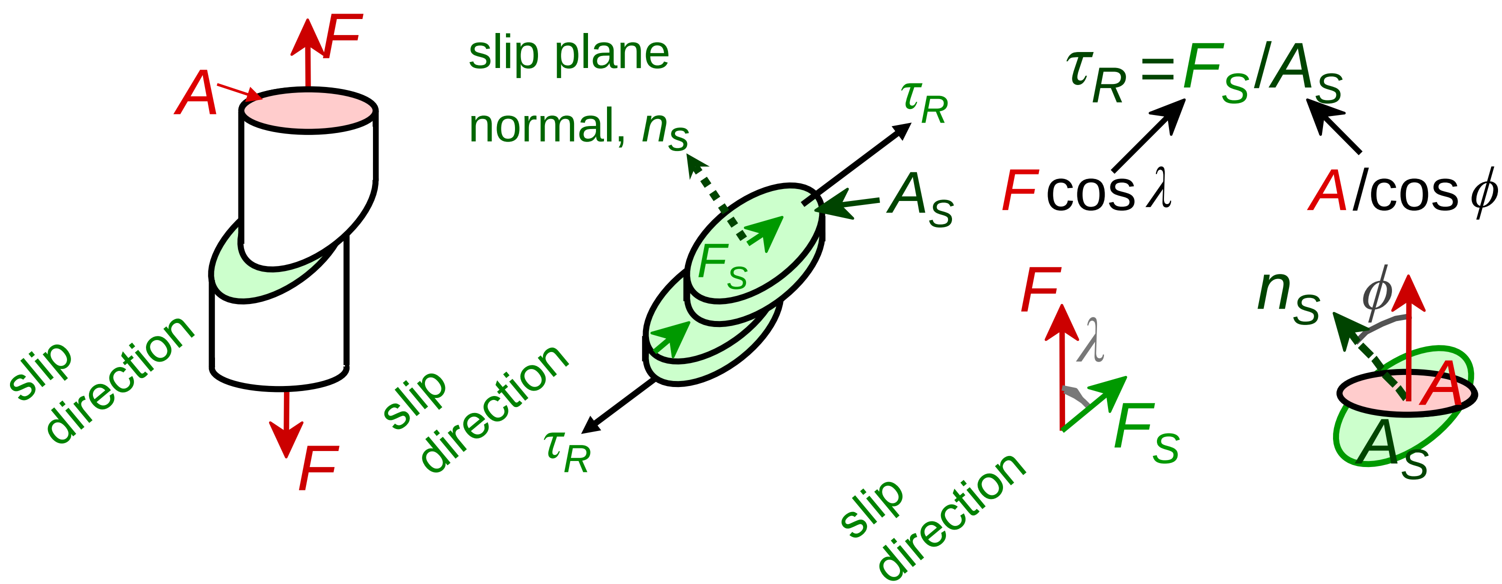
# III. Stress → Dislocation Motion

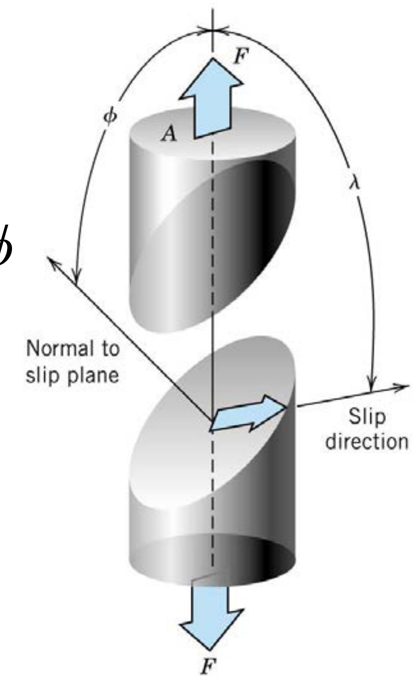
- Crystals slip due to a (1) <u>resolved shear stress, $\tau_R$</u>
- Applied tension can produce such a stress $\tau_R = \sigma \cos\lambda \cos\phi$

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

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

Relation between σ and $\tau_R$



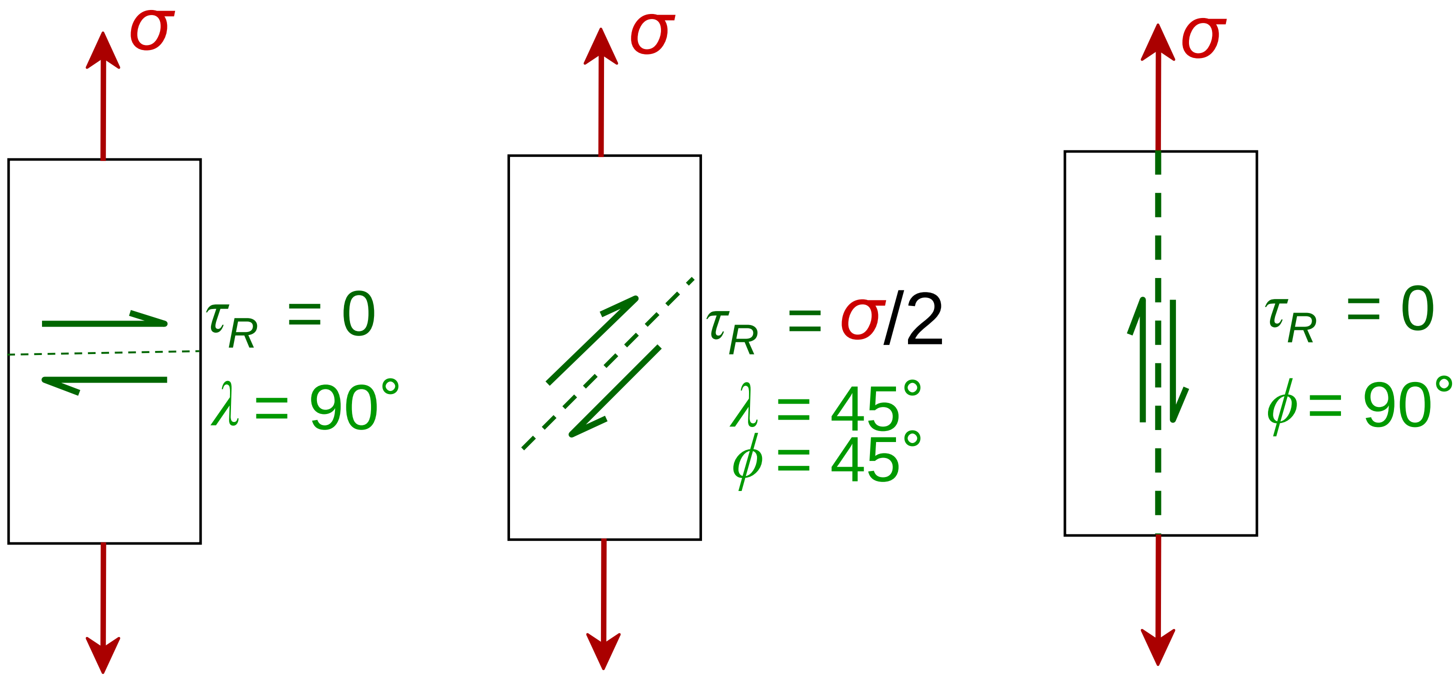




## <u>(2) Critical Resolved Shear Stress, $\tau_{CRSS}$</u>

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

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

The $\tau_R$ normally differs for each slip systems because the orientation of each relative to the stress axis (Φ and λ angles) also differs. However, one slip system is generally oriented most favorably-that is, has the largest $\tau_R$(max):




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

(3) $\tau$ maximum at $\lambda = \phi = 45^o$

: Ease of dislocation motion depends on crystallographic orientation

## (4) Plastic deformation in single crystal, $\tau_R(\max) = \tau_{CRSS}$

e.g. Minimum stress necessary to introduce yielding: $\sigma_y = 2\tau_{CRSS}$

# Critical resolved shear stress

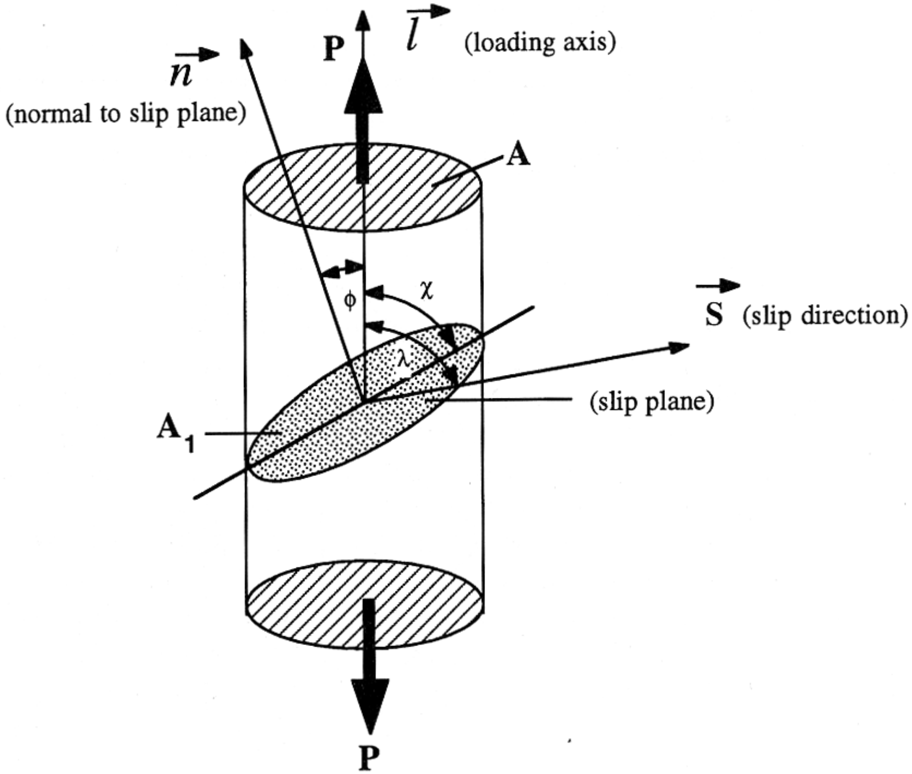



**Figure 6.8** Relationship between stress axis and slip plane and direction.

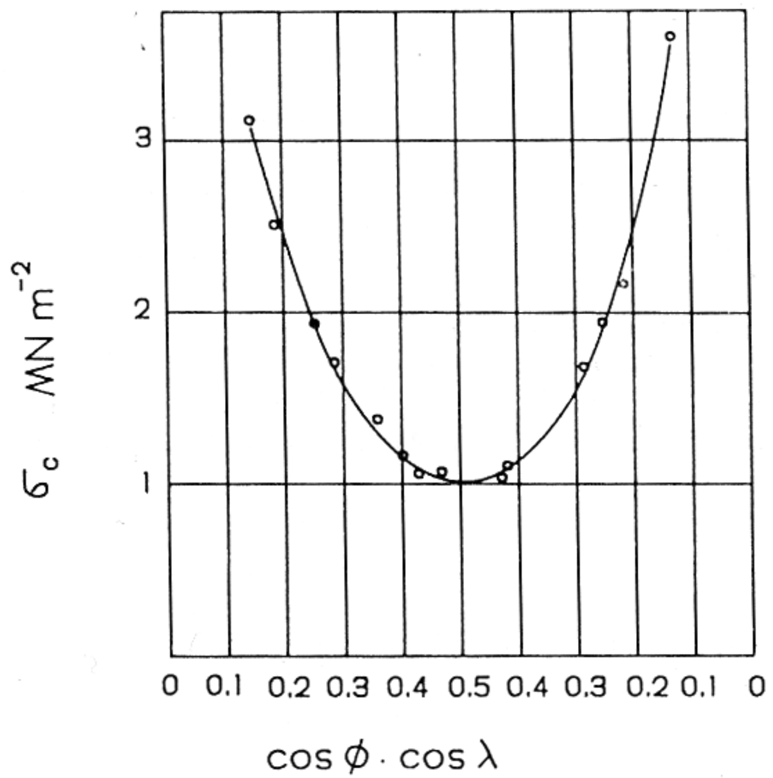



**Fig. 10.2** The variation of $\sigma_c$ with orientation

$$\tau_c = \sigma_0 \cos\phi \cos\lambda = M\sigma_0$$

$$M = \cos\phi \cos\lambda$$

*M=Schmid factor*

1. Specimen size
2. Temperature
3. Stacking fault energy
4. Solute atoms

# d. Slip Motion in Polycrystals

- **Slip planes & directions ($\lambda$, $\phi$)** change from one grain to another.
- $\tau_R$ will vary from one grain to another.
- The grain with the **largest $\tau_R$** yields first.
- Other (less favorably oriented) grains yield later.

→ Two slip systems operated for most of the grains

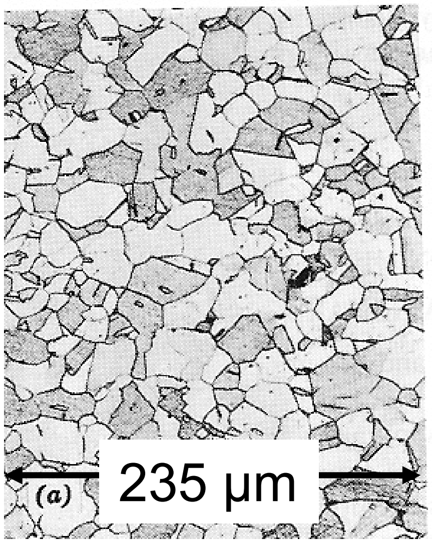
- Polycrystals stronger than single crystals – **grain boundaries are barriers to dislocation motion.**


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].)

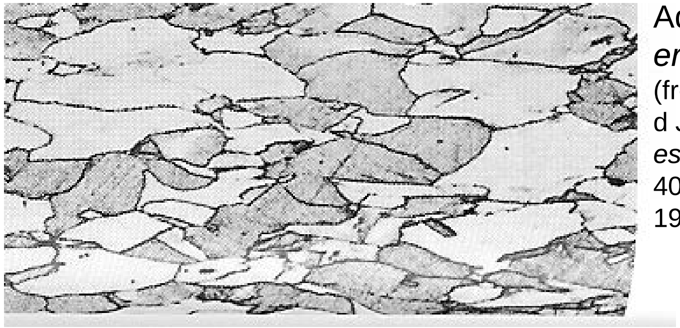
# (1) Anisotropy in $\sigma_y$

- Can be induced by rolling a polycrystalline metal

- before rolling




- after rolling



rolling direction

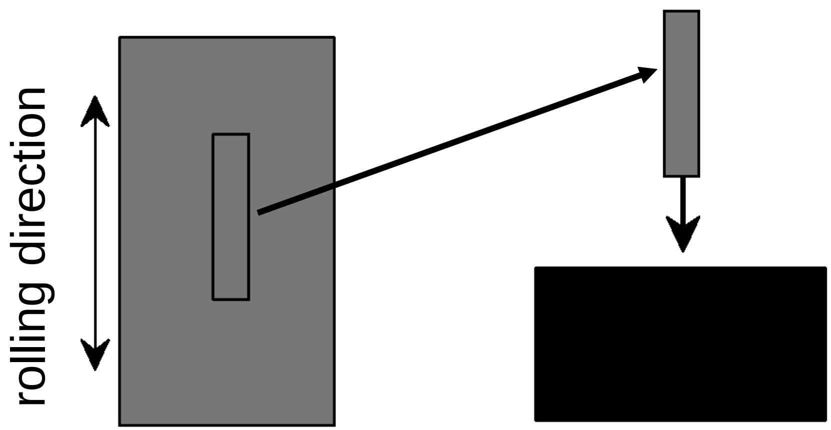
Adapted from Fig. 9.11, *Callister & Rethwisch 9e.* (from W.G. Moffatt, G.W. Pearsall, and J. Wulff, *The Structure and Properties of Materials*, Vol. I, *Structure*, p. 140, John Wiley and Sons, New York, 1964.)

- isotropic since grains are equiaxed & randomly oriented.

- anisotropic since rolling affects grain orientation and shape.

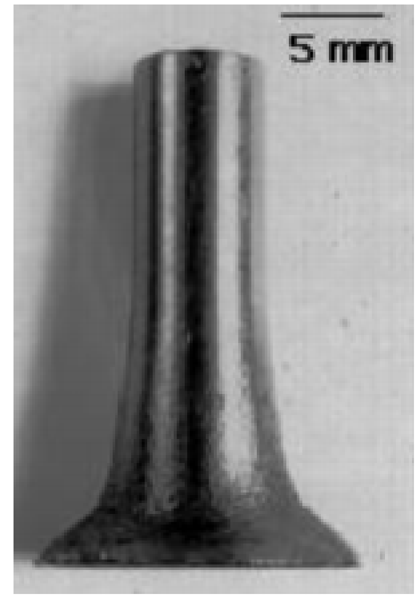
# (2) Anisotropy in Deformation

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.

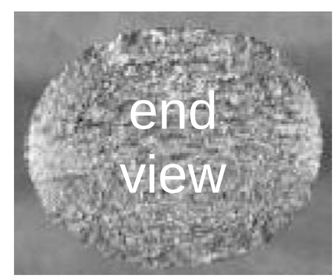



plate thickness direction

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

# e. Plastic deformation by twinning

The two primary methods of deformation in metals are **slip and twinning.** **Slip** occurs by dislocation glide of either screw or edge dislocations within a slip plane. Slip is by far the most common mechanism. **Twinning** is less common but readily occurs under some circumstances.

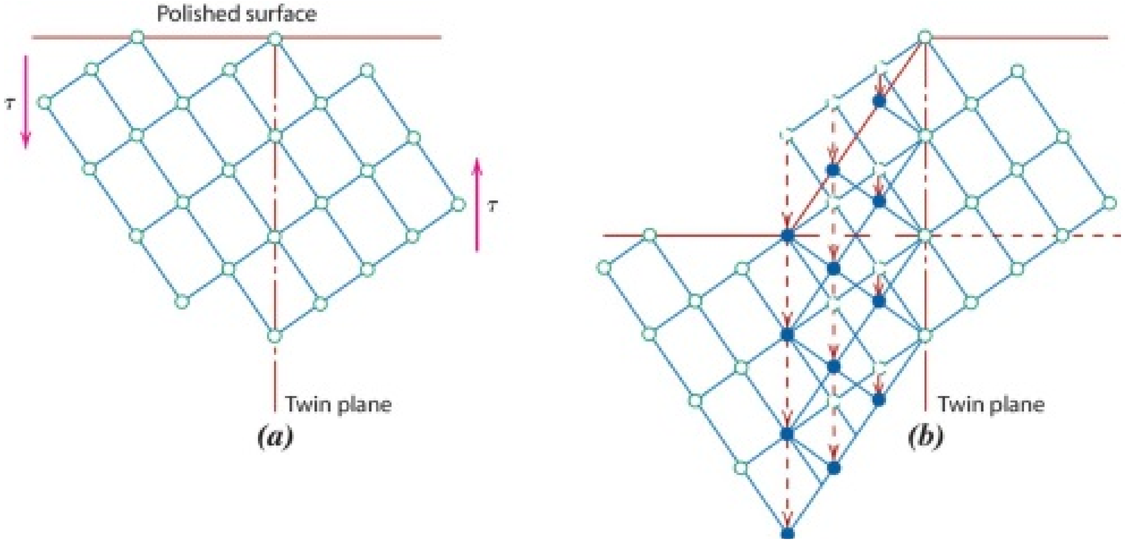


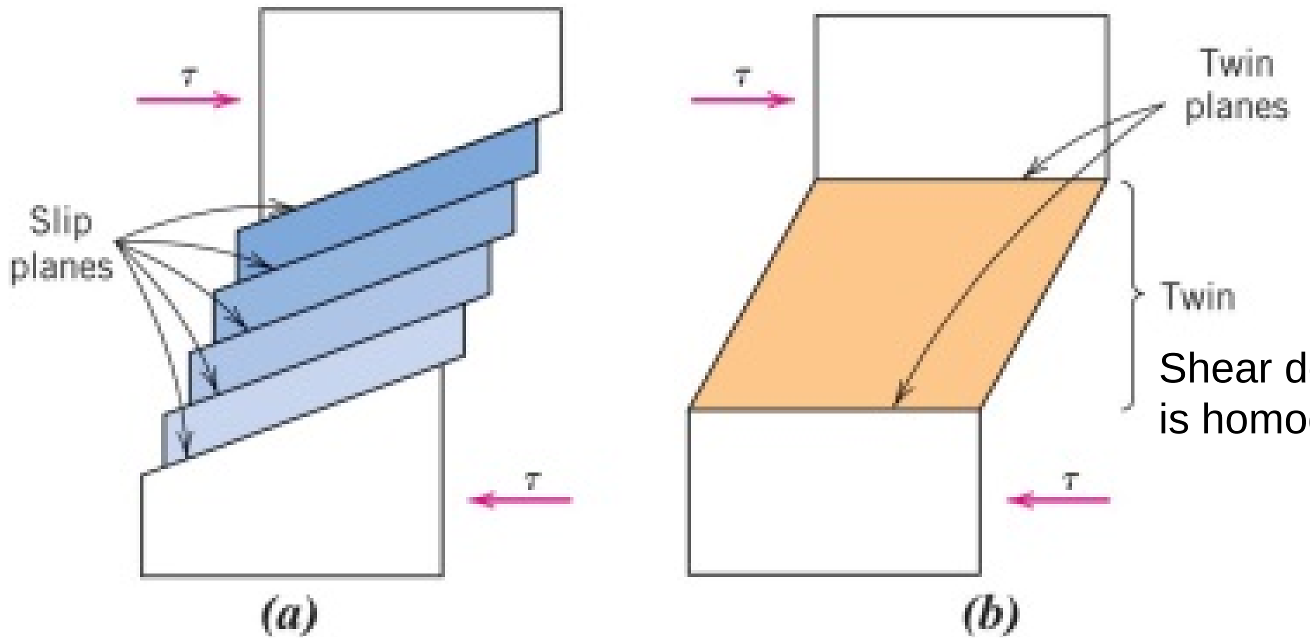

**TABLE 5.2** Twinning Planes, Directions, and Shears

| *Structure* | *Twin Plane and Direction* | *Shear Strain, γ* |
|---|---|---|
| FCC | (111) [112] | 0.707 |
| BCC | (112) [111] | 0.707 |
| HCP | (10$\bar{1}$2) [10$\bar{1}\bar{1}$] | Cd: 0.171<br>Zn: 0.139<br>Mg: 0.129<br>Ti: 0.139<br>Be: 0.199 |

Figure 9.12 Schematic diagram showing how twinning results from an applied shear stress $\tau$. In (b), open circles represent atoms that did not change position; dashed and solid circles represent original and final atom positions.

**Twining** occurs a definite crystallographic plane and in a specific direction that depend on crystal structural. For examples, **for BCC metals**, the twin plane and direction are **(112) and [111]**, respectively.

# e. Plastic deformation by twinning




Shear deformation is homogeneous.

Figure 9.13 For a single crystal subjected to a shear stress $\tau$, (a) **deformation by slip**; (b) **deformation by twinning**.

Differences between two processes:

(1) For **slip**, the crystallographic orientation above and below the slip lane is the same both before and after the deformation; for **twinning**, there is a reorientation across the twin plane.

**(2) Slip** occurs in distinct atomic spacing multiples, whereas the atomic displacement for **twining** is less than the interatomic separation.

# e. Plastic deformation by twinning

(1) **Twinning occurs when there are not enough slip systems to accommodate deformation and/or when the material has a very low SFE.** **In BCC and HCP crystal structure, mechanical twinning** occurs **at low temperatures, and at high rates of loading (shock loading),** conditions under which the slip process is restricted-that is, there are few operable slip systems

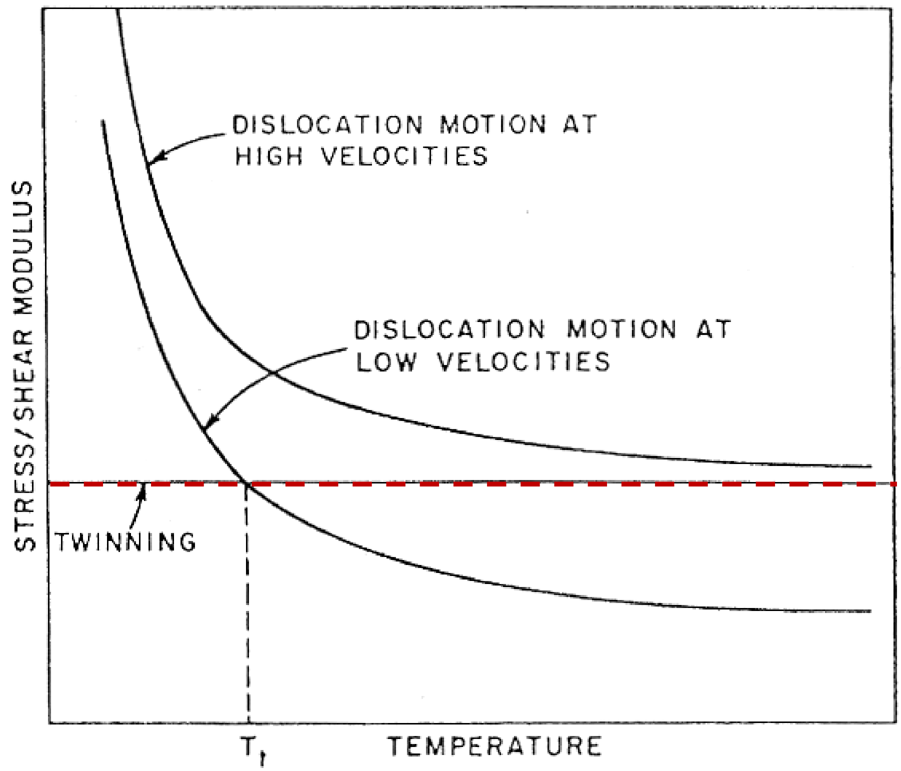



**Figure 5.18** Effect of temperature on the stress required for twinning and slip (at low and high strain rates). (Courtesy of G. Thomas)

# e. Plastic deformation by twinning

**(2) In FCC crystal structure,** twins are abundant in many low stacking fault energy (SFE) metals like copper alloys, but are rarely seen in high SFE metals like aluminum. In particular, **FCC alloys with low SFE** exhibits **twin-induced plasticity** during deformation. e.g. TWIP steel.

(3) The **amount of bulk plastic deformation from twinning** is **normally small** relative to that resulting from slip.

(4) However, **the real importance of twinning** lies with the accompanying **crystallographic reorientations**; <u>twinning may place new slip systems in orientations that are favorable relative to the stress axis such that the slip process can now take place</u>.

# Summary I

- Two primary methods of deformation in metals are **Slip** **and** **Twinning**.
- **Slip** occurs in close-packed direction (Slip direction) on highest-density planes (Slip plane) : **Slip system = Slip plane + Slip direction**

$\tau_R = \sigma \cos\lambda \cos\phi$ : $\tau_R(\max) = \tau_{CRSS}$ ⇨ $\tau_R > \tau_{CRSS}$

- Importance of **twinning ~ crystallographic reorientations**

→ Additional slip process can take place

- 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.

Strengthening of materials ⇔ Hindering ***dislocation*** movement (blocking, resistance,,,,)

**Four Strategies for Strengthening:**

1. Limit the space to move : **Reduce Grain Size**
2. Make irregular pattern in the lattice : **SS strengthening**
3. Block them using foreign substances: **Precipitation strengthening**
4. Tangle the ***D*** lines with each other: **Strain hardening by 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.

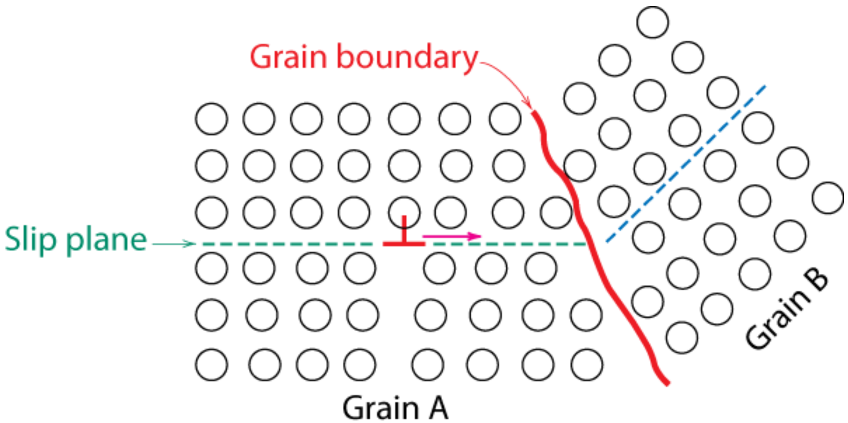



Fig. 9.14, *Callister & Rethwisch 9e.*
(From L. H. Van Vlack, *A Textbook of Materials Technology*, Addison-Wesley Publishing Co., 1973. Reproduced with the permission of the Estate of Lawrence H. Van Vlack.)

- **Hall-Petch Equation:**

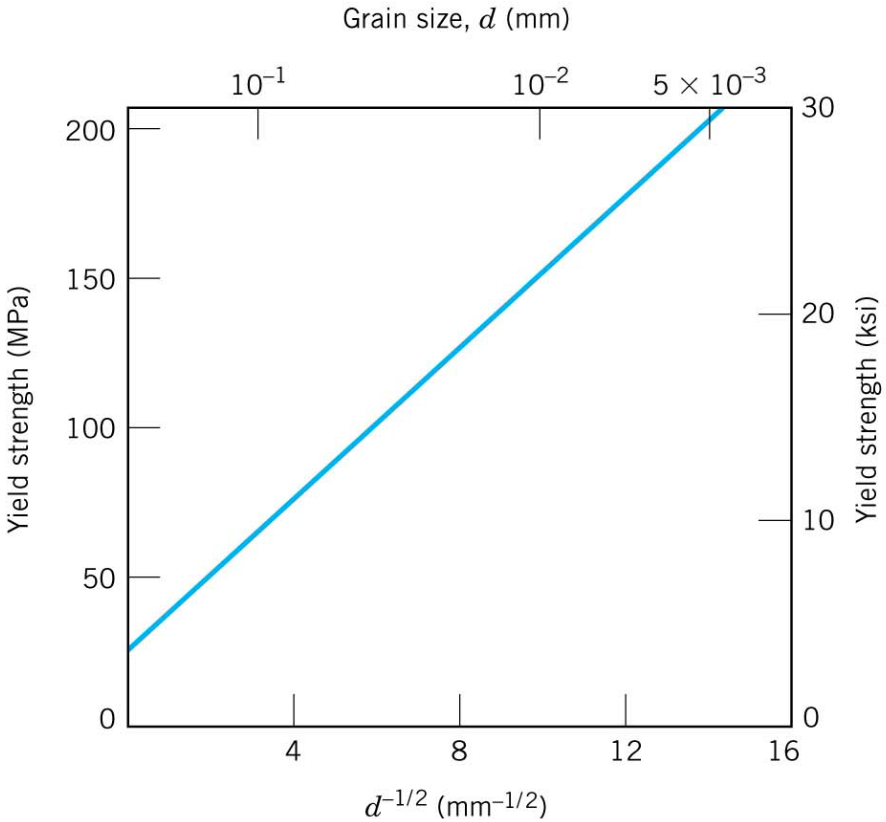
$$\sigma_{yield} = \sigma_0 + k_y d^{-1/2}$$

# Grain Size Strengthening: an example

- 70wt%Cu-30wt%Zn brass alloy

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

- Data:




0.75mm

# Grain Size Influences Properties

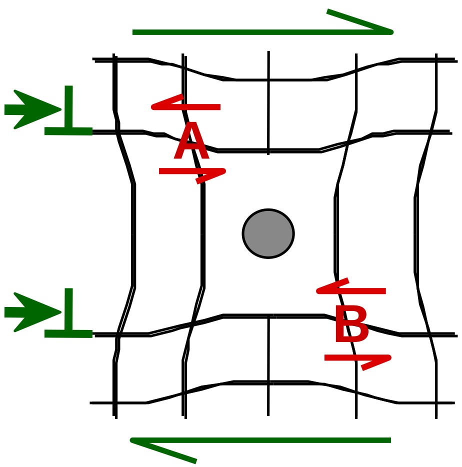
- Metals having small grains – relatively strong and tough at low temperatures

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

# Four Strategies for Strengthening: 2: Form Solid Solutions

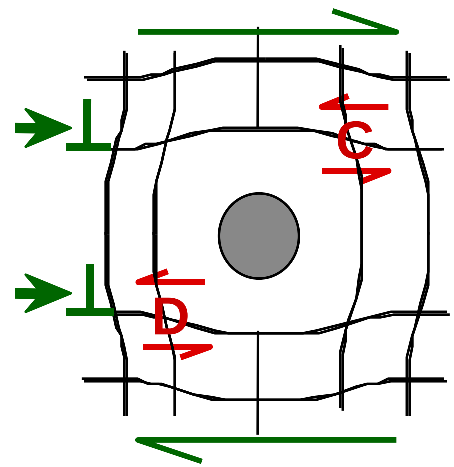
- **Impurity atoms** distort the lattice & generate lattice strains.
- <u>These strains can act as barriers to dislocation motion</u>.

- Smaller substitutional impurity




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

- Larger substitutional impurity




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

# Lattice Strains Around Dislocations

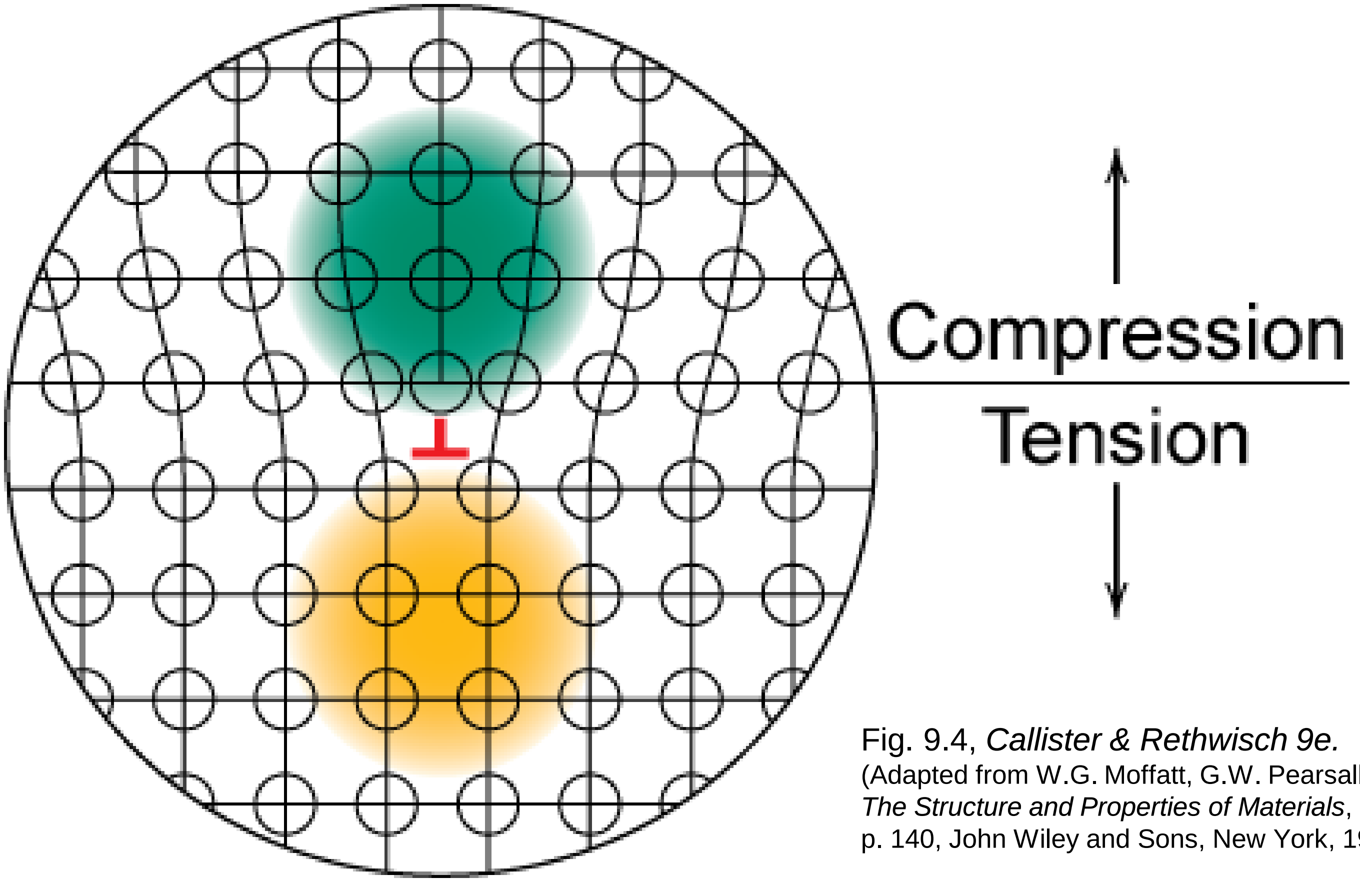
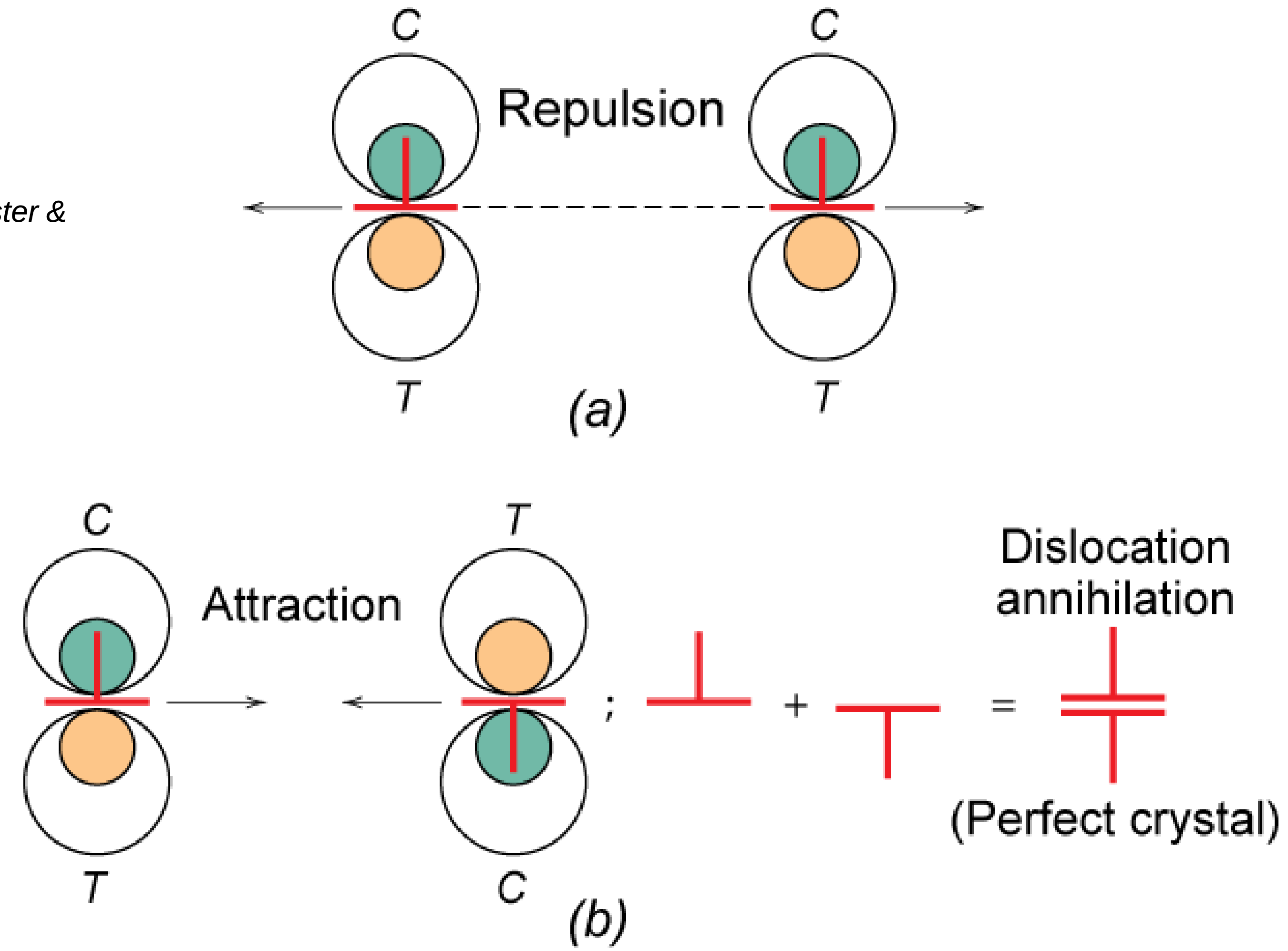



Fig. 9.4, *Callister & Rethwisch 9e.*
(Adapted from W.G. Moffatt, G.W. Pearsall, and J. Wulff, *The Structure and Properties of Materials*, Vol. I, *Structure*, p. 140, John Wiley and Sons, New York, 1964.)

# Lattice Strain Interactions Between Dislocations

Fig. 9.5, *Callister & Rethwisch 9e.*



# Strengthening by Solid Solution Alloying

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

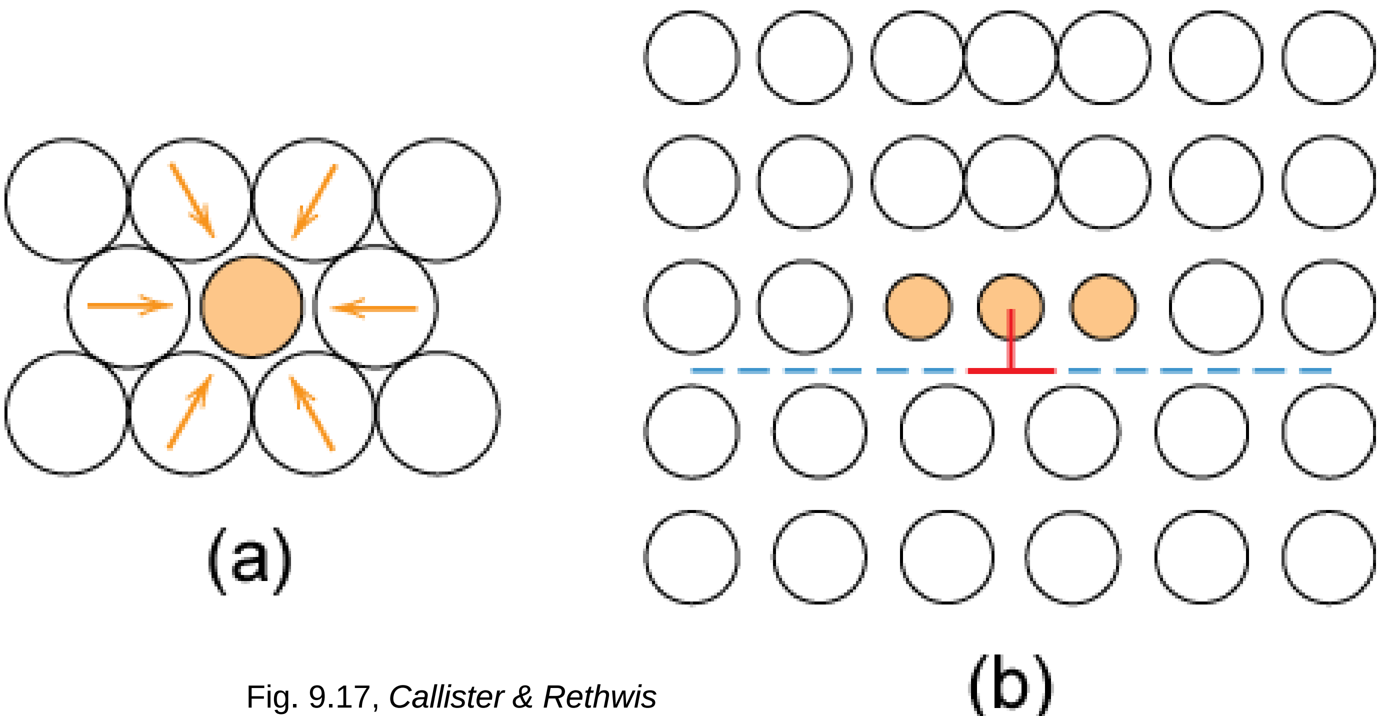



Fig. 9.17, *Callister & Rethwisch 9e.*

# Strengthening by Solid Solution Alloying

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

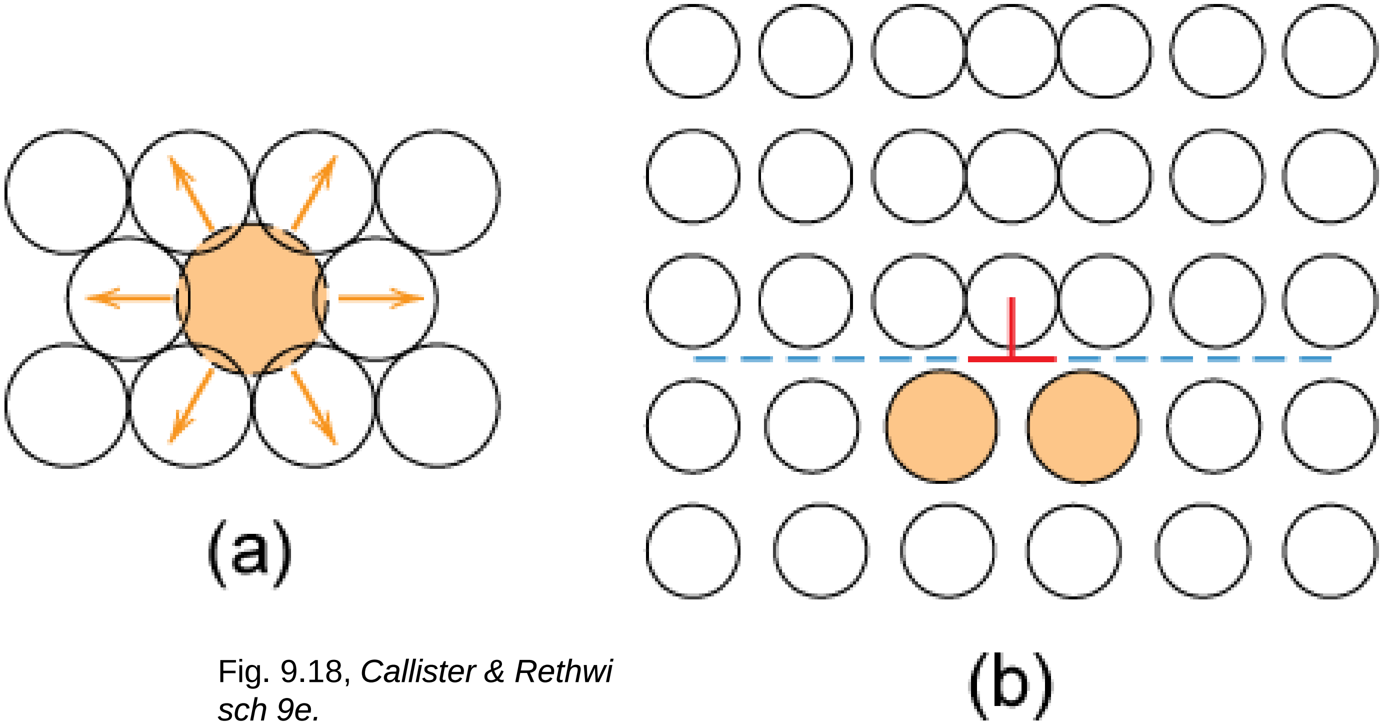
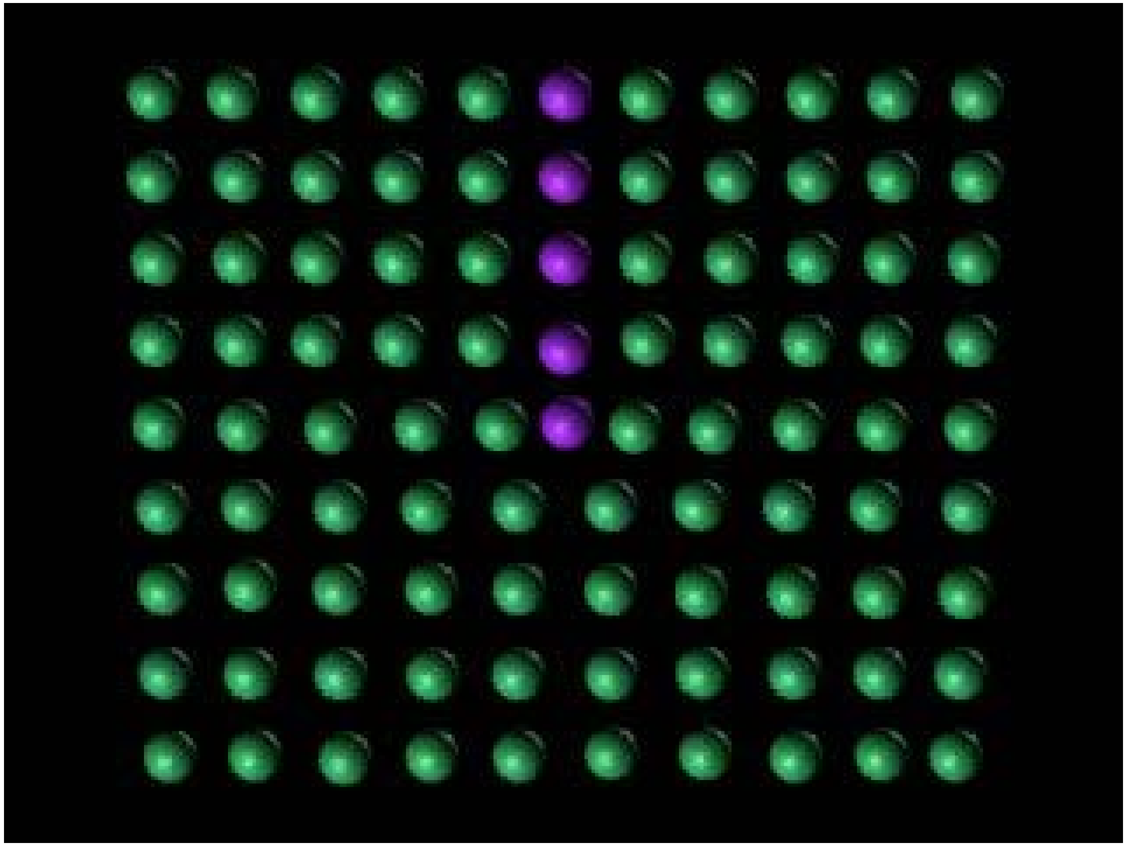



Fig. 9.18, *Callister & Rethwisch 9e.*

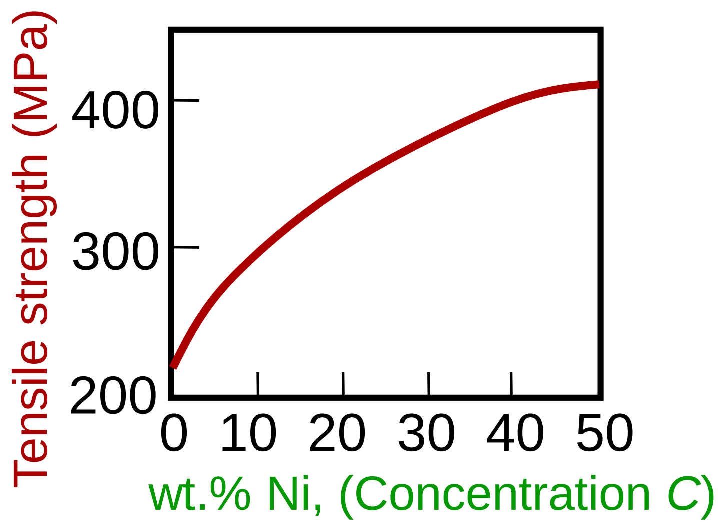
# Dislocation motion

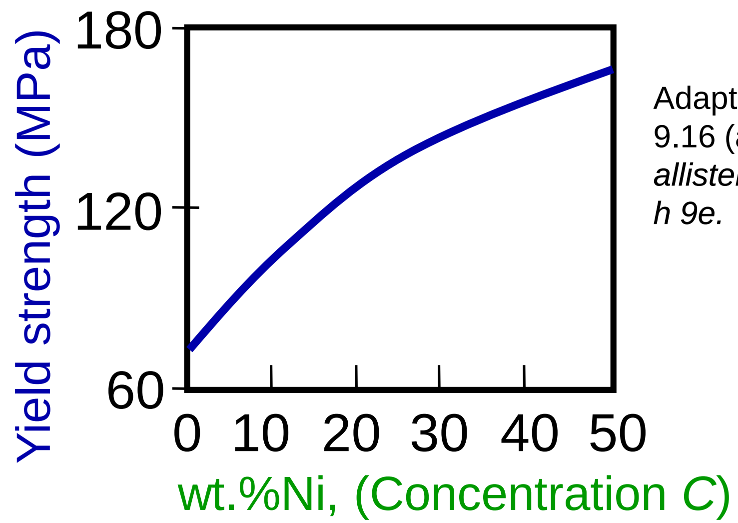


https://www.youtube.com/watch?v=RUuLusenhfA

# Ex: Solid Solution Strengthening in Copper

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



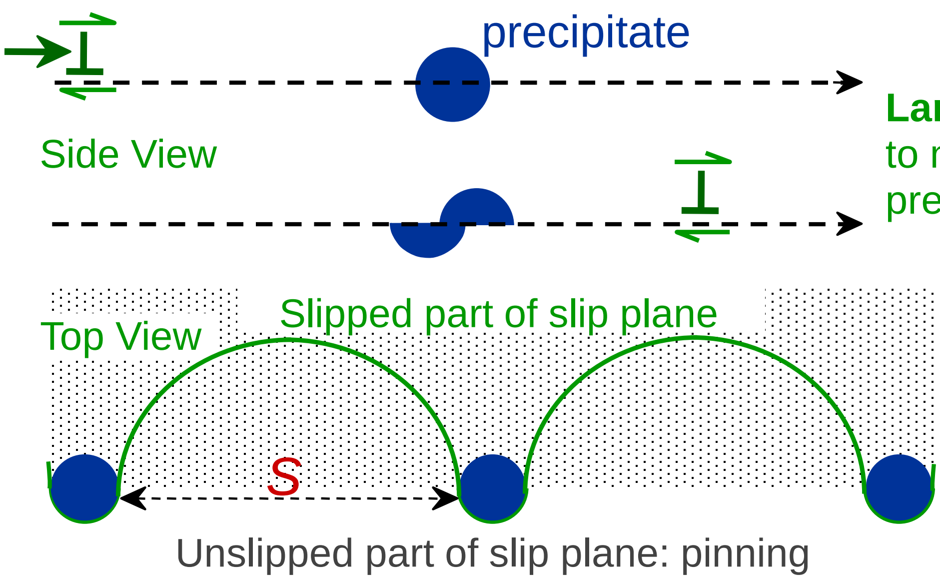

Adapted from Fig. 9.16 (a) and (b), *Callister & Rethwisch 9e.*

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

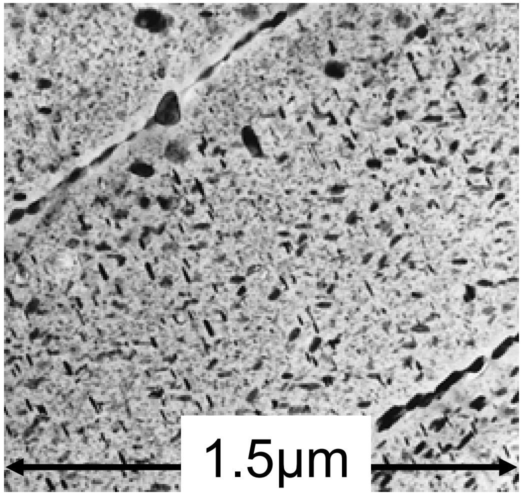
- Result: $\sigma_y \sim \dfrac{1}{S}$

# Application: Precipitation Strengthening

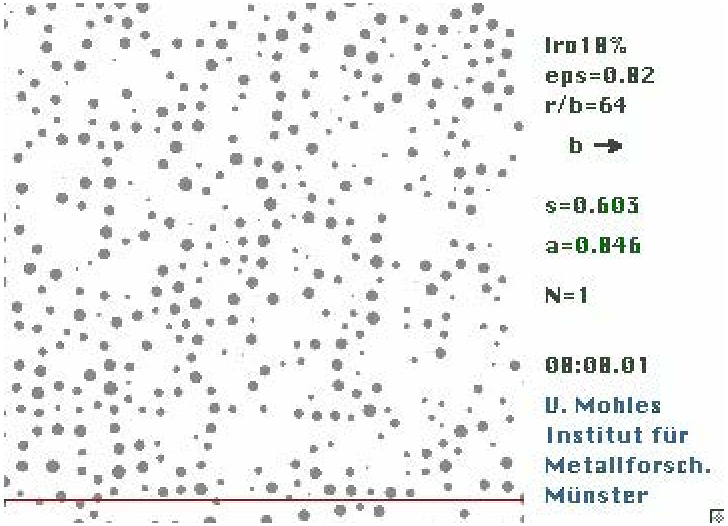
- Internal wing structure on Boeing 767


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



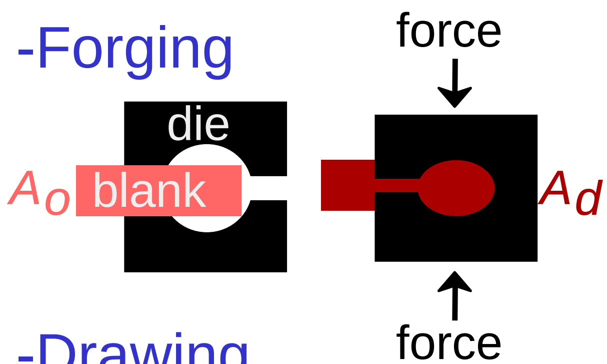

Adapted from Fig. 17.20, *Callister & Rethwisch 9e.*
(Courtesy of G.H. Narayanan and A .G. Miller, Boeing Commercial Airplane Company.)



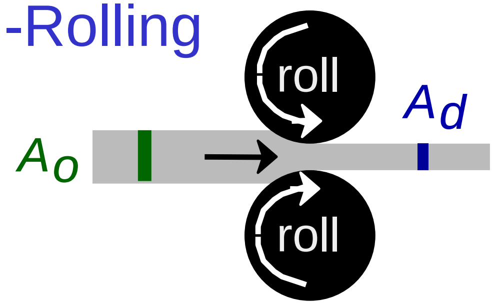
# Four Strategies for Strengthening: 4: Cold Work (Strain Hardening)

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

-Forging

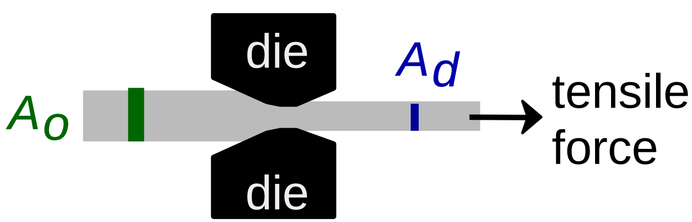



-Rolling

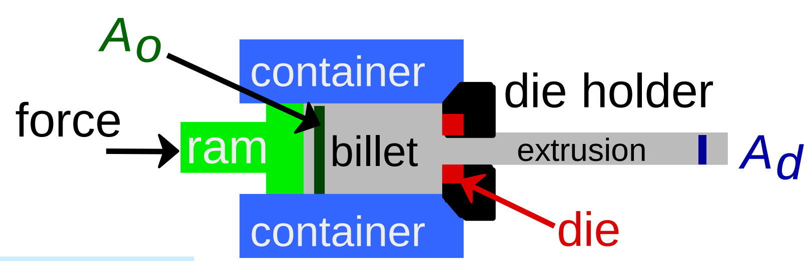



Adapted from Fig. 17.2, *Callister & Rethwisch 9e.*

-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.

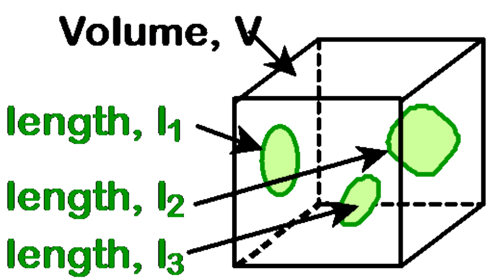

- **Dislocations entangle** with one another during cold work.
- Dislocation motion becomes **more difficult**.

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

# Dislocation Density Increases During Cold Working

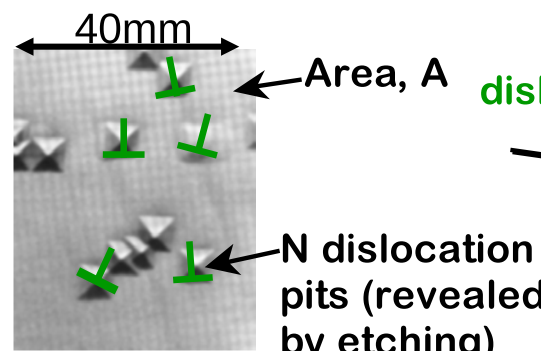
- Dislocation density ($\rho_d$) goes up:
  - Carefully grown single crystals: $\rho_d \sim 10^3$ mm/mm$^3$
  - Heavily deformed sample: $\rho_d \sim 10^{10}$ mm/mm$^3$
  - Annealed sample after severe deformation: $\rho_d \sim 10^6$ mm/mm$^3$

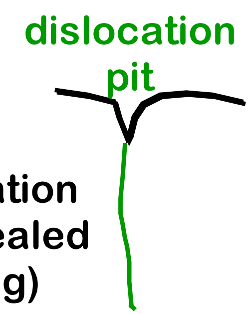
- Ways of measuring dislocation density:




$$\rho_d = \frac{l_1 + l_2 + l_3}{V} \quad \frac{\text{total dislocation length}}{\text{unit volume}}$$

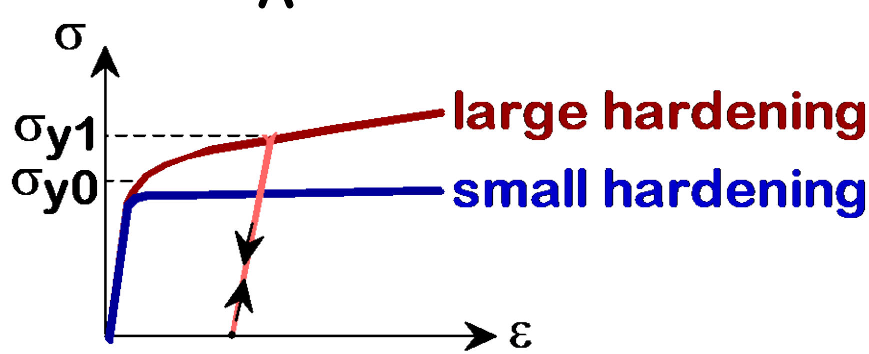
OR




$$\rho_d = \frac{N}{A}$$

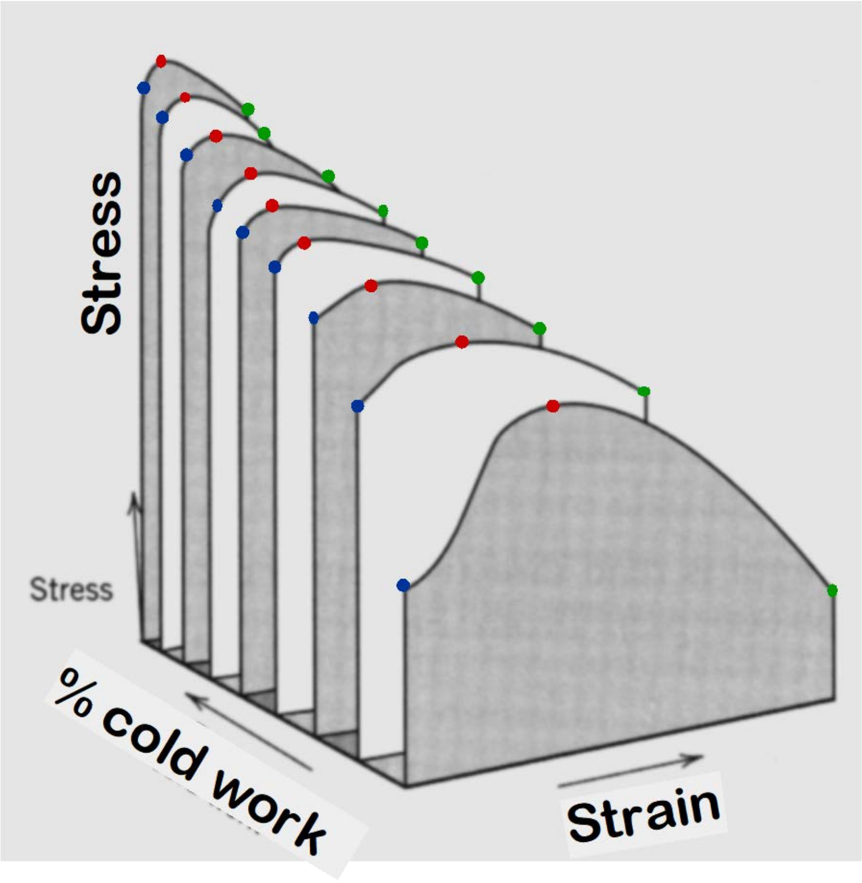
- Yield stress increases as $\rho_d$ increases:



# Impact of Cold Work

As cold work is increased

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



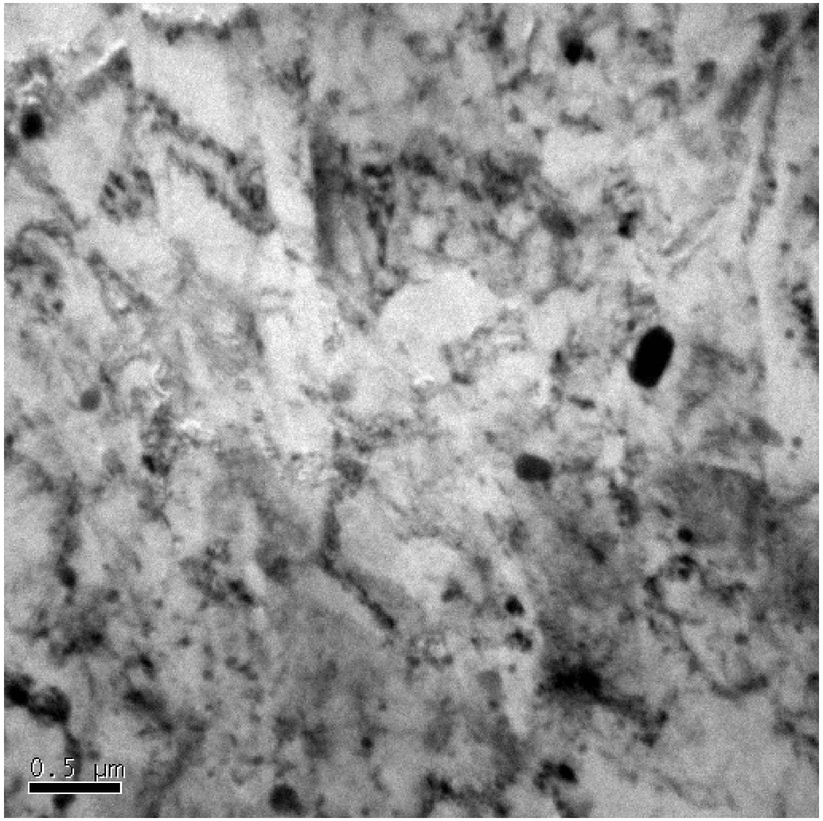
# In-situ (실시간) observation of deformation in high-Mn steel

# *In-situ experiment*

- Advantages
  - ✓ *Sequence of transition*
  - ✓ *Quick troubleshooting*
  - ✓ *Nano-scale properties*
  - ✓ *Reliability test*
  - ✓ *Cost effective*

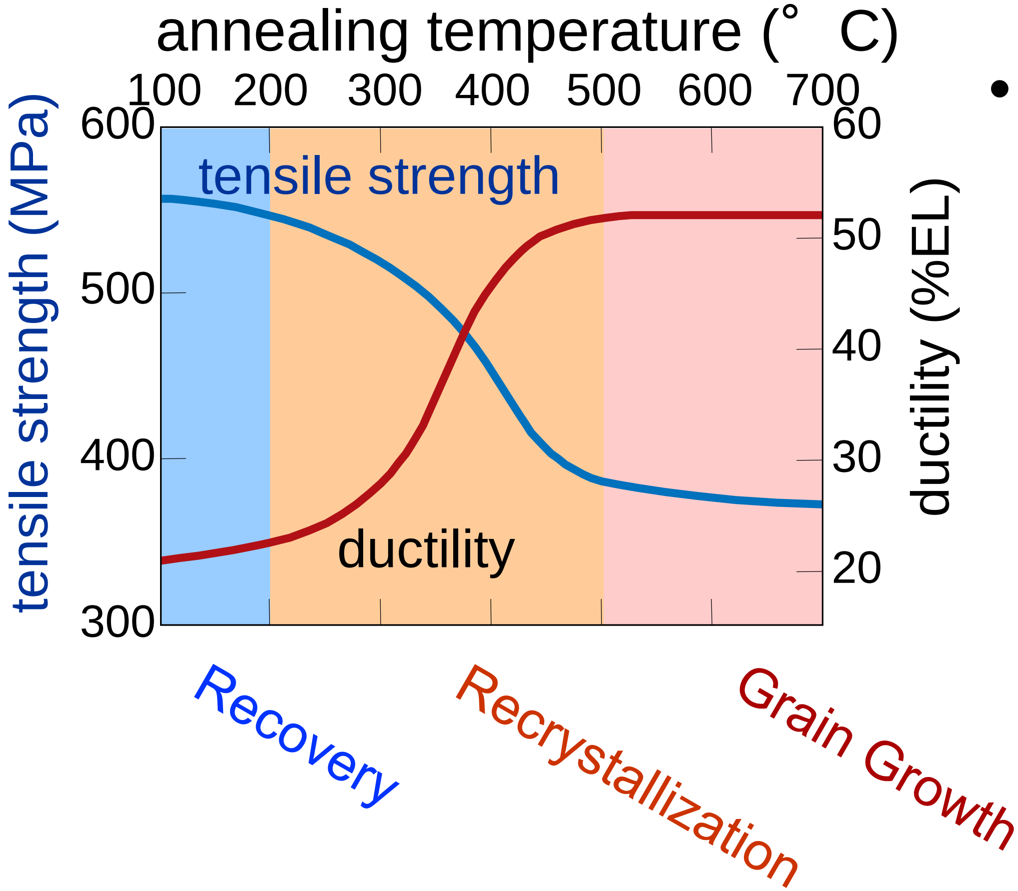
- Hurdles
  - ✓ *Cost for Development*
  - ✓ *Quantification*
  - ✓ *Artifacts*

Grain growth of Mg alloy
: 8X real time



# 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

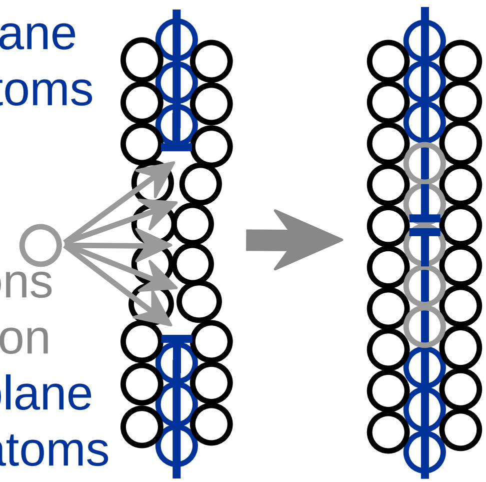
Fig. 9.22, *Callister & Rethwisch 9e.*
(Adapted from G. Sachs and K. R. Van Horn, *Practical Metallurgy, Applied Metallurgy and the Industrial Processing of Ferrous and Nonferrous Metals and Alloys*, 1940. Reproduced by permission of ASM International, Materials Park, OH.)

# Three Stages During Heat Treatment:
# 1. Recovery

Reduction of dislocation density by annihilation.

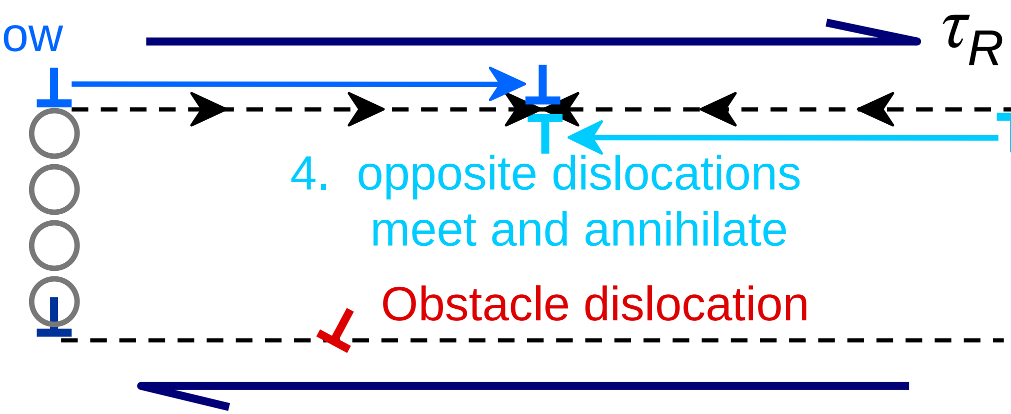
- Scenario 1

  Results from diffusion



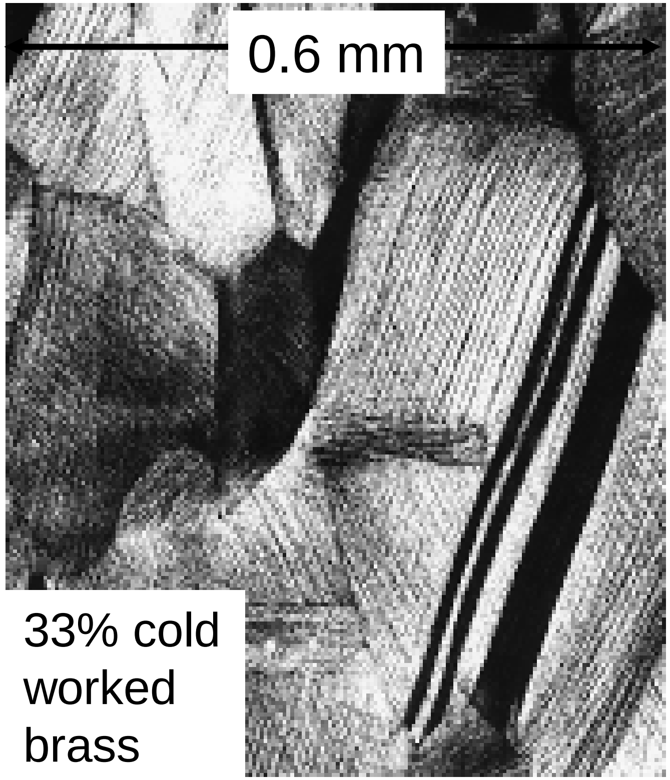

- Scenario 2

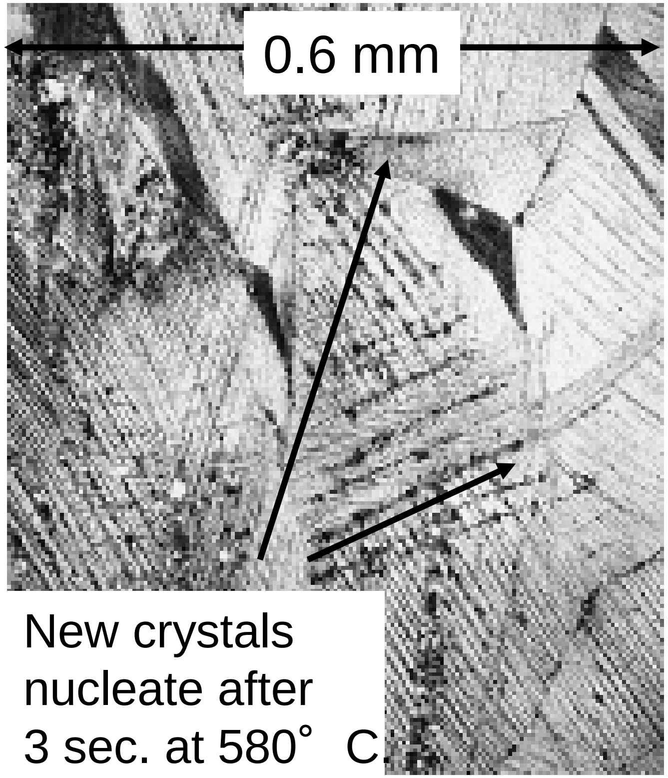
  3. “Climbed” disl. can now move on new slip plane
  2. grey atoms leave by vacancy diffusion allowing disl. to “climb”
  1. dislocation blocked; can’t move to the right



# 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.

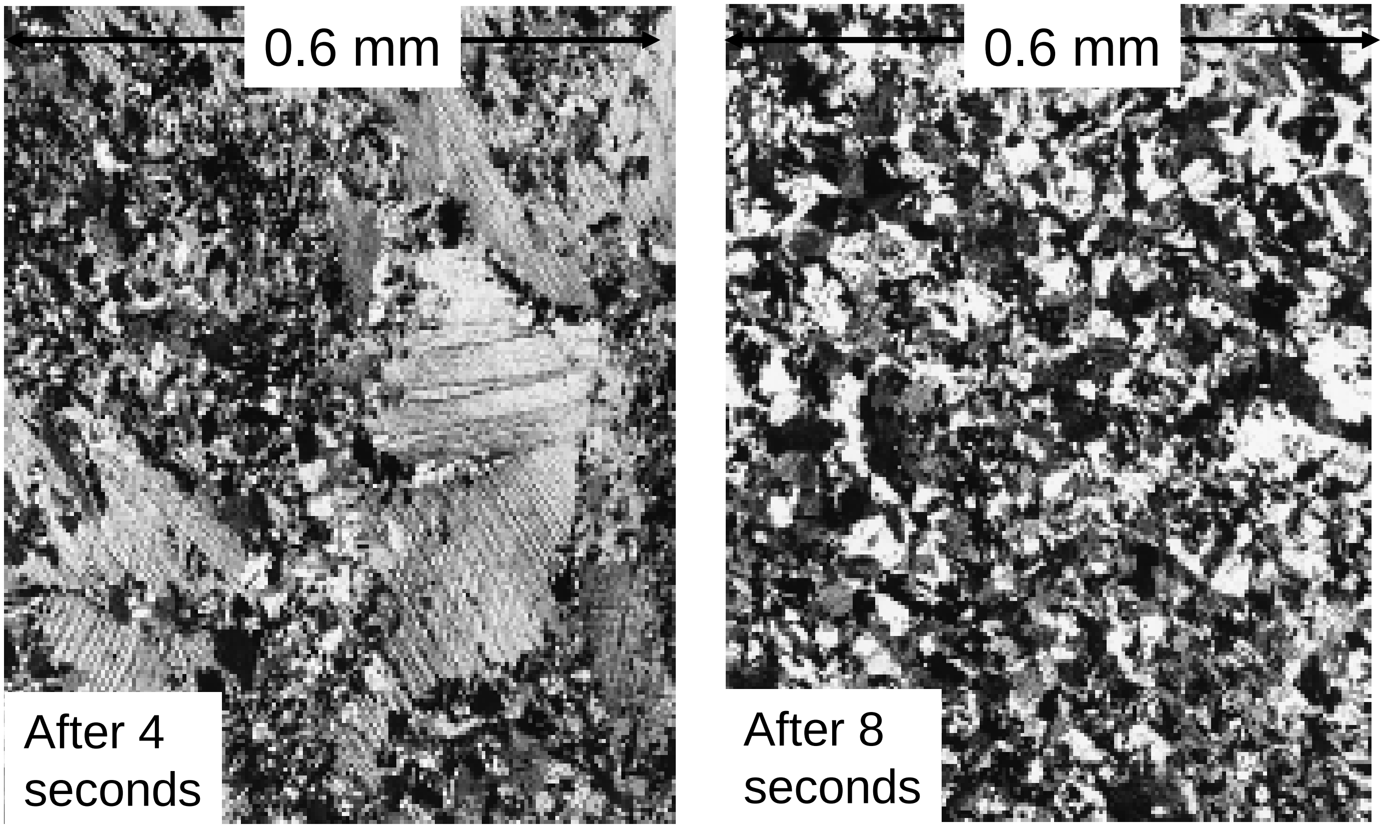



Adapted from Fig. 9.21 (a),(b), *Callister & Rethwisch 9e*. (Photomicrographs courtesy of J.E. Burke, General Electric Company.)

# As Recrystallization Continues…

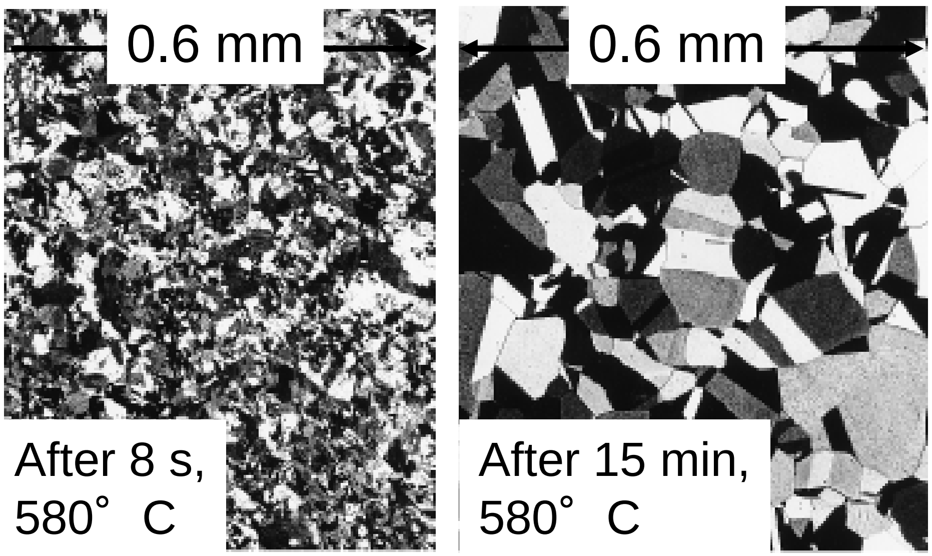
- All cold-worked grains are eventually consumed/replaced.




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:

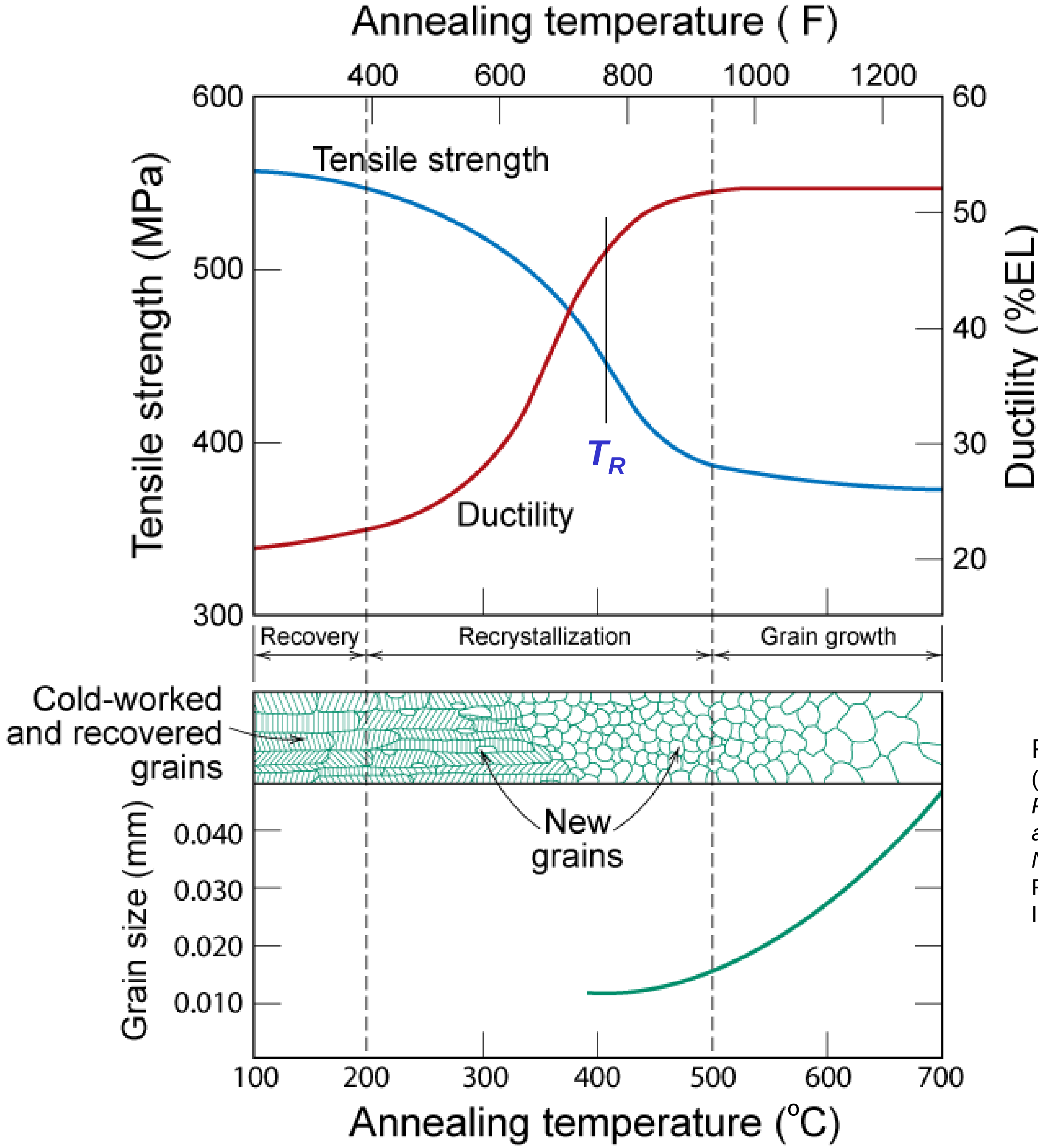
exponent typ. ~ 2

grain diam. at time t.

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

coefficient dependent on material and *T*.

elapsed time

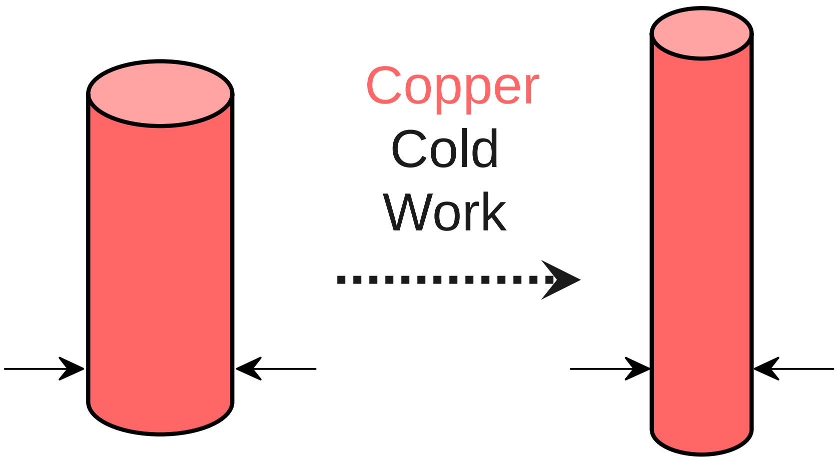



$T_R$ = recrystallization temperature

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.)

# 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

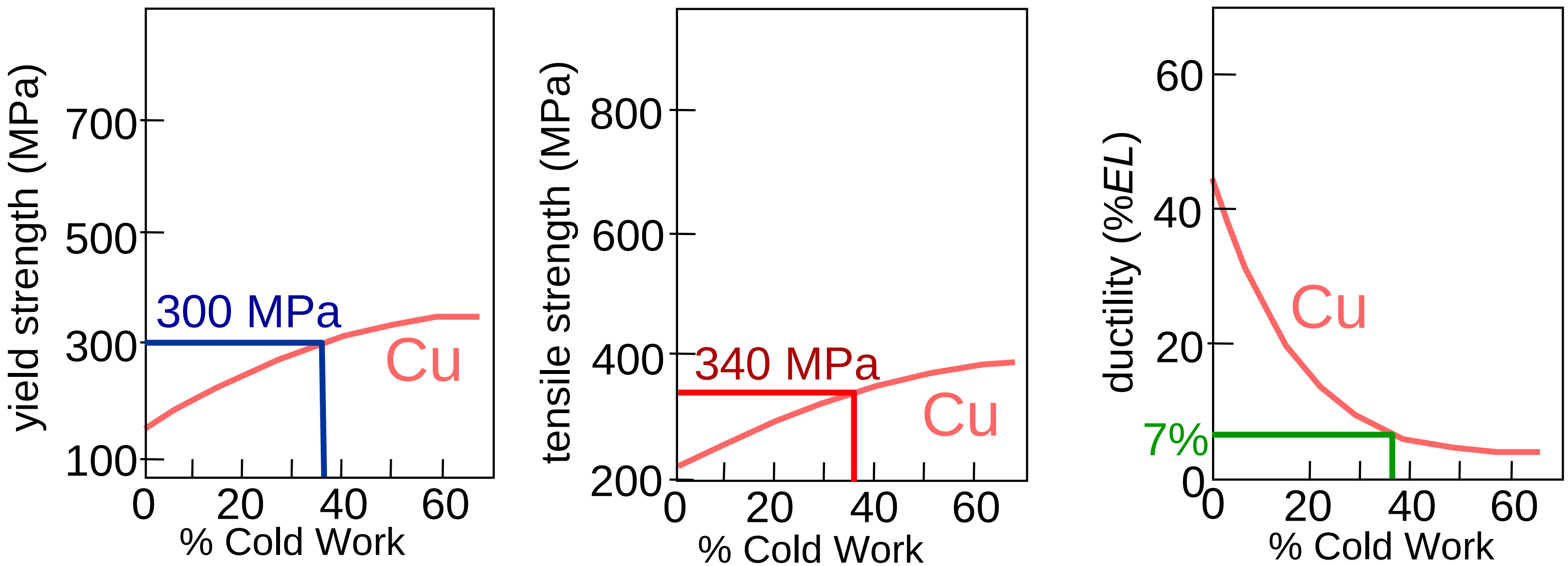
$$\%CW = \frac{\dfrac{\pi D_o^2}{4} - \dfrac{\pi D_d^2}{4}}{\dfrac{\pi D_o^2}{4}} \times 100$$

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

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

# Mechanical Property Alterations due to Cold Working

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




$\sigma_y$ = 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.]

# 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, $\boldsymbol{T_R}$ **depends on:**

**(1) %CW** -- $T_R$ decreases with increasing %CW

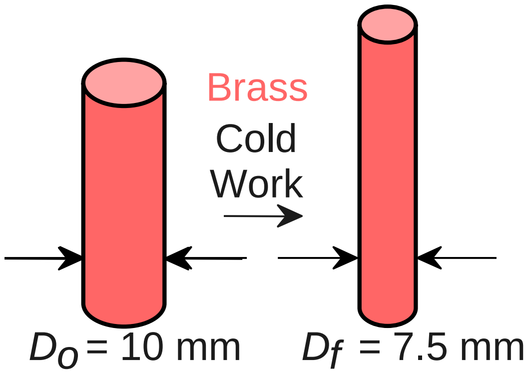
**(2) Purity of metal** -- $T_R$ decreases with increasing purity

# 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

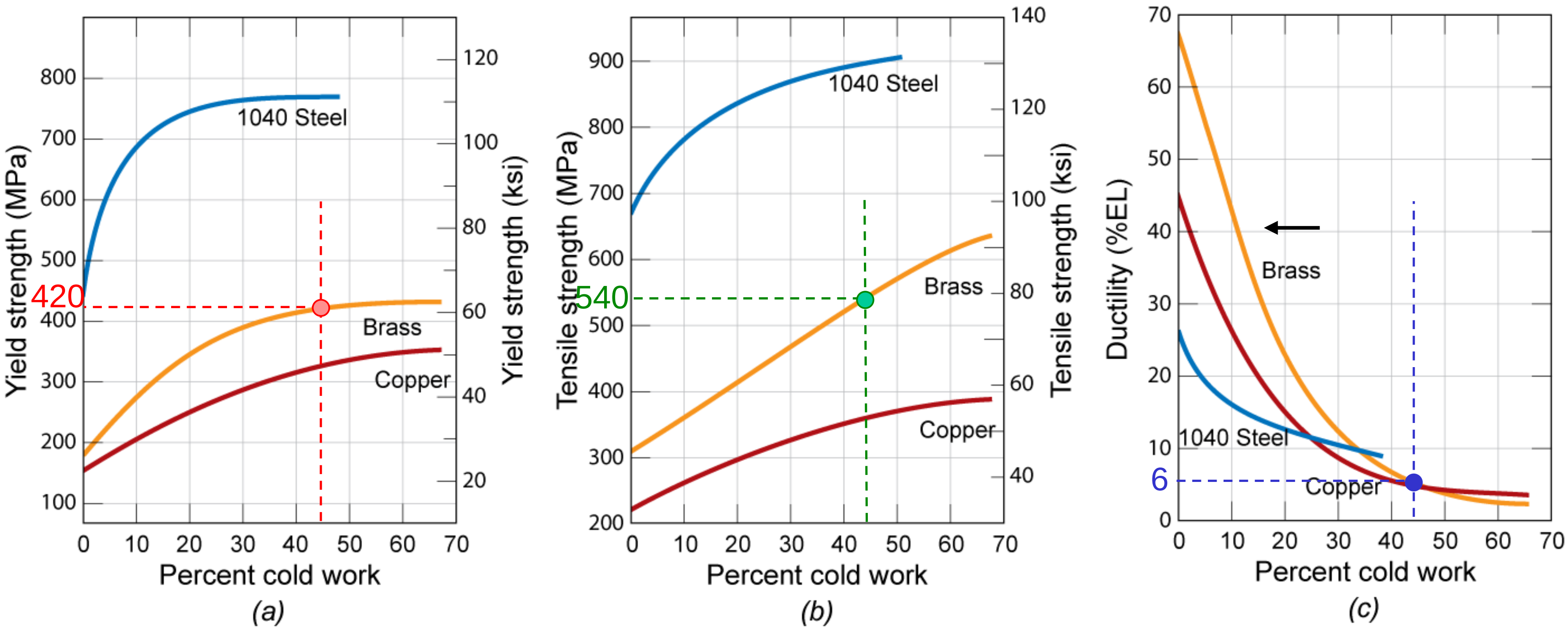
What are the consequences of directly drawing to the final diameter?




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

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

# Diameter Reduction Procedure – Solution (Cont.)




- For %CW = 43.8%
  - $\sigma_y$ = 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 – Solution (cont.)

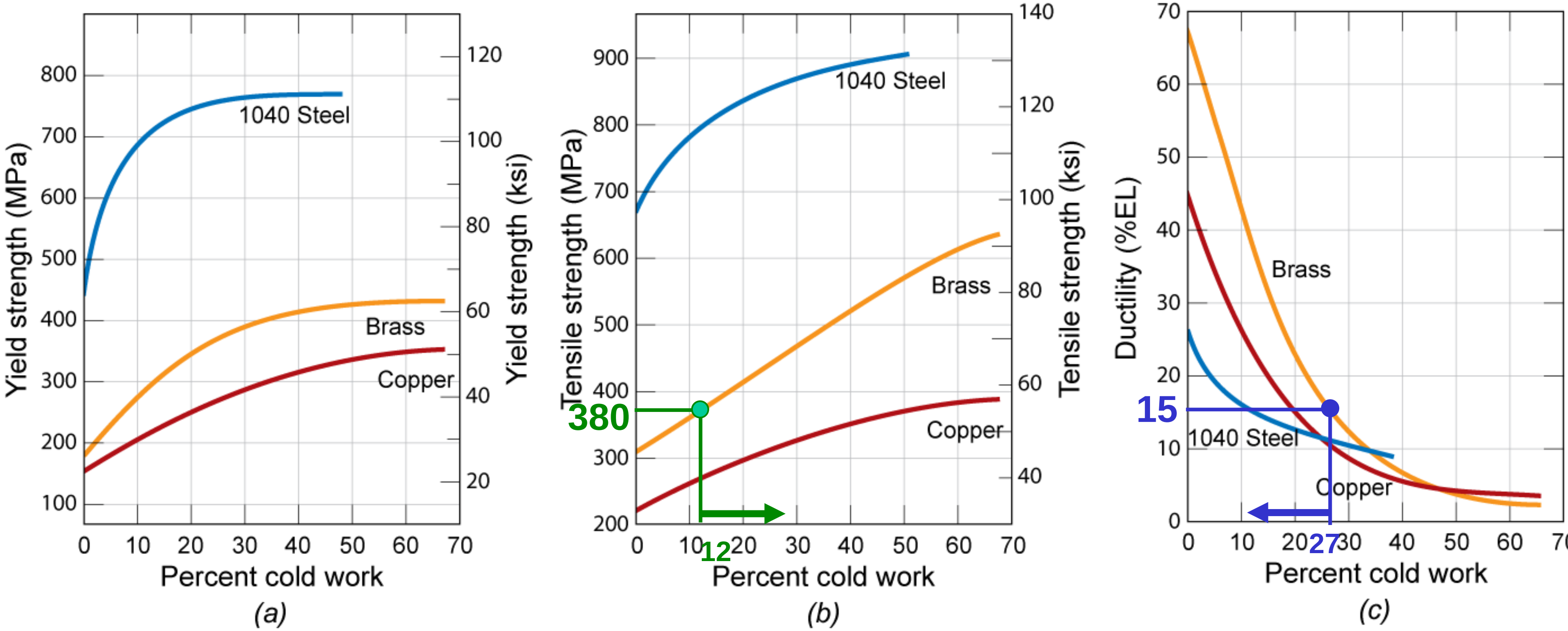



Fig. 9.19, *Callister & Rethwisch 9e.*
[Adapted from *Metals Handbook: Properties and Selection: Irons and Steels*, Vol. 1, 9th edition, B. Bardes (Editor), 1978; and *Metals Handbook: Properties and Selection: Nonferrous Alloys and Pure Metals*, Vol. 2, 9th edition, H. Baker (Managing Editor), 1979.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

For *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

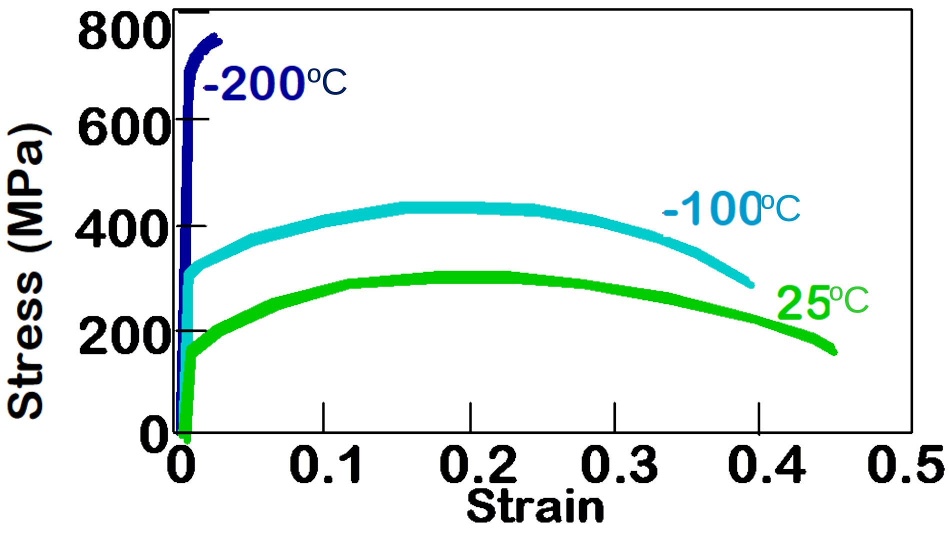
$$\%CW_2 = \left(1 - \left(\frac{7.5}{8.49}\right)^2\right) x\ 100 = 20 \quad \overset{\text{Fig 7.19}}{\Longrightarrow}$$

$$\boxed{\begin{array}{l} \sigma_y = 340\ \text{MPa} \\ TS = 400\ \text{MPa} \\ \%EL = 24 \end{array}}$$

Therefore, all criteria satisfied

# σ-ε Behavior vs Temperature

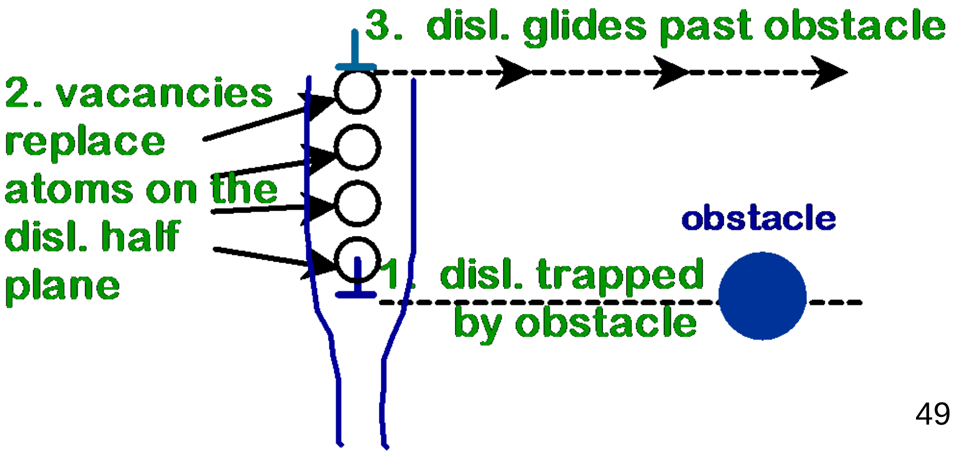
- Results for polycrystalline iron (BCC)




- $\sigma_y$ and TS *decrease* with increasing test temperature
- %EL *increases* with increasing test temperature
- Why? Vacancies

  help dislocations

  past obstacles



# Cold Working vs. Hot Working

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

# Summary II

- Two primary methods of deformation in metals are **Slip** **and** **Twinning**.
- **Slip** occurs in close-packed direction (Slip direction) on highest-density planes (Slip plane) : **Slip system = Slip plane + Slip direction**

$\tau_R = \sigma \cos\lambda \cos\phi$ : $\underline{\tau_R(\max) = \tau_{CRSS}}$ ⇒ $\tau_R > \tau_{CRSS}$

- Importance of **twinning ~ crystallographic reorientations**

  → Additional slip process can take place

- **Strength** is increased by <u>making dislocation motion difficult</u>.
- Strength of metals may be increased by:

  -- decreasing grain size

  -- solid solution strengthening

  -- precipitate hardening

  -- cold working

**Four Strategies for Strengthening**

- A **cold-worked metal** that is **heat treated** may experience **recovery**, **recrystallization**, and **grain growth** – its properties will be altered.