2020 Fall

Introduction to Materials Science and Engineering

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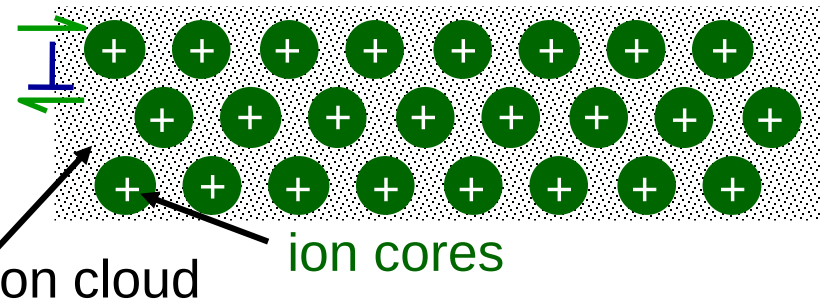
I. Dislocation motion in different material classes

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

  Dislocation motion easiest

  - non-directional bonding

  - close-packed directions for slip



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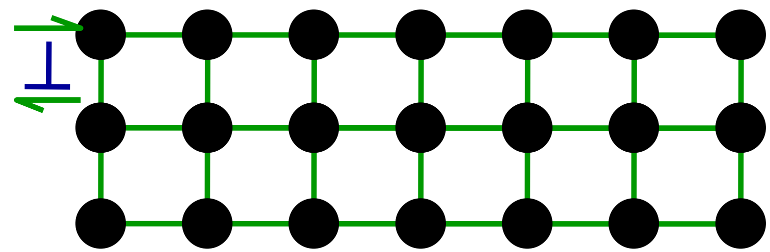
- Covalent Ceramics

  (Si, diamond): Motion difficult

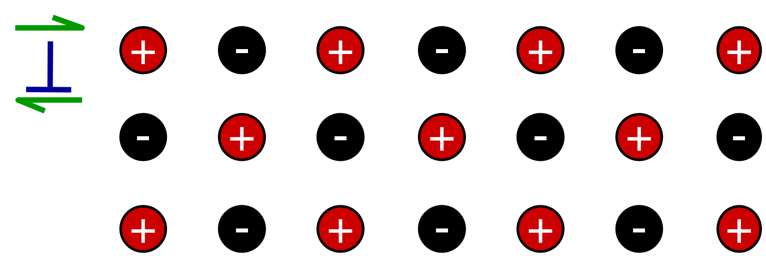
  - directional (angular) bonding



- 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 ⟨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

Quite ductile (FCC, BCC)

Quite brittle (HCP)

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

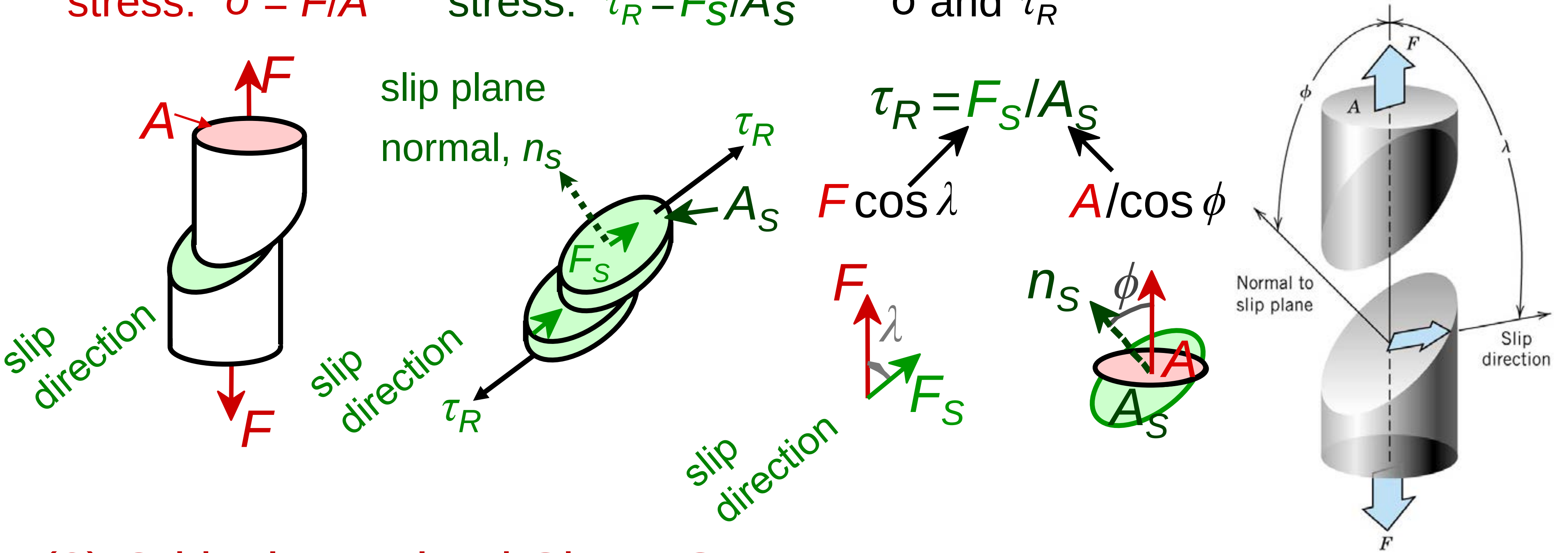
III. Stress → Dislocation Motion

- Crystals slip due to a (1) resolved shear stress, τ_R
- 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 τ_R



(2) Critical Resolved Shear Stress, τ_{CRSS}

- Condition for dislocation motion: $\tau_R > \tau_{CRSS}$ ← typically 10^{-4} GPa to 10^{-2} GPa

Critical resolved shear stress

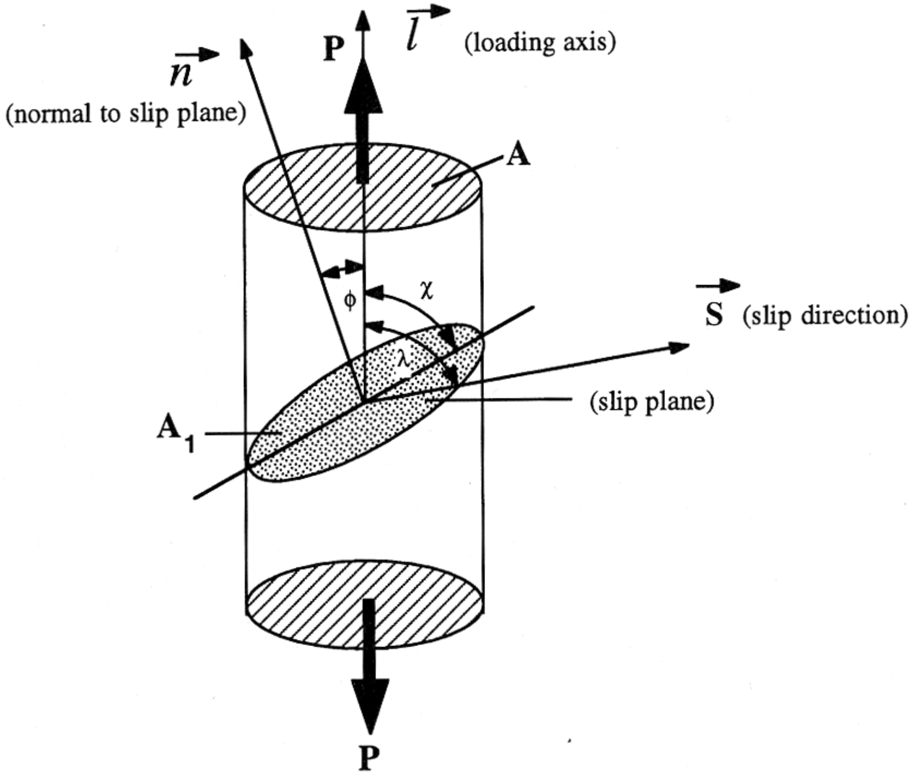


Figure 6.8 Relationship between stress axis and slip plane and direction.

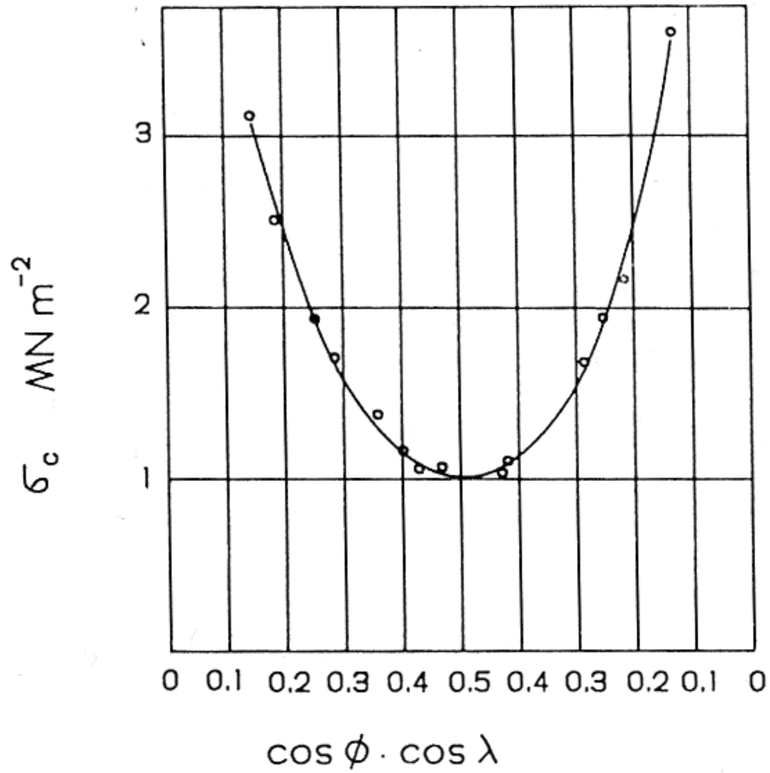


Fig. 10.2 The variation of σ_c with orientation

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

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

M=Schmid factor

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

d. Slip Motion in Polycrystals

- **Slip planes & directions (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.

→ Two slip systems operated for most of the grains

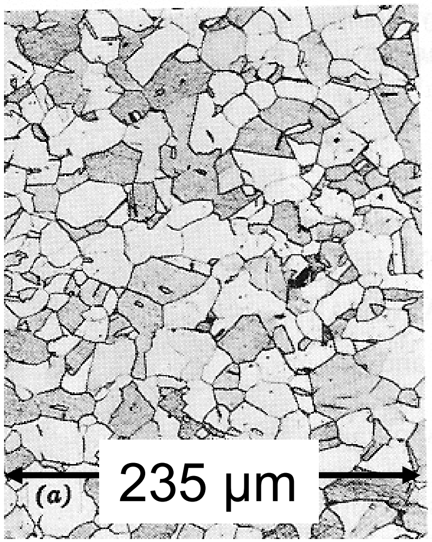
- Polycrystals stronger than single crystals – **grain boundaries are barriers to dislocation motion.**

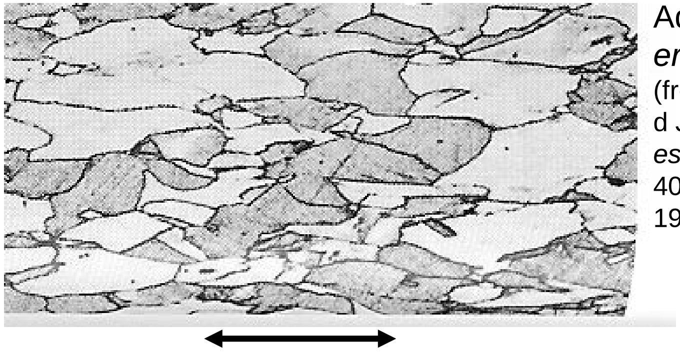
Adapted from Fig. 9.10, *Callister & Rethwisch 9e.* (Photomicrograph courtesy of C. Brady, National Bureau of Standards [now the National Institute of Standards and Technology, Gaithersburg, MD].)

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.

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 <u>the most common mechanism</u>. **Twinning** is less common but readily occurs under some circumstances.

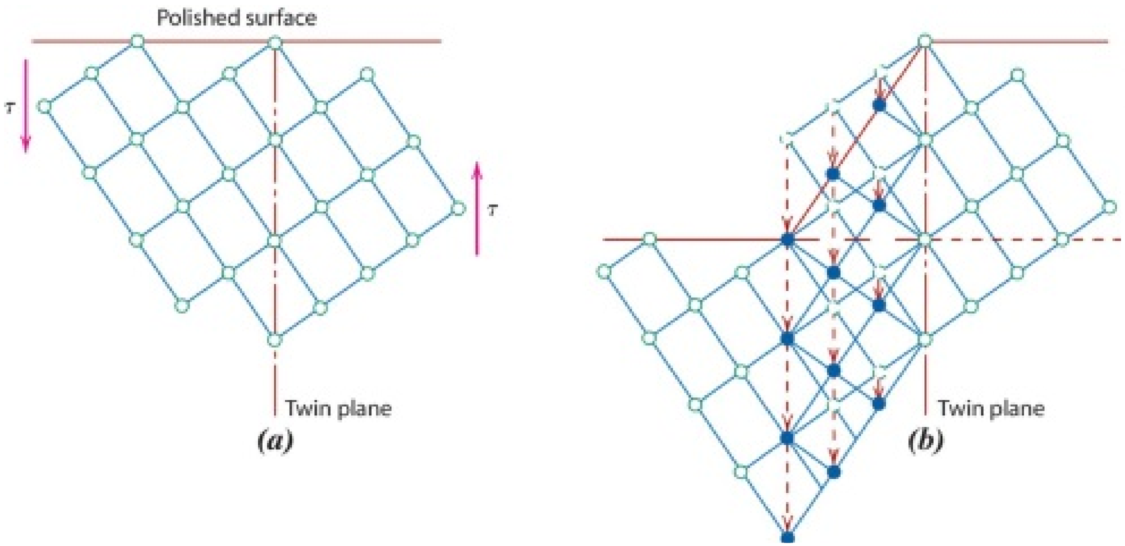


TABLE 5.2 Twinning Planes, Directions, and Shears

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 Zn: 0.139 Mg: 0.129 Ti: 0.139 Be: 0.199

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

Twining occurs <u>a definite crystallographic plane and in a specific direction</u> 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

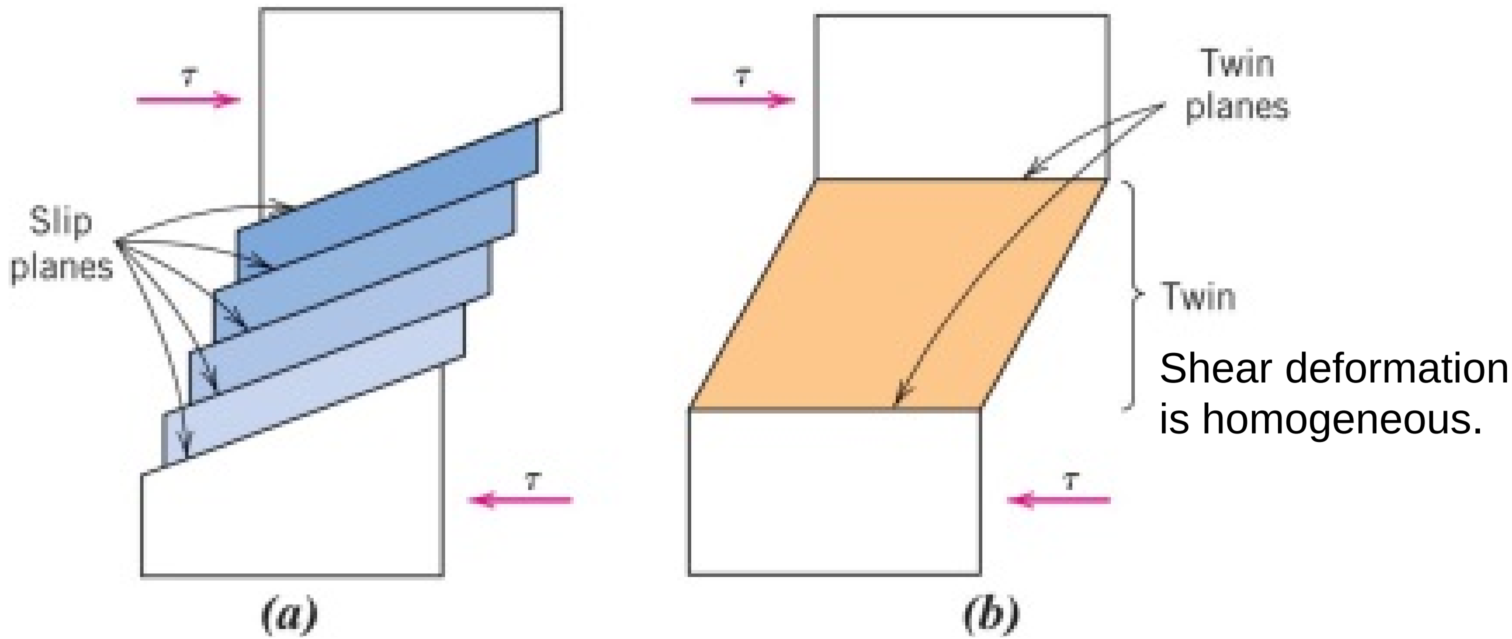


Figure 9.13 For a single crystal subjected to a shear stress τ, (a) **deformation by slip**; (b) **deformation by twinning**.

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

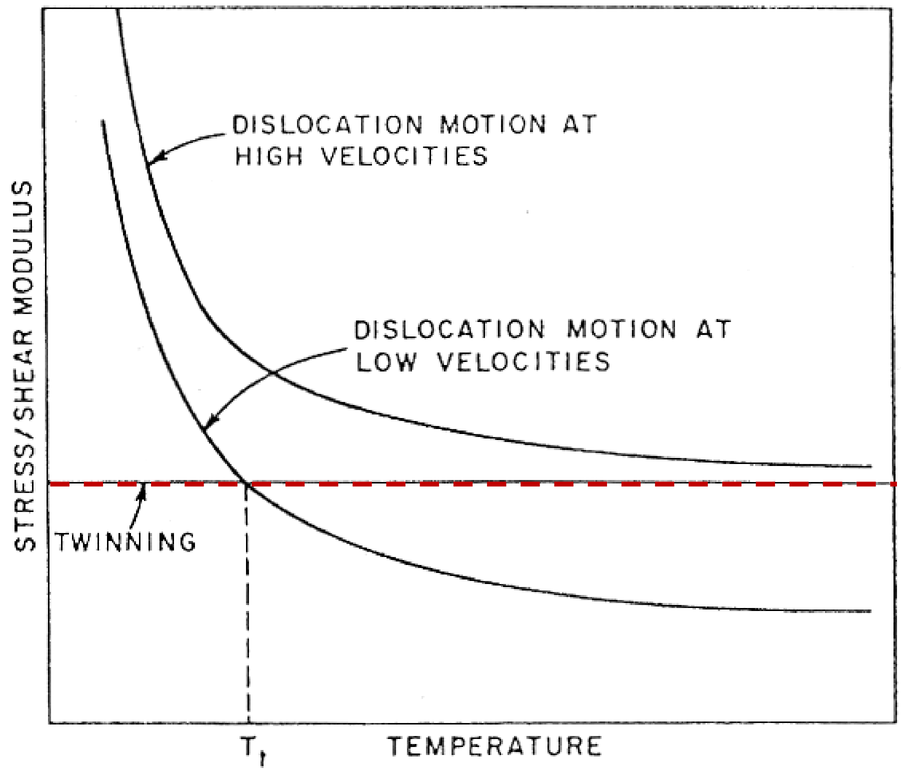


Figure 5.18 Effect of temperature on the stress required for twinning and slip (at low and high strain rates). (Courtesy of G. Thomas)

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,,,,)

I. 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.

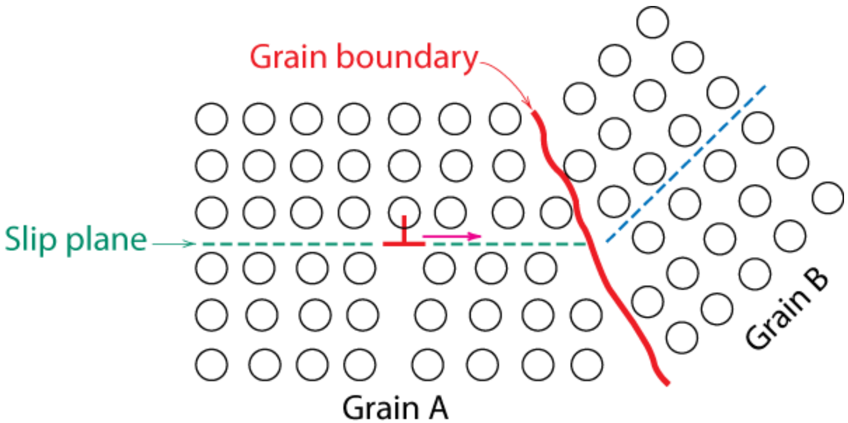


Fig. 9.14, *Callister & Rethwisch 9e.*
(From L. H. Van Vlack, *A Textbook of Materials Technology*, Addison-Wesley Publishing Co., 1973. Reproduced with the permission of the Estate of Lawrence H. Van Vlack.)

- **Hall-Petch Equation:**

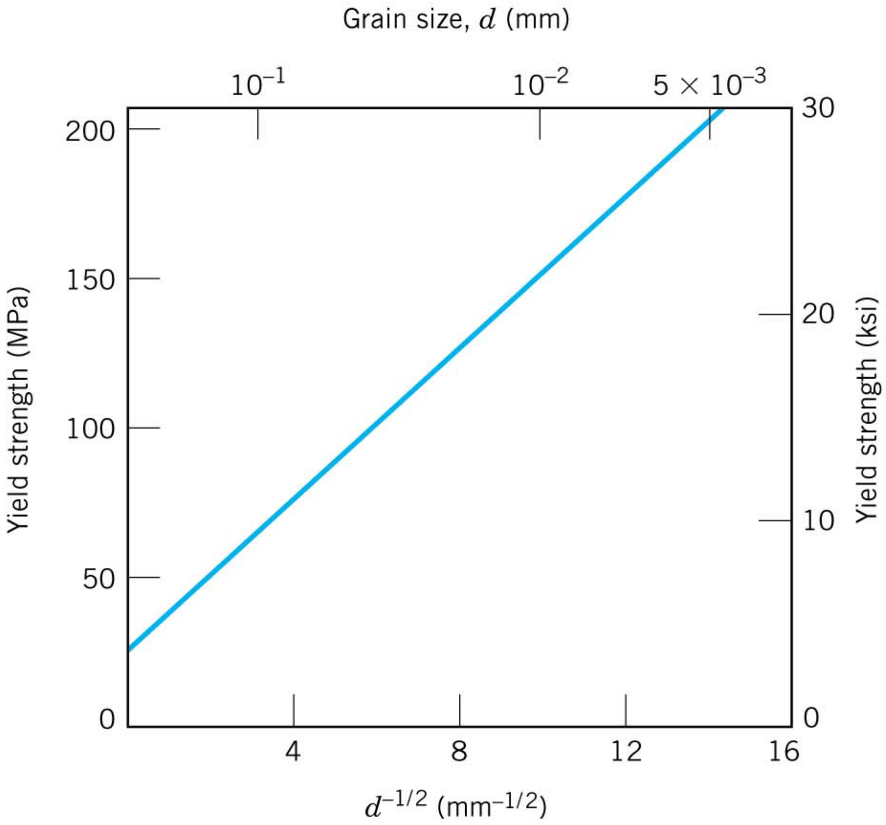
$$\sigma_{yield} = \sigma_0 + k_y d^{-1/2}$$

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

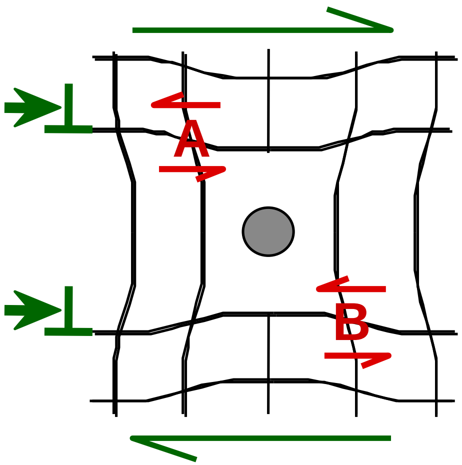
- Metals having small grains – relatively strong and tough at low temperatures

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

Four Strategies for Strengthening: 2: Form Solid Solutions

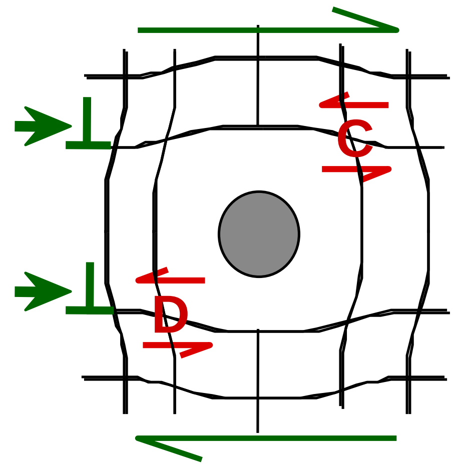
- **Impurity atoms** distort the lattice & generate lattice strains.
- These strains can act as barriers to dislocation motion.

- 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

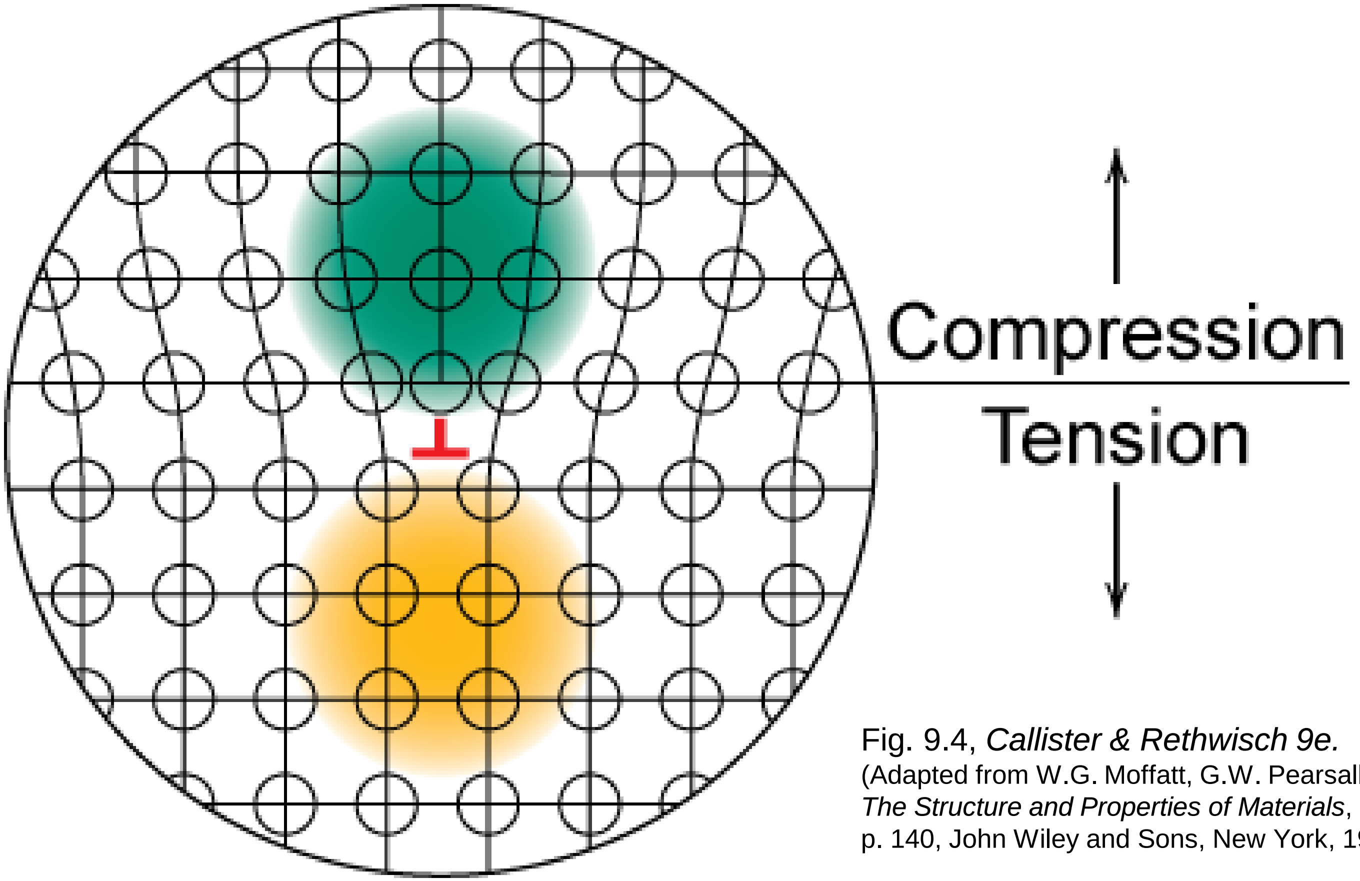


Fig. 9.4, *Callister & Rethwisch 9e.*
(Adapted from W.G. Moffatt, G.W. Pearsall, and J. Wulff, *The Structure and Properties of Materials*, Vol. I, *Structure*, p. 140, John Wiley and Sons, New York, 1964.)

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

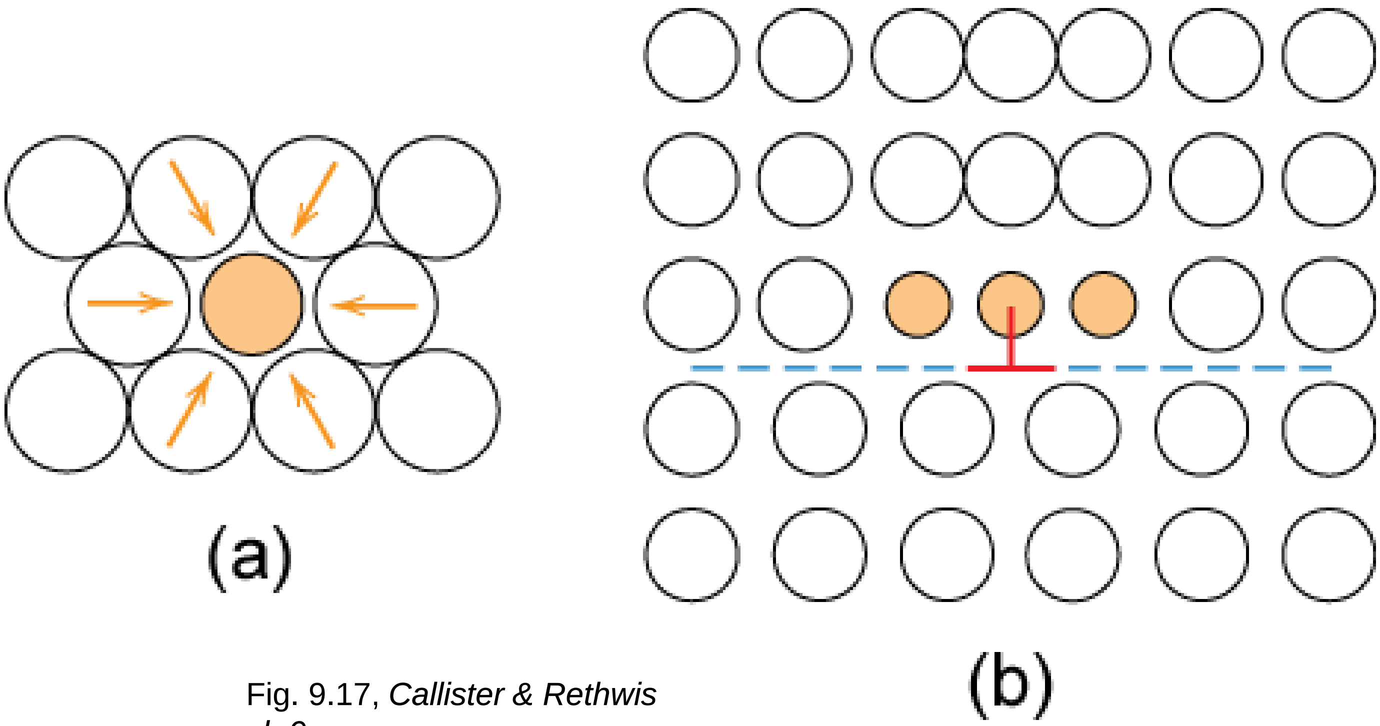
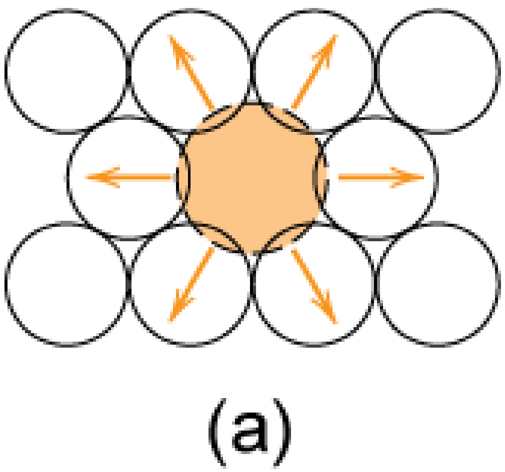


Fig. 9.17, *Callister & Rethwisch 9e.*

Strengthening by Solid Solution Alloying

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



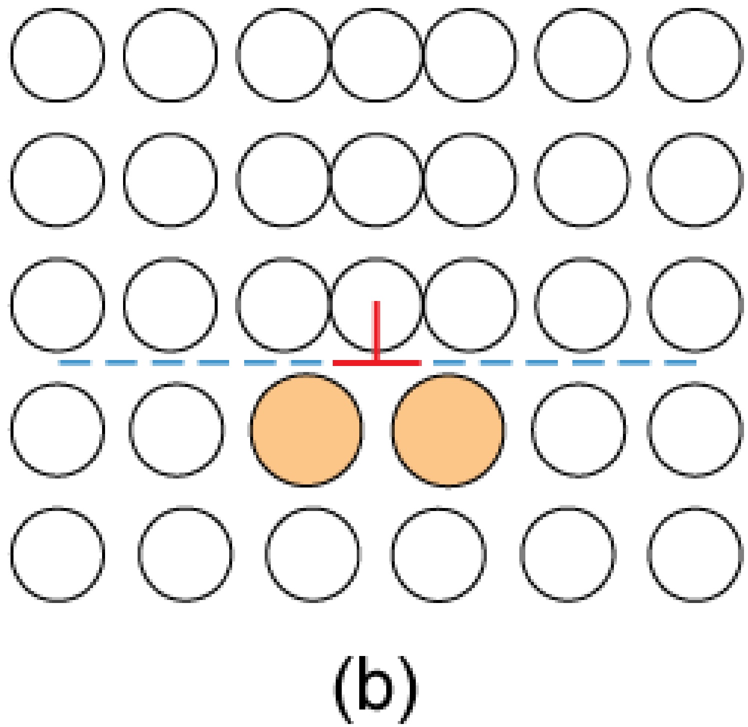
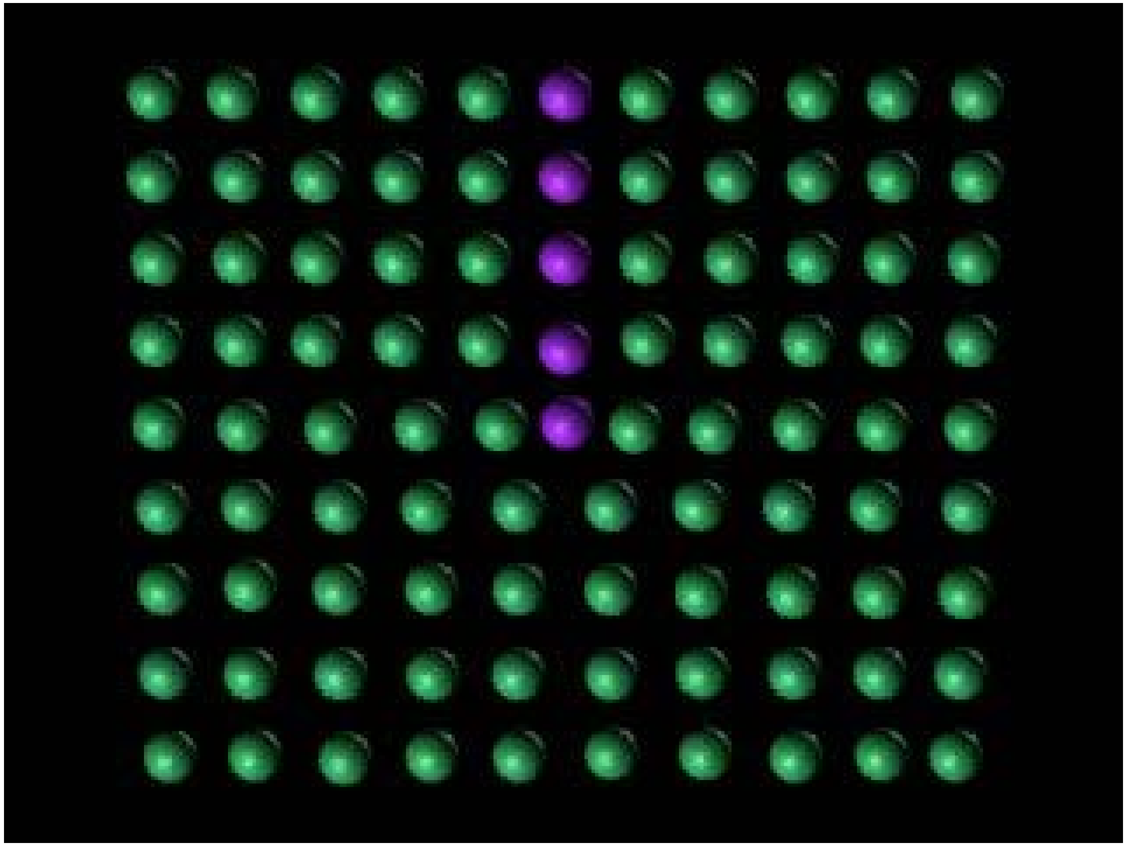


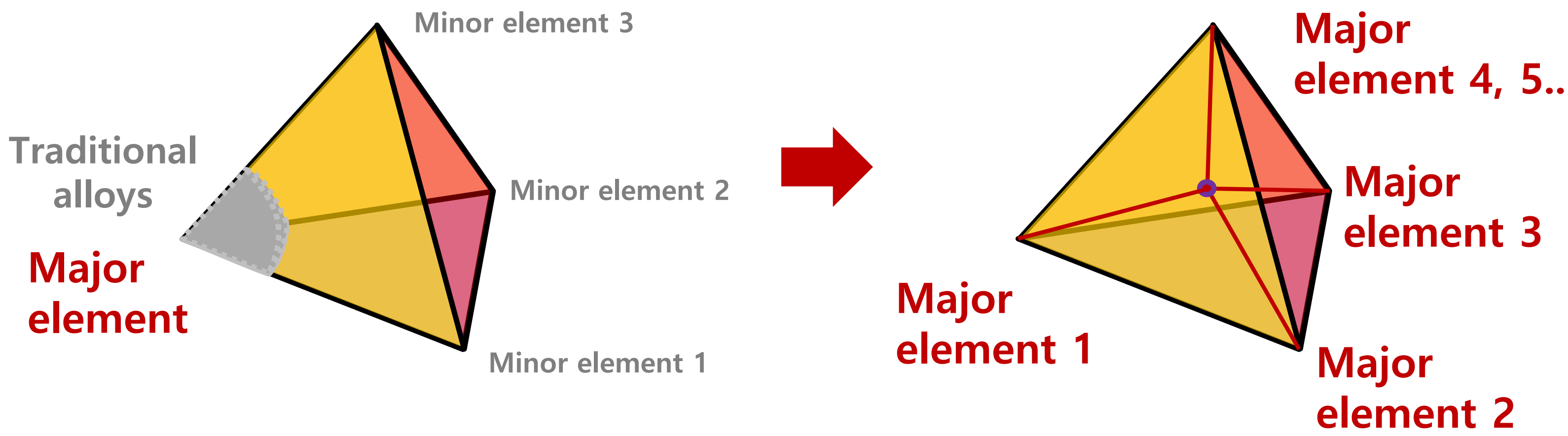
Fig. 9.18, *Callister & Rethwisch 9e.*

Dislocation motion



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

High Entropy alloy : Multi-principal Element-Single Phase Alloy

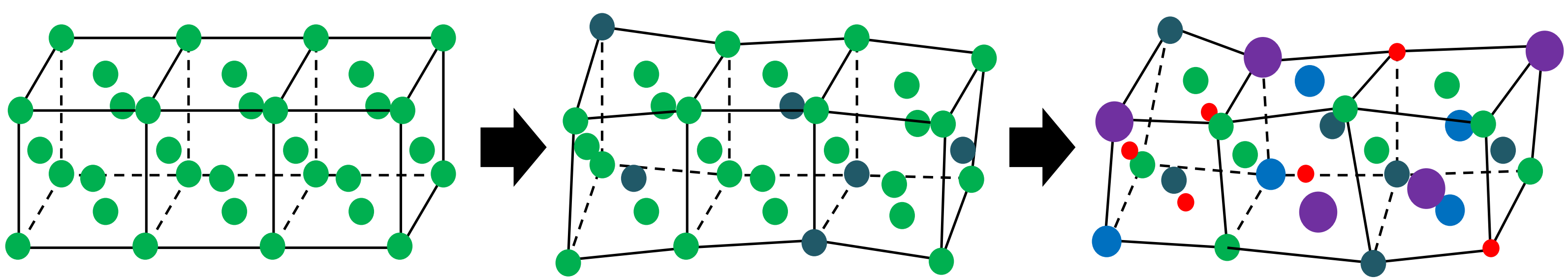


Conventional alloy system

Ex) 304 steel - $Fe_{74}Cr_{18}Ni_{8}$

High entropy alloy system

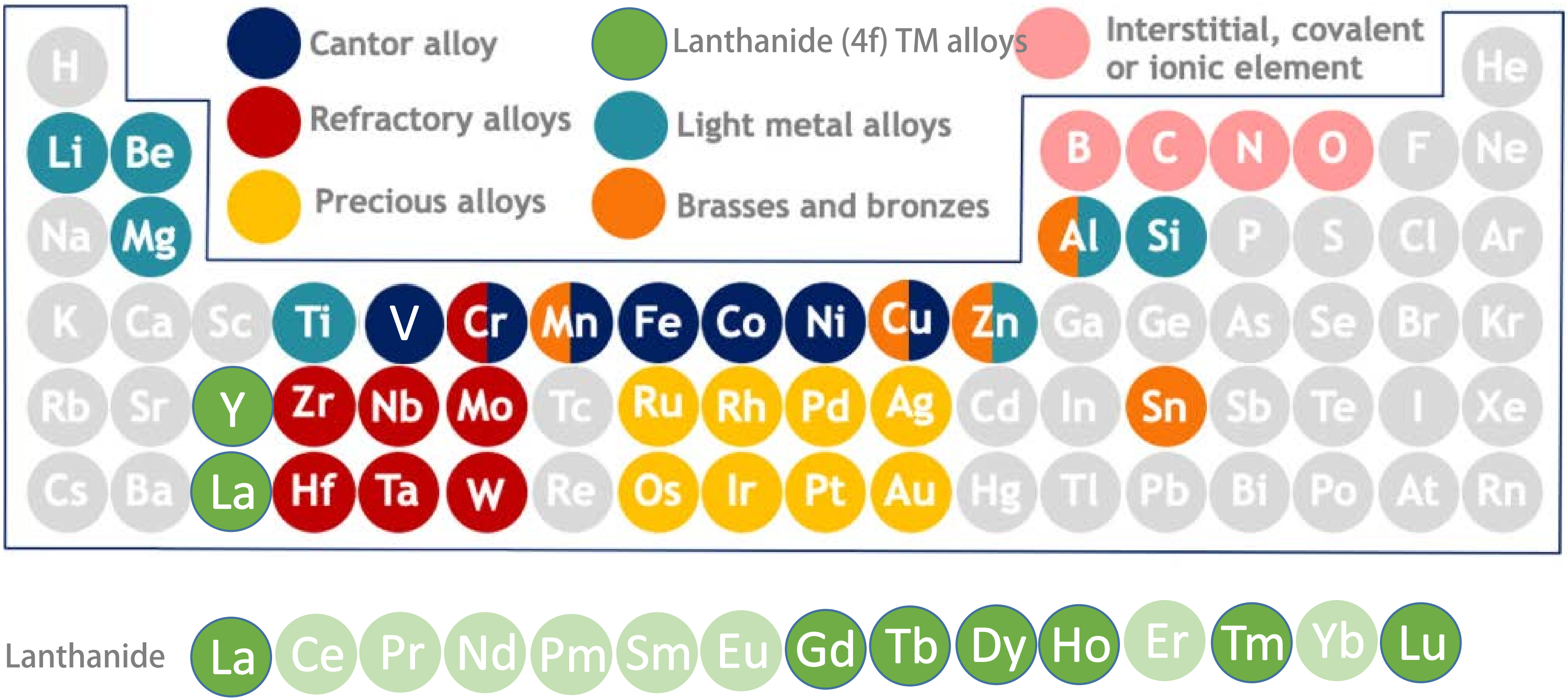
Ex) $Al_{20}Co_{20}Cr_{20}Fe_{20}Ni_{20}$



Pure metal　　Conventional alloy　　High entropy alloy

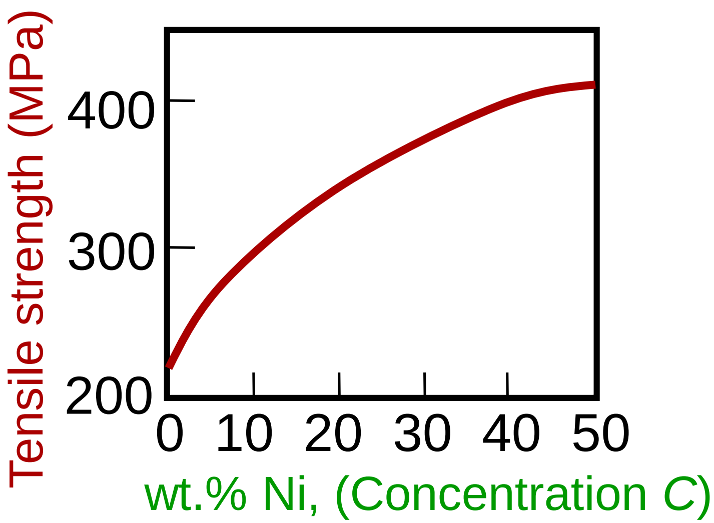
HEAs : Single-phase-disordered solid solutions stabilized by $S_{conf.}$

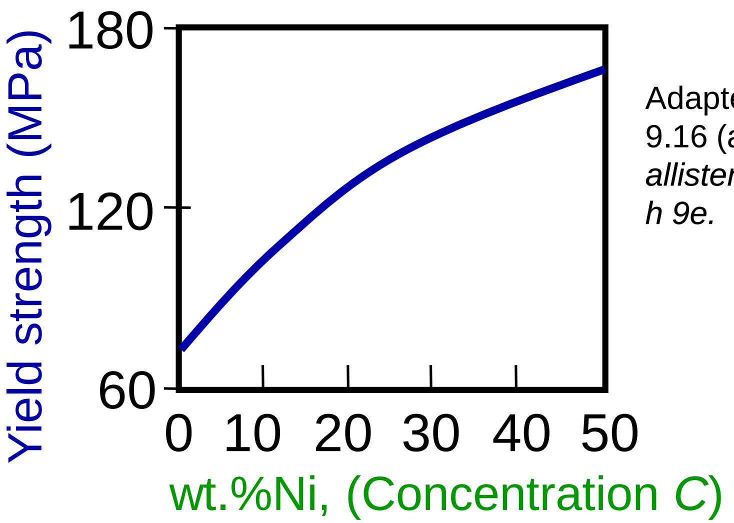
HEAs and CCAs : Six different families



Ex: Solid Solution Strengthening in Copper

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





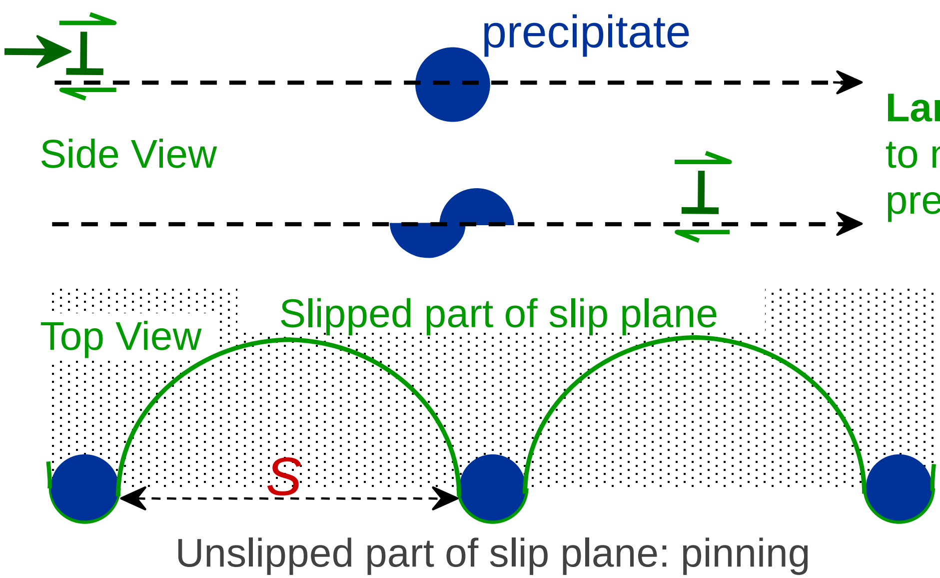
Adapted from Fig. 9.16 (a) and (b), *Callister & Rethwisch 9e.*

- 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*.

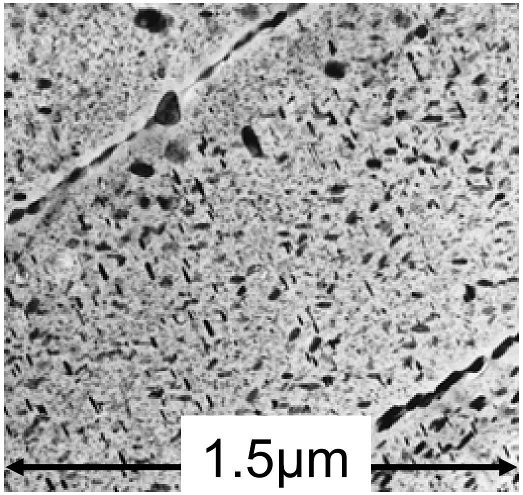
- Result: $\sigma_y \sim \frac{1}{S}$

Application:
Precipitation Strengthening

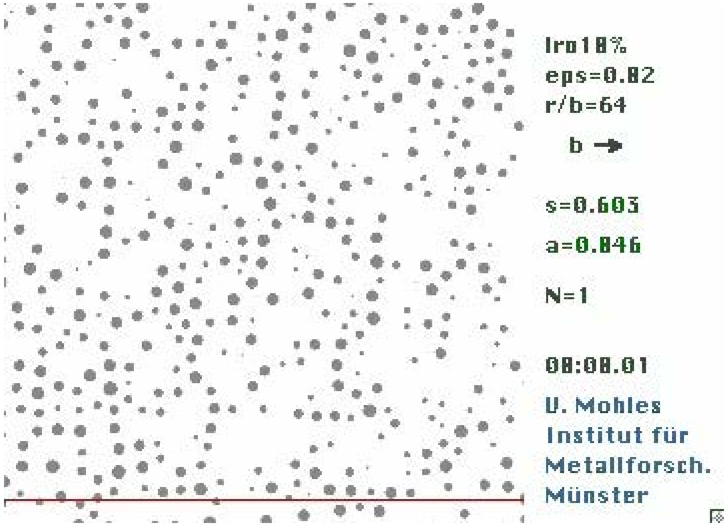
- Internal wing structure on Boeing 767

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



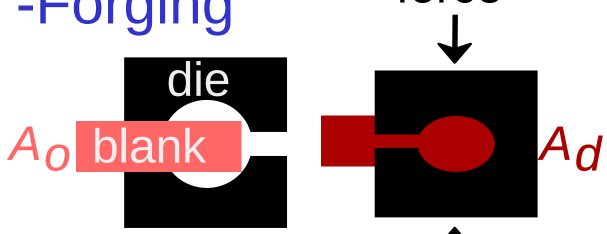
Adapted from Fig. 17.20, *Callister & Rethwisch 9e.*
(Courtesy of G.H. Narayanan and A .G. Miller, Boeing Commercial Airplane Company.)



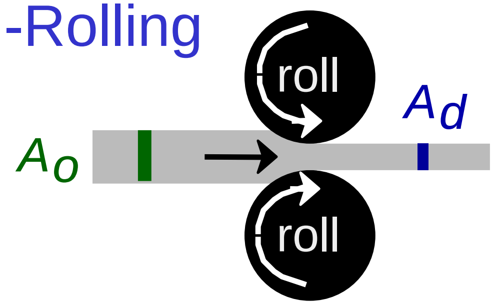
Four Strategies for Strengthening: 4: Cold Work (Strain Hardening)

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

-Forging

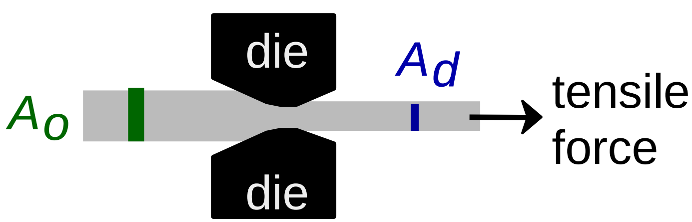


-Rolling

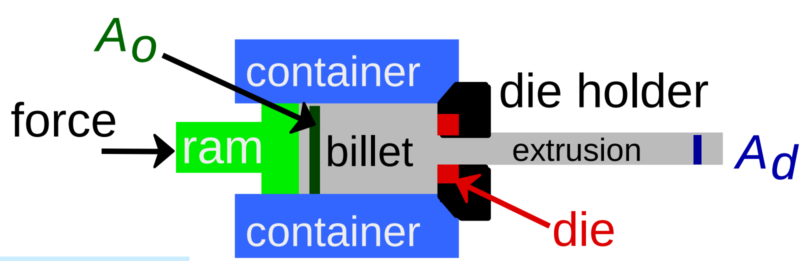


Adapted from Fig. 17.2, *Callister & Rethwis ch 9e.*

-Drawing



-Extrusion



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

Dislocation Structures Change During Cold Working

- Dislocation structure in Ti after cold working.

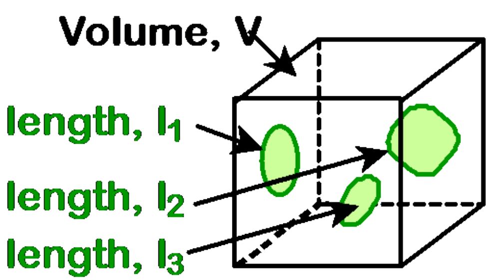
- **Dislocations entangle** with one another during cold work.
- Dislocation motion becomes **more difficult**.

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

Dislocation Density Increases During Cold Working

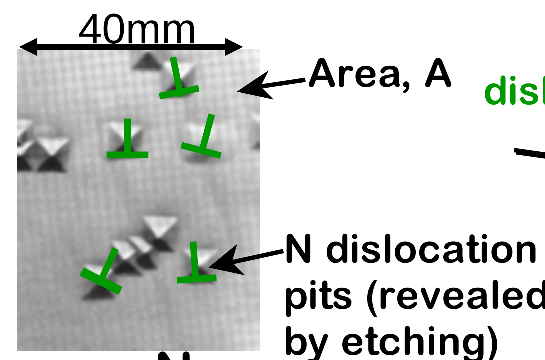
- Dislocation density (ρ_d) goes up:
  - Carefully grown single crystals: $\rho_d \sim 10^3$ mm/mm^3
  - Heavily deformed sample: $\rho_d \sim 10^{10}$ mm/mm^3
  - Annealed sample after severe deformation: $\rho_d \sim 10^6$ mm/mm^3

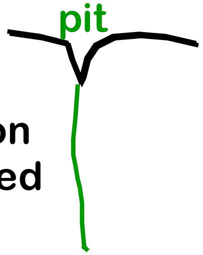
- Ways of measuring dislocation density:



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

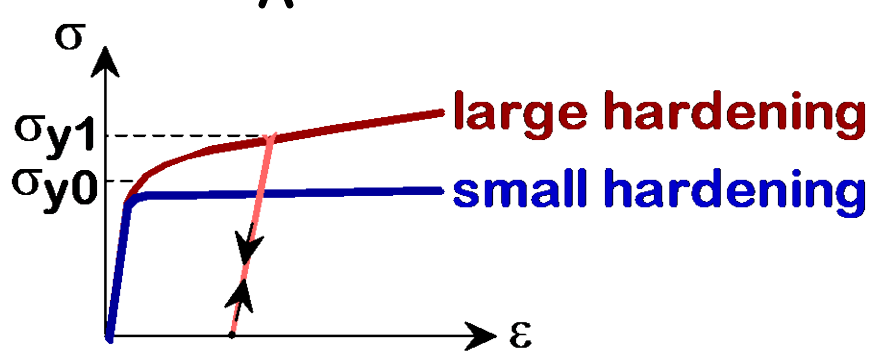
OR





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

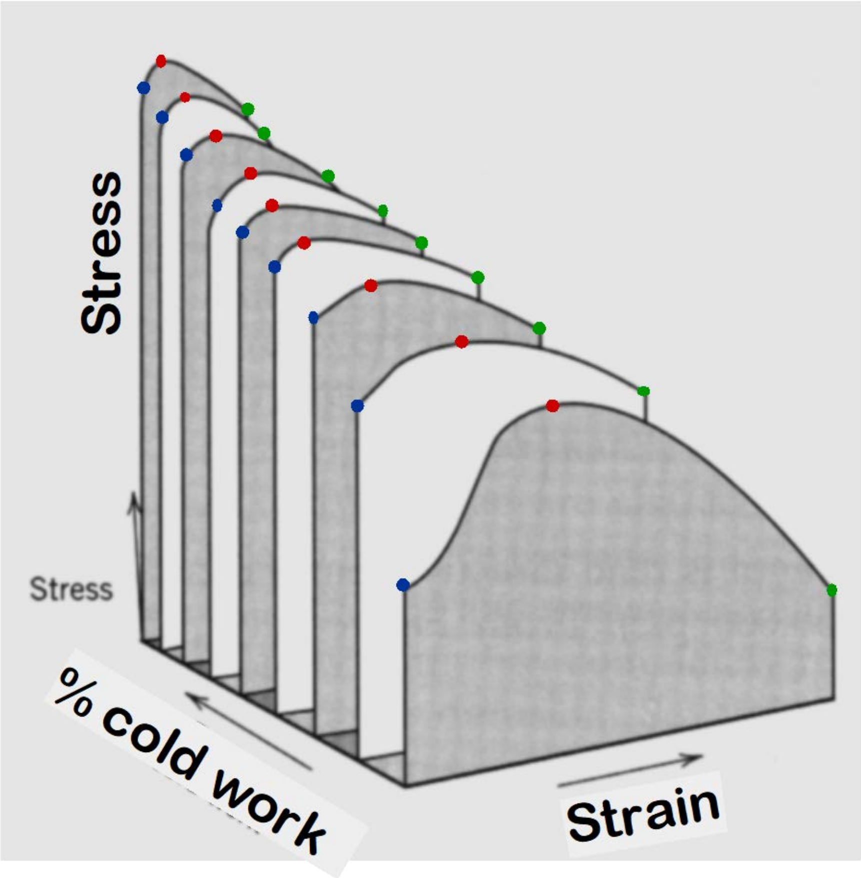
- Yield stress increases as ρ_d increases:



Impact of Cold Work

As cold work is increased

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



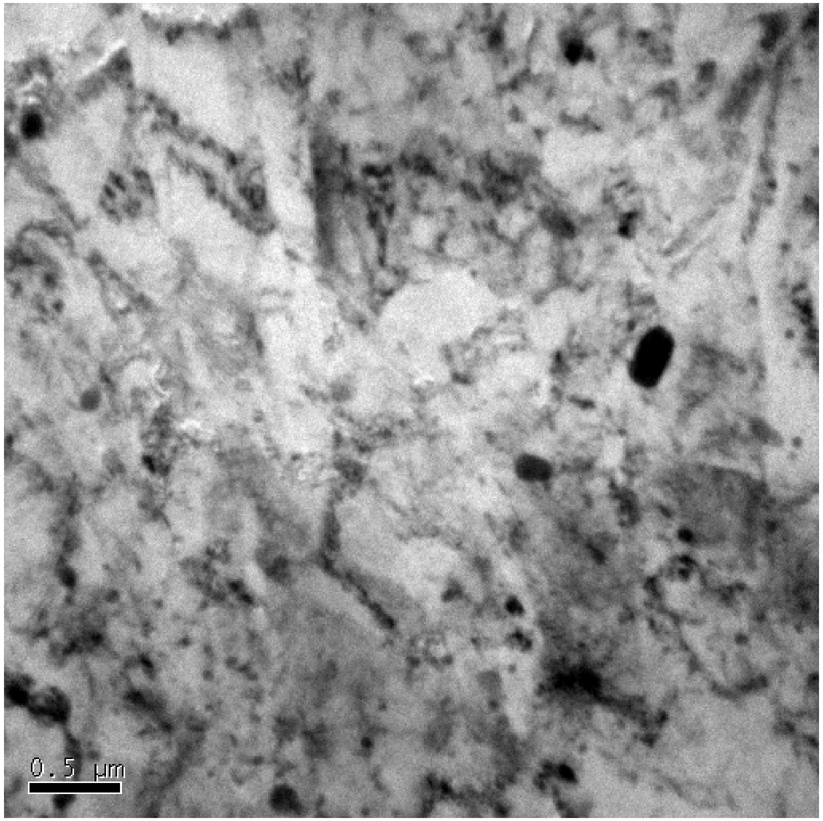
In-situ (실시간) observation of deformation in high-Mn steel

In-situ experiment

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

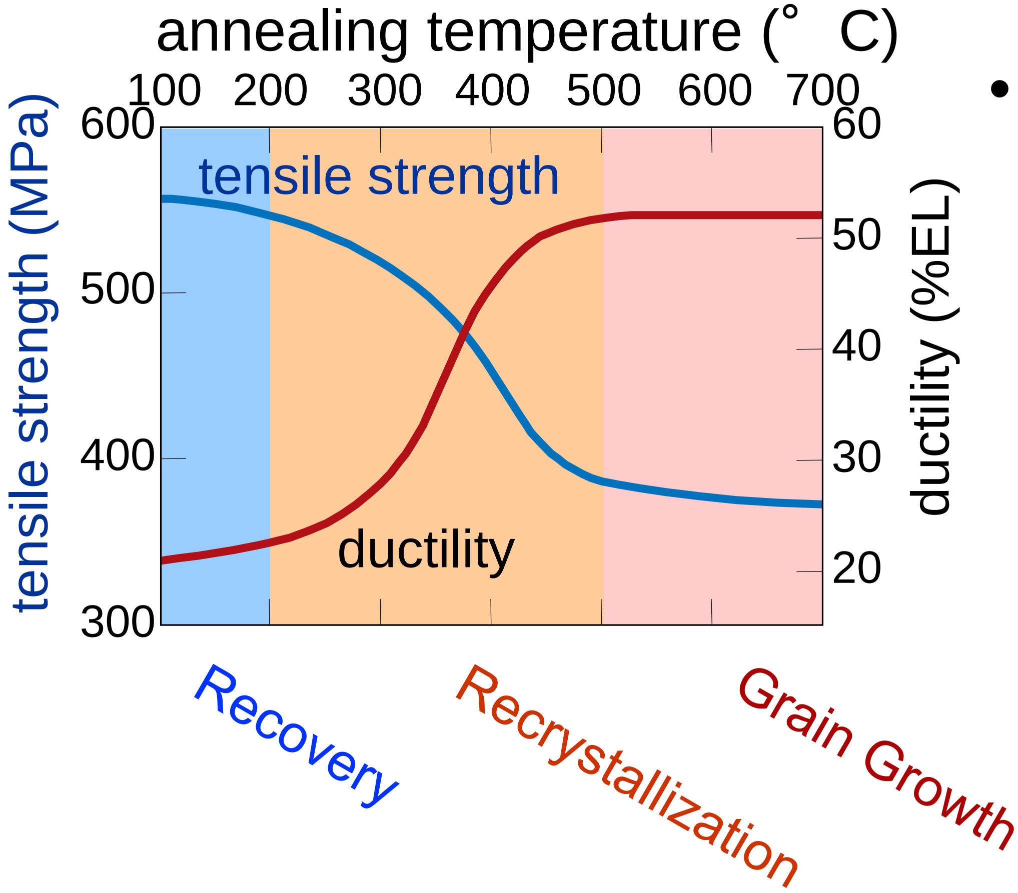
- **Hurdles**
  - *Cost for Development*
  - *Quantification*
  - *Artifacts*

Grain growth of Mg alloy
: 8X real time



II. 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

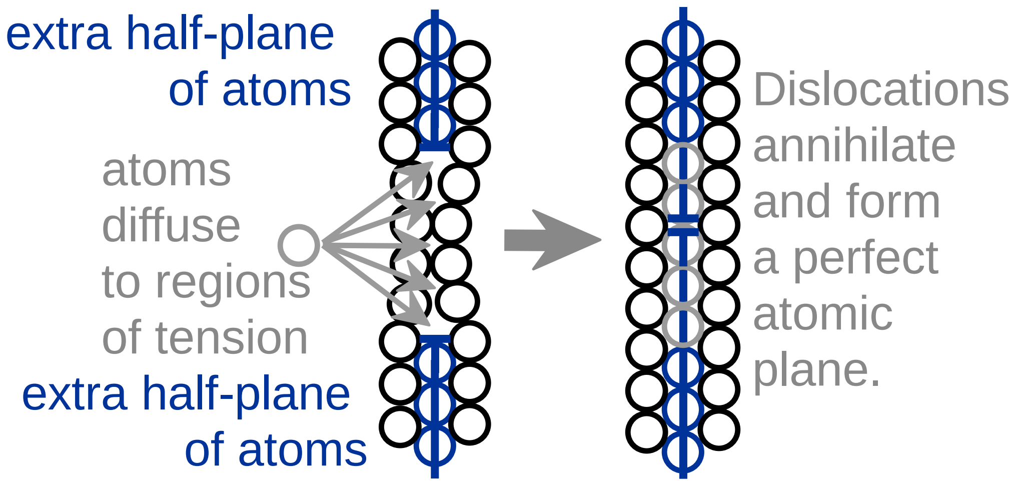
Fig. 9.22, *Callister & Rethwisch 9e.* (Adapted from G. Sachs and K. R. Van Horn, *Practical Metallurgy, Applied Metallurgy and the Industrial Processing of Ferrous and Nonferrous Metals and Alloys*, 1940. Reproduced by permission of ASM International, Materials Park, OH.)

Three Stages During Heat Treatment:
1. Recovery

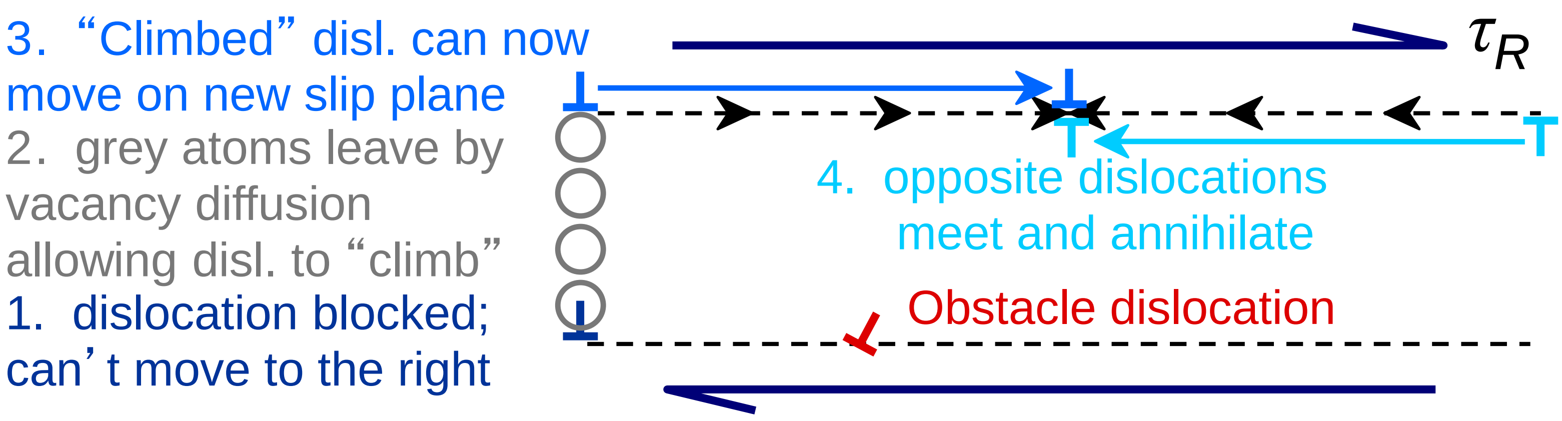
Reduction of dislocation density by annihilation.

- Scenario 1

  Results from diffusion



- Scenario 2



Lattice Strain Interactions Between Dislocations

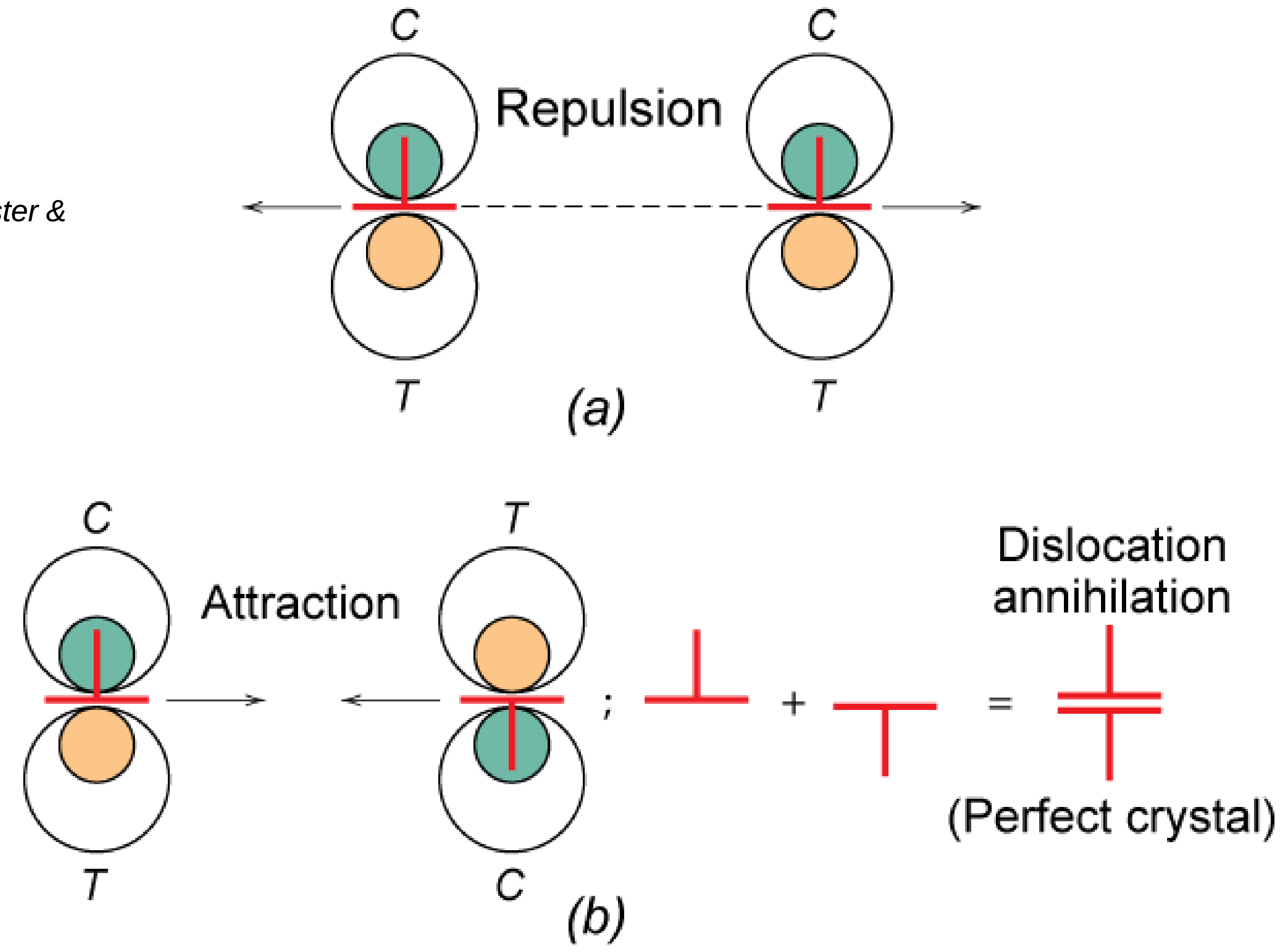
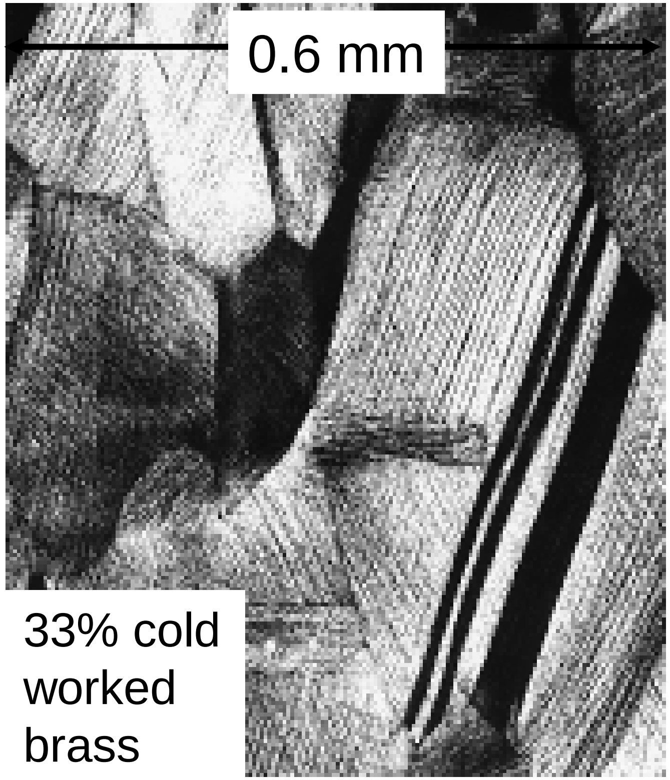
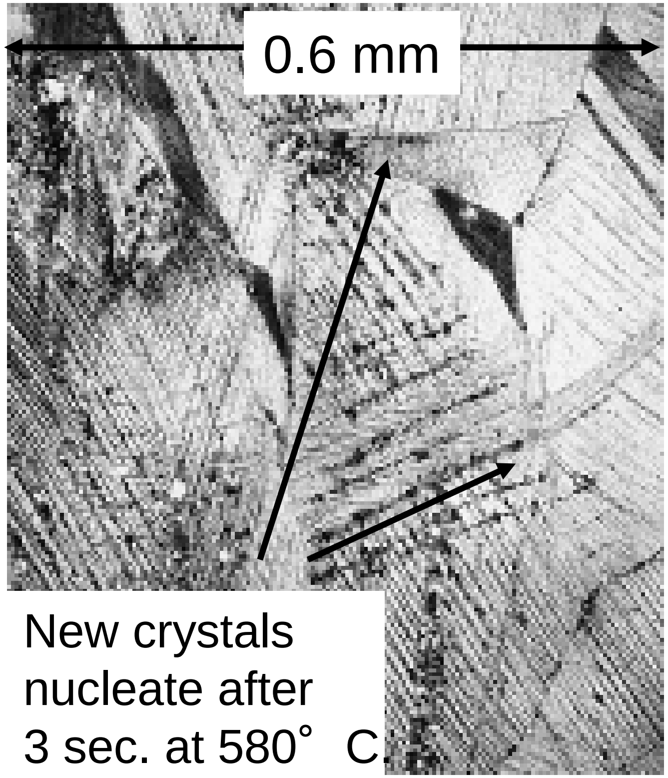


Fig. 9.5, *Callister & Rethwisch 9e.*

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.

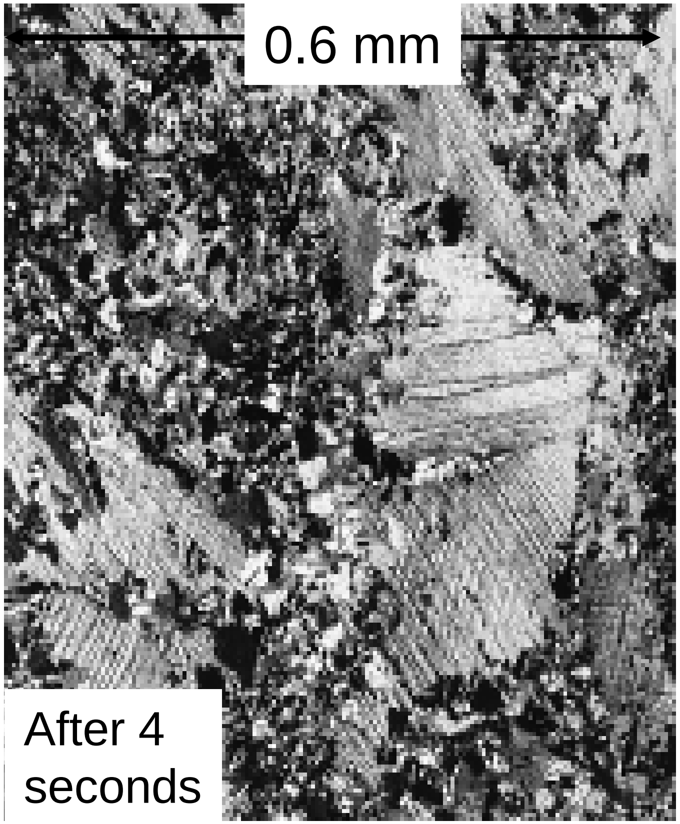


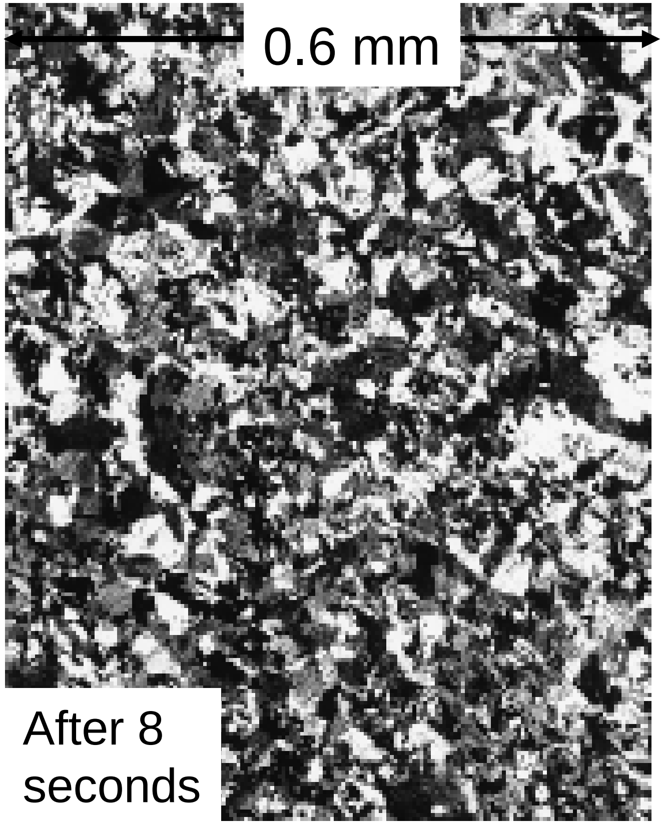


Adapted from Fig. 9.21 (a),(b), *Callister & Rethwisch 9e*. (Photomicrographs courtesy of J.E. Burke, General Electric Company.)

As Recrystallization Continues…

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

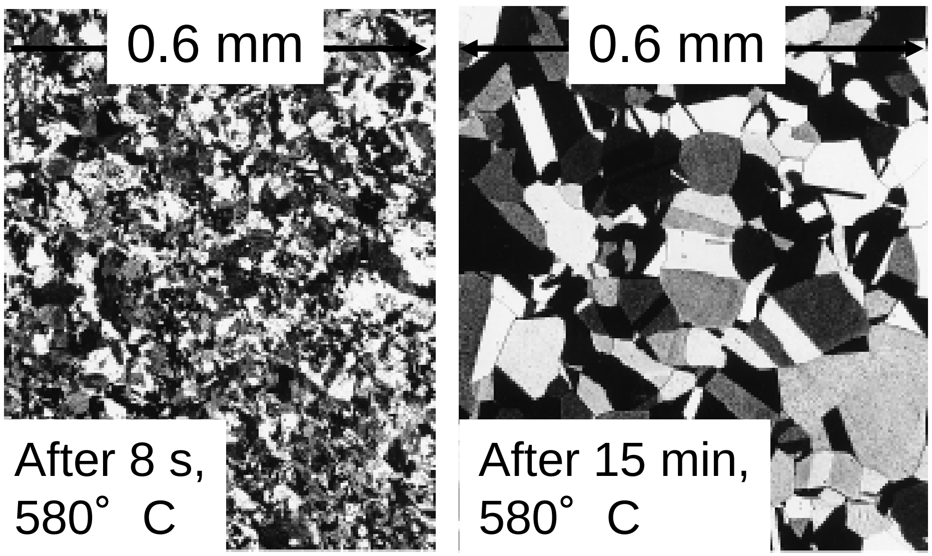




Adapted from Fig. 9.21 (c),(d), *Callister & Rethwisch 9e.* (Photomicrographs courtesy of J.E. Burke, General Electric Company.)

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.* (Photo micrographs courtesy of J .E. Burke, General Electri c Company.)

- Empirical Relation:

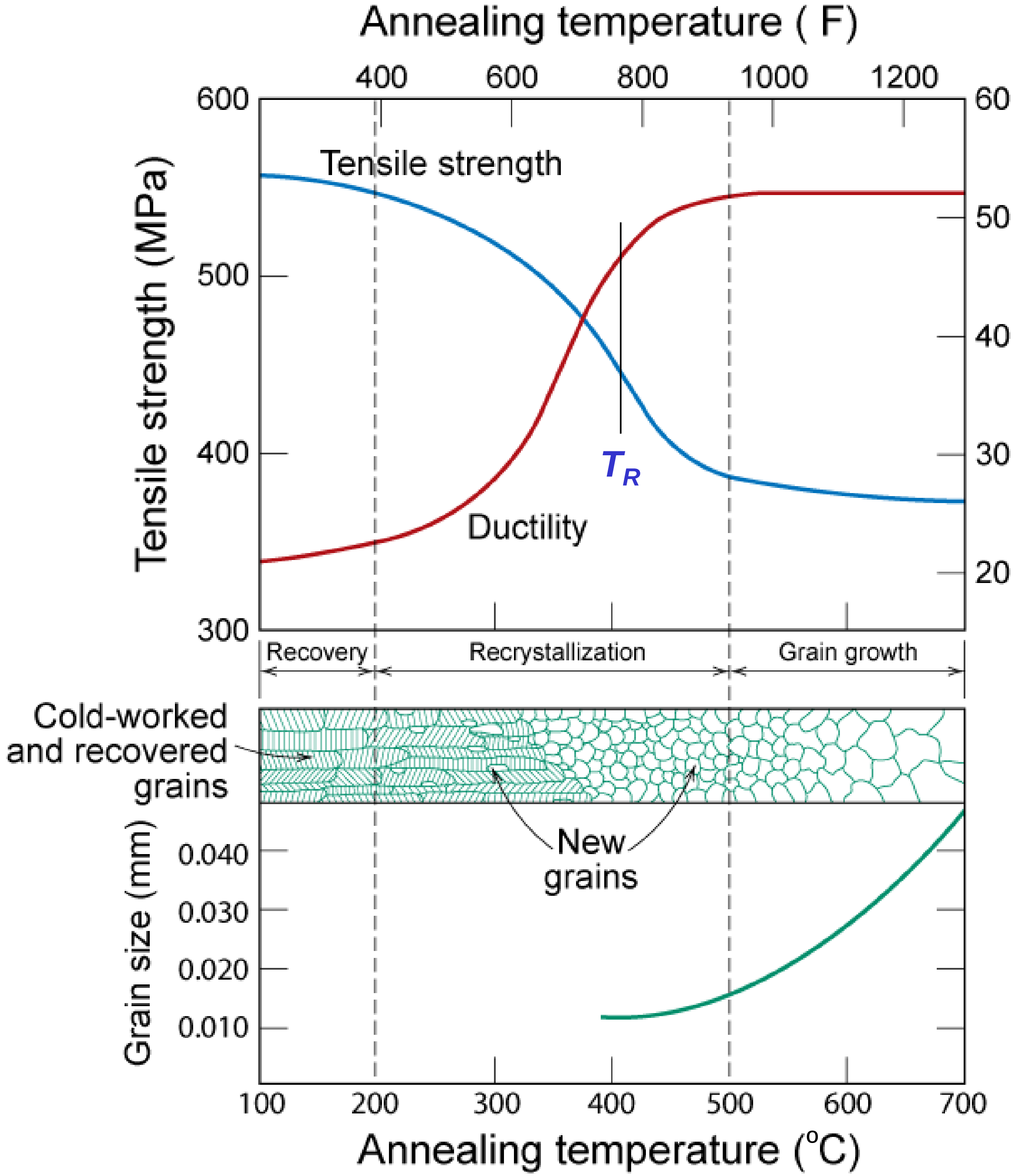
exponent typ. ~ 2

grain diam. at time t.

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

coefficient dependent on material and *T*.

elapsed time

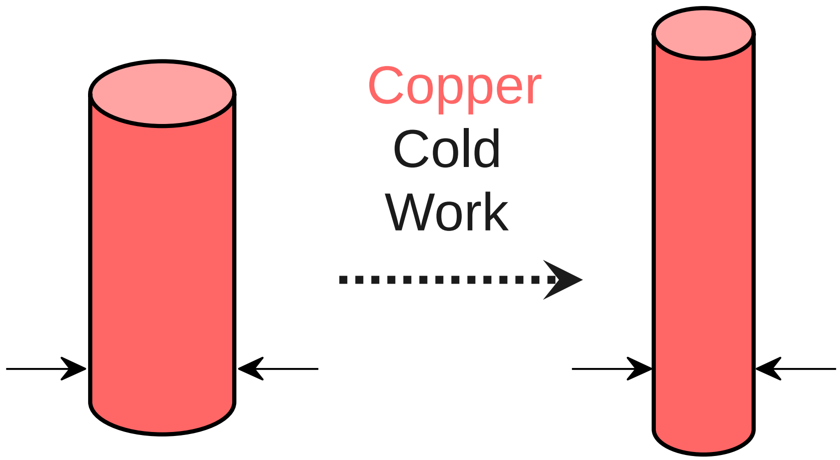


T_R = recrystallization temperature

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

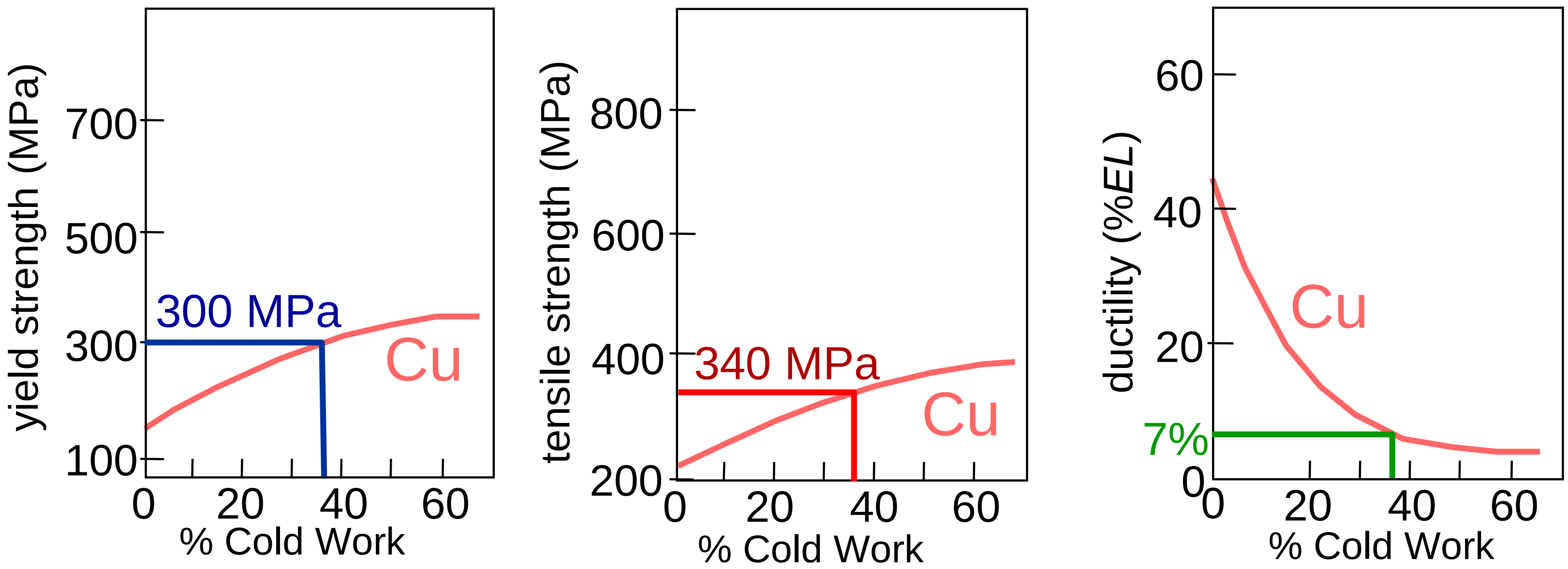
$$\%CW = \frac{\dfrac{\pi D_o^2}{4} - \dfrac{\pi D_d^2}{4}}{\dfrac{\pi D_o^2}{4}} \times 100$$

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

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

Mechanical Property Alterations due to Cold Working

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



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 Int ernational, 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

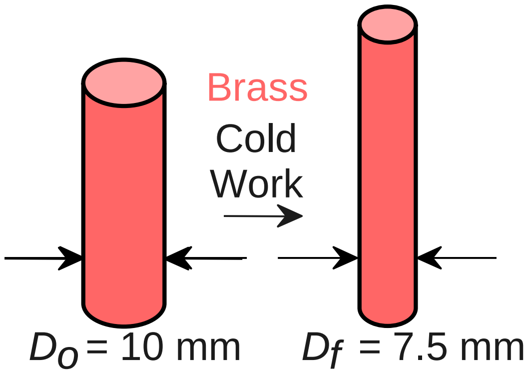
(2) Purity of metal -- T_R decreases with increasing purity

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

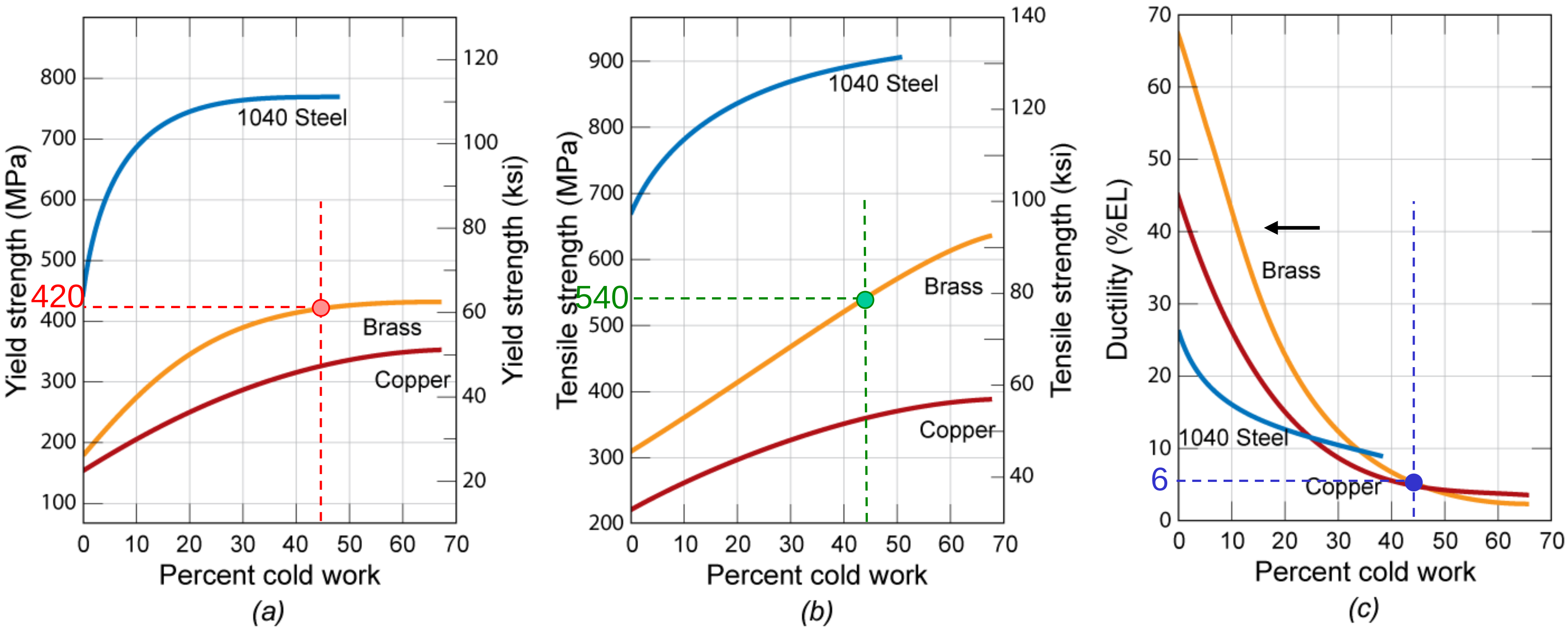
What are the consequences of directly drawing to the final diameter?



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

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

Diameter Reduction Procedure – Solution (Cont.)



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

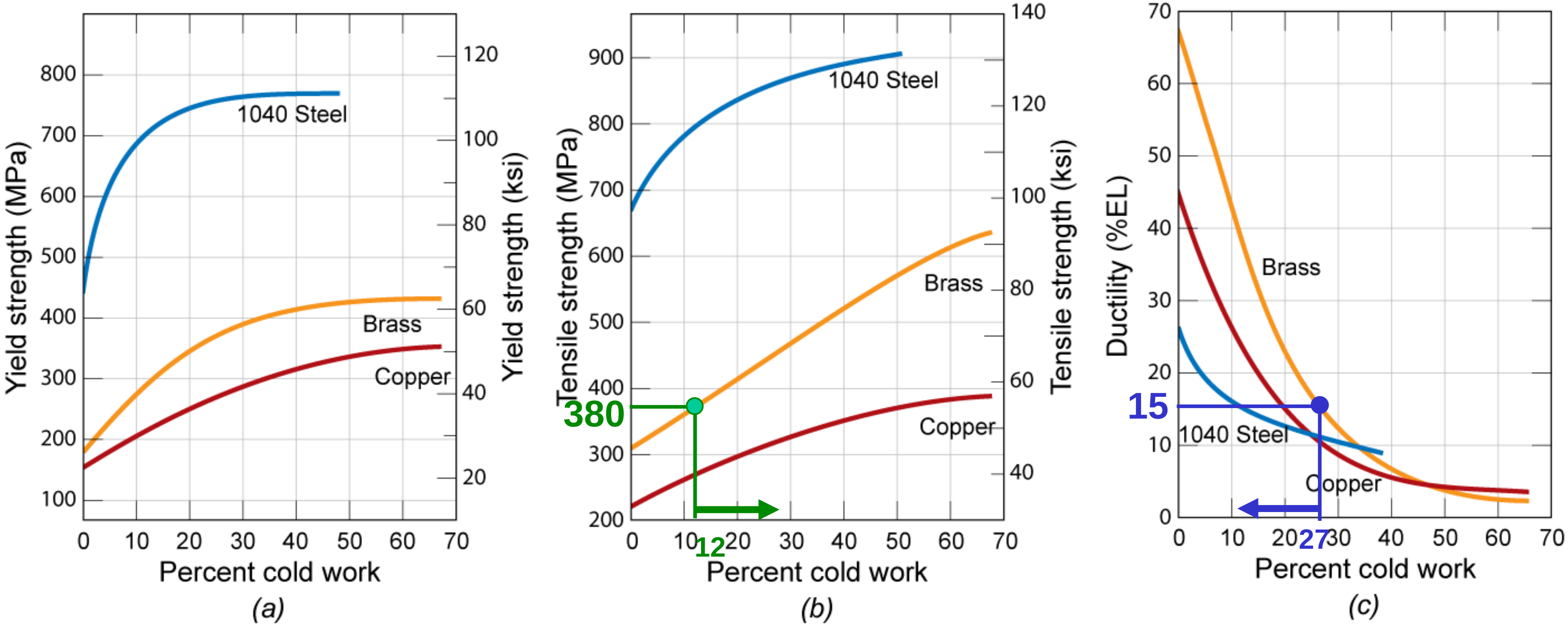


Fig. 9.19, *Callister & Rethwisch 9e.*
[Adapted from *Metals Handbook: Properties and Selection: Irons and Steels*, Vol. 1, 9th edition, B. Bardes (Editor), 1978; and *Metals Handbook: Properties and Selection: Nonferrous Alloys and Pure Metals*, Vol. 2, 9th edition, H. Baker (Managing Editor), 1979. 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 = $D_{f1} = D_{02} = 7.5 \text{ mm} \Big/ \left(1 - \frac{20}{100}\right)^{0.5} = 8.39 \text{ mm}$

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

$$\%CW_2 = \left(1 - \left(\frac{7.5}{8.49}\right)^2\right) x\ 100 = 20$$

Fig 7.19 $\Rightarrow$

$\sigma_y = 340\text{ MPa}$

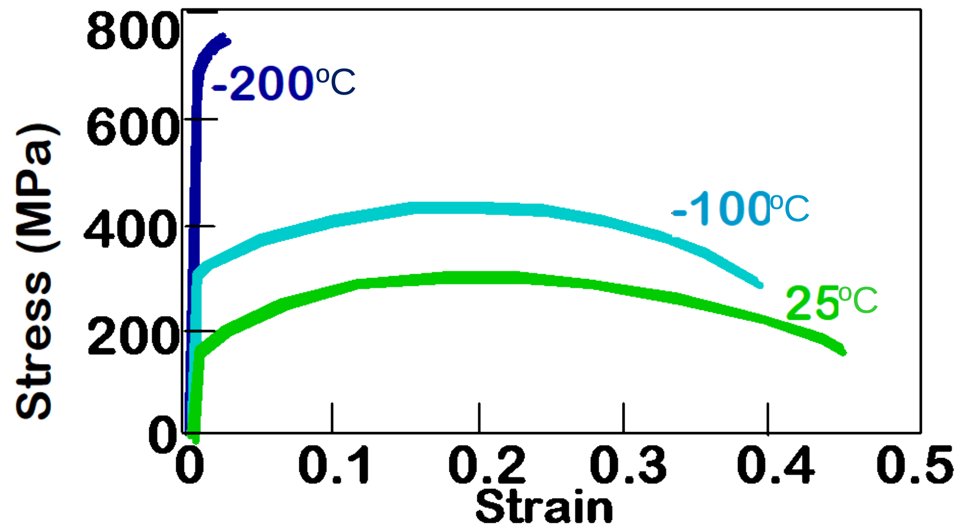
$TS = 400\text{ MPa}$

$\%EL = 24$

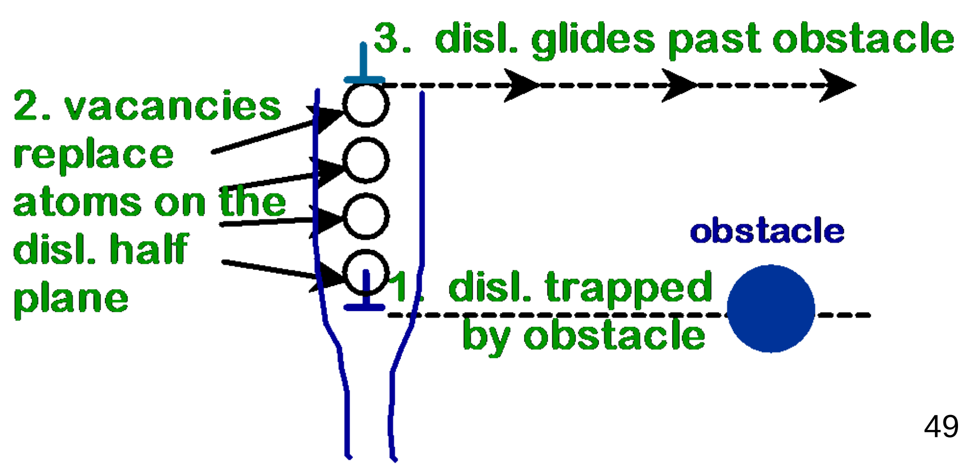
Therefore, all criteria satisfied

σ-ε Behavior vs Temperature

- Results for polycrystalline iron (BCC)



- σ_y and TS *decrease* with increasing test temperature
- %EL *increases* with increasing test temperature
- Why? Vacancies help dislocations past obstacles



III. 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**

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

- 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

Four Strategies for Strengthening

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