2019 Fall

Introduction to Materials Science and Engineering

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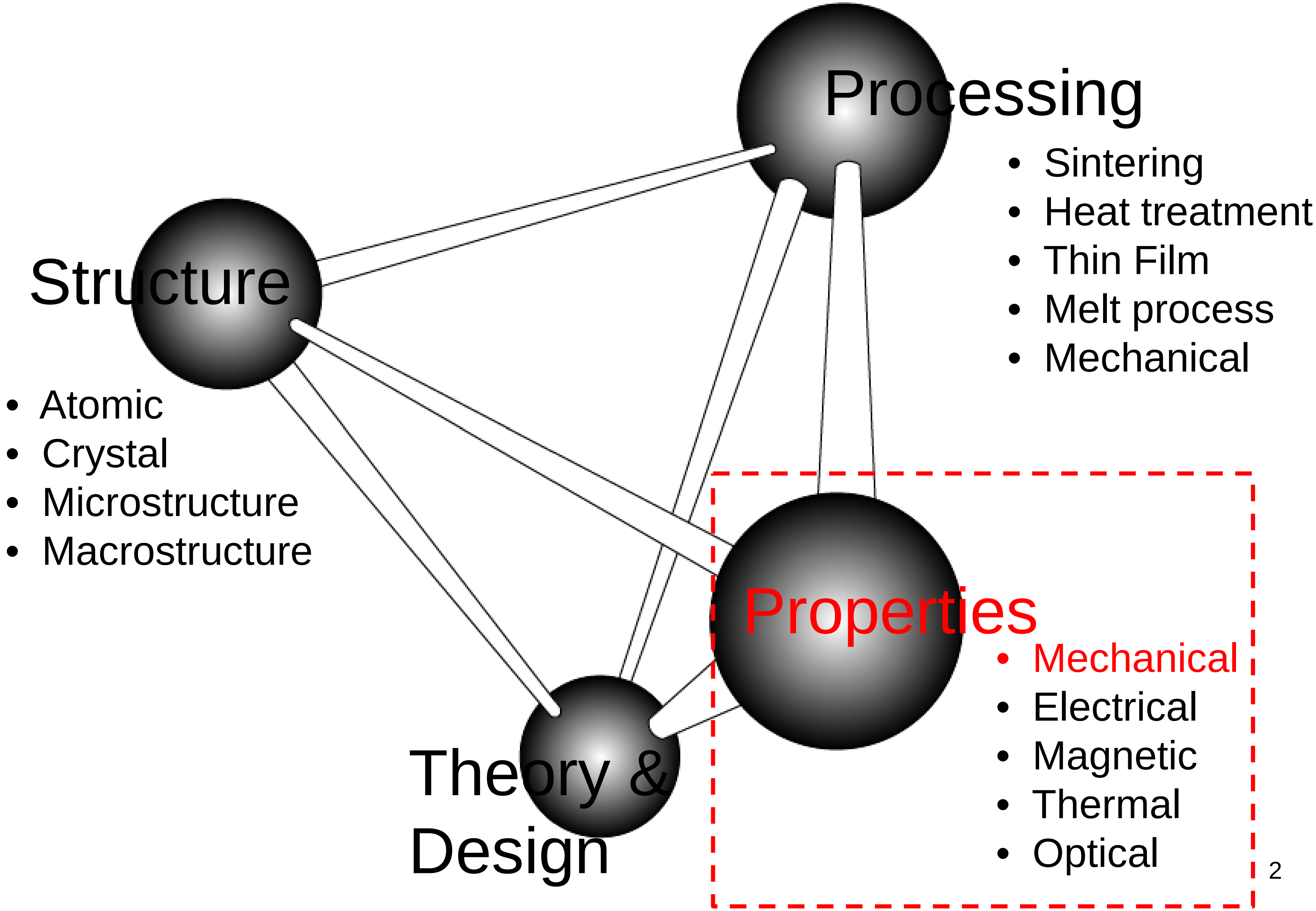
Contents for previous class

Materials Science and Engineering



Processing

- Sintering
- Heat treatment
- Thin Film
- Melt process
- Mechanical

Structure

- Atomic
- Crystal
- Microstructure
- Macrostructure

Properties

- Mechanical
- Electrical
- Magnetic
- Thermal
- Optical

Theory & Design

Summary

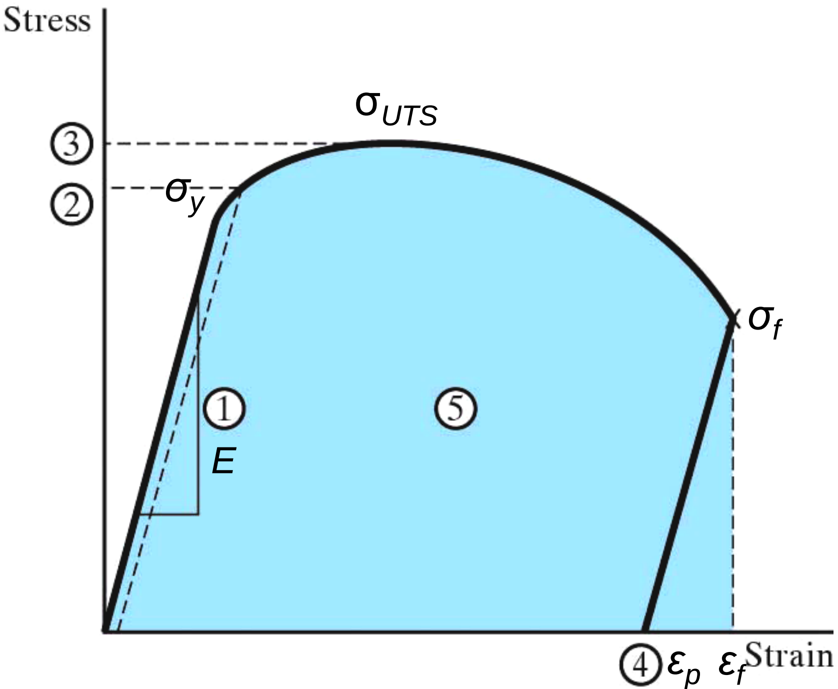
Chapter 8: Mechanical Properties of Metals

- Stress and strain: These are size-independent measures of load and displacement, respectively.
- Elastic behavior: This reversible behavior often shows a linear relation between stress and strain. To minimize deformation, select a material with a large elastic modulus (E or G).
- Plastic behavior: This permanent deformation behavior occurs when the tensile (or compressive) uniaxial stress reaches σ_y.
- Toughness: The energy needed to break a unit volume of material.
- Ductility: The plastic strain at failure.

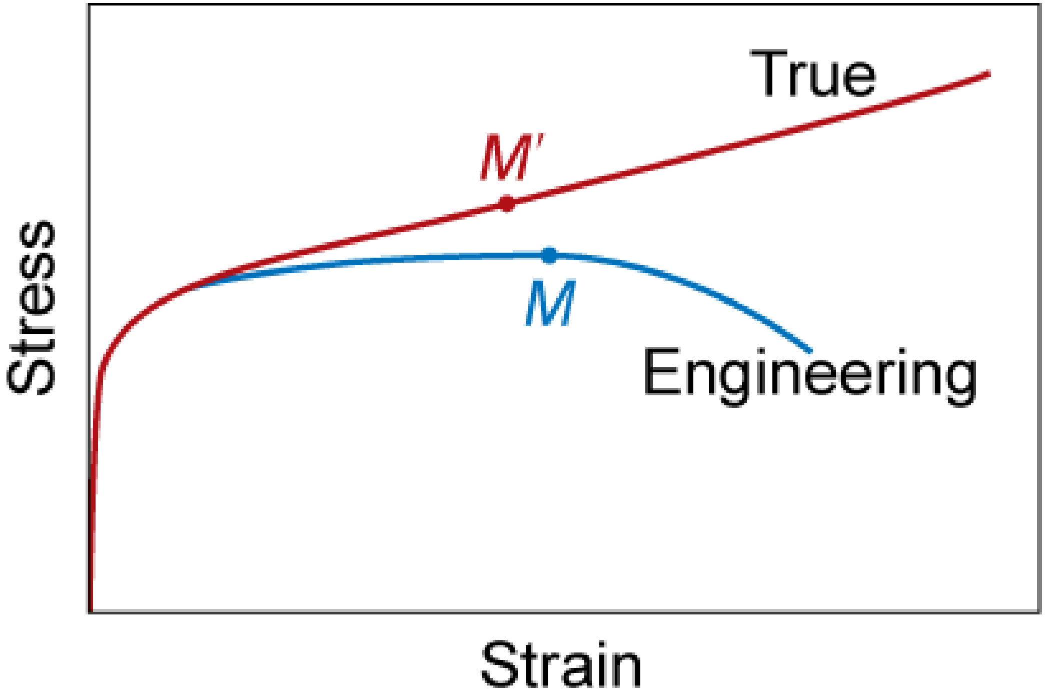
Deformation

- Elastic vs. Plastic region
- Key points

    1. Elastic modulus (=Young's modulus), E
    2. 0.2% (0.002 strain) yield stress, σ_y
    3. Ultimate yield stress, σ_{UTS}
    4. Ductility, ε_p
    5. Toughness → $\boxed{\int \sigma d\varepsilon}$
    6. Fracture stress, σ_f
    7. Fracture strain, ε_f



Engineering vs True Stress & Strain



Adapted from Fig. 8.16, *Callister & Rethwisch 9e.*

Hardness : resistance to permanently indenting the surface

e.g. large hardness means better wear properties

Variability in Material Properties : need to Statistics

Material design considering Safety factor:

$$\sigma_{working} = \frac{\sigma_y}{N}$$

Often *N* is between 1.2 and 4

제 8 장 재료의 기계적 성질: 탄성 변형 vs 소성변형

a. **재료의 강도 (및 경도)**는 **소성변형에 대한 저항성**을 나타냄

b. 소성변형은 작용 응력에 의해 원자가 움직인 결과로

전위, Dislocation (쌍정, Twin)의 움직임에 의해

원자간 결합이 끊어진 후 재결합되는 과정을 통해 **슬립현상 발생**으로

c. **이론 강도 >> 실제 측정 강도_선 결정 결합 때문**

: 결정 재료의 많은 물리적·기계적 현상을 **전위 이론으로 설명**

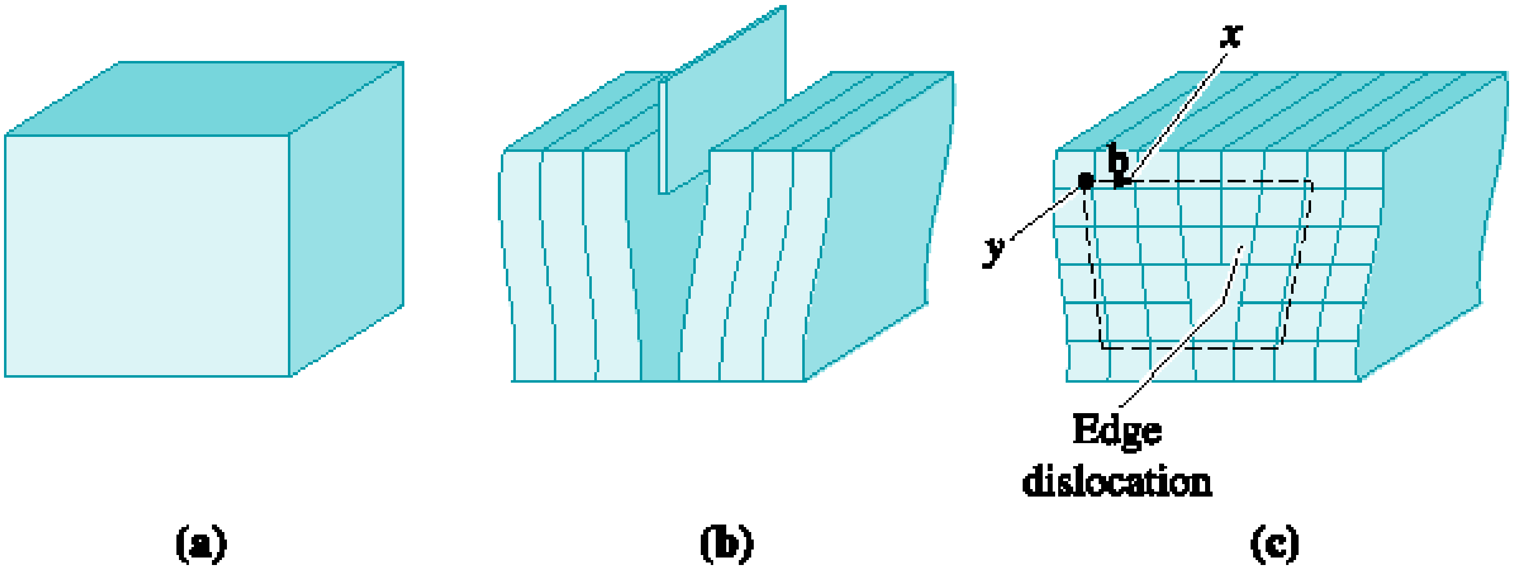
Chapter 9
Dislocations and Strengthening

- Why are dislocations observed primarily in metals and alloys?
- How are strength and dislocation motion related?
- How do we increase strength?
- How can heating change strength and other properties?

I. Basic concept of plastic deformation

a. Dislocation

(1) Edge Dislocation

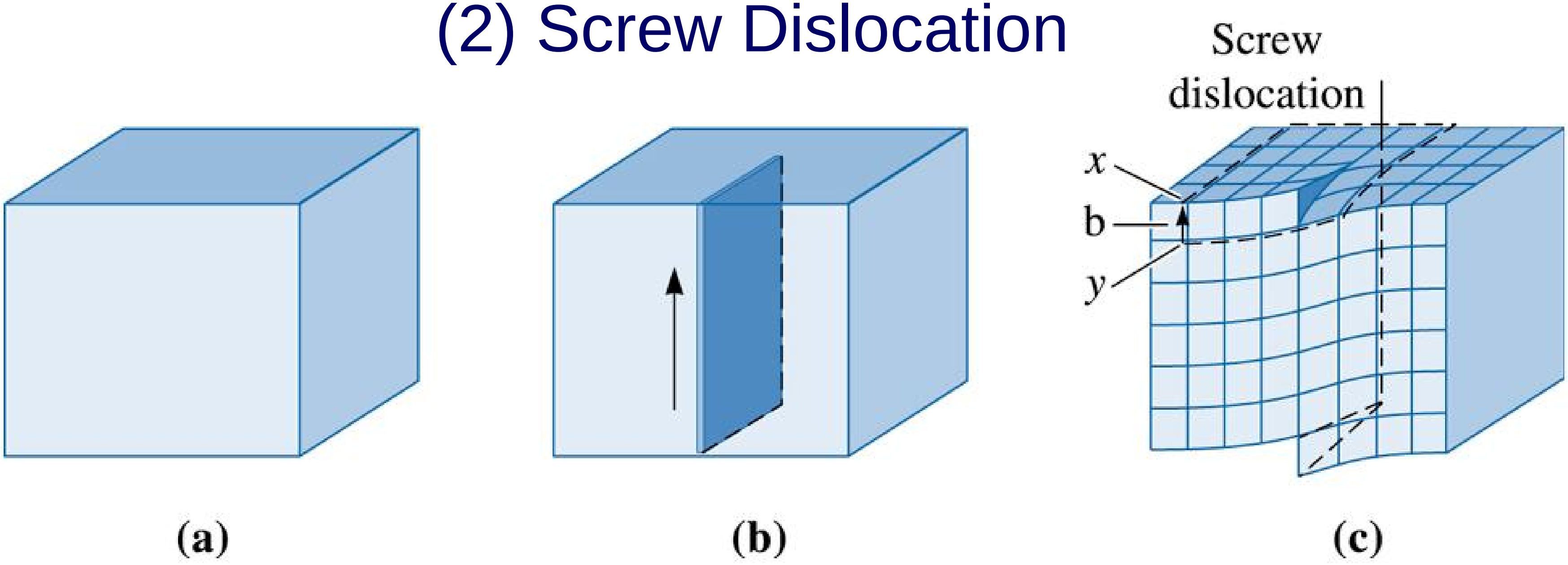


- The perfect crystal in (a) is cut and an extra plane of atoms is inserted (b). The bottom edge of the extra plane is an edge dislocation (c).

- A Burgers vector b is required to close a loop of equal atom spacings around the edge dislocation → magnitude & direction of the lattice distortion

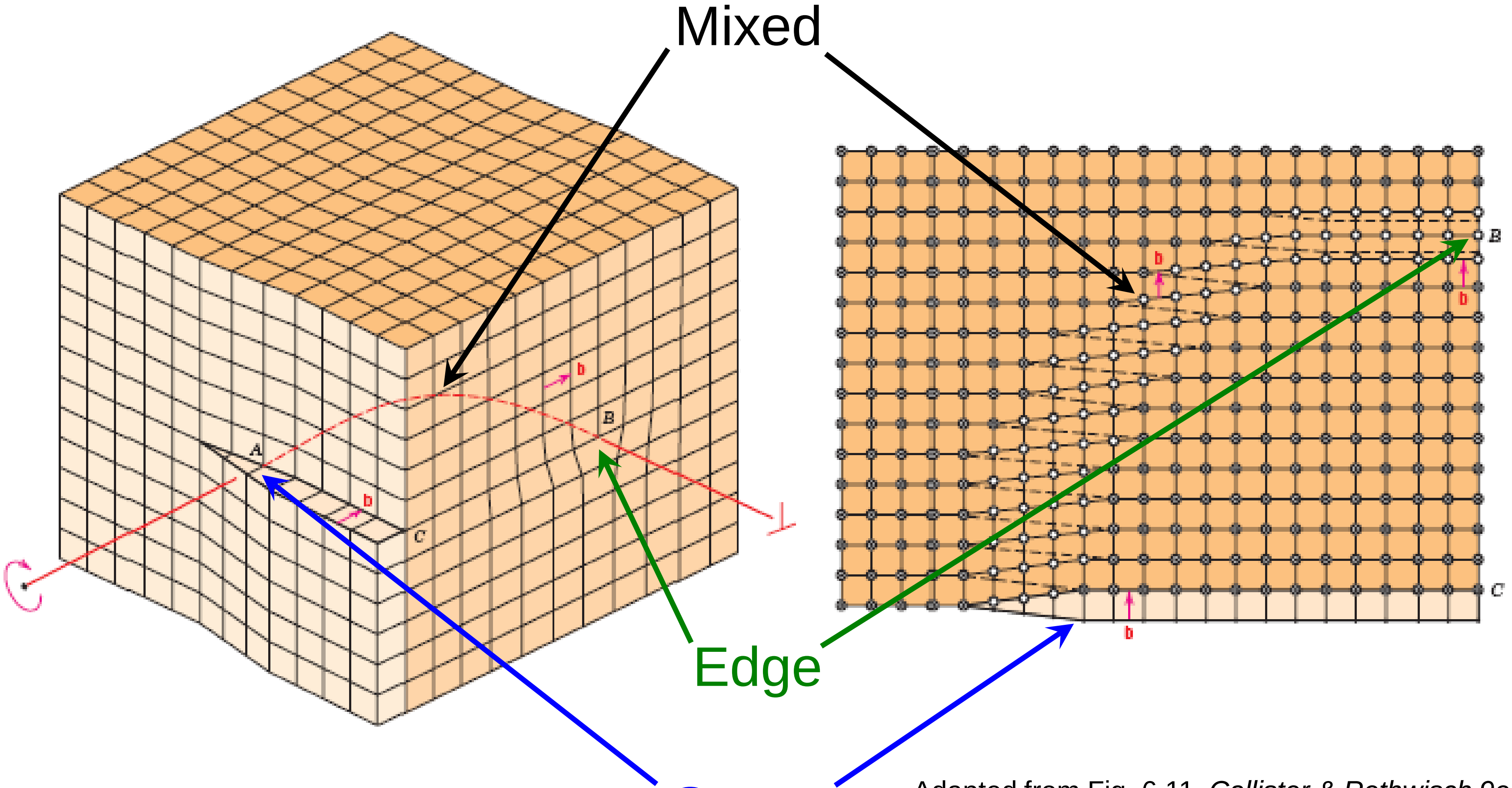
- Burgers vector *b* ⊥ dislocation line

(2) Screw Dislocation



- The perfect crystal (a) is cut and sheared one atom spacing, (b) and (c). The line along which shearing occurs is a screw dislocation.
- A Burgers vector *b* is required to close a loop of equal atom spacings around the screw dislocation → magnitude & direction of the lattice distortion
- Burgers vector *b* // dislocation line

(3) Edge, Screw, and Mixed Dislocations


Mixed

Edge

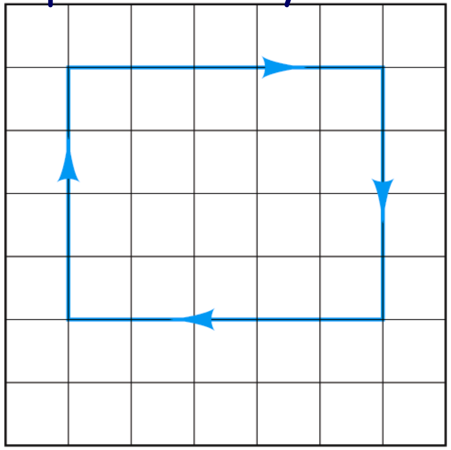
Screw

Adapted from Fig. 6.11, *Callister & Rethwisch 9e.*
[Figure (b) from W. T. Read, Jr., Dislocations in Crystals, McGraw-Hill Book Company, New York, NY, 1953.]

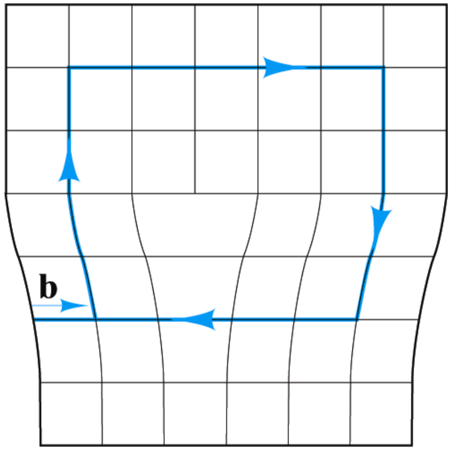
Burgers vector b

Represents the magnitude of the structural defect

perfect crystal

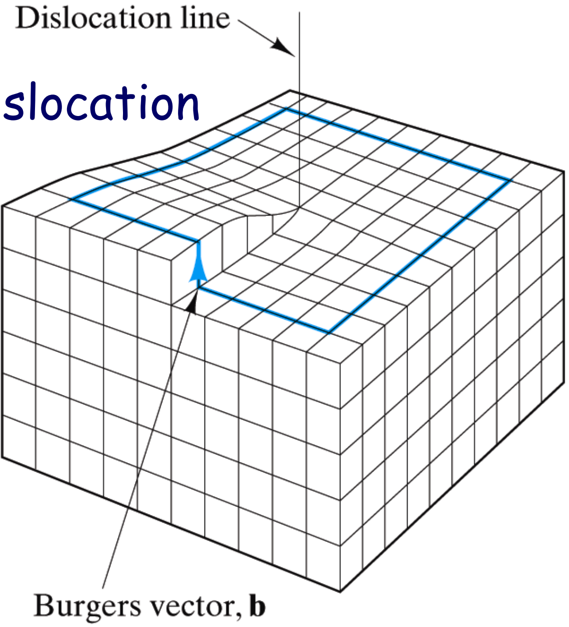


edge dislocation

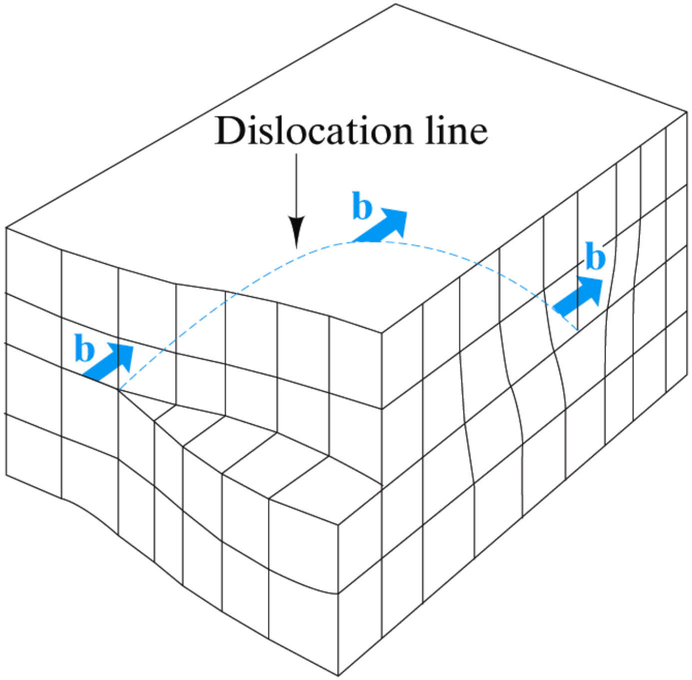


b ⊥ dislocation line

screw dislocation



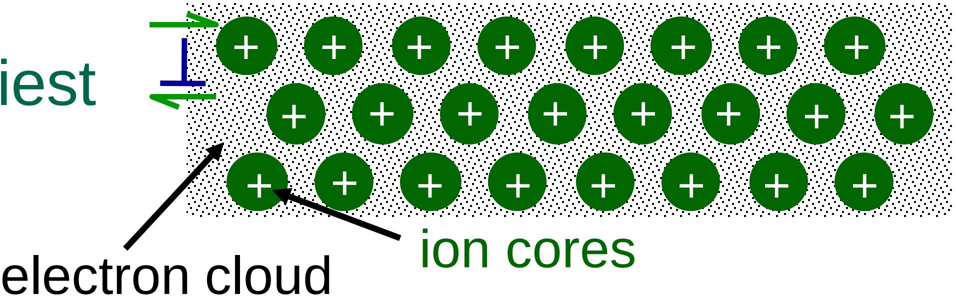
b // dislocation line



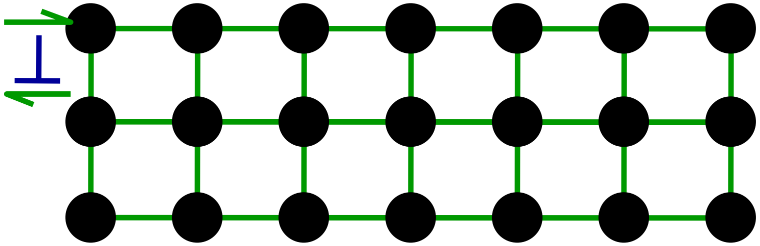
mixed dislocation

b. Dislocation motion in different material classes

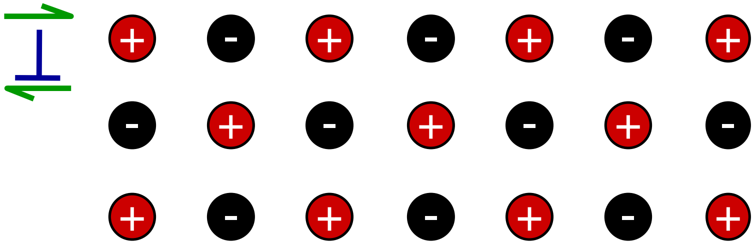
- **Metals (Cu, Al):**
  Dislocation motion easiest
  - non-directional bonding
  - close-packed directions
    for slip



- Covalent Ceramics
  (Si, diamond): Motion difficult
  - directional (angular) bonding



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



II. Dislocation Motion

a. Dislocation motion, Slip & Plastic deformation

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

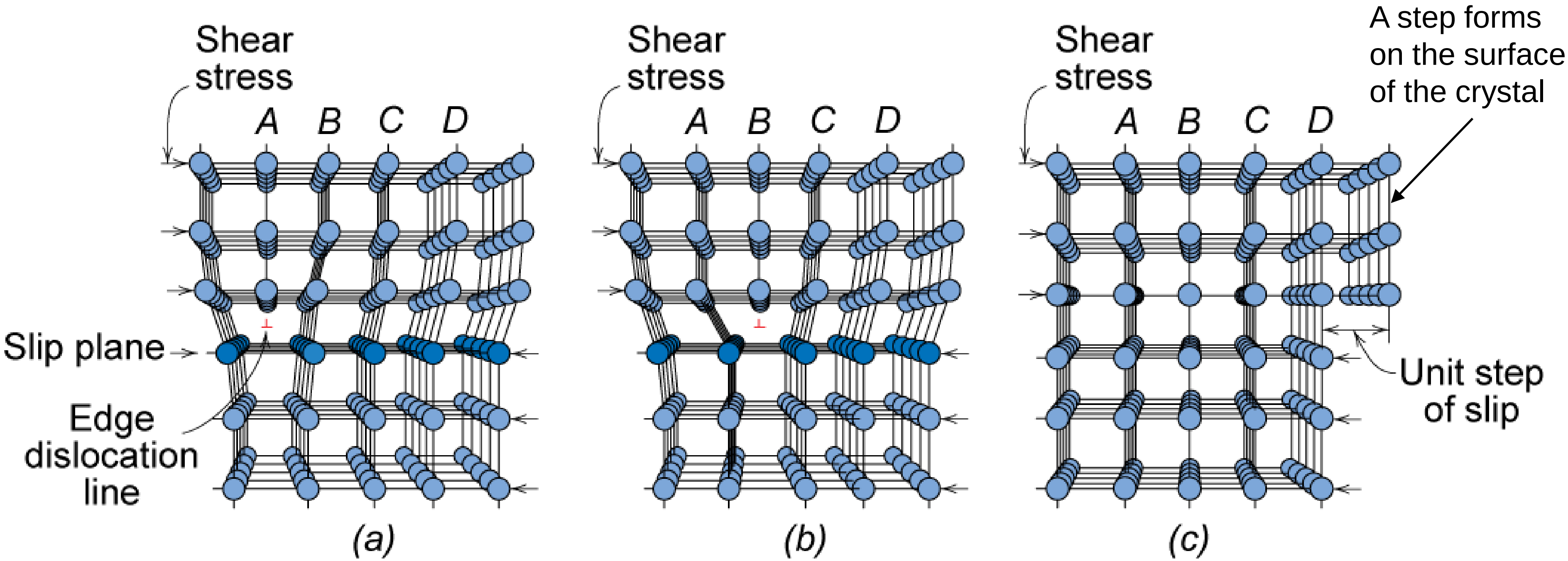


Fig. 9.1, *Callister & Rethwisch 9e.* (Adapted from A. G. Guy, Essentials of Materials Science, McGraw-Hill Book Company, New York, 1976, p. 153.)

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

b. 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.

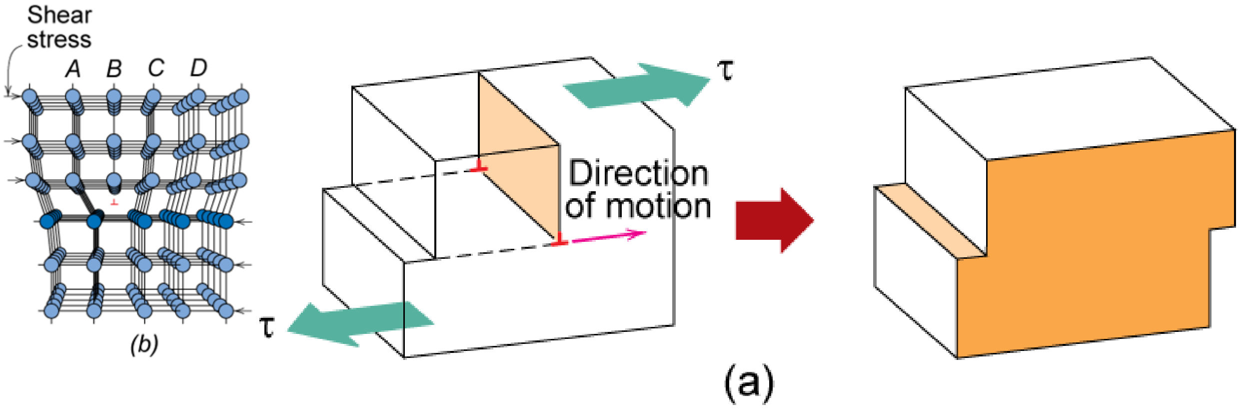
Atomic view of edge dislocation motion from left to right as a crystal is sheared.

(Courtesy P.M. Anderson)

c. Dislocation Motion

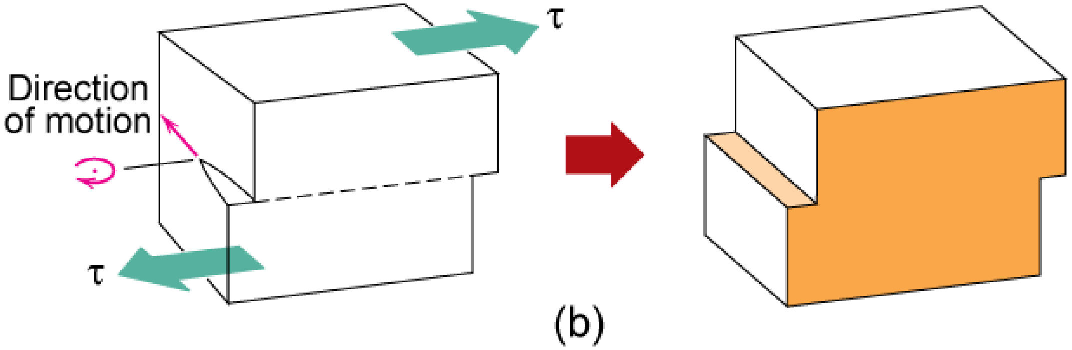
- A dislocation moves along a slip plane in a slip direction perpendicular to the dislocation line

- The slip direction is the same as the Burgers vector direction



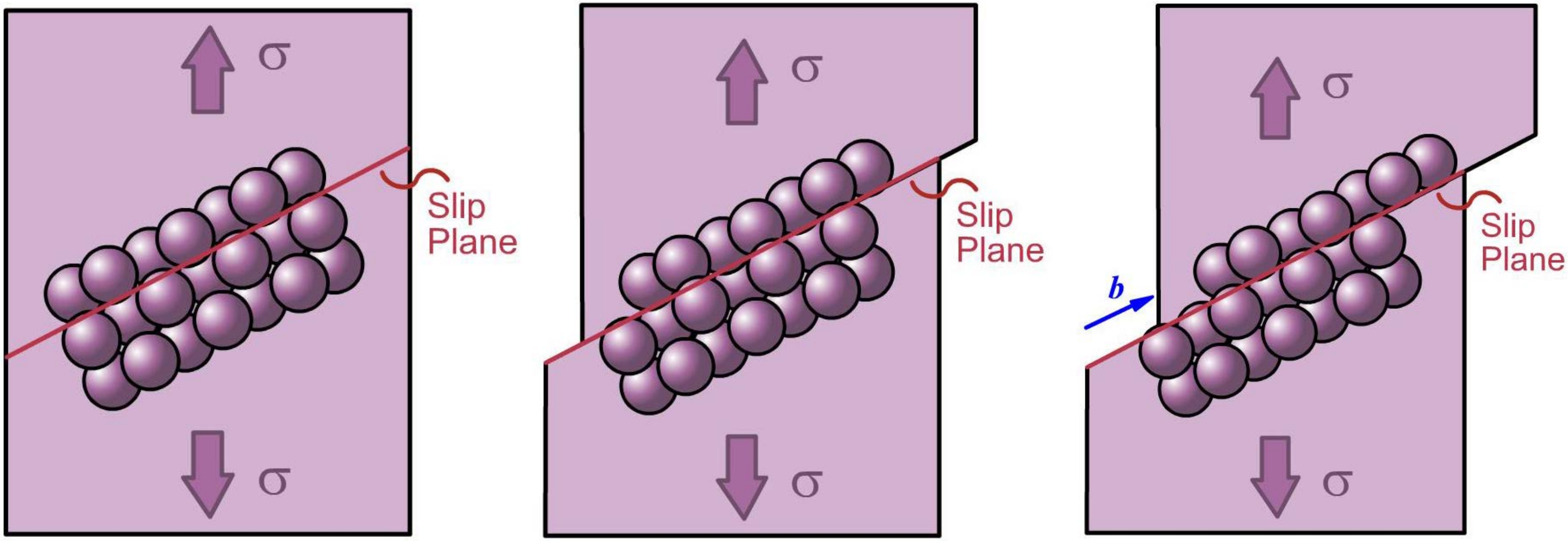
Edge dislocation

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

d. Slip



II. Characteristics of dislocations

a. Lattice Strains Around Dislocations

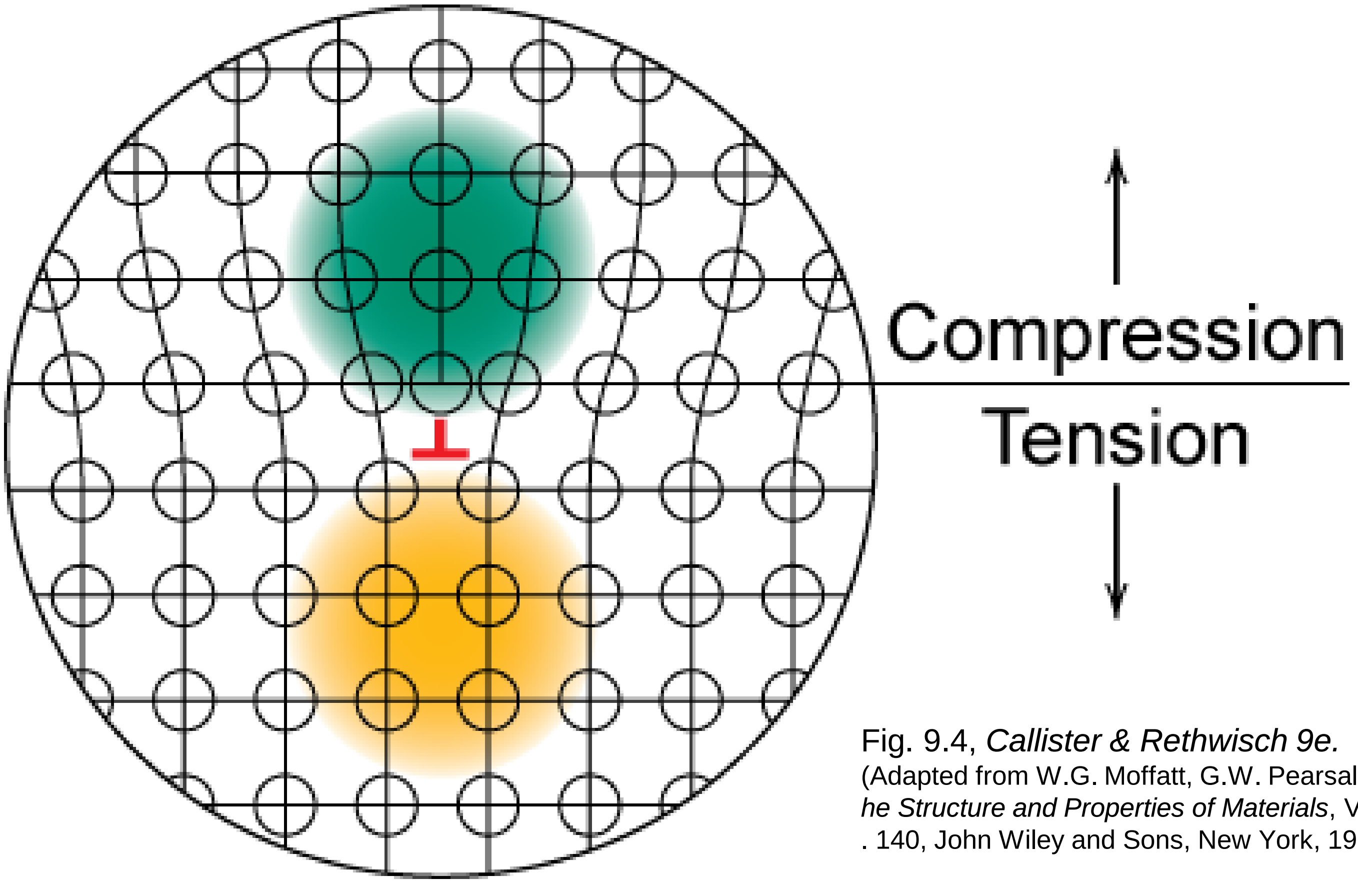
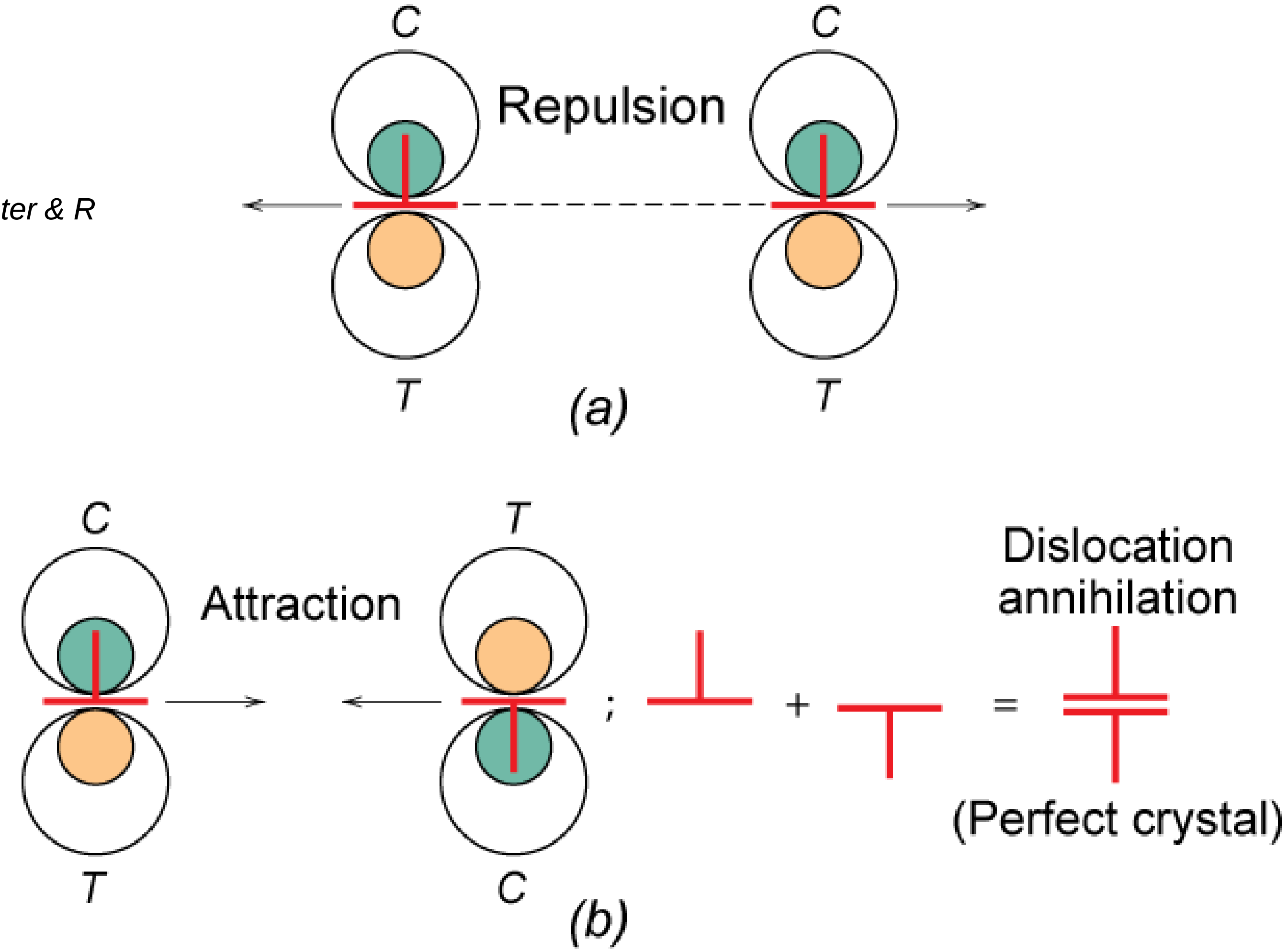


Fig. 9.4, *Callister & Rethwisch 9e.*
(Adapted from W.G. Moffatt, G.W. Pearsall, and J. Wulff, *The Structure and Properties of Materials*, Vol. I, *Structure*, p. 140, John Wiley and Sons, New York, 1964.)

b. Lattice Strain Interactions Between Dislocations

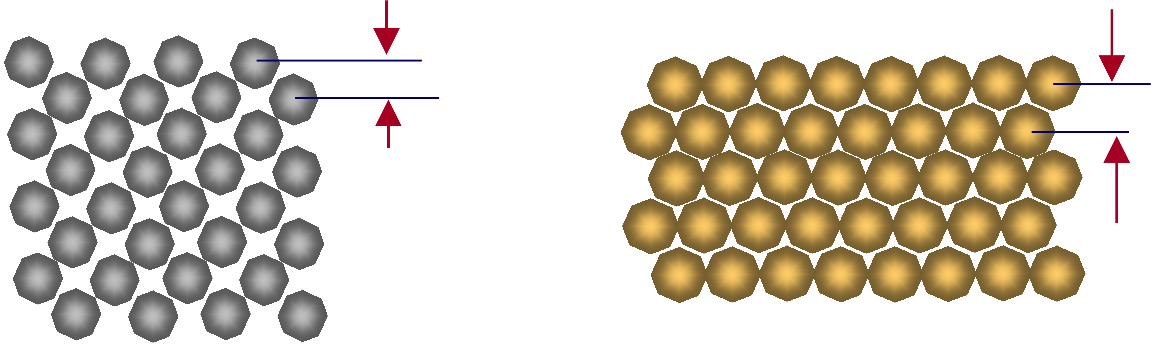
Fig. 9.5, *Callister & Rethwisch 9e.*



III. Deformation Mechanisms

a. **Slip System = Slip plane + Slip direction**

- Dislocation mobility is not the same in all crystallographic planes or directions
- There are preferred planes (*slip planes*) and preferred directions (*slip directions*) along which dislocations move with greater ease
  - ✓ **Slip plane** - plane on which easiest slippage occurs
    - Highest planar densities (and large interplanar spacings)



  - ✓ **Slip directions** - directions of movement
    - Highest linear densities
- Slip occurs in close-packed directions on highest-density planes

The **slip system** 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

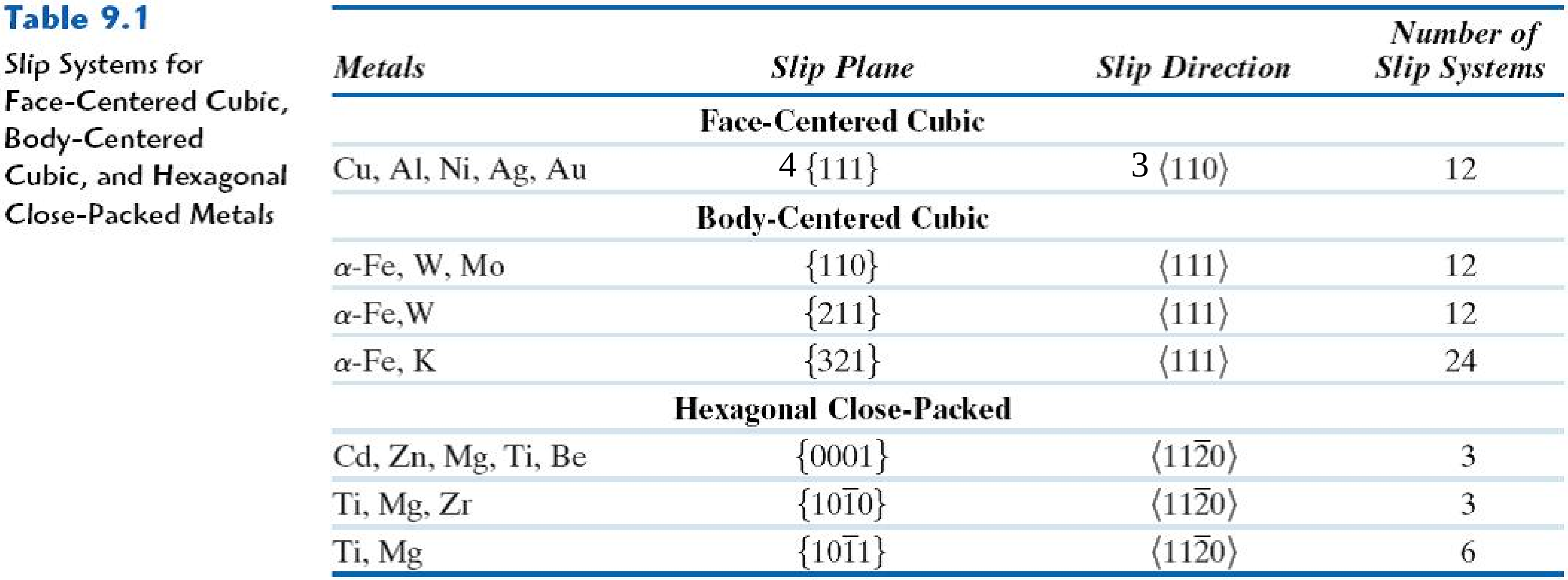


Table 9.1

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

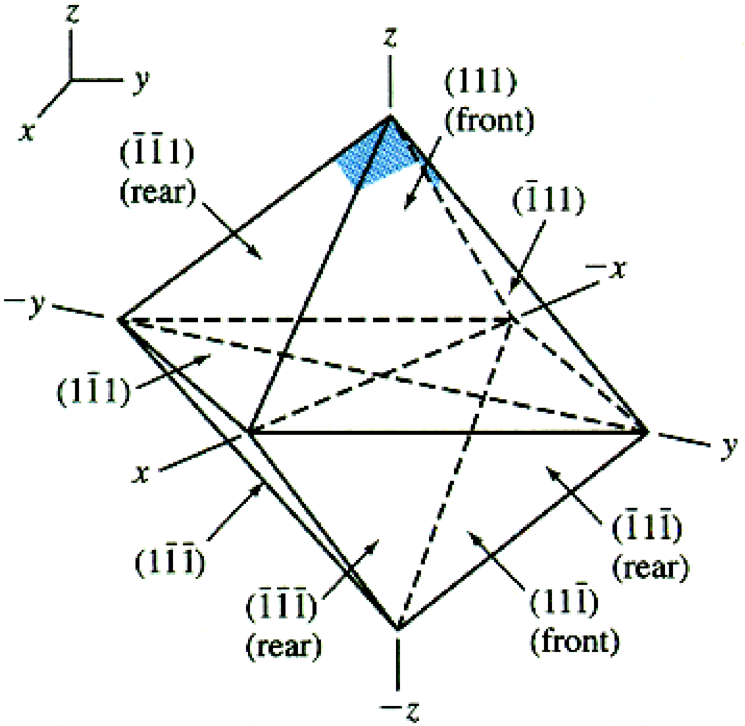
Metals	*Slip Plane*	*Slip Direction*	*Number of Slip Systems*
Face-Centered Cubic			
Cu, Al, Ni, Ag, Au	4 $\{111\}$	3 $\langle 110\rangle$	12
Body-Centered Cubic			
α-Fe, W, Mo	$\{110\}$	$\langle 111\rangle$	12
α-Fe,W	$\{211\}$	$\langle 111\rangle$	12
α-Fe, K	$\{321\}$	$\langle 111\rangle$	24
Hexagonal 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

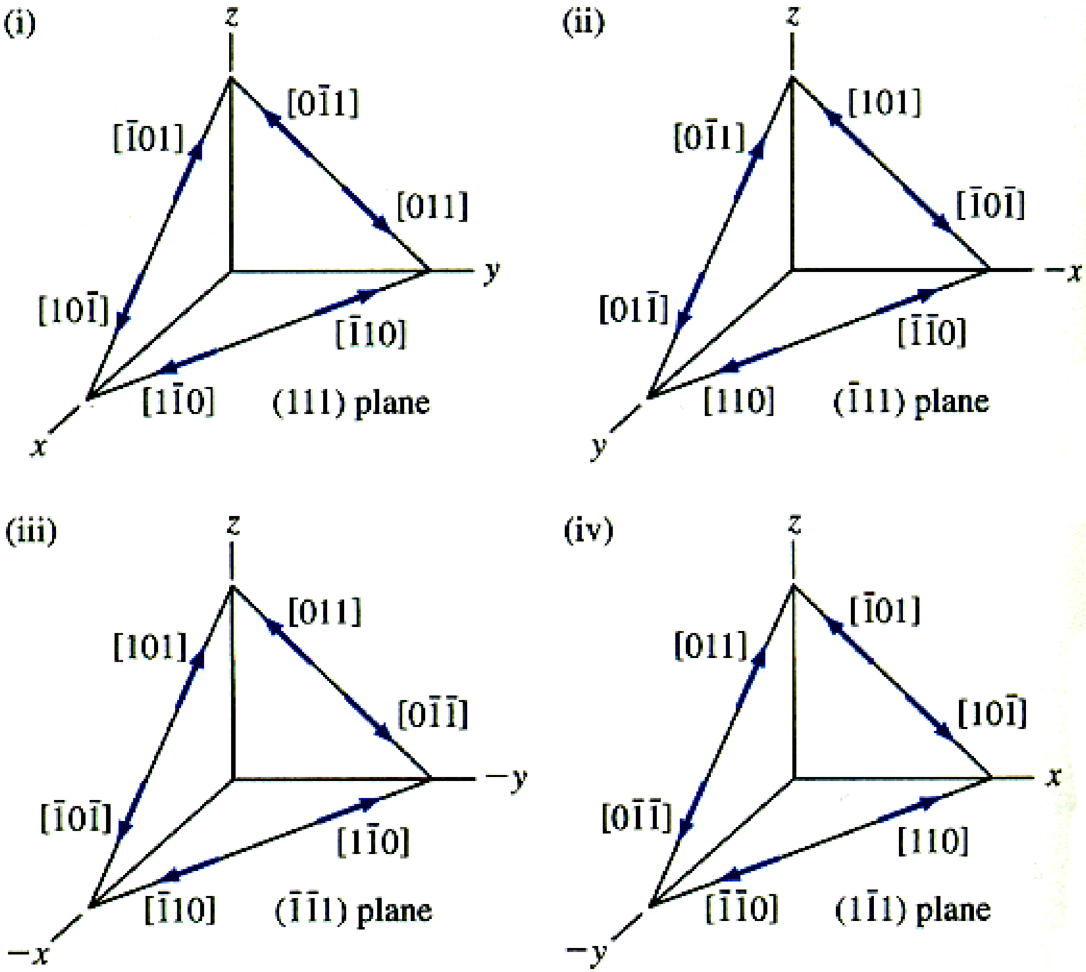
Quite ductile

Quite brittle

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

(1) Slip Systems in FCC

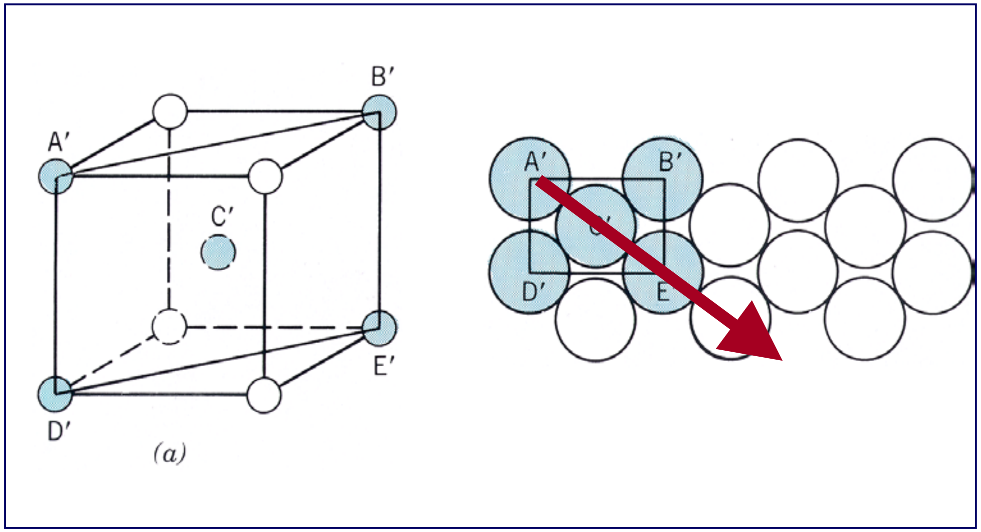




{111}<110>

4 x 3 = 12 slip system

(2) Slip Systems in BCC

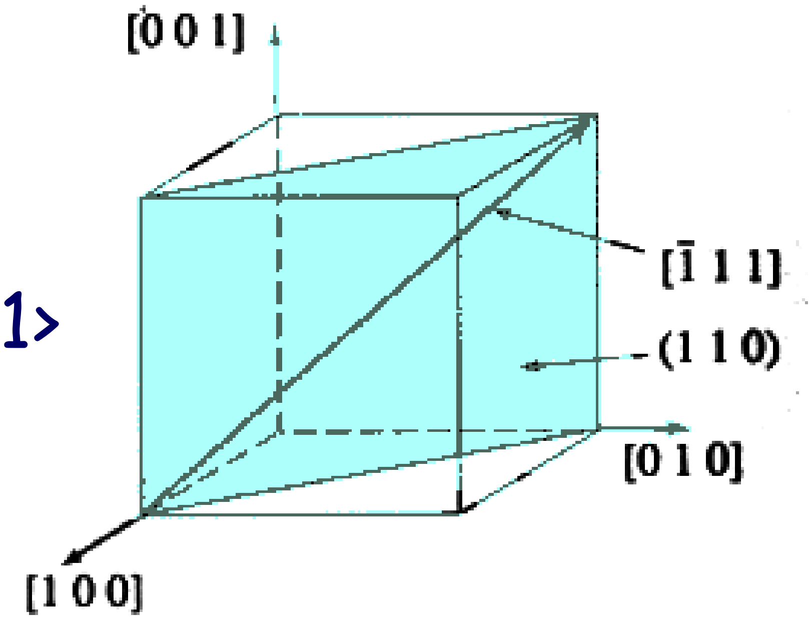


Highest density plane$-\{110\}$

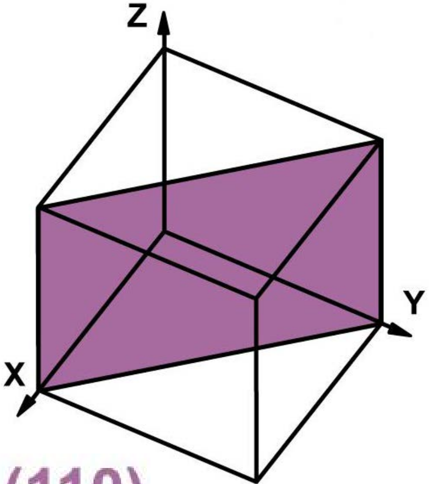
Burger vector $-\ \frac{a}{2} < 111 >$

$6 \times 2 = 12$ slip system

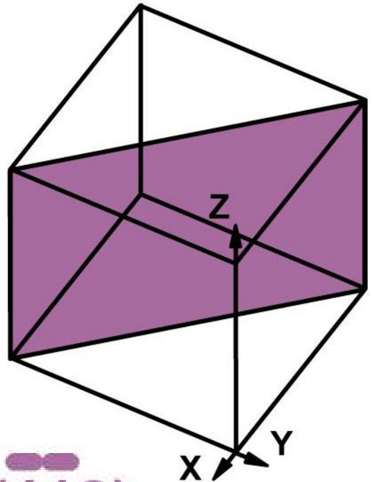
{110}<111>



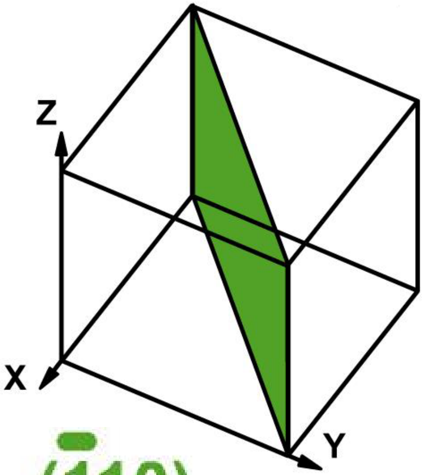
{110} Family



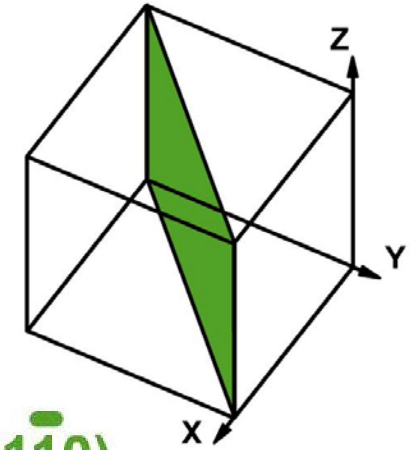
(110)



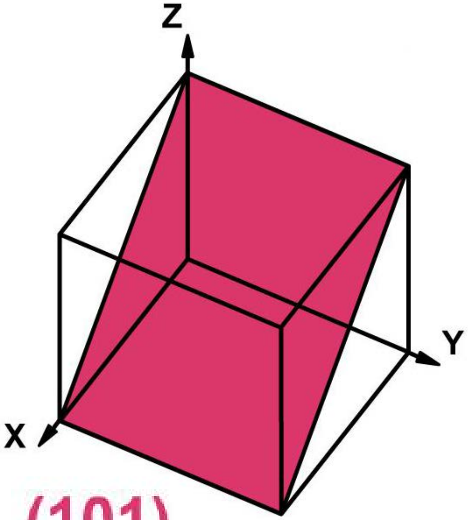
$(\bar{1}\bar{1}0)$



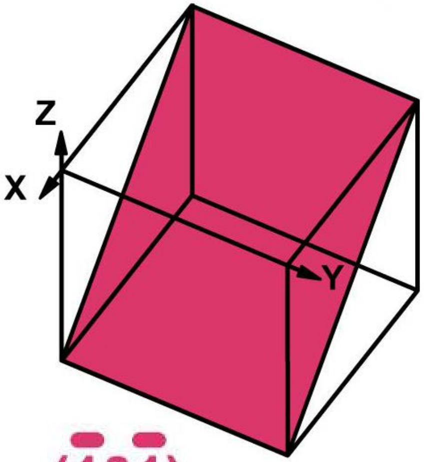
$(\bar{1}10)$



$(1\bar{1}0)$

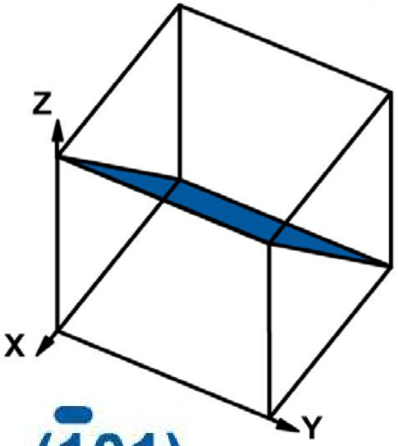


(101)

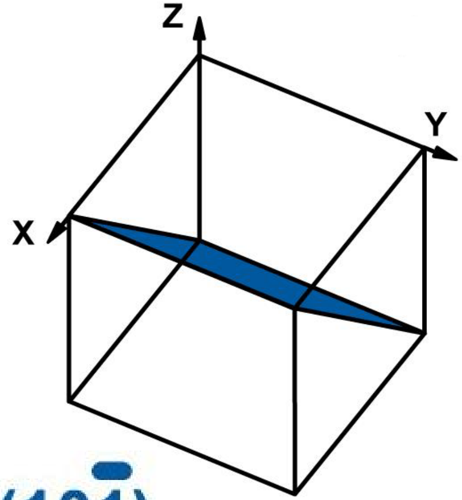


$(\bar{1}0\bar{1})$

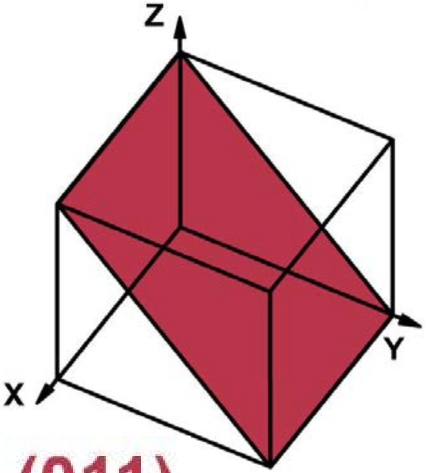
{110} Family



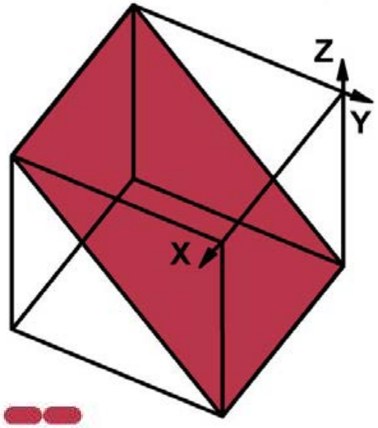
$(\bar{1}01)$



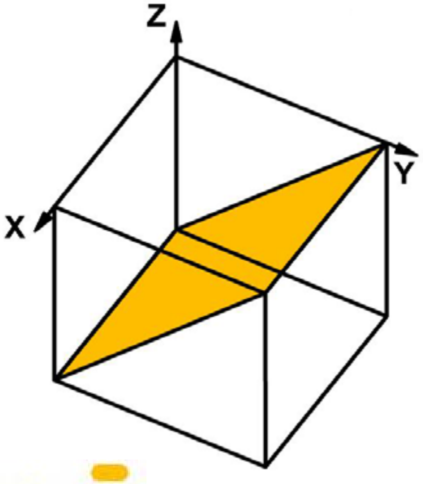
$(10\bar{1})$



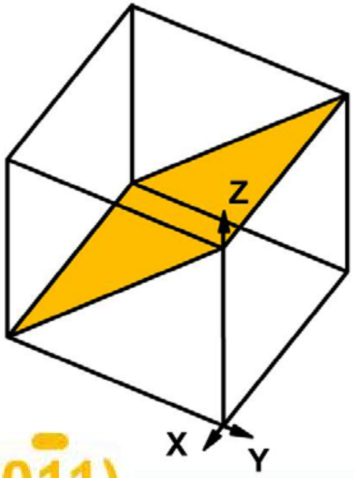
(011)



$(0\bar{1}\bar{1})$

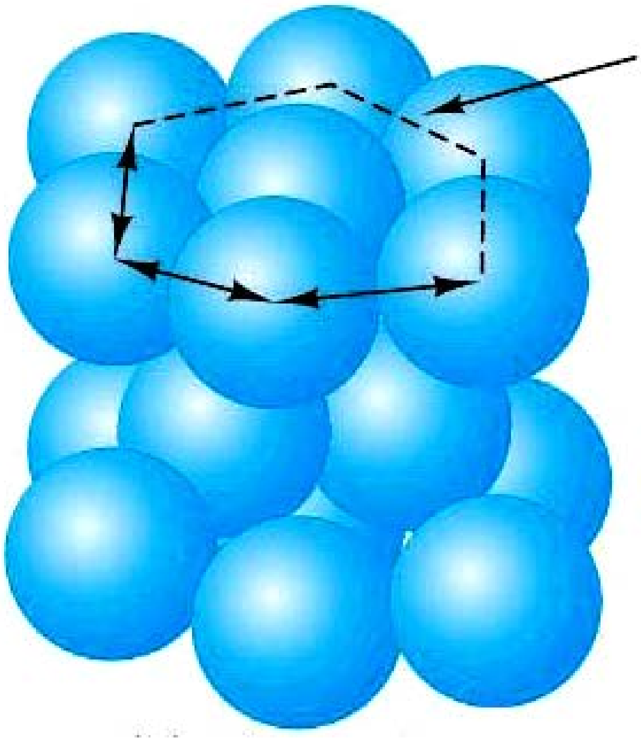


$(01\bar{1})$



$(0\bar{1}1)$

(3) Slip Systems in HCP



$(0001)\langle 11\bar{2}0\rangle =$

$(0001)[11\bar{2}0] \quad (0001)[1\bar{2}10] \quad (0001)[\bar{2}110]$

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

1 x 3 = 3 slip systems

(4) Dislocations & Crystal Structure

- **Ductility** ~ # of slip system, whether they intersect, and planar density of slip planes
- **FCC – ductile** (many close-packed planes/directions)
- **BCC – poor low temp ductility due to DBTT**
- **HCP – brittle** (only one plane, 3 directions)

- Results of tensile testing

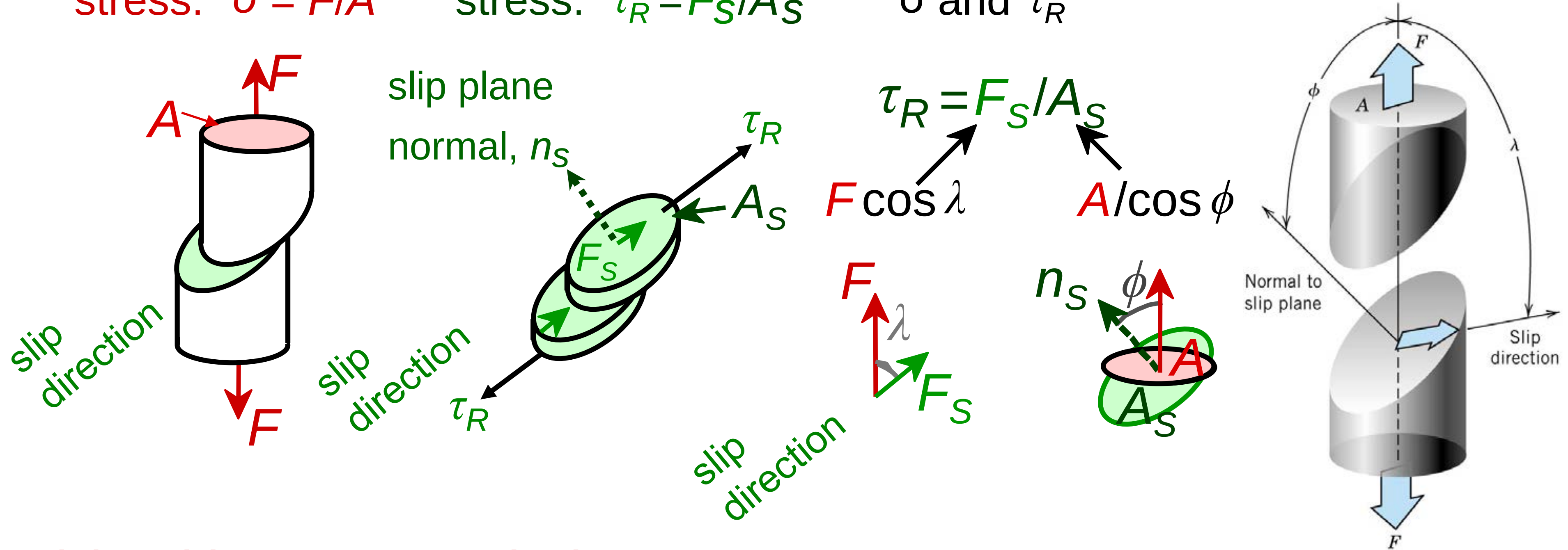
b. Stress and Dislocation Motion

- 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

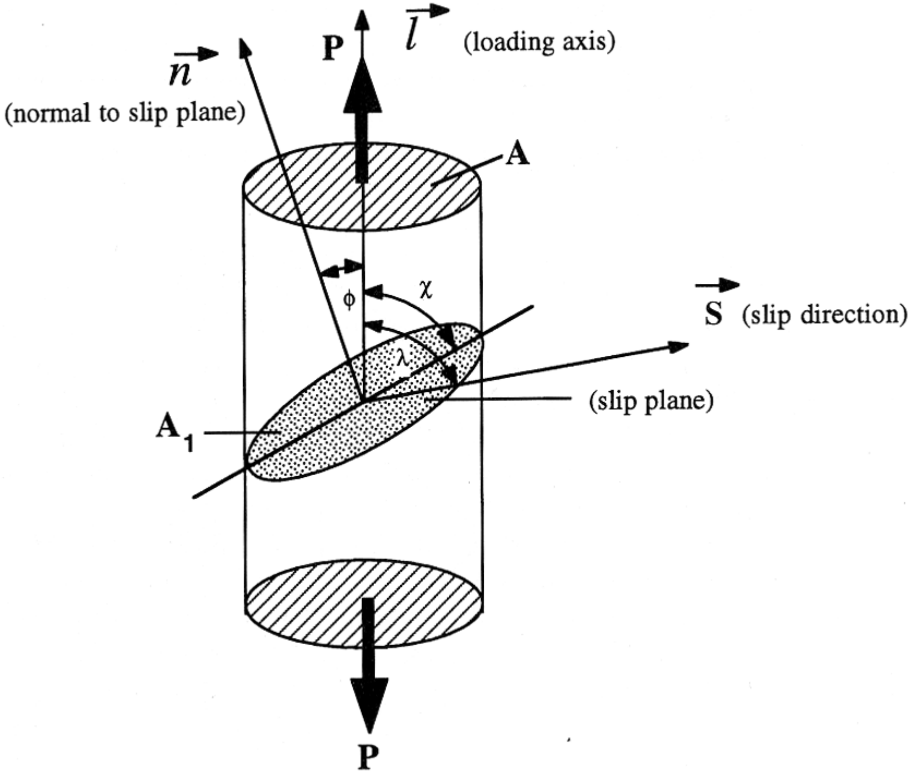


Figure 6.8 Relationship between stress axis and slip plane and direction.

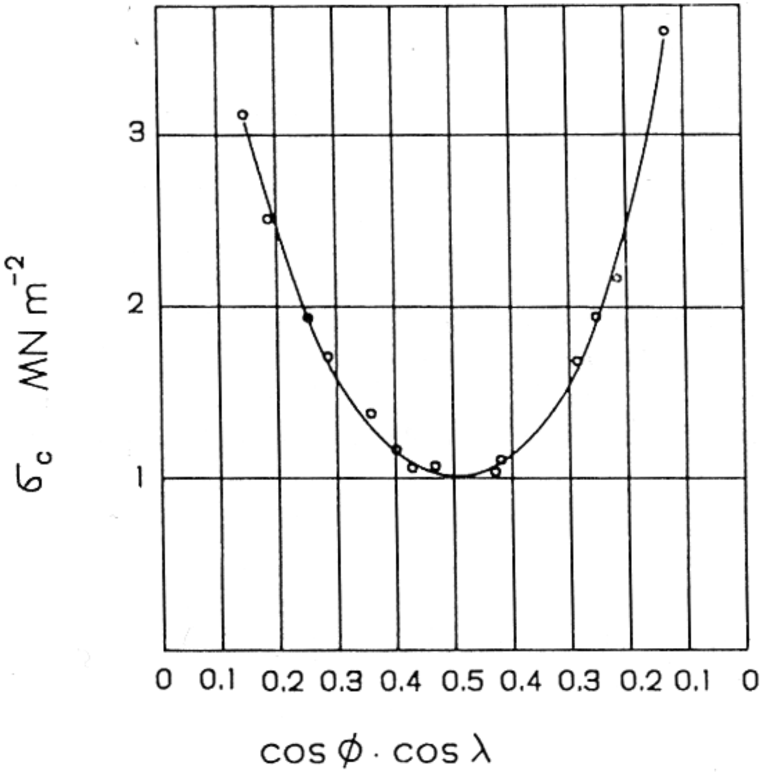


Fig. 10.2 The variation of σ_c with orientation

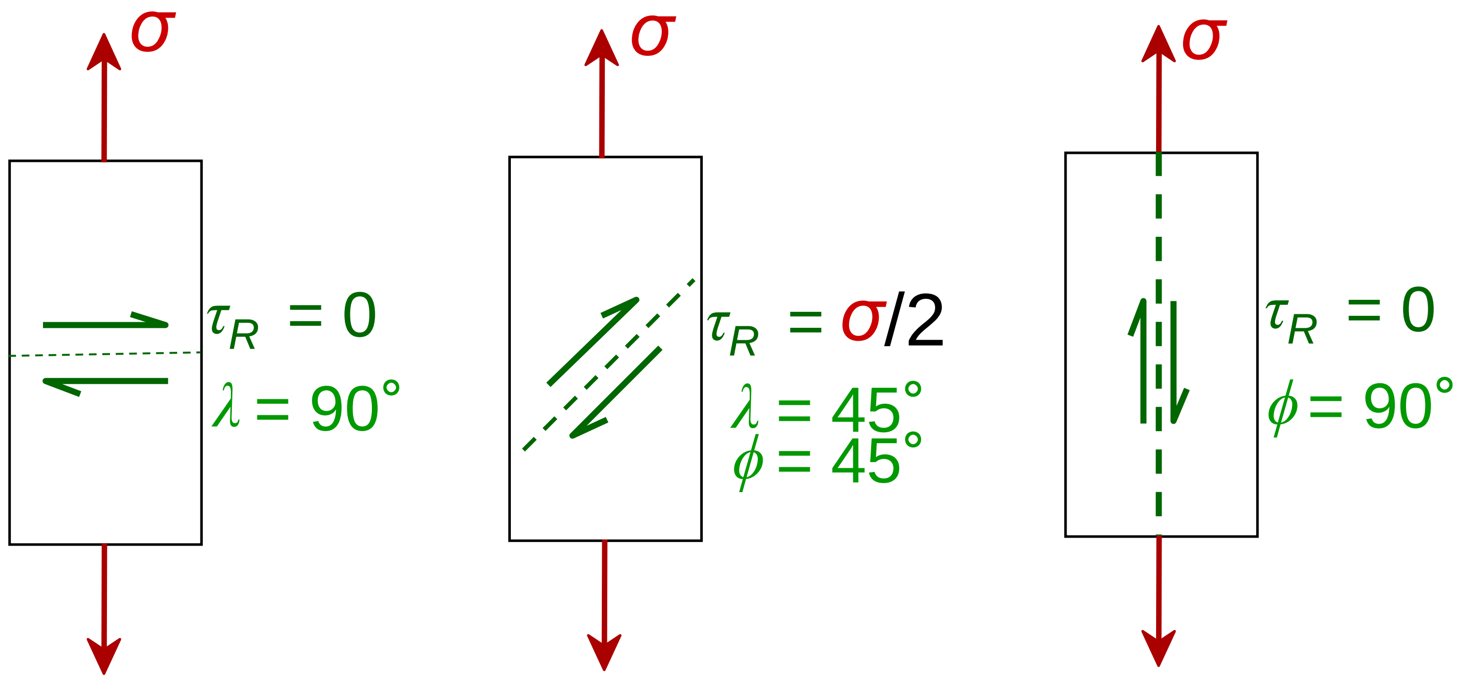
$$\tau_c = \sigma_0 \cos\phi \cos\lambda = M\sigma_0$$

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

M=Schmid factor

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

The τ_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 τ_R(max):



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

(3) τ maximum at $\lambda = \phi = 45°$

: 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: $\boldsymbol{\sigma_y = 2\tau_{CRSS}}$

c. Single Crystal Slip

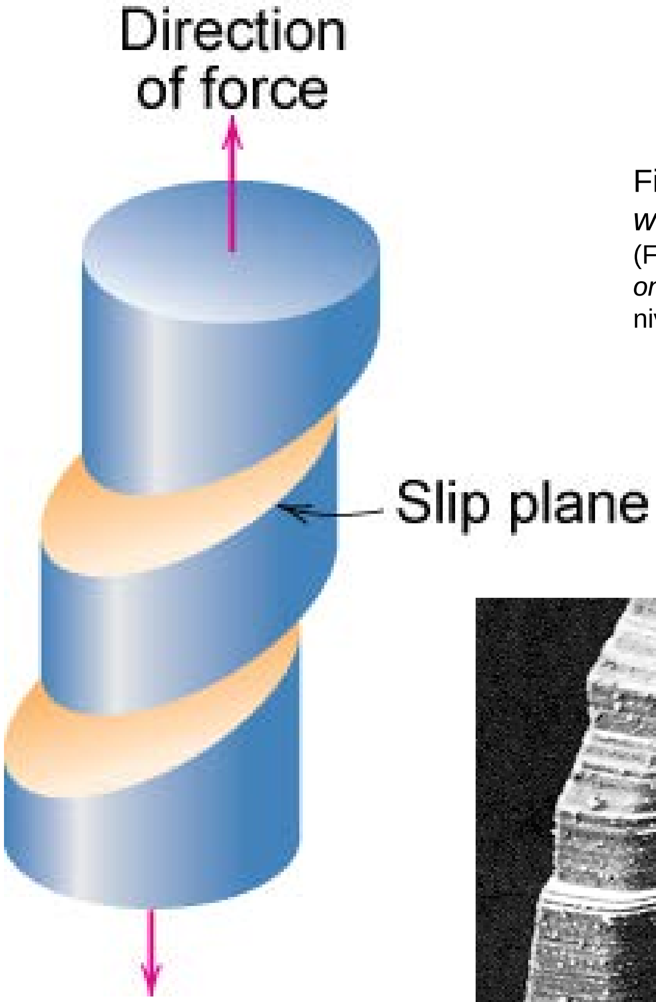


Fig. 9.8, *Callister & Rethwisch 9e.*

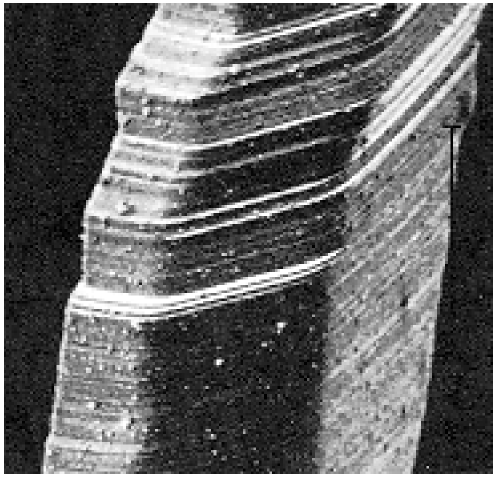
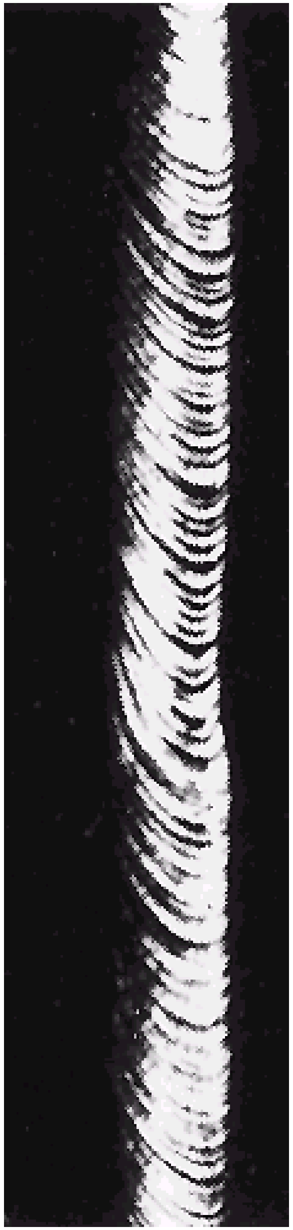


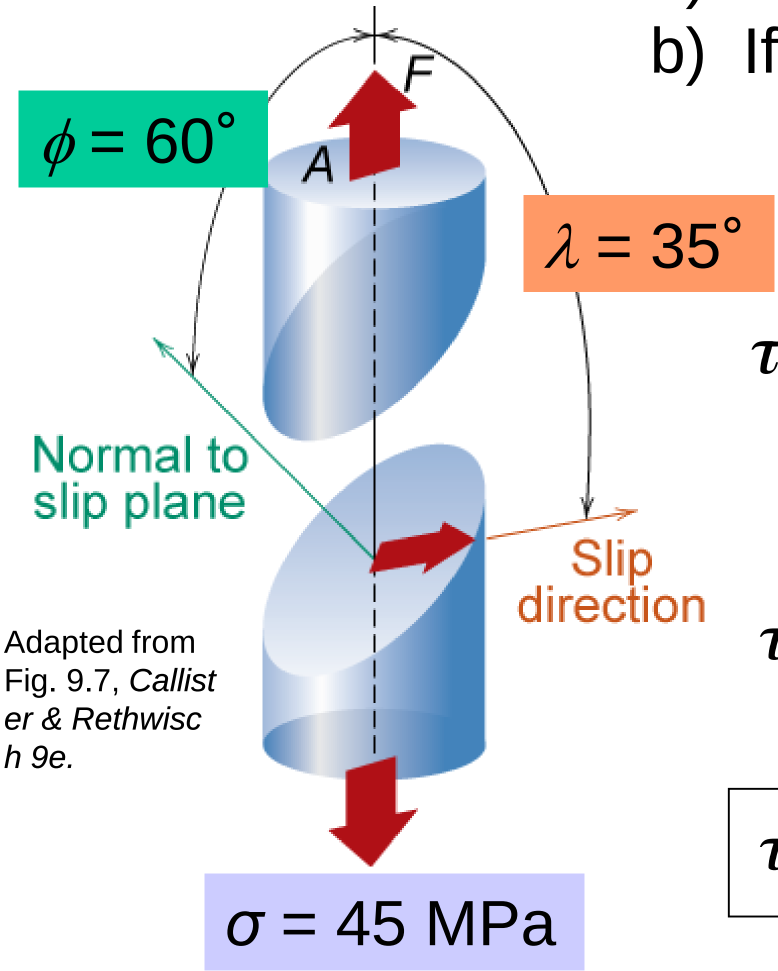
Fig. 9.9, *Callister & Rethwisch 9e.*
(From C. F. Elam, *The Distortion of Metal Crystals*, Oxford University Press, London, 1935.)



Ex: Deformation of single crystal

a) Will the single crystal yield?

b) If not, what stress is needed?



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

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

CRSS: Shear stress to initiate deformation

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

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

$$\tau = (45 \text{ MPa})\,(\cos 35^\circ)(\cos 60^\circ)$$

$$= (45 \text{ MPa})\,(0.41)$$

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

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

Ex: Deformation of single crystal (Cont.)

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

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

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

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

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

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

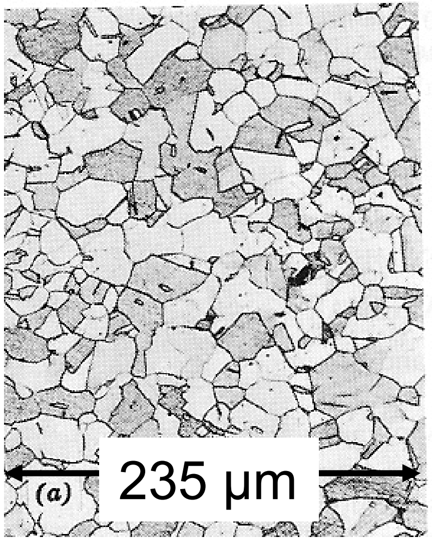
- Polycrystals stronger than single crystals – grain boundaries are barriers to dislocation motion.

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].)

(1) Anisotropy in σ_y

- Can be induced by rolling a polycrystalline metal

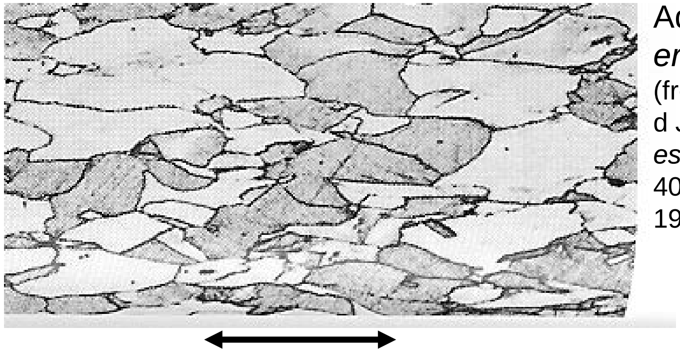
- before rolling



- isotropic

since grains are equiaxed & randomly oriented.

- after rolling



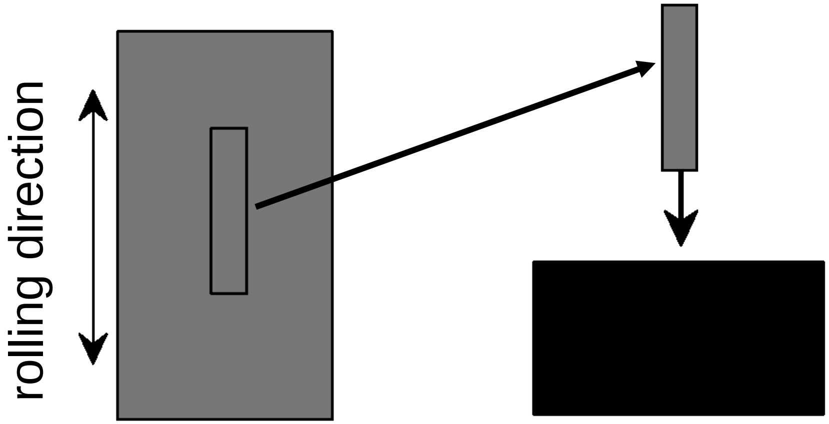
- anisotropic

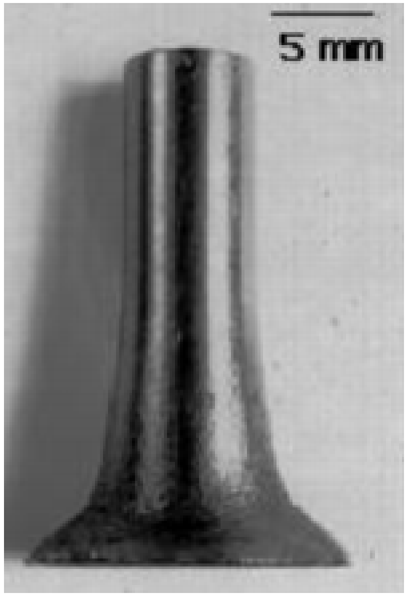
since rolling affects grain orientation and shape.

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.)

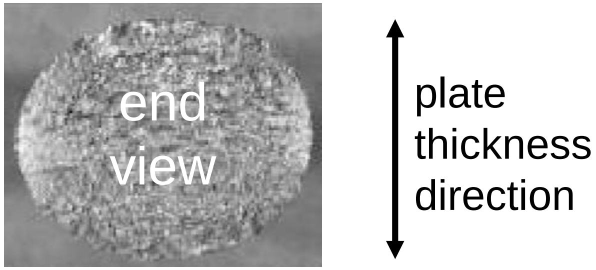
(2) Anisotropy in Deformation

1. Cylinder of tantalum machined from a rolled plate:
2. Fire cylinder at a target.
3. Deformed cylinder





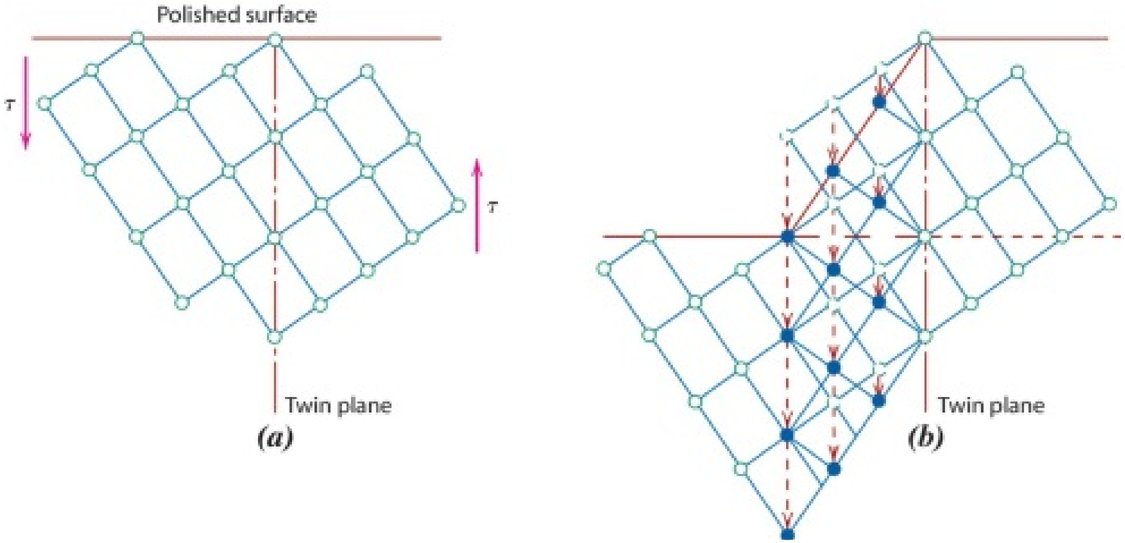
Photos courtesy of G. T. Gray III, Los Alamos National Labs. Used with permission.



- 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.



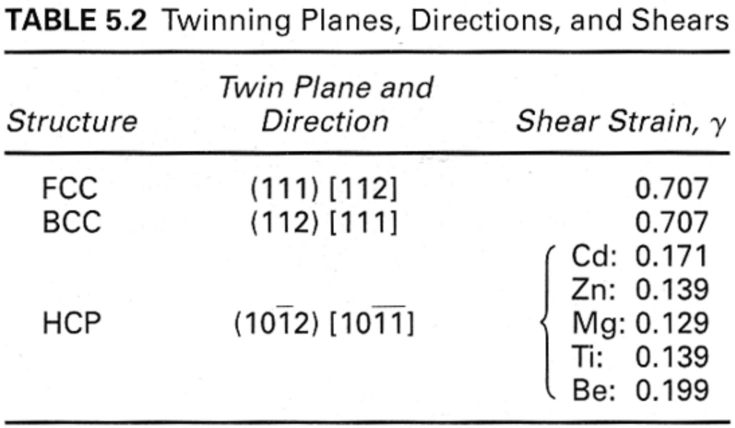


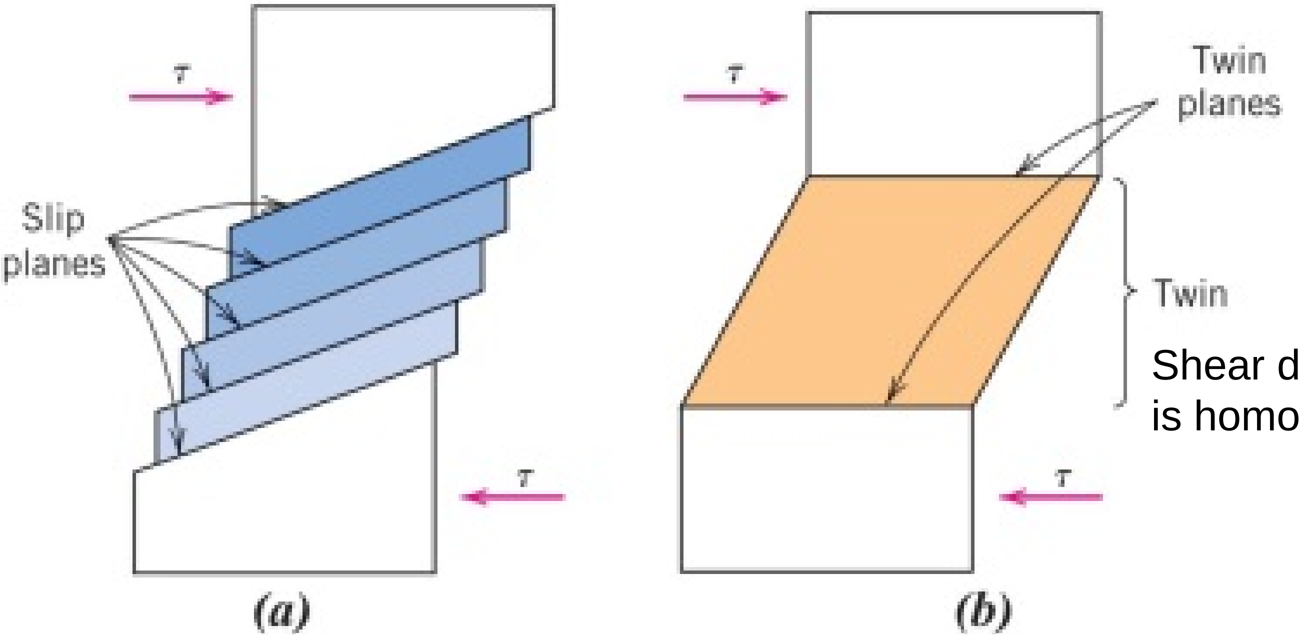
TABLE 5.2 Twinning Planes, Directions, and Shears

Structure	*Twin Plane and Direction*	*Shear Strain, γ*
FCC	$(111)\,[11\bar{2}]$	0.707
BCC	$(112)\,[\bar{1}\bar{1}1]$	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; 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 ***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

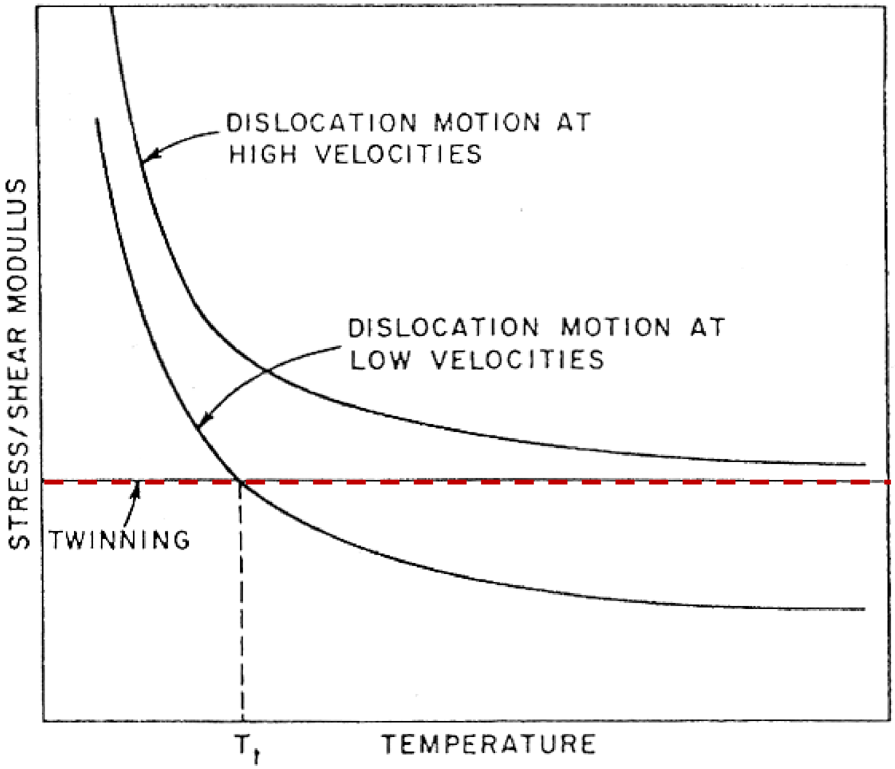


Figure 5.18 Effect of temperature on the stress required for twinning and slip (at low and high strain rates). (Courtesy of G. Thomas)

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**; 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.

Summary

- 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**

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

- 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.