



Material Science

ME 221

Fall 2020

Dr. Raed Alharbi

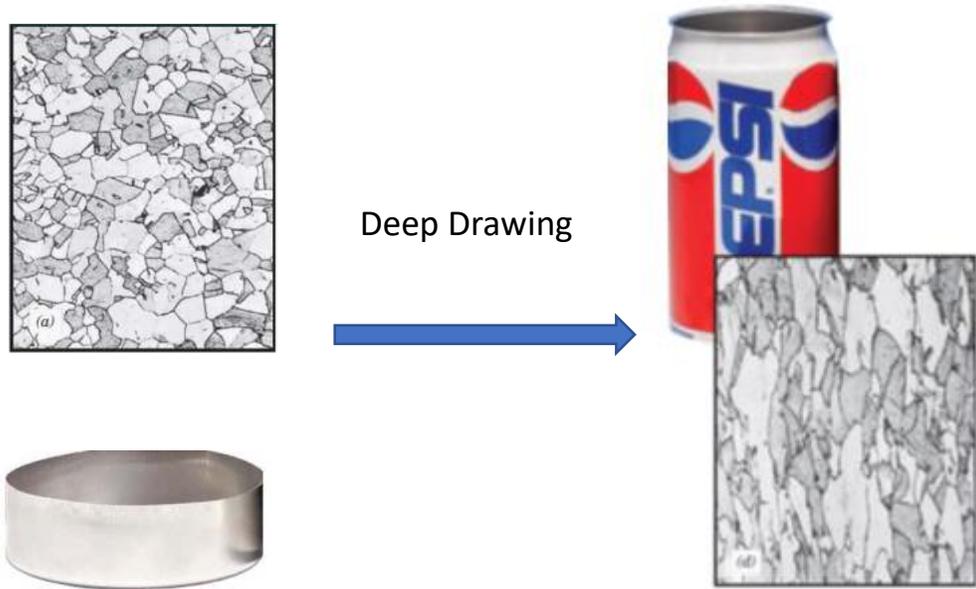


Chapter 7: Dislocations and Strengthening Mechanisms

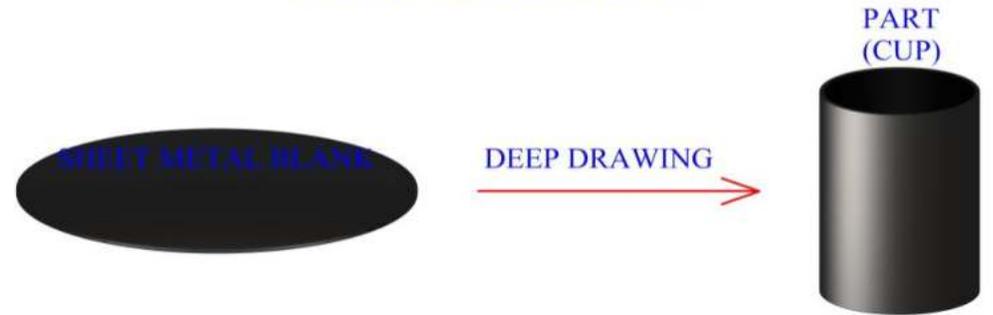
- **INTRODUCTION**
- **DISLOCATIONS AND PLASTIC DEFORMATION**
- **CHARACTERISTICS OF DISLOCATIONS**
- **SLIP SYSTEMS**



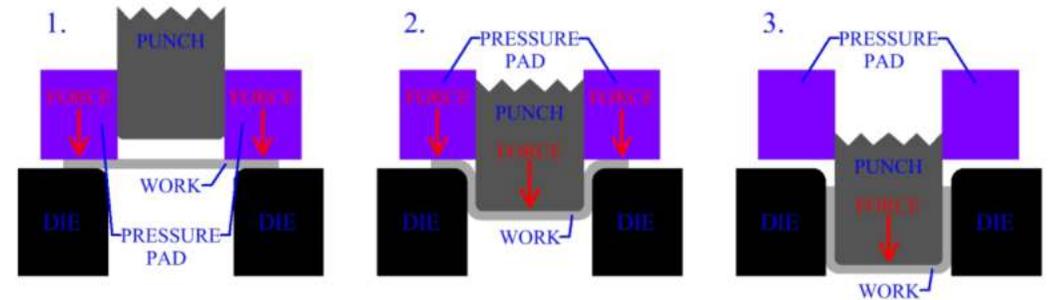
Introduction



DEEP DRAWING



DEEP DRAWING OF SHEET METAL





Introduction

- It is possible to design and tailor the mechanical properties of materials.
 - For example: the strength or toughness of a metal

Processing/Structure/Properties/Performance



Introduction

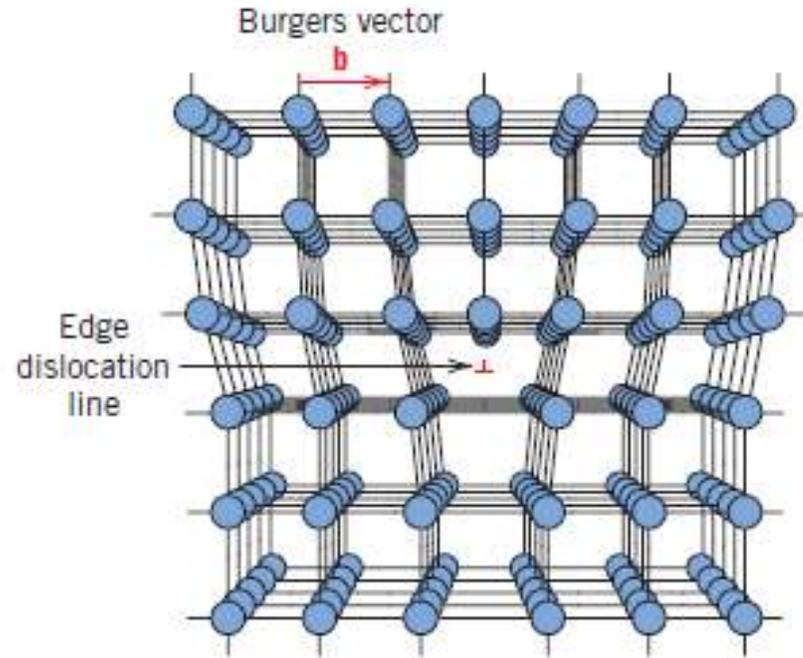
- In Chapter 6: Elastic and Plastic deformations.
- Plastic deformation (on a microscopic scale): movement of large numbers of atoms in response to an applied stress.
 - Interatomic bonds ruptured and then re-formed

Plastic deformation (In crystalline solids) involves motion of dislocations, linear crystalline defects.

Linear Defects: Dislocations (Ch 4)

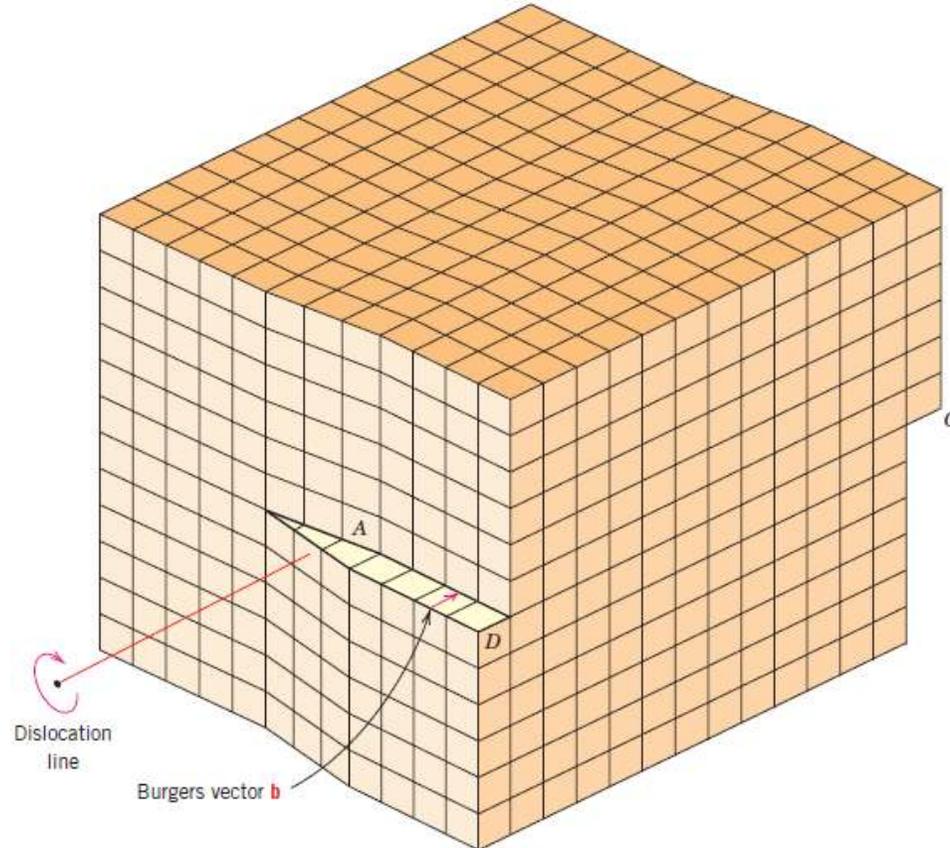
“A *dislocation* is a linear or one-dimensional defect around which some of the atoms are misaligned”

- **Edge dislocation**



Linear Defects: Dislocations (Ch 4)

- Screw dislocation

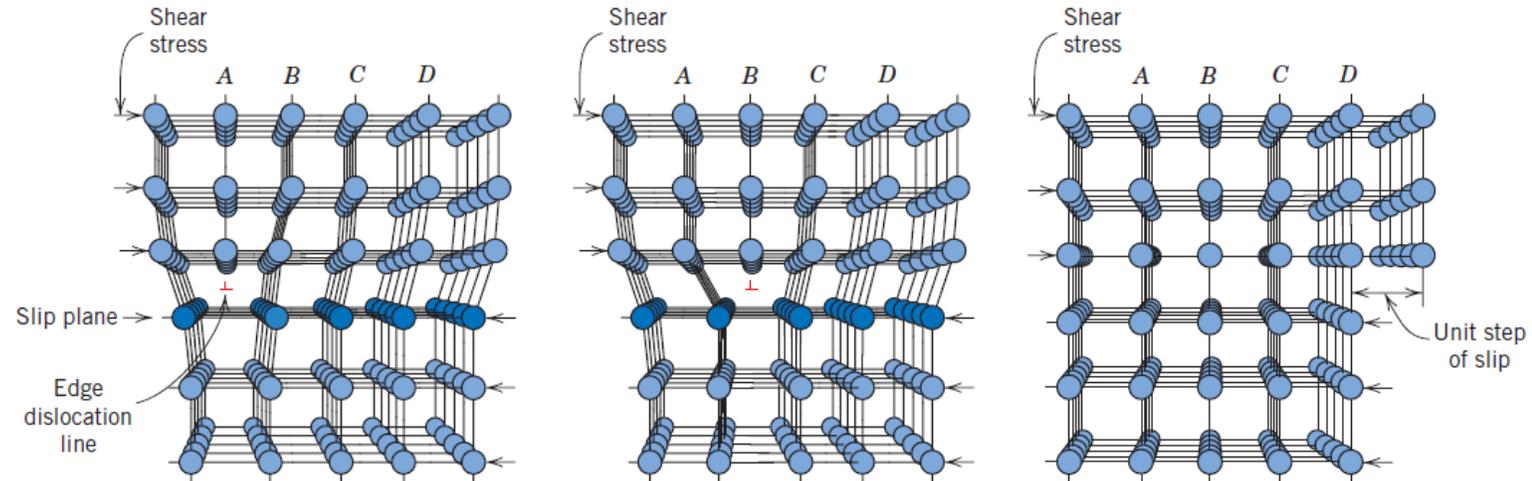




Dislocations and Plastic Deformation

- **BASIC CONCEPTS**

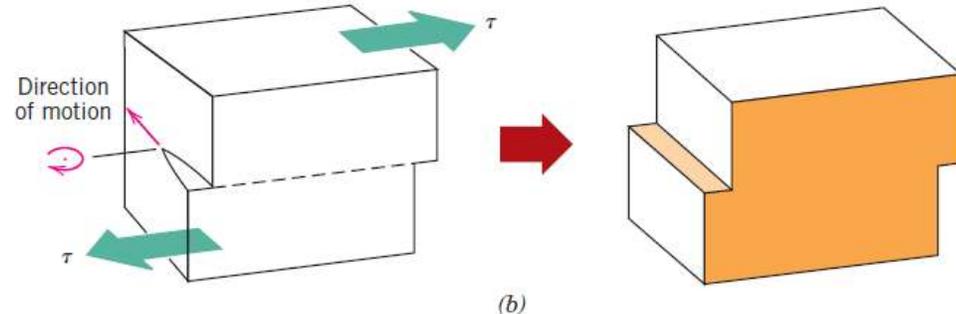
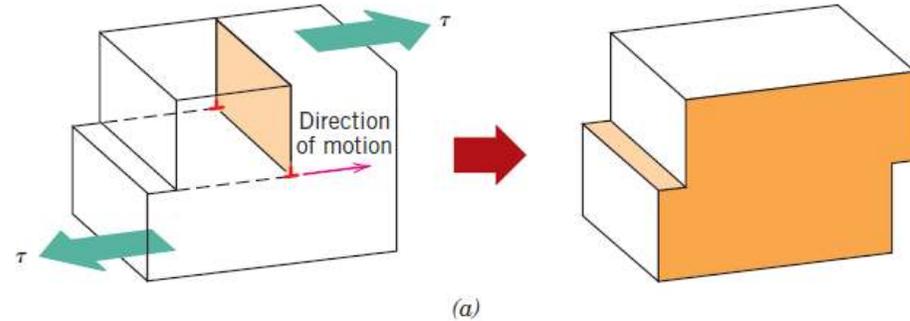
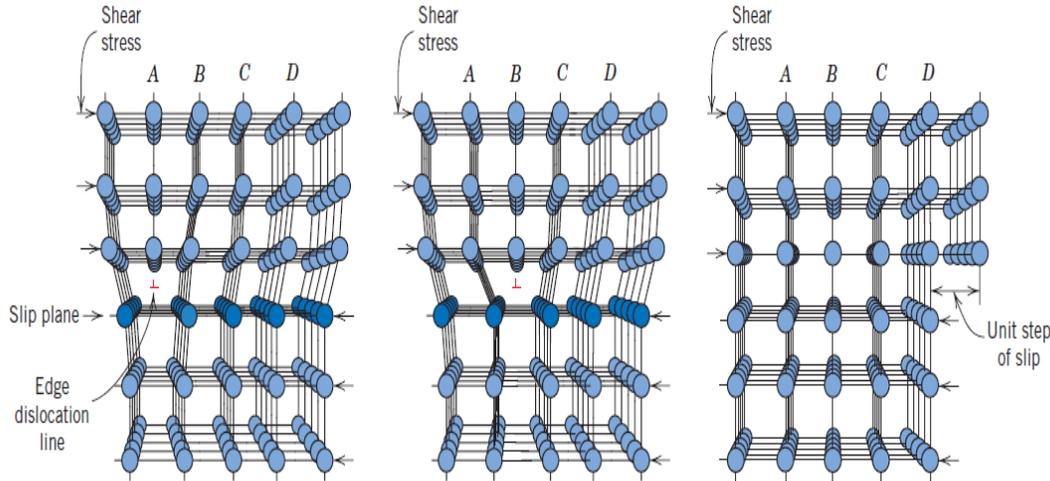
- **Slip:** “process by which plastic deformation is produced by dislocation motion”
- **Slip plane:** “crystallographic plane along which the dislocation line traverses”



Edge dislocation:
localized lattice
distortion exists along
the end of an extra
half-plane of atoms



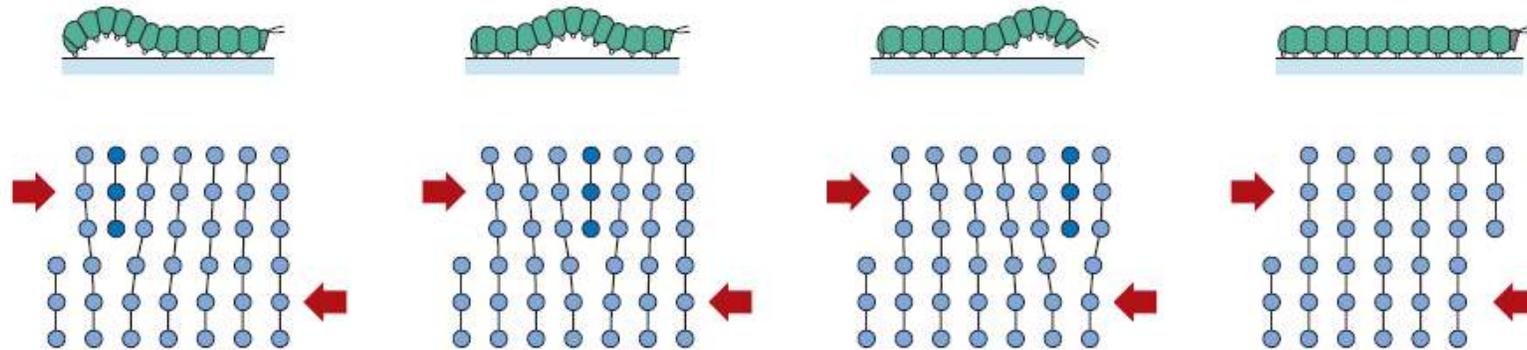
Dislocations and Plastic Deformation



The net plastic deformation for the motion of both dislocation types is the same

The formation of a step on the surface of a crystal by the motion of (a) an edge dislocation and (b) a screw dislocation.

Dislocations and Plastic Deformation



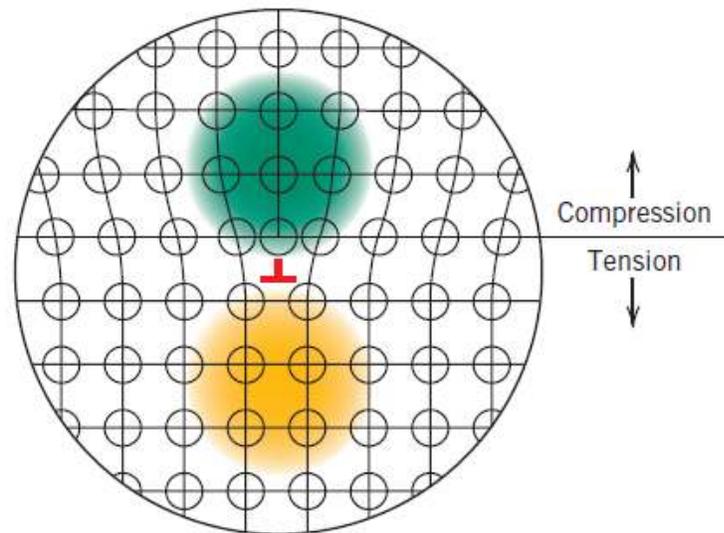
Representation of the analogy between caterpillar and dislocation motion.



CHARACTERISTICS OF DISLOCATIONS

“When metals are plastically deformed, some fraction of the deformation energy (approximately 5%) is retained internally; the remainder is dissipated as heat”

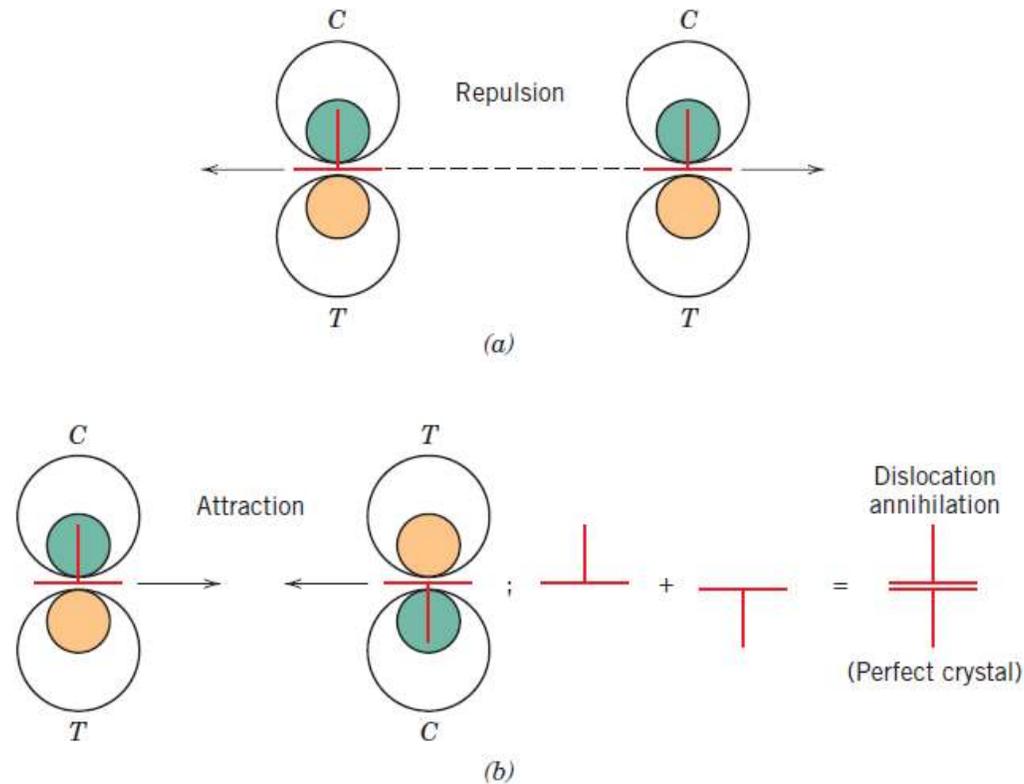
- “major portion of this stored energy is as strain energy associated with dislocations”





CHARACTERISTICS OF DISLOCATIONS

Two edge dislocations lying on the same slip plane





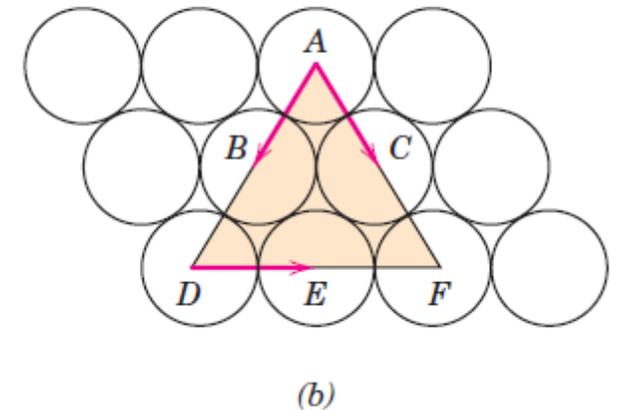
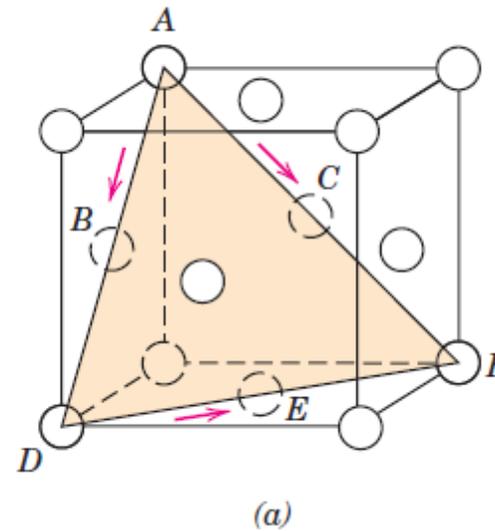
SLIP SYSTEMS

“Dislocations do not move with the same degree of ease on all crystallographic planes of atoms and in all crystallographic directions”

- *slip plane: (preferred plane)* : there are specific directions along which dislocation motion occurs
- *slip direction:* direction of movement.

Slip System = slip plane + slip direction

(a) A $\{111\}$ slip system shown within an FCC unit cell. (b) The (111) plane from (a) and three slip directions (as indicated by arrows) within that plane constitute possible slip systems.

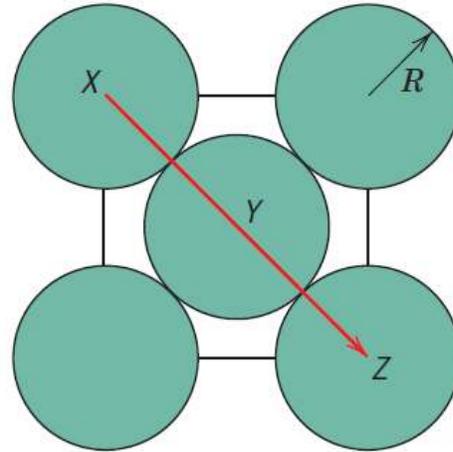
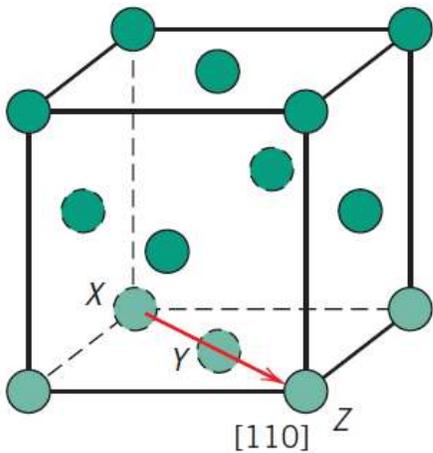




Linear Density (Ch 3)

“number of atoms per unit length whose centers lie on the direction vector for a specific crystallographic direction”

$$LD = \frac{\text{number of atoms centered on direction vector}}{\text{length of direction vector}}$$



$$LD_{110} = \frac{2 \text{ atoms}}{4R} = \frac{1}{2R}$$



Planner Density (Ch 3)

“number of atoms per unit area that are centered on a particular crystallographic plane”

$$PD = \frac{\text{number of atoms centered on a plane}}{\text{area of plane}}$$



SLIP SYSTEMS

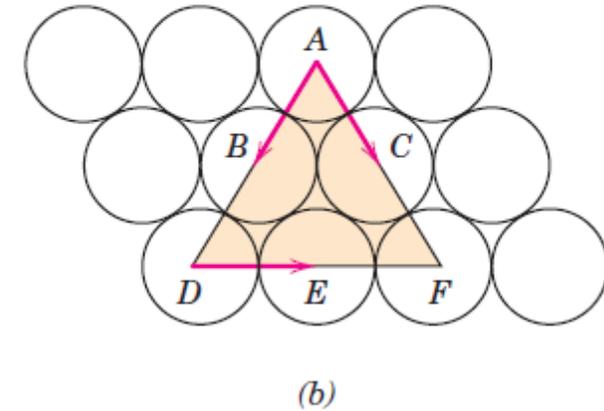
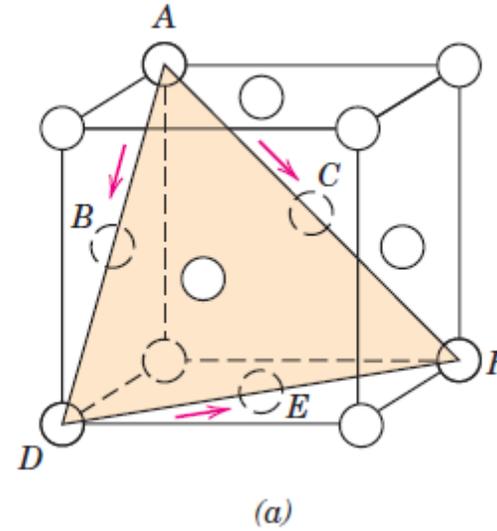
- How to define the slip plane and slip direction for a particular crystal structure?
- **Slip plane:** plane that has the most dense atomic packing (greatest planar density)
- **Slip direction:** direction, in the slip plane, that is most closely packed with atoms (highest linear density).



SLIP SYSTEMS

Slip occurs along $\langle 110 \rangle$ -type directions within the $\{111\}$ planes

Therefore, $\langle 110 \rangle, \{111\}$ represents the slip system for FCC





SLIP SYSTEMS

- Number of slip systems:

“For face-centered cubic (FCC), there are 12 slip systems: four unique {111} planes and, within each plane, three independent $\langle 110 \rangle$ directions”

<i>Metals</i>	<i>Slip Plane</i>	<i>Slip Direction</i>	<i>Number of Slip Systems</i>
	Face-Centered Cubic		
Cu, Al, Ni, Ag, Au	{111}	$\langle \bar{1}10 \rangle$	12
	Body-Centered Cubic		
α -Fe, W, Mo	{110}	$\langle \bar{1}11 \rangle$	12
α -Fe, W	{211}	$\langle \bar{1}11 \rangle$	12
α -Fe, K	{321}	$\langle \bar{1}11 \rangle$	24
	Hexagonal Close-Packed		
Cd, Zn, Mg, Ti, Be	{0001}	$\langle 11\bar{2}0 \rangle$	3
Ti, Mg, Zr	{1010}	$\langle 11\bar{2}0 \rangle$	3
Ti, Mg	{1011}	$\langle 11\bar{2}0 \rangle$	6



SLIP SYSTEMS

- From the number of slip system, it is possible to indicate the ductility of material.
- Larger number of slip system → extensive plastic deformation is normally possible → ductile material (and vice versa lower number of slip system, brittle material)
- Metals with FCC or BCC crystal structures → quite ductile
- HCP metals → quite brittle



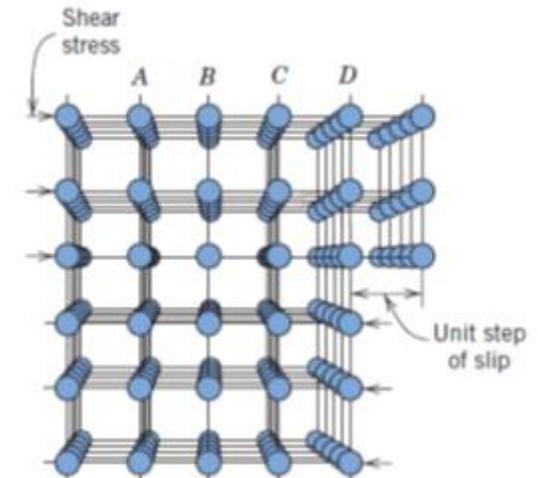
SLIP SYSTEMS

- Burgers vector (**b**):
 - Its direction corresponds to a dislocation's slip direction
 - its magnitude is equal to the unit slip distance.
- Therefore, the direction and the magnitude of **b** will depend on crystal structure.

$$\mathbf{b}(\text{FCC}) = \frac{a}{2} \langle 110 \rangle$$

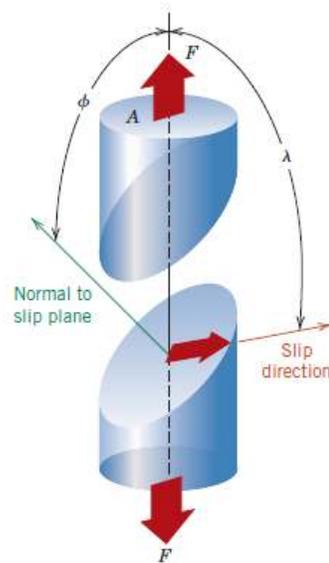
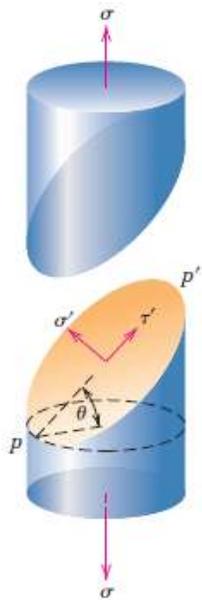
$$\mathbf{b}(\text{BCC}) = \frac{a}{2} \langle 111 \rangle$$

$$\mathbf{b}(\text{HCP}) = \frac{a}{3} \langle 11\bar{2}0 \rangle$$



SLIP IN SINGLE CRYSTALS

Resolved shear stresses: “even though an applied stress may be pure tensile (or compressive), shear components exist at all but parallel or perpendicular alignments to the stress direction”



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

$$\phi + \lambda \neq 90^\circ$$



SLIP IN SINGLE CRYSTALS

- A metal single crystal has a number of different slip systems
 - Because they have different orientations, the resolved shear stress normally differs for each one

“most favorably slip system is the one has the largest resolved shear stress”

$$\tau_R(\max) = \sigma(\cos \phi \cos \lambda)_{\max}$$



SLIP IN SINGLE CRYSTALS

Critical resolved shear stress: minimum shear stress required to initiate slip

- it determines when yielding occurs.
- Plastic deformation or yields start when :

$$\tau_R(\max) = \tau_{\text{crss}}$$

Applied stress required to initiate yielding

$$\sigma_y = \frac{\tau_{\text{crss}}}{(\cos \phi \cos \lambda)_{\max}}$$

Minimum stress necessary to introduce yielding occurs when:

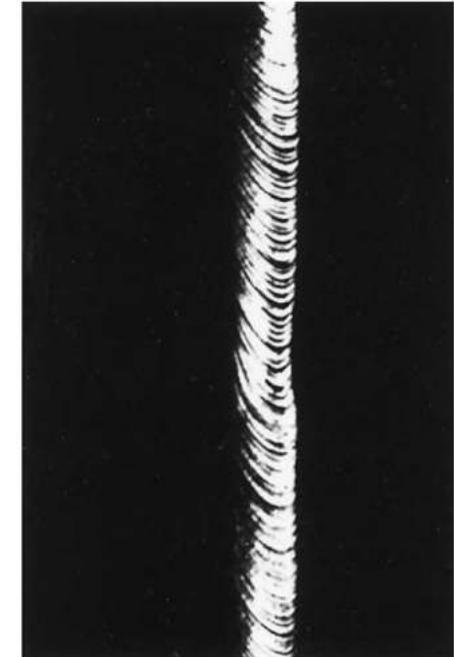
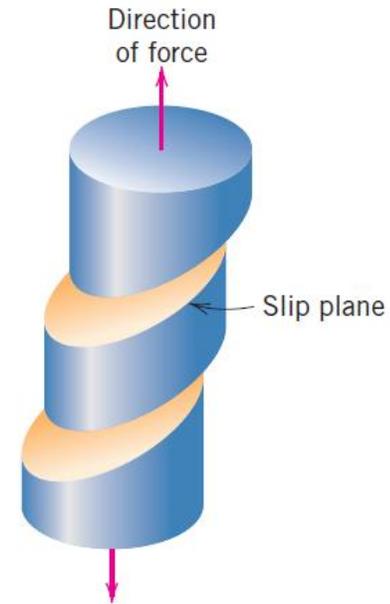
$$\longrightarrow \sigma_y = 2\tau_{\text{crss}}$$

$$\phi = \lambda = 45^\circ$$



SLIP IN SINGLE CRYSTALS

FCC and BCC metals have large number of slip system; so, with continued extension of a single crystal, both the number of slip lines and the slip step width will increase (Plastic deformation, ductile material)



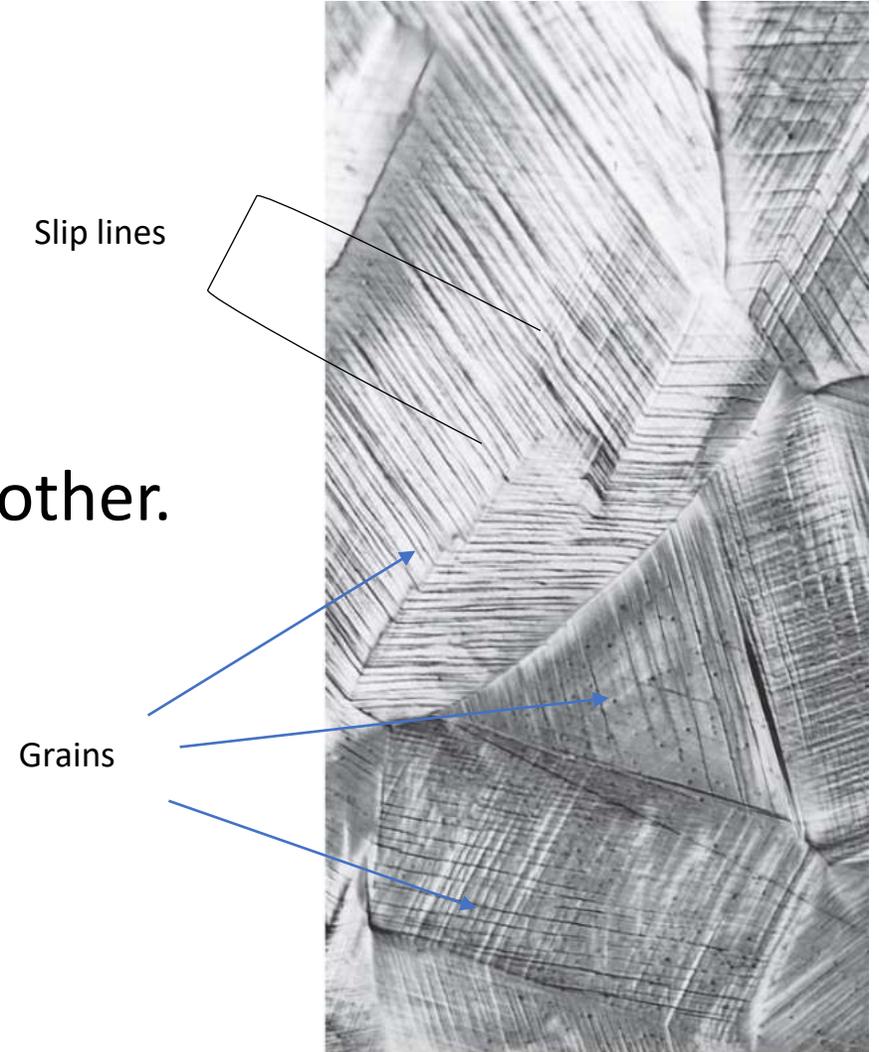
Slip in a zinc single crystal



PLASTIC DEFORMATION OF POLYCRYSTALLINE MATERIALS

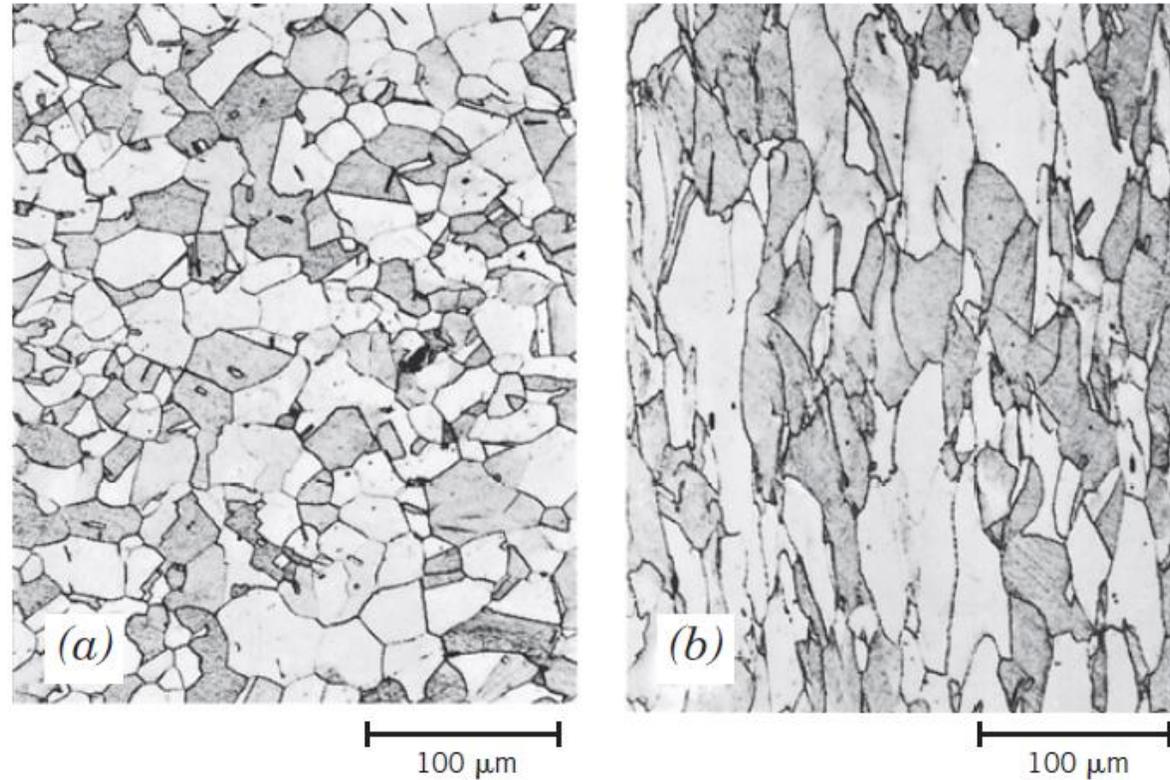
“Deformation and slip in polycrystalline materials is somewhat more complex”

The direction of slip varies from one grain to another.



100 μm

PLASTIC DEFORMATION OF POLYCRYSTALLINE MATERIALS





Mechanisms of Strengthening in Metals

“The ability of a metal to plastically deform depends on the ability of dislocations to move”

Restricting or reducing dislocation mobility produce a harder and stronger material → Strengthening process

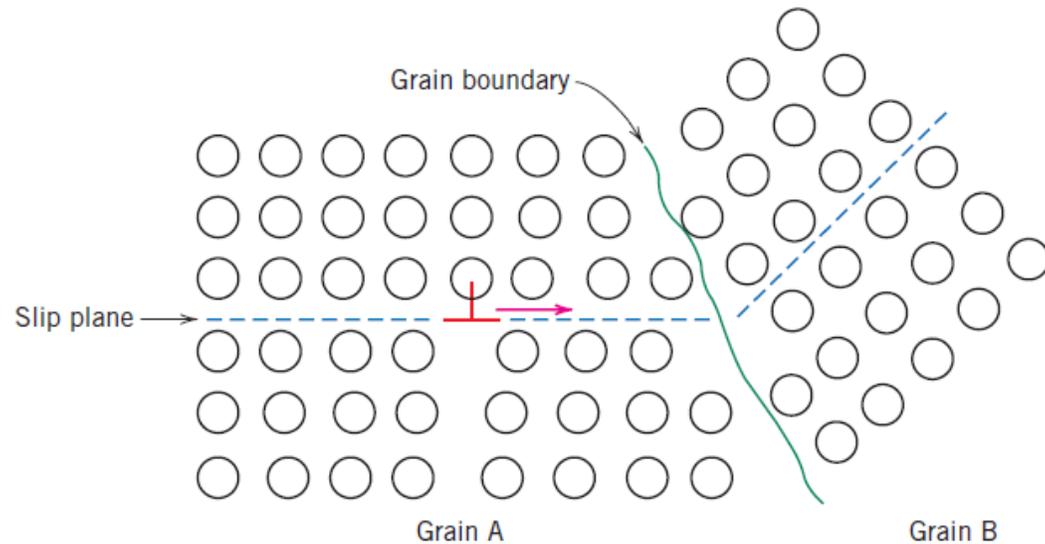
Strengthening Mechanisms:

- Grain size reduction
- Solid-solution alloying
- Strain hardening



STRENGTHENING BY GRAIN SIZE REDUCTION

“Because the two grains are of different orientations, a dislocation passing into grain B will have to change its direction of motion; this becomes more difficult as the crystallographic misorientation increases”

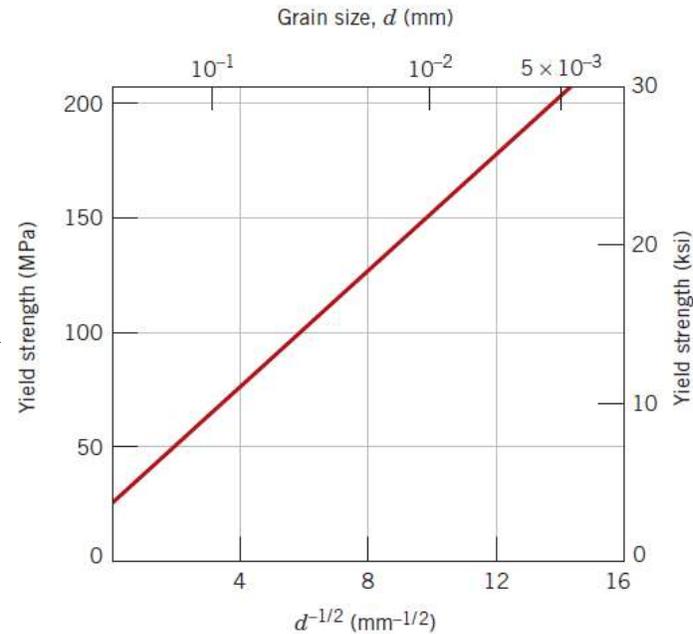


“A fine-grained material (one that has small grains) is harder and stronger than one that is coarse grained, because the former has a greater total grain boundary area to impede dislocation motion”



STRENGTHENING BY GRAIN SIZE REDUCTION

The influence of grain size on the yield strength of a 70 Cu–30 Zn brass alloy



Hall–Petch equation

d is the average grain diameter

σ_0 and k_y are constants for a particular material

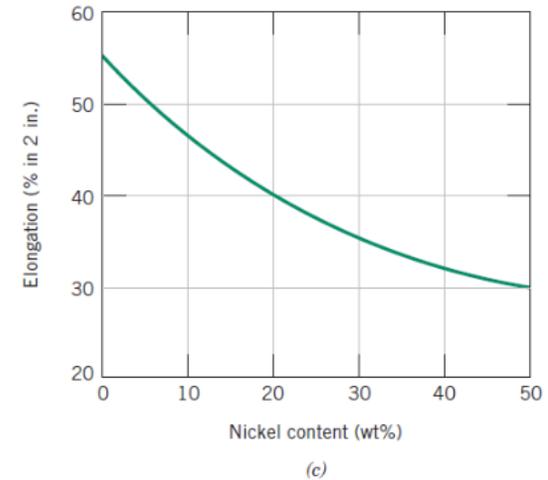
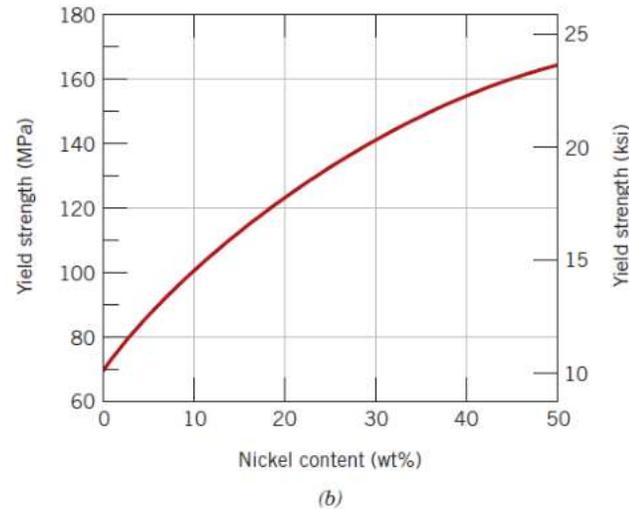
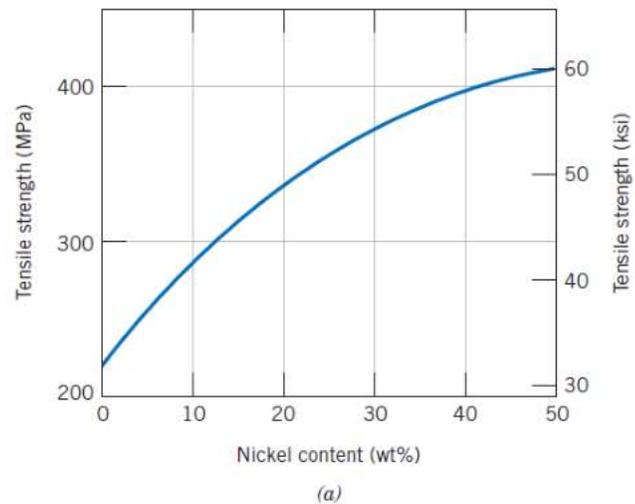
$$\sigma_y = \sigma_0 + k_y d^{-1/2}$$



SOLID-SOLUTION STRENGTHENING

- Alloying metal with impurity atoms that go into either substitutional or interstitial solid solution.

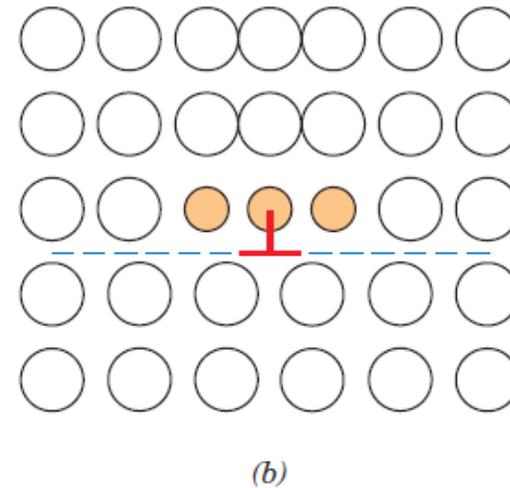
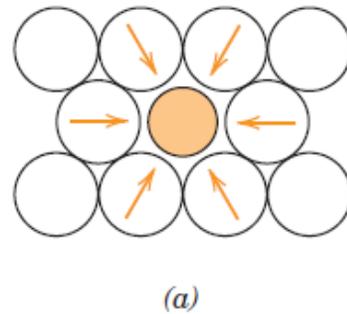
“High-purity metals are almost always softer and weaker than alloys composed of the same base metal”



Variation with nickel content of (a) tensile strength, (b) yield strength, and (c) ductility (%EL) for copper–nickel alloys, showing strengthening.

SOLID-SOLUTION STRENGTHENING

Impurity atoms restrict dislocation movement





STRAIN HARDENING

“**Strain hardening** is the phenomenon whereby a ductile metal becomes harder and stronger as it is plastically deformed” “Ductility reduction”

- Also called:
 - *work hardening*
 - *Cold working* : “temperature at which deformation takes place is “cold” relative to the absolute melting temperature of the metal”



STRAIN HARDENING

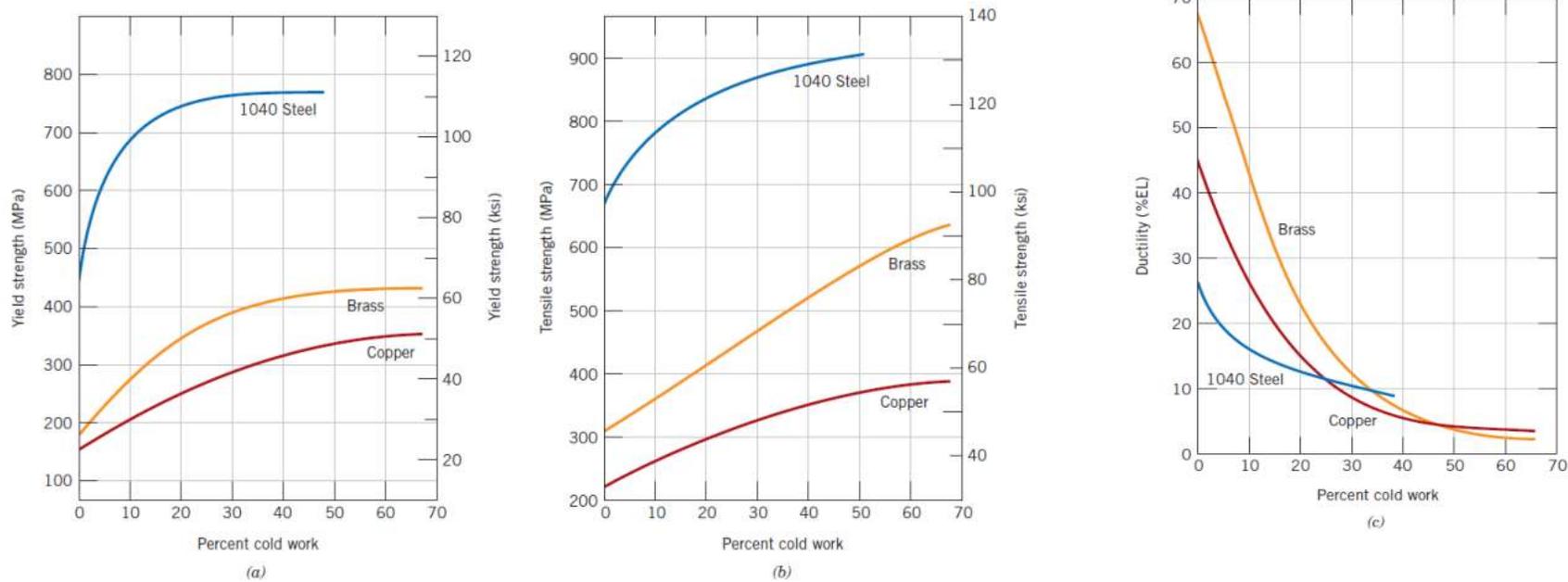
Degree of plastic deformation is express as *percent cold work(%CW)*:

$$\%CW = \left(\frac{A_0 - A_d}{A_0} \right) \times 100$$

A_0 is the original area of the cross section that experiences deformation and A_d is the area after deformation



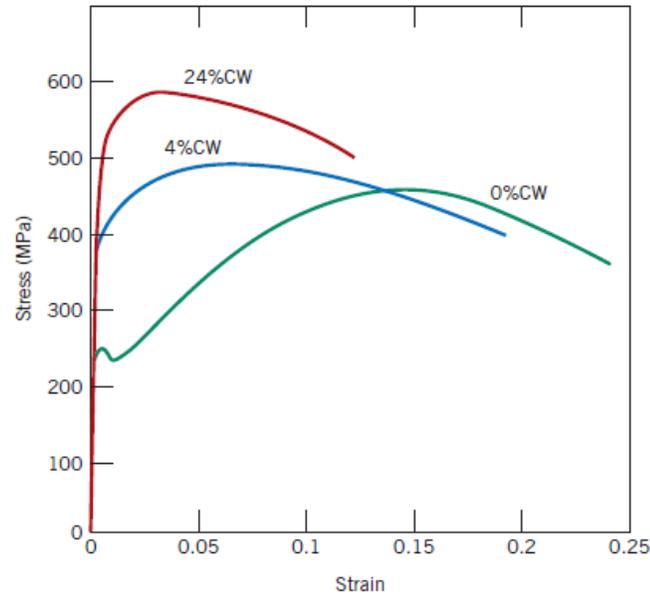
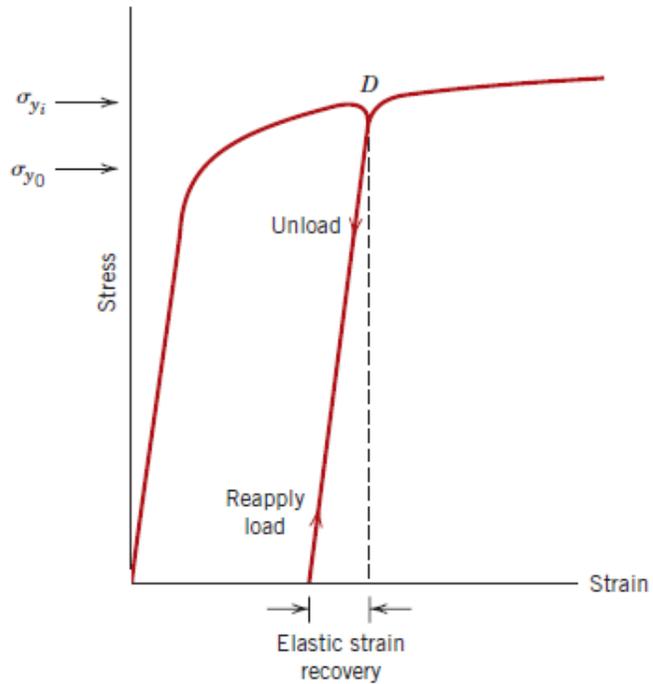
STRAIN HARDENING



For 1040 steel, brass, and copper, (a) the increase in yield strength, (b) the increase in tensile strength, and (c) the decrease in ductility (%EL) with percent cold work.



STRAIN HARDENING



The dislocation density in a metal increases with deformation or cold work

As a result, increasing in the resistance to dislocation motion