ENGINEERING MATERIALS I(ME 281)

DISLOCATION AND STRENGTHENING MECHANISMS

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Outline

❖ Dislocations and Plastic Deformation

✓ Mechanisms of plastic deformation in metals

❖ Strengthening mechanisms

✓ Grain Size Reduction

✓ Solid Solution Strengthening

✓ Strain Hardening

❖ Recovery, Recrystallization, and Grain Growth

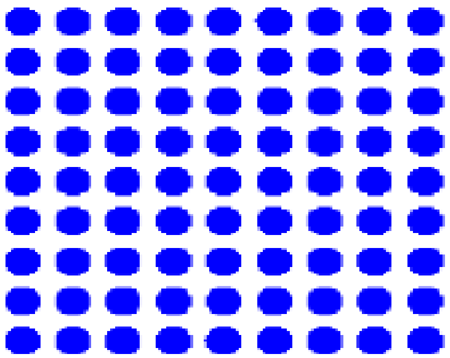
Learning Objectives

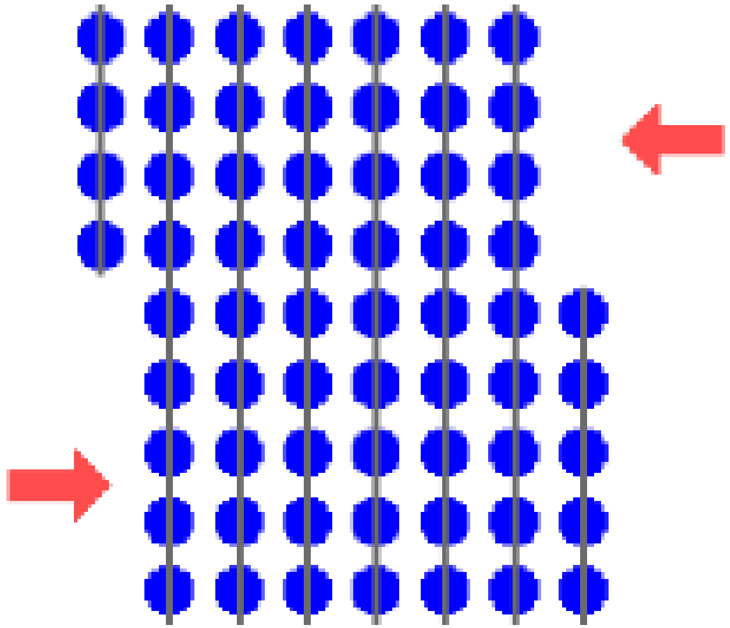
After studying this topic, you should be able to do the following:

- Explain the mechanics of dislocation motion in relation to plastic deformation.
- Describe slip and twinning mechanisms of plastic deformation.
- Define slip system and cite examples.
- Explain grain size reduction and solid solution strengthening mechanisms in metals.
- Describe the phenomenon of strain hardening (or cold working) in terms of dislocations and strain field interactions.
- Explain the processes of recovery, and recrystallization grain growth in annealing.

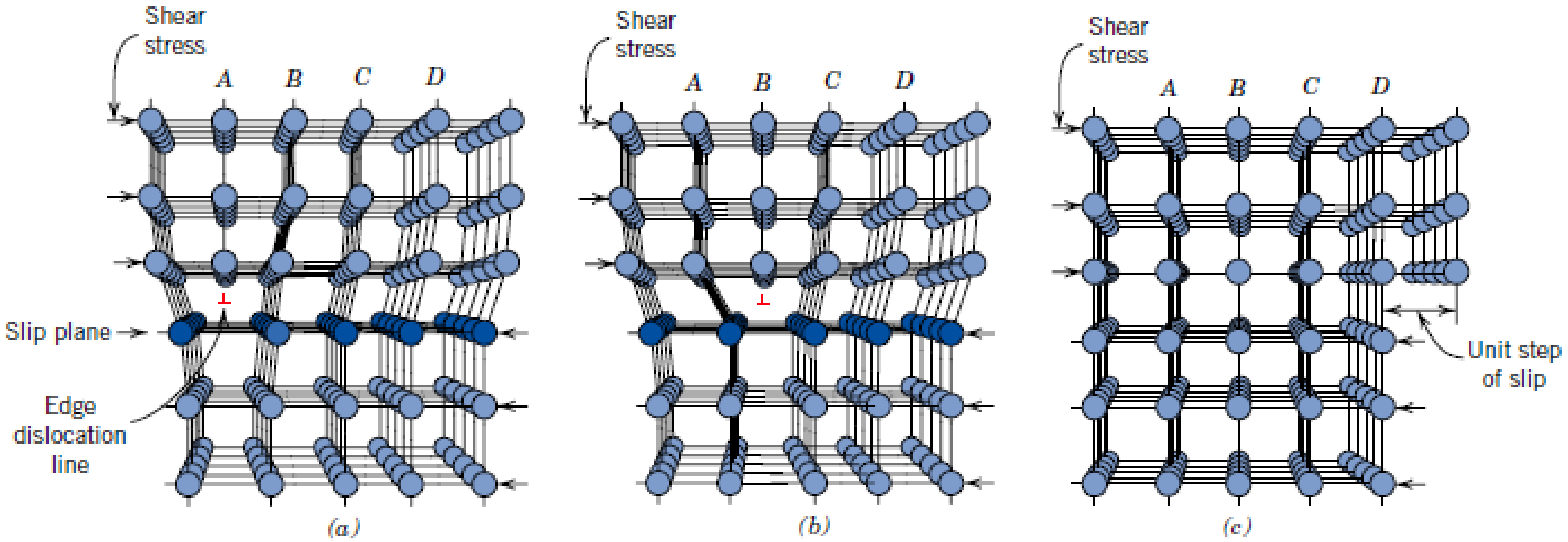
Dislocations and Plastic deformation

- A **dislocation** is a linear crystallographic defect or irregularity within a crystal structure which contains an abrupt change in the arrangement of atoms.
- Plastic deformation involves the relative sliding of atomic planes in organized manner in crystalline solids.
- Dislocations can move under applied external stresses and the cumulative movement of dislocations leads to the gross plastic deformation.
- Dislocation motion, at the microscopic level, involves rupture and reformation of inter-atomic bonds.





Mechanics of Dislocation Motion



(a) The extra half-plane of atoms is labeled A. The shear stress applied forces plane A to the right

(b) The dislocation moves one atomic distance to the right as A links up to the lower portion of plane B; in the process, the upper portion of B becomes the extra half-plane.

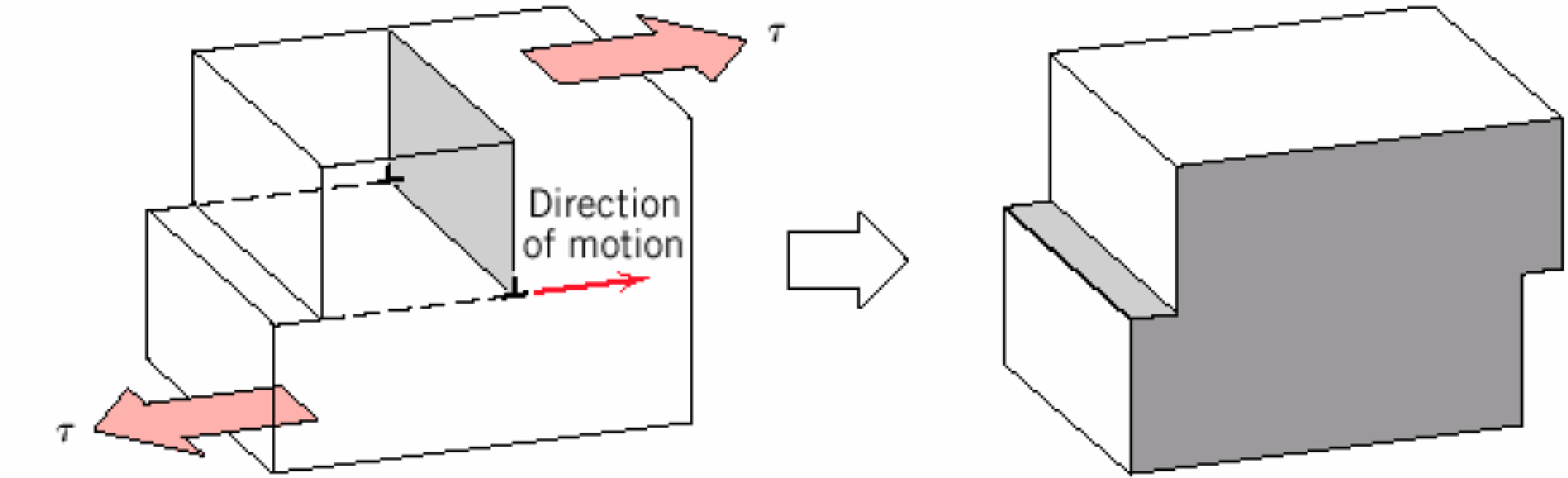
(c) A step forms on the surface of the crystal as the extra half-plane exits.

Mechanics of Dislocation Motion

- ❖ The process by which plastic deformation is produced by dislocation motion is termed slip.
- ❖ The crystallographic plane along which the dislocation line traverses is the slip plane,
- ❖ The onset of plastic deformation involves initial motion of existing dislocations in real crystal.
- ❖ **Intersection of two dislocations results in a sharp break in the dislocation line.**
- ❖ A break in dislocation line moving it out of slip plane is called **jog**.
- ❖ A break in dislocation line that remains in slip plane is called **kink**.
- ❖ Other hindrances to dislocation motion include interstitial and substitutional atoms, foreign particles, grain boundaries, external grain surface, and change in structure due to phase change.
- ❖ The number of dislocations increases dramatically during plastic deformation.
- ❖ As additional movement of dislocations requires increase of stress, material can be said to be strengthened i.e. materials can be strengthened by controlling the motion of dislocation.

Direction of the dislocation motion

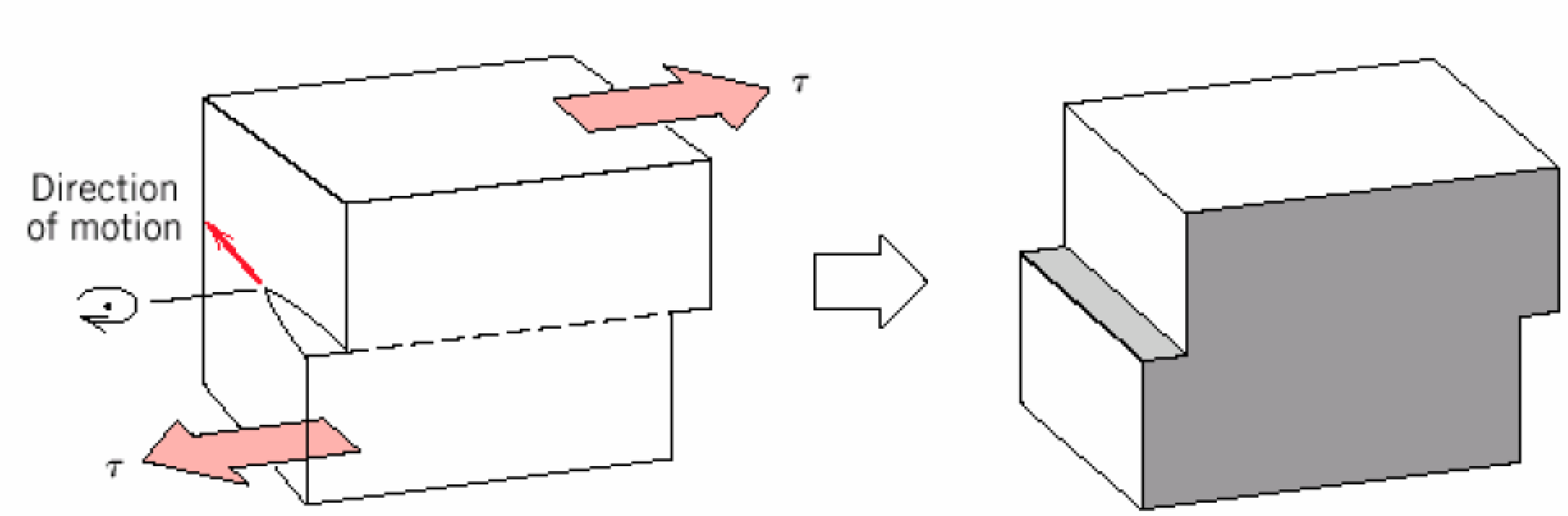
Edge dislocation



- Edge dislocation line moves parallel to applied stress

Direction of the dislocation motion

Screw dislocation



- Screw dislocation line moves perpendicular to applied stress

Mechanisms of Plastic Deformation

- Plastic deformation involves motion of dislocations.
- There are two prominent mechanisms of plastic deformation, namely ***slip*** and ***twinning***.
- Slip occurs when shear stress applied exceeds a critical value.
- During slip each atom usually moves same integral number of atomic distances along the slip plane producing a step, but the orientation of the crystal remains the same.
- In single crystals there are planes where dislocations move (slip planes). Within the slip planes are preferred directions for dislocation movement (slip directions).
- **The set of slip planes and directions constitute slip systems**.
- BCC and FCC crystals have more slip systems as compared to HCP.
  - ✓ This means there are more ways for dislocation to propagate ⇒ FCC and BCC crystals are more ductile than HCP crystals.

Mechanisms of Plastic Deformation

Slip systems for metals with different crystal structures

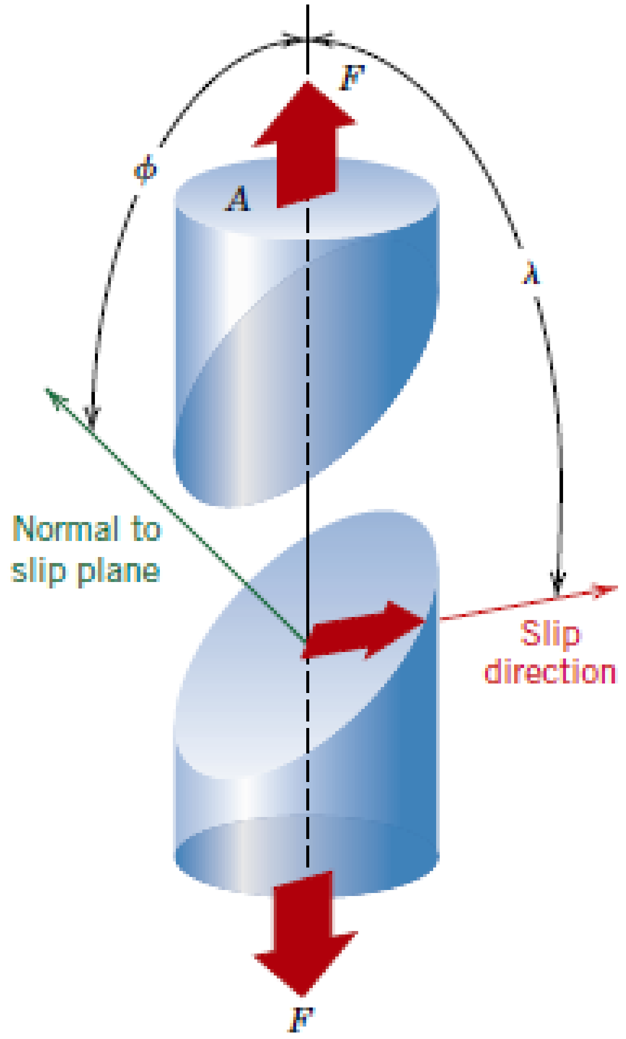
Metals	*Slip Plane*	*Slip Direction*	*Number of Slip Systems*
	Face-Centered Cubic		
Cu, Al, Ni, Ag, Au	$\{111\}$	$\langle 1\bar{1}0 \rangle$	12
	Body-Centered Cubic		
α-Fe, W, Mo	$\{110\}$	$\langle \bar{1}11 \rangle$	12
α-Fe, W	$\{211\}$	$\langle \bar{1}11 \rangle$	12
α-Fe, K	$\{321\}$	$\langle \bar{1}11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

Mechanisms of Plastic Deformation

- Dislocations move in particular directions on particular planes (the slip system) in response to shear stresses applied along these planes and directions.
- There is the need to determine how the applied stress is resolved onto the slip systems.
- **We define the resolved shear stress, τ_R, (which produces plastic deformation) that result from application of a simple tensile stress, σ.**

$$\tau_R = \frac{F\cos\lambda}{A/\cos\phi} = \frac{F\cos\lambda\cos\phi}{A} = \sigma\cos\lambda\cos\phi = \sigma m$$

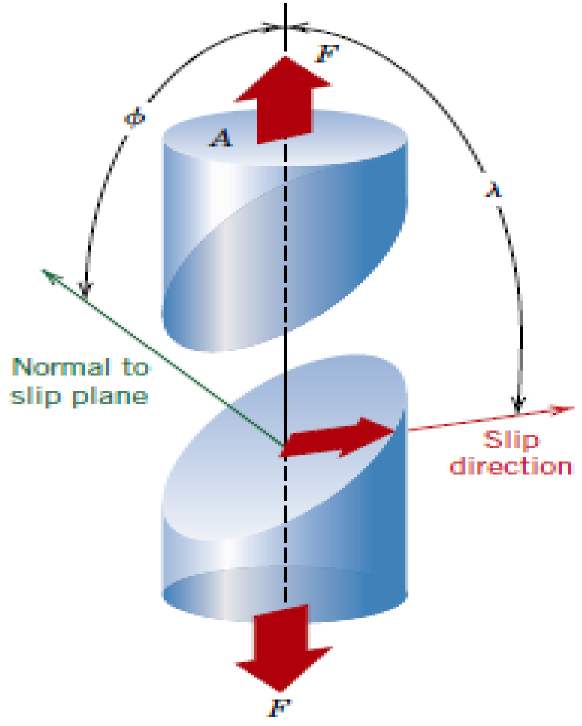
- Where m=cosλcosϕ is the Schmid factor and σ is the applied stress.



Mechanisms of Plastic Deformation

- When the resolved shear stress becomes sufficiently large, the crystal will start to yield (dislocations start to move along the most favorably oriented slip system).
- The onset of yielding corresponds to the yield stress, σ_y.
- **The minimum shear stress required to initiate slip is termed the critical resolved shear stress:**

$$\boxed{\tau_{CRSS} = \sigma_y (\cos\phi \cos\lambda)_{MAX}}$$



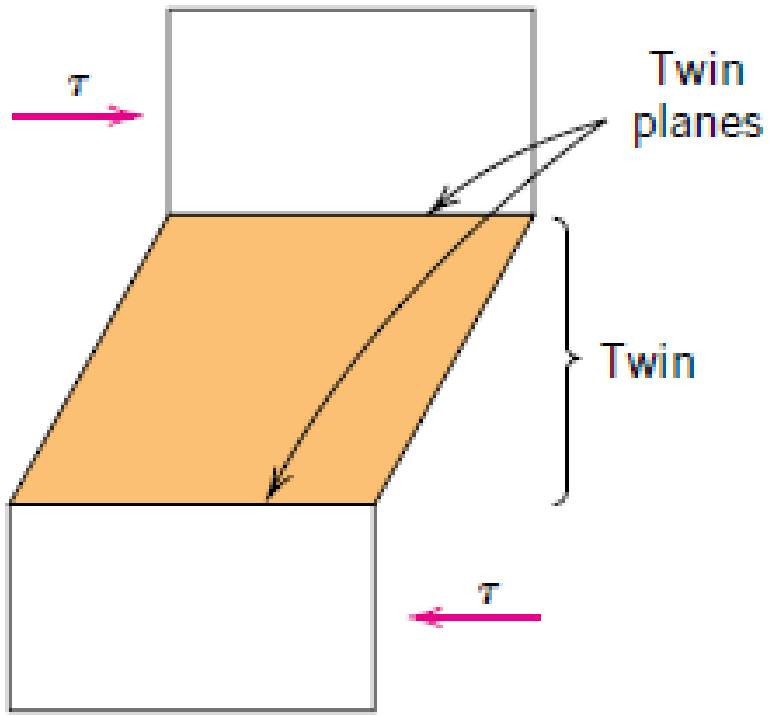
Maximum value of $(\cos\phi \cos\lambda)$ corresponds to

$$\phi = \lambda = 45^{o} \Rightarrow \cos\phi \cos\lambda = 0.5 \Rightarrow \sigma_y = 2\tau_{CRSS}$$

Slip will occur first in slip systems oriented close to these angles ($\varphi = \lambda = 45°$) with respect to the applied stress

Mechanisms of Plastic Deformation

- The second mechanism of plastic deformation is **twinning.**
- It results when a portion of crystal takes up an orientation that is related to the orientation of the rest of the untwined lattice in a definite, symmetrical way.
- **The twinned portion of the crystal is a mirror image of the parent crystal.**
- The plane of symmetry is called twinning plane.
- Each atom in the twinned region moves by a shear a distance proportional to its distance from the twin plane.
- Twinning also occurs in a definite direction on a specific plane for each crystal structure. However, it is not known if there exists resolved shear stress for twinning.
- **Twinning generally occurs when slip is restricted, because the stress necessary for twinning is usually higher than that for slip.**



Mechanisms of Plastic Deformation

❖Comparison of mechanism of plastic deformation.

	During/In Slip	During/In Twinning
Crystal orientation	Same above and below the slip plane	Differ across the twin plane
Size (in terms of inter-atomic distance)	Multiples	Fractions
Occurs on	Widely spread planes	Every plane of region involved
Time required	Milli seconds	Micro seconds
Occurrence	On many slip systems simultaneously	On a particular plane for each crystal

Strengthening Mechanisms in Metals

- The ability of a metal to deform plastically depends on ease of dislocation motion under applied external stresses.
- **Strengthening of a metal involves hindering or restricting dislocation motion.**
- Ordinarily, strengthening reduces ductility.

Strengthening mechanisms in single-phase metals:

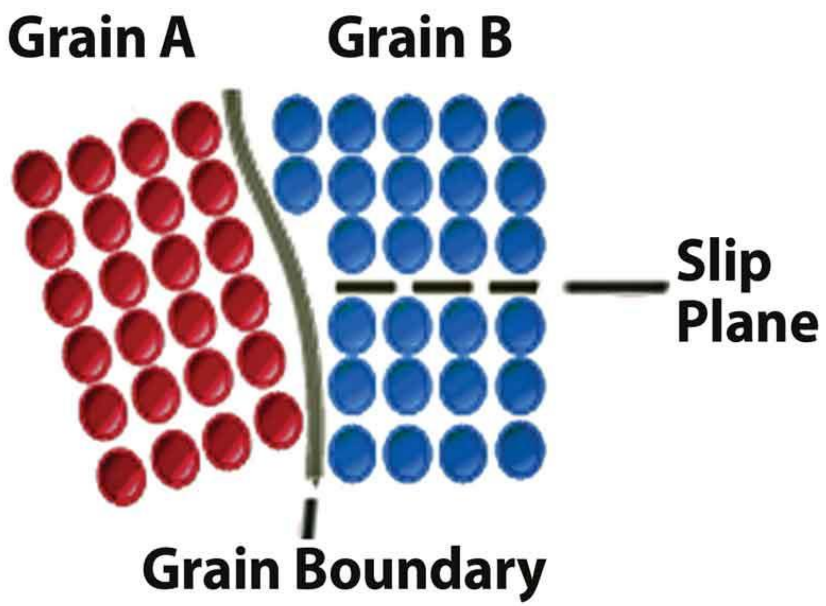
- Grain-size reduction
- Solid-solution alloying
- Strain hardening

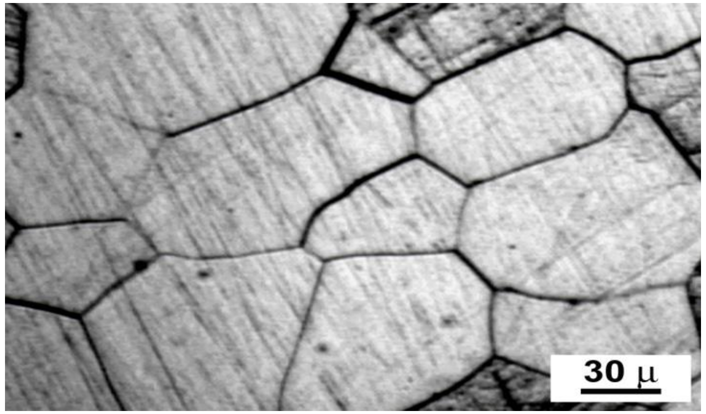
Strengthening mechanisms in multi-phase metals:

- Precipitation and dispersion hardening,
- Fibre strengthening
- Martensitic strengthening

Strengthening by Grain Size Reduction

- Grain boundary barrier to dislocation motion: slip plane discontinues or change orientation.
- Atomic disorder within a grain boundary region will result in a discontinuity of slip planes from one grain into the other.
- Effectiveness of grain boundary depends on its characteristic misalignment, represented by an angle.
- Small angle grain boundaries(misalignment < 1°) are not very effective in blocking dislocations.
- High-angle grain boundaries(misalignment > 5°) block slip and increase strength of the material.
- The smaller the grain size, the more frequent is the pile up of dislocations against each other.



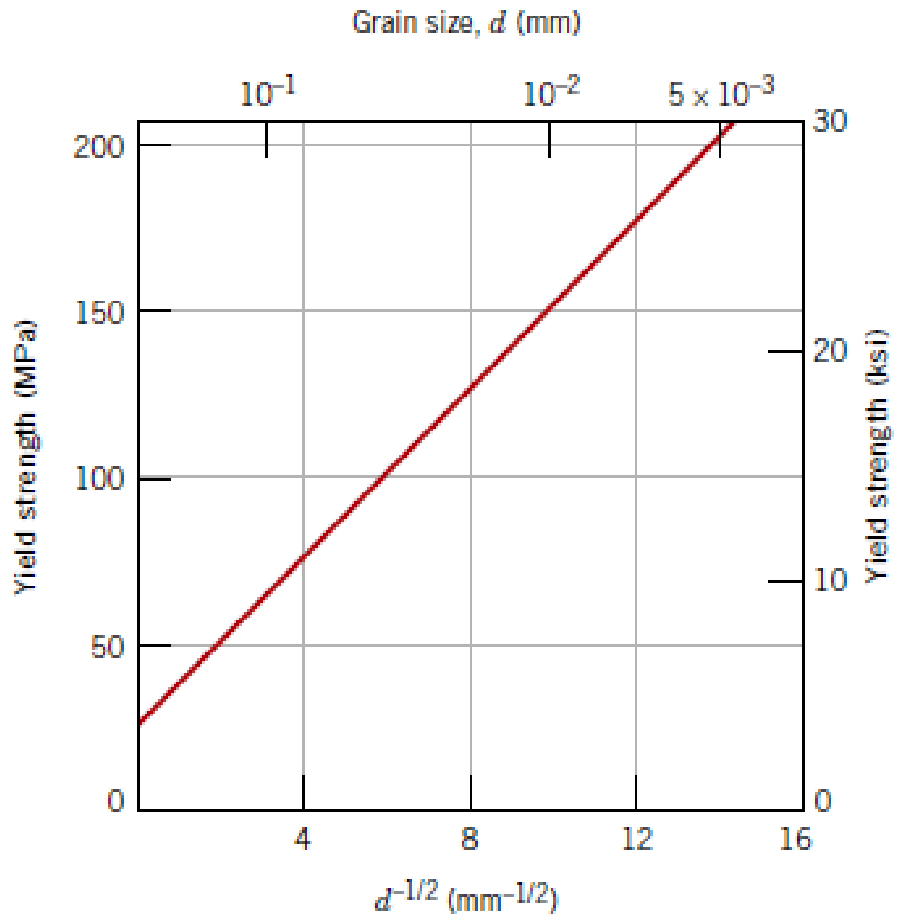


Strengthening by Grain Size Reduction

- The finer the grains, the larger the area of grain boundaries that impedes dislocation motion.
- Grain-size reduction improves toughness.
- Usually, the yield strength varies with grain size according to Hall-Petch equation:

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

- where σ_o and k_y are constants for a particular material and d is the average grain diameter.
- Grain size, d, can be controlled by the rate of solidification, by plastic deformation and by appropriate heat treatment.



The influence of grain size on the yield strength of a brass alloy

Strengthening by Grain Size Reduction

- Grain size is usually measured using a light microscope to observe a polished specimen by;
  - ✓ Counting the number of grains within a given area,
  - ✓ Determining the number of grains that intersect a given length of random line,
  - ✓ Comparing with standard-grain-size charts.

$$S_v = 2N_L, \qquad d = \frac{3}{S_v} = \frac{3}{2N_L} \quad \text{and} \quad d = \sqrt{\frac{6}{\pi N_A}}$$

- d is average grain diameter,
- S_v is grain boundary area per unit volume,
- N_L is mean number of intercepts of grain boundaries per unit length of test line, and
- N_A is number of grains per unit area on a polished surface;

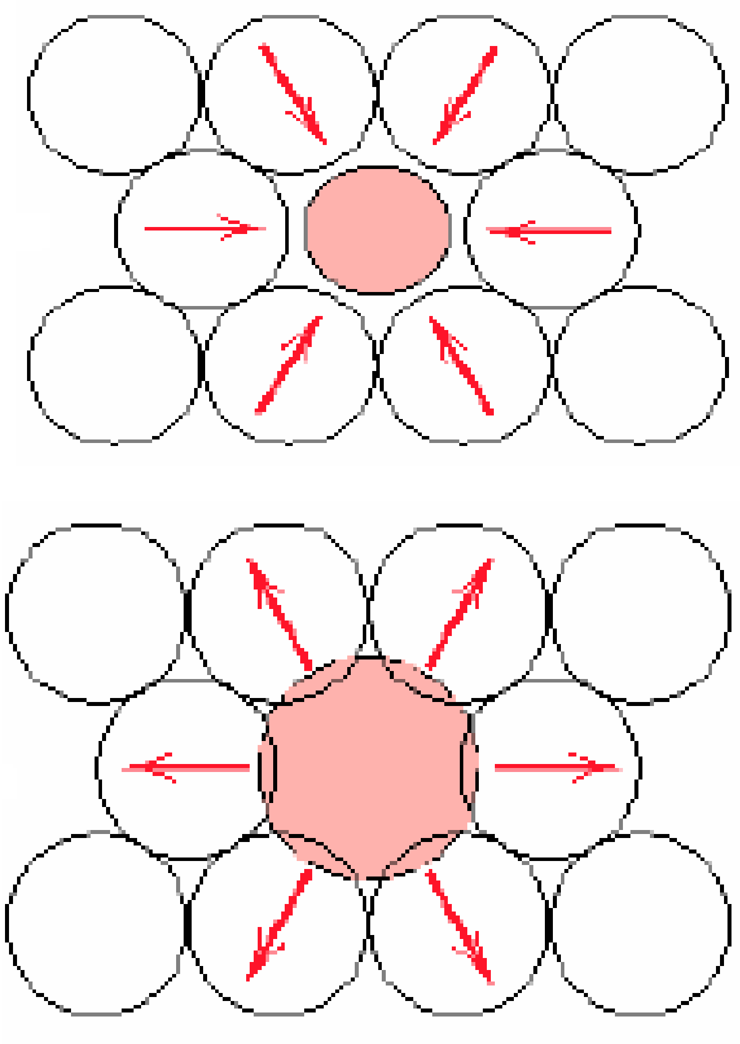
- Another common method of measuring the grain size is by comparing the grains at a fixed magnification with standard grain size charts.
- Charts are coded with ASTM grain size number, *G*, and is related with n_a – number of grains per mm^2 at 1X magnification as

$$G = -2.9542 + 1.4427\, lm_a$$

$$D = \frac{1}{100}\sqrt{\frac{645}{2^{G-1}}}$$

Solid Solution Strengthening

- The technique works by adding atoms of one element (the alloying element) to occupy interstitial or substitutional positions in the crystalline of the parent element (base metal) forming a solid solution.
- The stress fields generated around the solute atoms interact with that of a moving dislocation, thereby increasing the stress required for plastic deformation i.e. the impurity atoms make plastic deformation more difficult by impeding dislocations.
- Solute strengthening effectiveness depends on two factors namely; size difference between solute and parent atoms, and concentration of solute atoms.



Strengthening by Strain Hardening

- **Strain hardening or work hardening** is the phenomenon whereby ductile metals become stronger and harder when they are deformed plastically at temperatures well below the melting point.
- **The reason for strain hardening is the increase of dislocation density with plastic deformation.**
- The average distance between dislocations decreases and dislocations start blocking the motion of each other.
- For some metals and alloys, the region of the true stress–strain curve from the onset of plastic deformation to the point at which necking begins may be approximated by;

$$\boldsymbol{\sigma_t = K\varepsilon_t^n}$$

- ✓ K and n are constants; vary from alloy to alloy and also depend on the condition of the material.
- ✓ n is often termed the strain hardening exponent with value less than unity. The higher the value of n, the greater is the strain hardening

Strengthening by Strain Hardening

Tabulation of n and K Values for Some Alloys

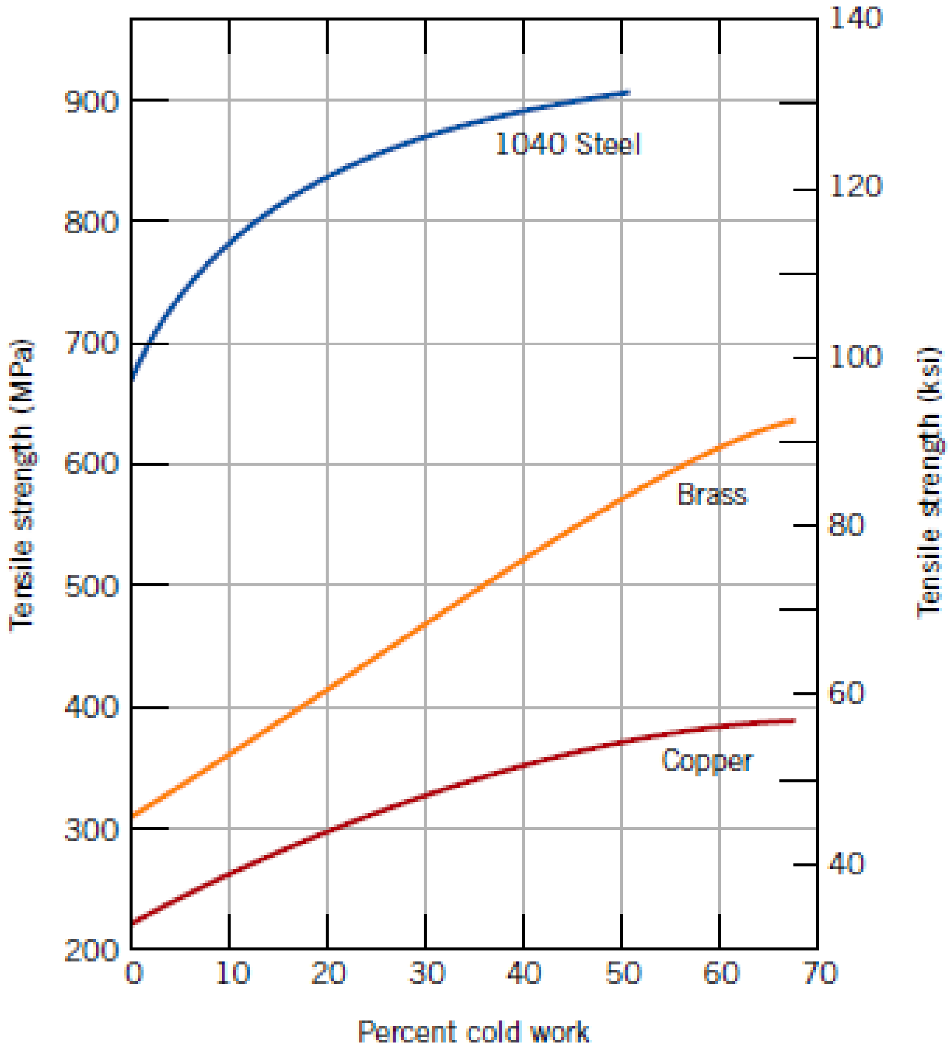
		K	
Material	n	*MPa*	*psi*
Low-carbon steel (annealed)	0.21	600	87,000
4340 steel alloy (tempered @ 315°C)	0.12	2650	385,000
304 stainless steel (annealed)	0.44	1400	205,000
Copper (annealed)	0.44	530	76,500
Naval brass (annealed)	0.21	585	85,000
2024 aluminum alloy (heat-treated—T3)	0.17	780	113,000
AZ-31B magnesium alloy (annealed)	0.16	450	66,000

Strengthening by Strain Hardening

- Most metals strain hardens at room temperature.
- The consequence of strain hardening a material is improved strength and hardness but material's ductility will be reduced.
- The percent cold work (%CW) is often used to express the degree of plastic deformation:

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

- Strain hardening is used commercially to enhance the mechanical properties of metals during fabrication procedures.



Strengthening by Strain Hardening: Ex

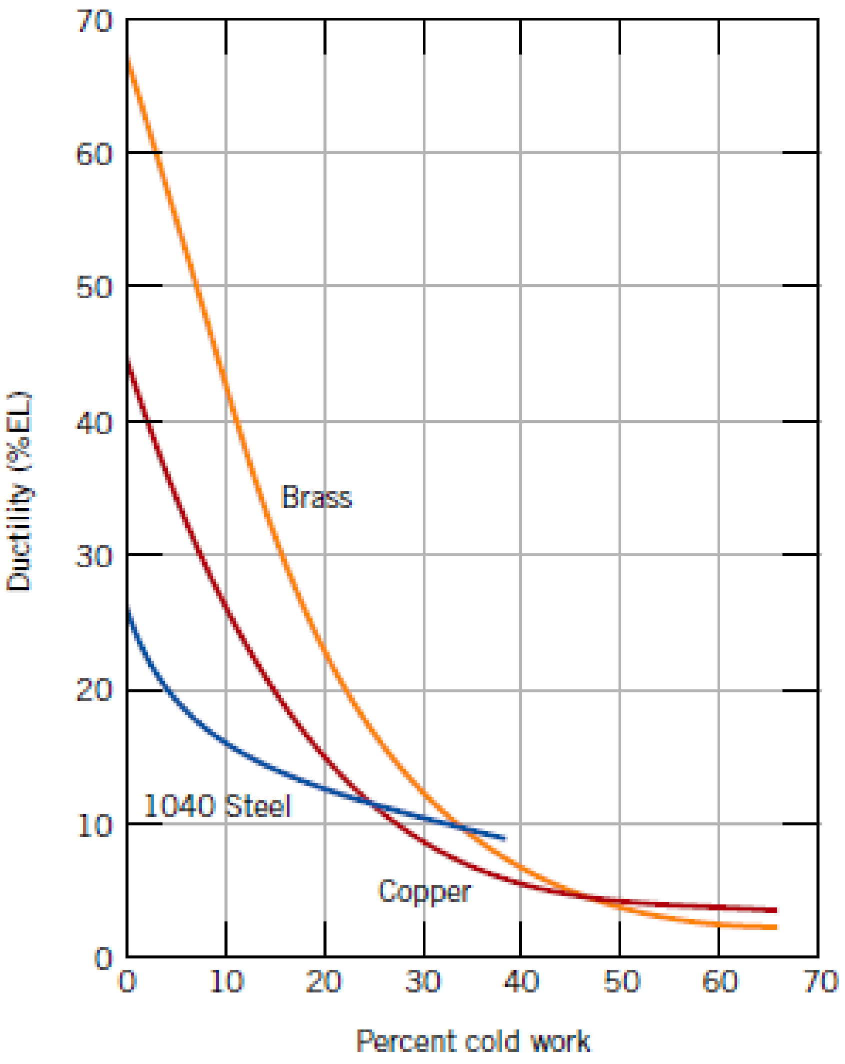
Question

Compute the tensile strength and ductility (%EL) of a cylindrical copper rod if it is cold worked such that the diameter is reduced from 15.2 mm to 12.2 mm.

Solution

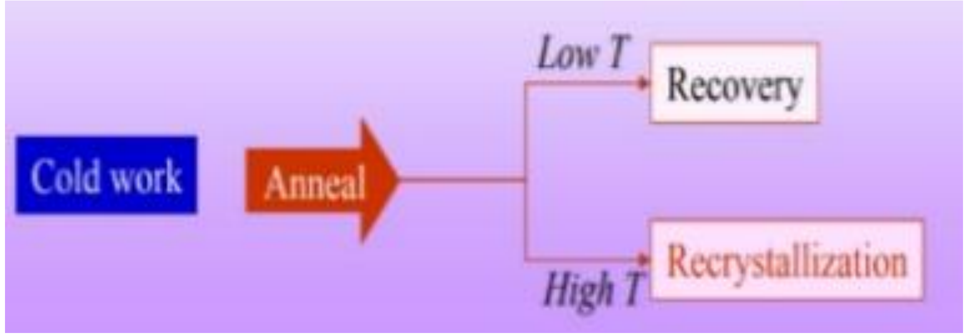
$$\%CW = \frac{\left(\frac{15.2\ mm}{2}\right)^2 \pi - \left(\frac{12.2\ mm}{2}\right)^2 \pi}{\left(\frac{15.2\ mm}{2}\right)^2 \pi} \times 100 = 35.6\%$$

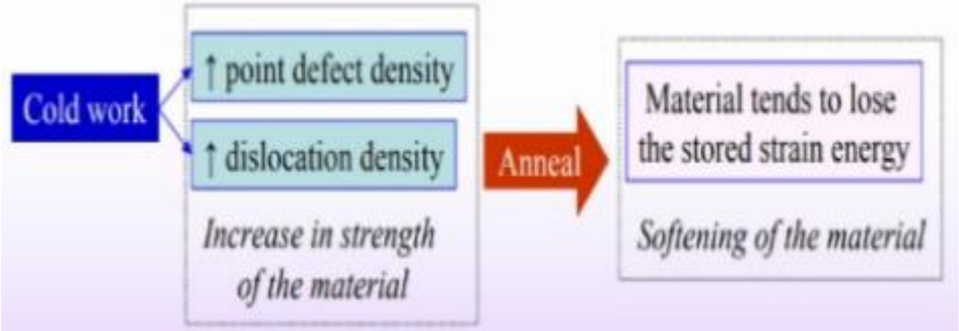
- ❖ The tensile strength is read directly from the curve for copper as 340 MPa.
- ❖ The ductility at 35.6%CW is about 7%EL.



Recovery, recrystallization, and grain growth

- ❖ Plastic deformation increases dislocation density and changes grain size distributions.
- ❖ This corresponds to stored strain energy in the system (dislocation strain fields and grain distortions).
- ❖ Between 1-10% of the energy of plastic deformation is stored in the form of strain energy associated with point defects and dislocations.
- ❖ Heating the deformed material (Annealing) tends to lose the extra strain energy and revert to the original condition before deformation by the processes of recovery and recrystallization.
- ❖ Grain growth may follow these in some instances.





Recovery, recrystallization, and grain growth

Recovery

- This takes place at low temperatures where some of the stored internal energy is relieved by virtue of dislocation motion as a result of enhanced atomic diffusion.
- Excess point defects that are created during deformation are destroyed either by absorption at grain boundaries or dislocation climbing process.
- Stored energy of cold work is the driving force for recovery.

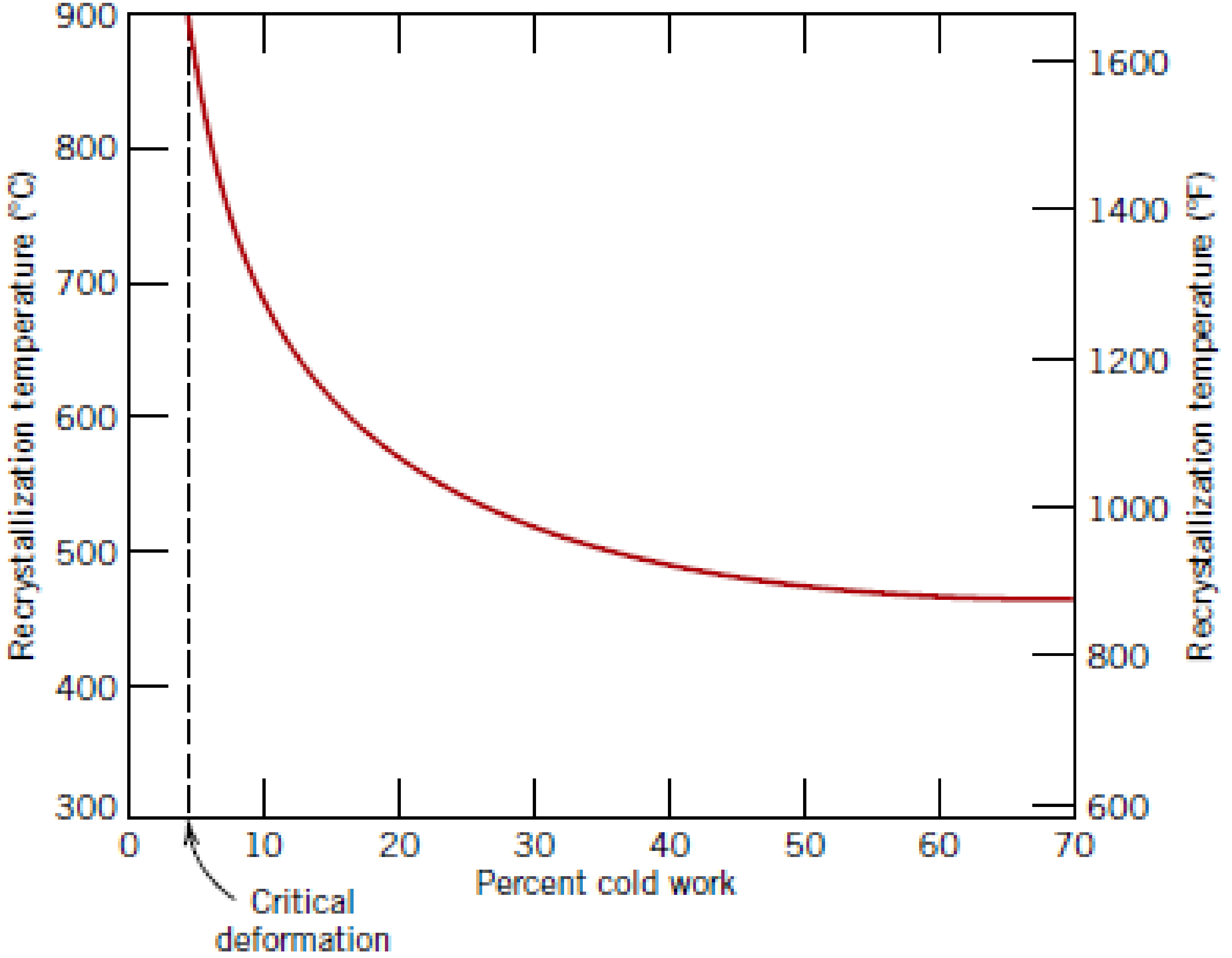
Recrystallization

- Replacement of deformed crystals of high dislocation density by strain free crystals of low dislocation density.
- Mechanical properties are restored to pre-cold worked values.
- Processes of recrystallization increases with time and temperature.
- Recrystallization is slower in alloys as compared to pure metals.
- The driving force for recrystallization is the strain energy associated with dislocations.

Recovery, recrystallization, and grain growth

Recrystallization

- Recrystallization temperature is the temperature at which the process is complete in one hour. It is typically one-third to half of the melting temperature (can be as high as 0.7 Tm in some alloys).
- Recrystallization temperature increases as the %CW is decreased. Below a 'critical deformation', recrystallization does not occur.

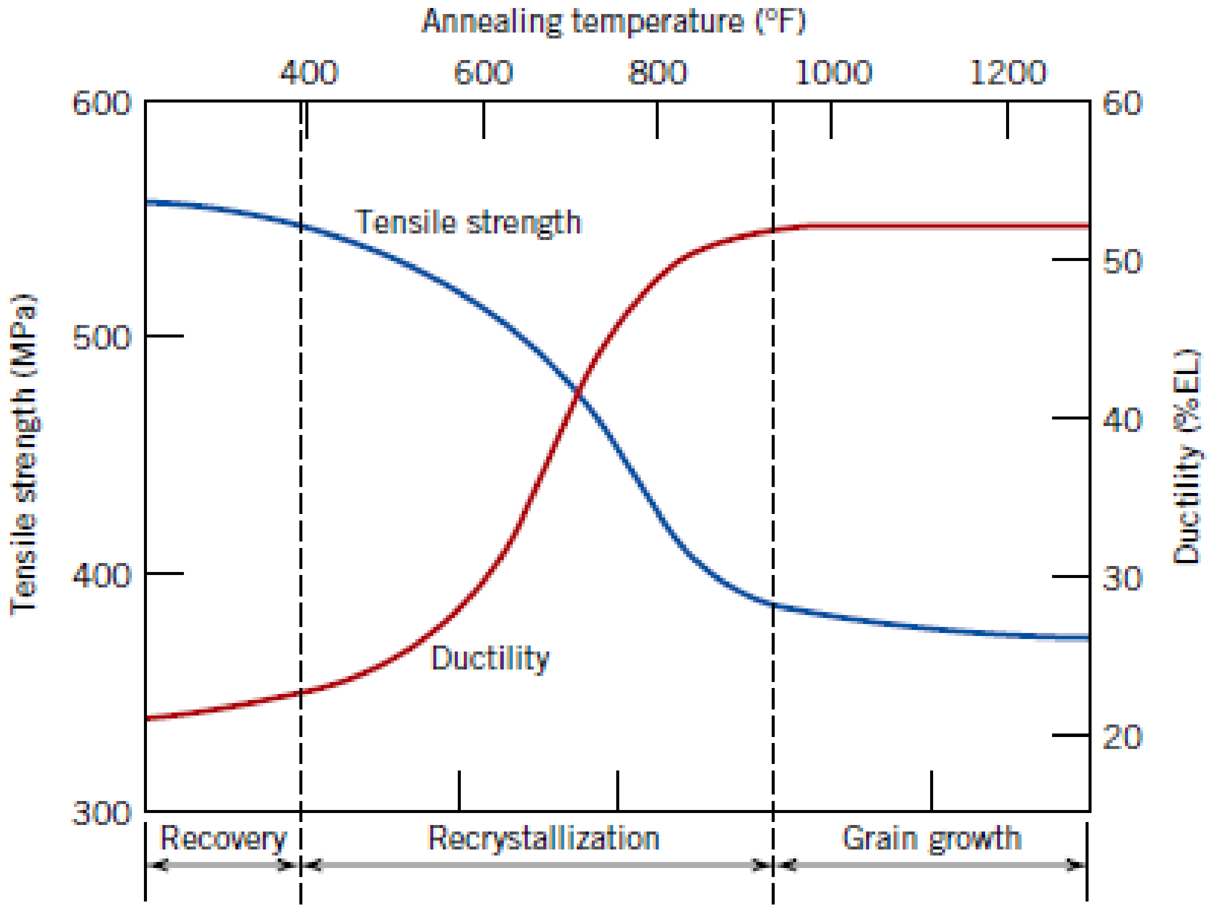


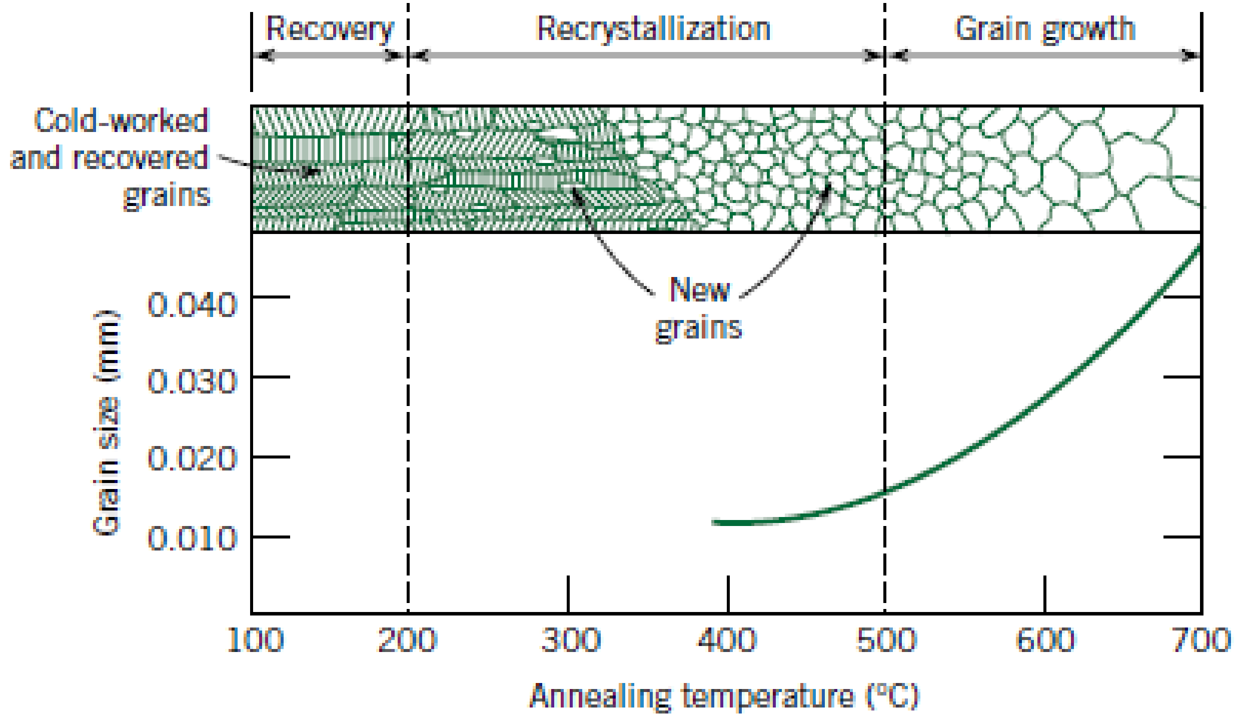
Recovery, recrystallization, and grain growth

Grain growth

- ❖ Newly formed strain-free grains tend to grow in size. This grain growth occurs by the migration of grain boundaries.
- ❖ Driving force for this process is reduction in grain boundary energy i.e. decreasing in free energy of the material. As the grains grow larger, the curvature of the boundaries becomes less. This results in a tendency for larger grains to grow at the expense of smaller grains.
- ❖ In practical applications, grain growth is not desirable.
- ❖ The driving force for grain growth is lower than that for recrystallization.
- ❖ Grain growth occurs slowly at a temperature where recrystallization occurs at substantially high speeds. However, grain growth is strongly temperature dependent.

Recovery, recrystallization, and grain growth



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