Properties of Engineering Materials

Dislocations & Strengthening Mechanisms

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Dislocations & Plastic Deformation (PD)
Basic Concepts

- PD corresponds to the motion of large numbers of dislocations.
  - An edge dislocation moves in response to a shear stress applied in a direction perpendicular to its line.

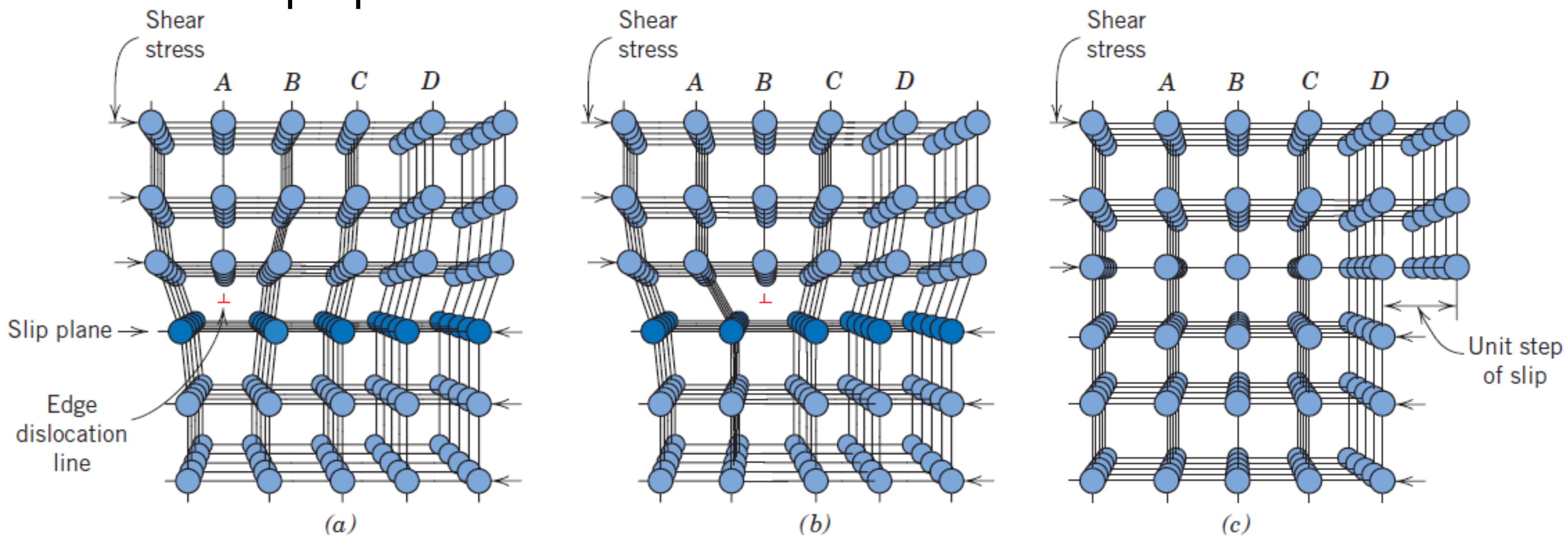


Figure 7.1 Atomic rearrangements that accompany the motion of an edge dislocation as it moves in response to an applied shear stress. (*a*) The extra half- lane of atoms is labeled *A*. (*b*) The dislocation moves one atomic distance to the right as *A* links up to the lower portion of plane *B*; in 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.

Dislocations & Plastic Deformation (PD)
Basic Concepts

- Before and after the movement of a dislocation through some particular region of the crystal, the atomic arrangement is ordered and perfect;
  - it is only during the passage of the extra half-plane that the lattice structure is disrupted.
- Ultimately this extra half-plane may emerge from the right surface of the crystal, forming an edge that is one atomic distance wide; this is shown in Figure 7.1*c*.

Dislocations & Plastic Deformation (PD)

Basic Concepts

- ***Slip***: the process by which plastic deformation is produced by dislocation motion.
  - ***Slip Plane***: the crystallographic plane along which the dislocation line traverses (Figure 7.1).
- Macroscopic plastic deformation simply corresponds to permanent deformation that results from the movement of dislocations, or slip, in response to an applied shear stress.

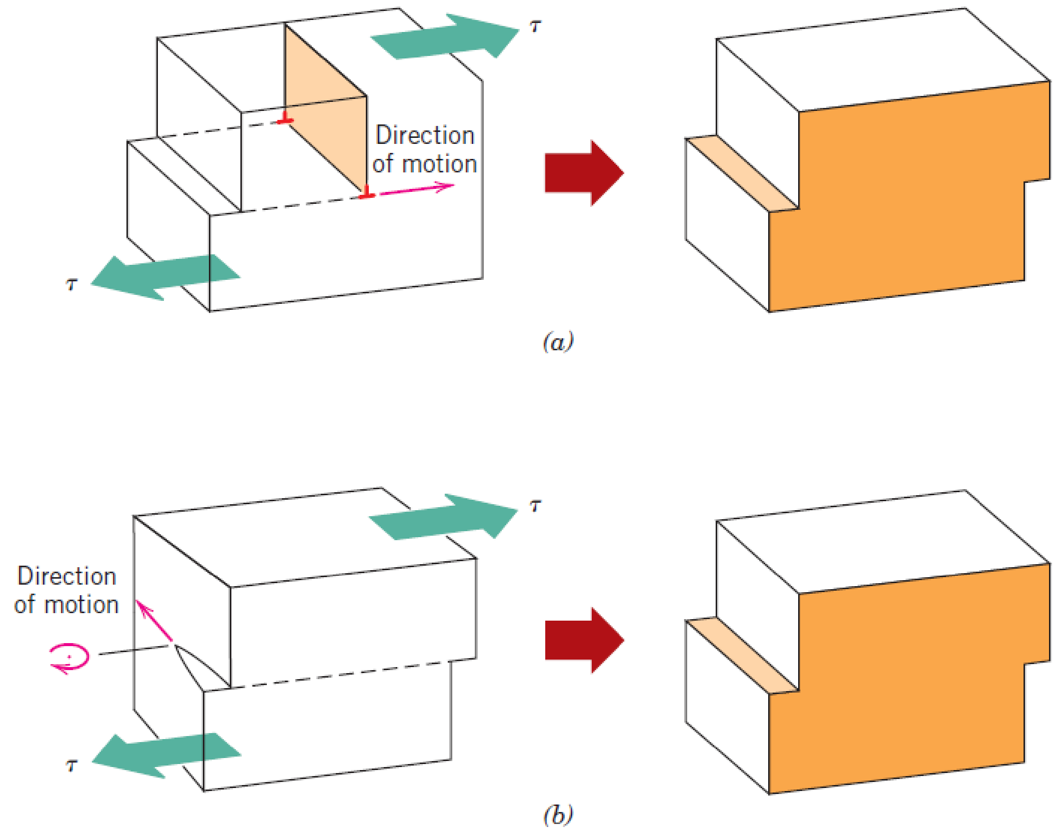


Figure 7.2 The formation of a step on the surface of a crystal by the motion of (*a*) an edge dislocation and (*b*) a screw dislocation. Note that for an edge, the dislocation line moves in the direction of the applied shear stress ; for a screw, the dislocation line motion is perpendicular to the stress direction.

Dislocations & Plastic Deformation (PD)
Basic Concepts

- Dislocation motion is analogous to the mode of locomotion employed by a caterpillar.
  - The caterpillar forms a hump near its posterior end by pulling in its last pair of legs a unit leg distance.
  - The hump is propelled forward by repeated lifting and shifting of leg pairs.
  - When the hump reaches the anterior end, the entire caterpillar has moved forward by the leg separation distance.
  - The caterpillar hump and its motion correspond to the extra half-plane of atoms in the dislocation model of plastic deformation.

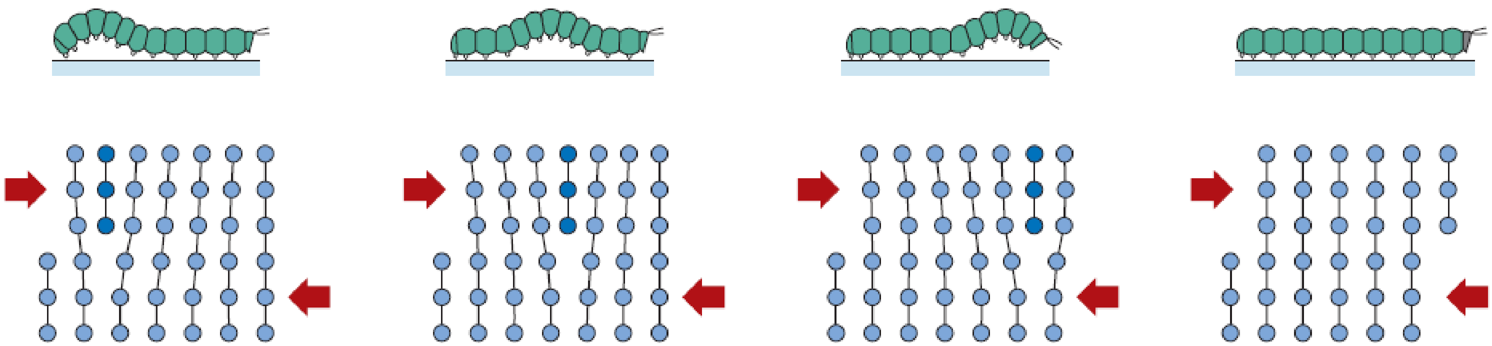
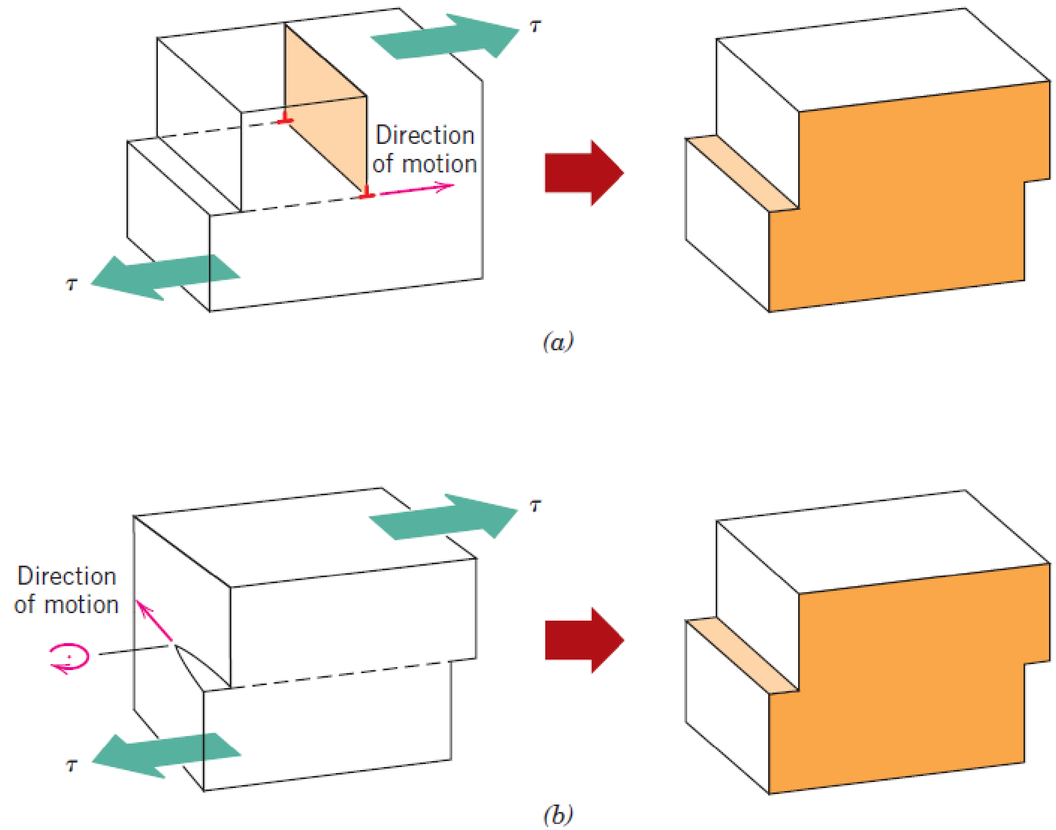


Figure 7.3 Representation of the analogy between caterpillar and dislocation motion.

Dislocations & Plastic Deformation (PD)

Basic Concepts

- The direction of movement of screw dislocation is perpendicular to the stress direction.
    - For an edge, motion is parallel to the shear stress. However, the net plastic deformation for the motion of both dislocation types is the same.
- The direction of motion of the mixed dislocation line is neither perpendicular nor parallel to the applied stress, but lies somewhere in between.



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Dislocations & Plastic Deformation (PD)
Basic Concepts

- All metals and alloys contain some dislocations that were introduced:
  - During solidification.
  - During plastic deformation.
  - Or as a consequence of thermal stresses that result from rapid cooling.
- ***Dislocation Density*** (millimeters of dislocation per cubic millimeter or just per square millimeter): the total dislocation length per unit volume or, equivalently, the number of dislocations that intersect a unit area of a random section.
  - E.g. Heavy dislocation density: in heavily deformed metals (10^9 – 10^{10} / mm^2).
  - Low Dislocation density: in carefully solidified metal crystals (10^3 / mm^2).

Dislocations & Plastic Deformation (PD)
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.
    - The major portion of this stored energy is as strain energy associated with dislocations.

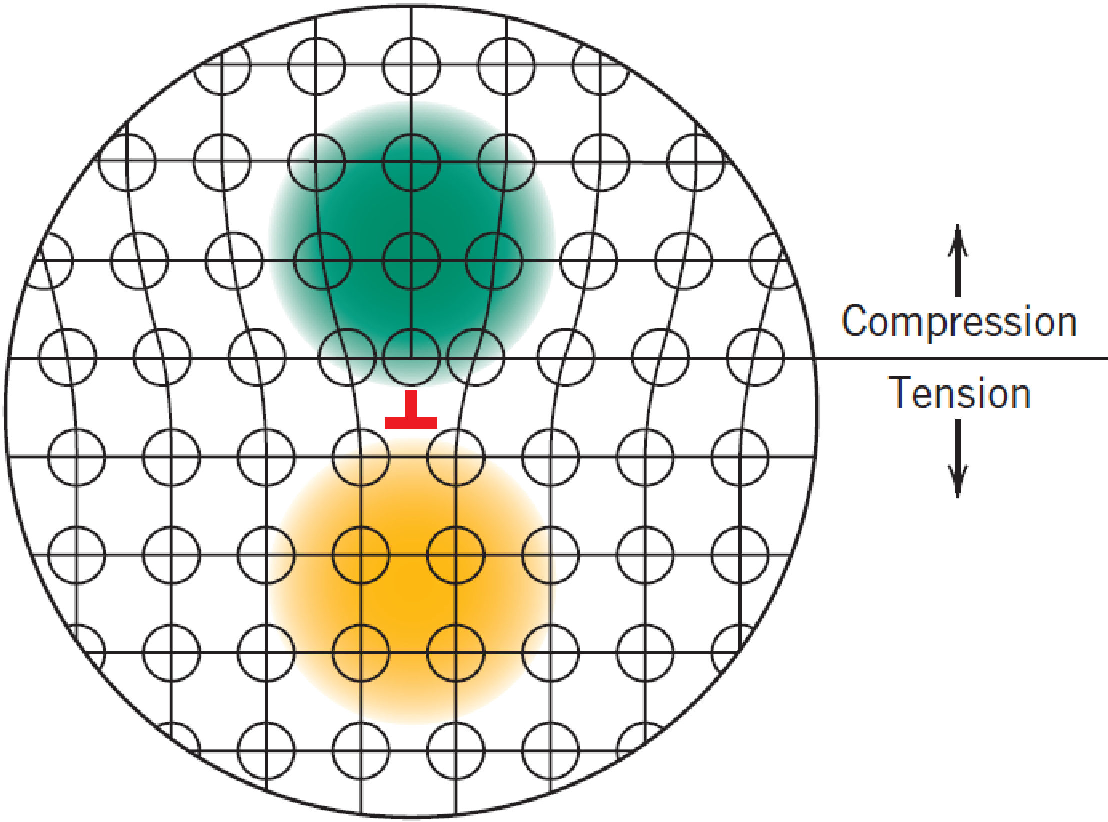


Figure 7.4 Regions of compression (green) and tension (yellow) located around an edge dislocation.

Dislocations & Plastic Deformation (PD)
Characteristics of Dislocations

- Some atomic lattice distortion exists around the dislocation line because of the presence of the extra half-plane of atoms.
- As a consequence, there are regions in which compressive, tensile, and shear **lattice strains** are imposed on the neighboring atoms.
  - E.g. atoms immediately above and adjacent to the dislocation line are squeezed together: hence, experiencing compressive strains.
  - Atoms below the half-plane: lattice atoms sustain an imposed tensile strain.
- For a screw dislocation, lattice strains are pure shear only.
- These lattice distortions may be considered to be strain fields that radiate from the dislocation line.

Dislocations & Plastic Deformation (PD)

Characteristics of Dislocations

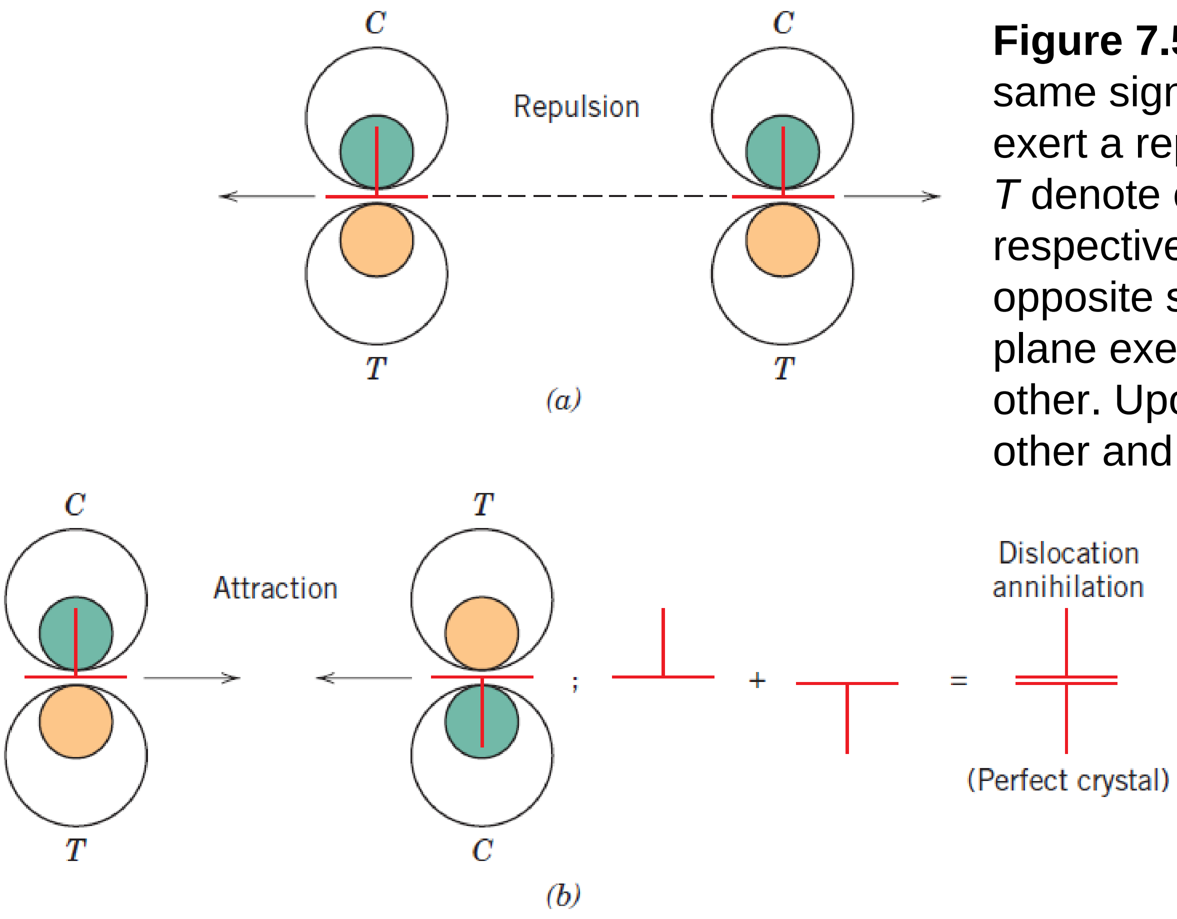


Figure 7.5 (*a*) Two edge dislocations of the same sign and lying on the same slip plane exert a repulsive force on each other; *C* and *T* denote compression and tensile regions, respectively. (*b*) Edge dislocations of opposite sign and lying on the same slip plane exert an attractive force on each other. Upon meeting, they annihilate each other and leave a region of perfect crystal.

Dislocations & Plastic Deformation (PD)
Characteristics of Dislocations

- Dislocation interactions are possible between edge, screw, and/or mixed dislocations, and for a variety of orientations.
  - These strain fields and associated forces are important in the strengthening mechanisms for metals.
- During plastic deformation, the number of dislocations increases dramatically.
  - One important source of these new dislocations is existing dislocations, which multiply; for example during plastic deformation.
  - Furthermore, grain boundaries, as well as internal defects and surface irregularities such as scratches and nicks, which act as stress concentrations, may serve as dislocation formation sites during deformation.

Dislocations & Plastic Deformation (PD)
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***: a preferred plane along which dislocation motion occurs.
  - ***Slip Direction***: the direction of movement of dislocation motion along the slip plane.
  - ***Slip System***: the combination of the slip plane and the slip direction.
- For a particular crystal structure, the slip plane and the slip direction are the plane and the direction that have the greatest planar and linear densities, respectively.

Dislocations & Plastic Deformation (PD)

Slip Systems

FCC: 12 slip systems; 4 unique {111} planes & 3 independent <110> directions within each plane.

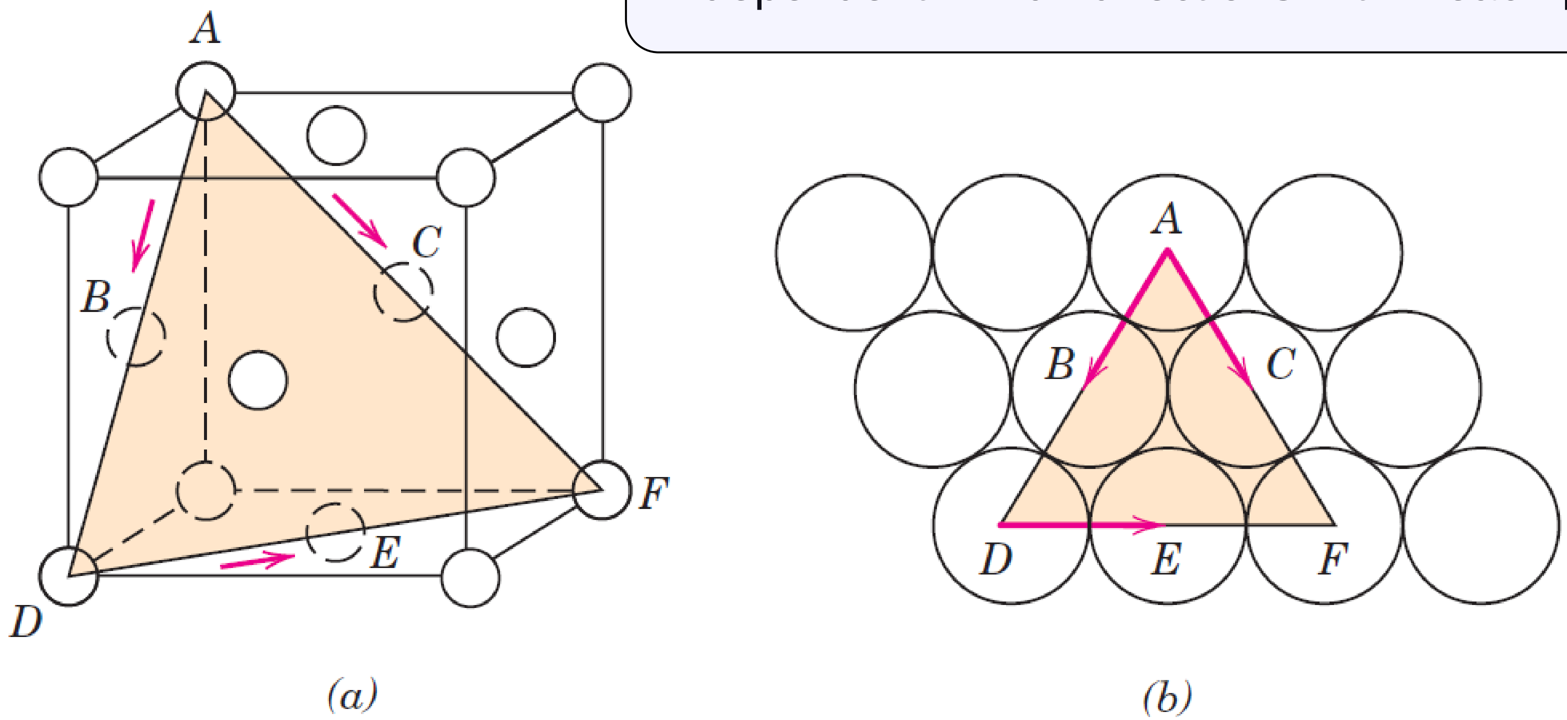


Figure 7.6 (*a*) A {111} <110>slip system shown within an FCC unit cell. (*b*) The (111) plane from (*a*) and three <110> slip directions (as indicated by arrows) within that plane constitute possible slip systems.

Dislocations & Plastic Deformation (PD)
Slip Systems

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

Table 7.1 Slip Systems for Face-Centered Cubic, Body-Centered Cubic, and Hexagonal Close-Packed Metals

Dislocations & Plastic Deformation (PD)
Slip Systems

- The larger the number of slip systems, the more ductile the metal.
  - E.g. BCC and FCC metals are ductile while the HCP ones are brittle.
- Slip & Burgers Vector (**b**): a Burgers vector's direction corresponds to a dislocation's slip direction, whereas its magnitude is equal to the unit slip distance (or interatomic separation in this direction).
  - it is convenient to specify a Burgers vector in terms of unit cell edge length (*a*) and crystallographic direction indices.

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

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

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

Dislocations & Plastic Deformation (PD)

Slip In Single Crystals

- ***Resolved Shear Stresses*** (τ_R): when materials that experience tensile (or compressive) stresses, shear components exist at all but parallel or perpendicular alignments to the stress direction.

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

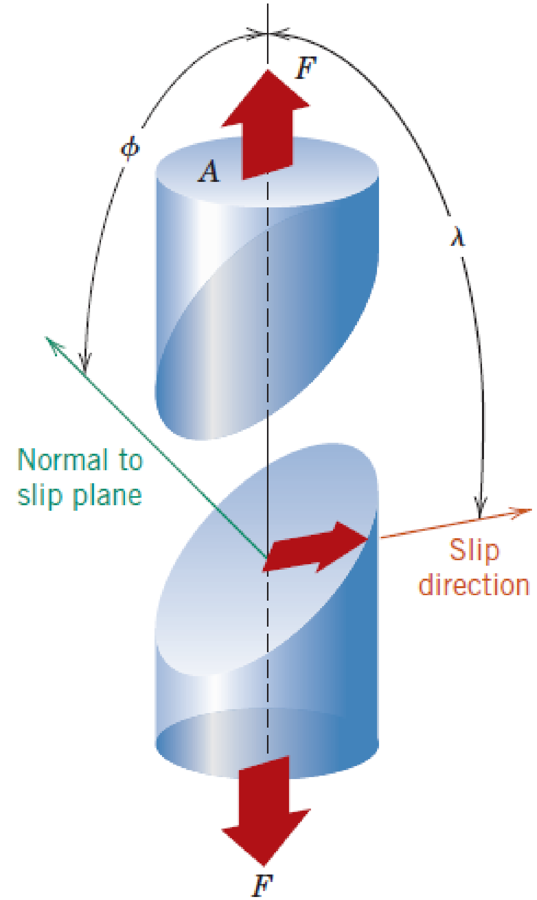


Figure 7.7 Geometrical relationships between the tensile axis, slip plane, and slip direction used in calculating the resolved shear stress for a single crystal.

Dislocations & Plastic Deformation (PD)
Slip In Single Crystals

- A metal single crystal has a number of different slip systems that are capable of operating.
  - The resolved shear stress normally differs for each one 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 resolved shear stress, τ_R(max):

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

Dislocations & Plastic Deformation (PD)
Slip In Single Crystals

- **Critical resolved shear stress** (τ_{CRSS}): the minimum shear stress required to initiate slip and is a property of the material that determines when yielding occurs.

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

→ Condition for plastic deformation in single crystals

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

→ Magnitude of the applied stress required to initiate yielding (yield stress)

When single crystal is oriented such that: $\phi = \lambda = 45°$ → We get the minimum stress necessary to introduce yielding →

$$\sigma_y = 2\tau_{\text{CRSS}}$$

Dislocations & Plastic Deformation (PD)

Slip In Single Crystals

- Example 7.1: Consider a single crystal of BCC iron oriented such that a tensile stress is applied along a [010] direction.

  - **(a)** Compute the resolved shear stress along a (110) plane and in a $[\bar{1}11]$ direction when a tensile stress of 52 MPa is applied.
  - **(b)** If slip occurs on a (110) plane and in a $[\bar{1}11]$ direction, and the critical resolved shear stress is 30 MPa, calculate the magnitude of the applied tensile stress necessary to initiate yielding.

Dislocations & Plastic Deformation (PD)
Plastic Deformation of Polycrystalline Materials

- Deformation and slip in polycrystalline materials is somewhat more complex.
  - Polycrystalline: random crystallographic orientations, different slip directions.
  - During deformation, mechanical integrity and coherency are maintained along the grain boundaries; that is, the grain boundaries usually do not come apart or open up.
    - As a consequence, each individual grain is constrained, to some degree, in the shape it may assume by its neighboring grains.

Dislocations & Plastic Deformation (PD)
Plastic Deformation of Polycrystalline Materials

• Slip lines (after deformation) are visible, and it appears that two slip systems operated for most of the grains, as evidenced by two sets of parallel yet intersecting sets of lines.

• Furthermore, variation in grain orientation is indicated by the difference in alignment of the slip lines for the several grains.

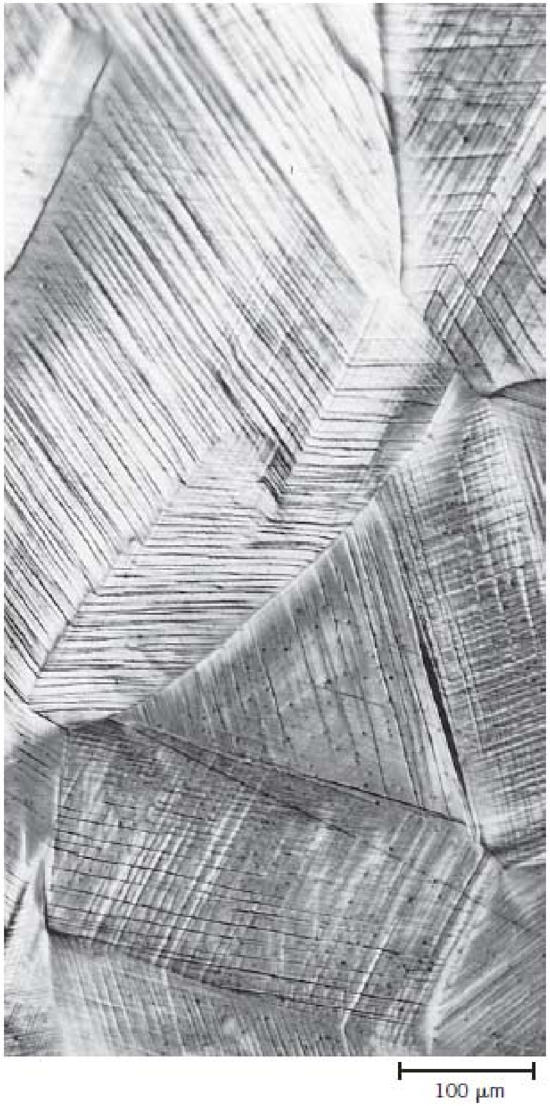


Figure 7.10 Slip lines on the surface of a polycrystalline specimen of copper that was polished and subsequently deformed. 173X.

Dislocations & Plastic Deformation (PD)
Plastic Deformation of Polycrystalline Materials

- Before deformation the grains are equiaxed, or have approximately the same dimension in all directions.
- For this particular deformation, the grains become elongated along the direction in which the specimen was extended.

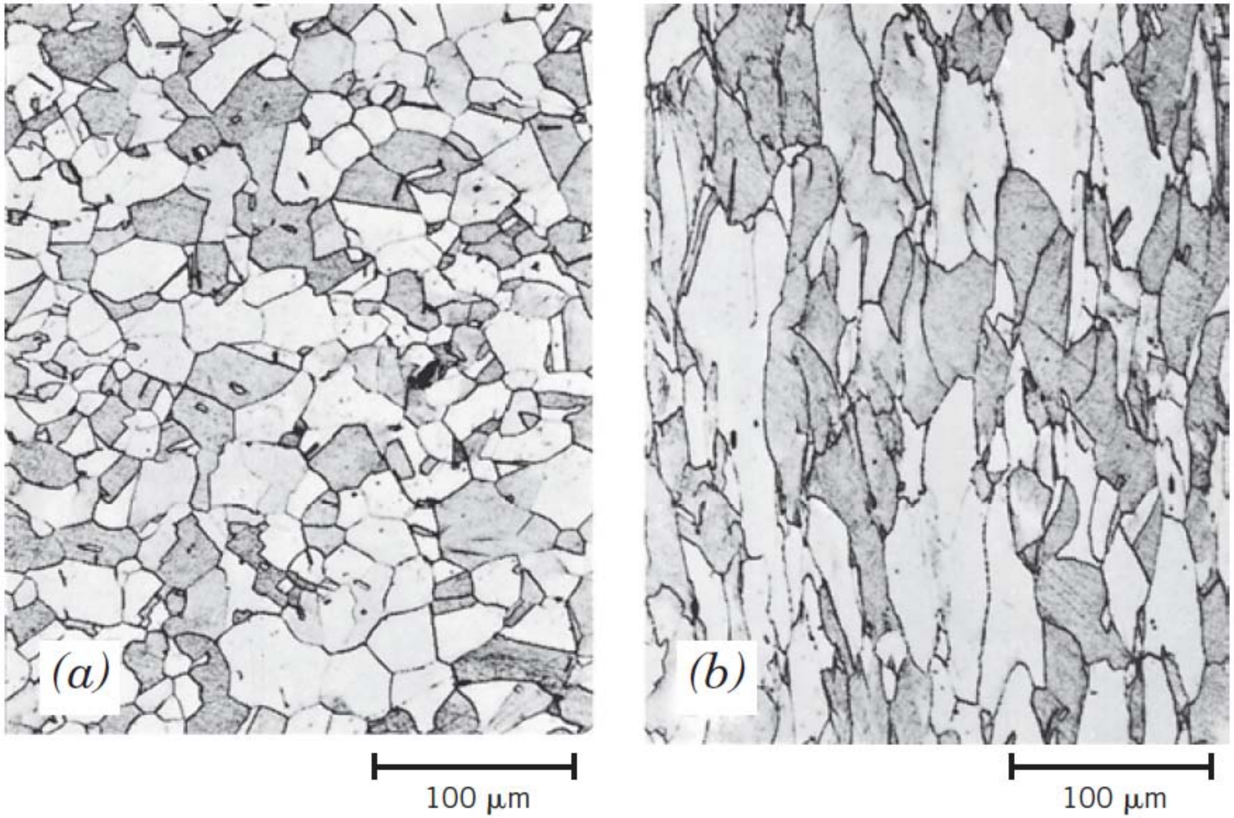


Figure 7.11 Alteration of the grain structure of a polycrystalline metal as a result of plastic deformation. (*a*) Before deformation the grains are equiaxed. (*b*) The deformation has produced elongated grains. 170X.

Dislocations & Plastic Deformation (PD)
Plastic Deformation of Polycrystalline Materials

- Polycrystalline metals are stronger than their single-crystal equivalents.
  - This is a result of geometrical constraints that are imposed on the grains during deformation.
- Even though a single grain may be favorably oriented with the applied stress for slip, it cannot deform until the adjacent and less favorably oriented grains are capable of slip also; this requires a higher applied stress level.

Dislocations & Plastic Deformation (PD)
Deformation by Twinning

- ***Mechanical Twinning***: deformation in some metallic materials can occur by ***twinning***.
  - Concept: a shear force can produce atomic displacements such that on one side of a plane (the twin boundary), atoms are located in mirror-image positions of atoms on the other side.

Dislocations & Plastic Deformation (PD)

Deformation by Twinning

BCC: twin Plane (112)
Direction: [111]

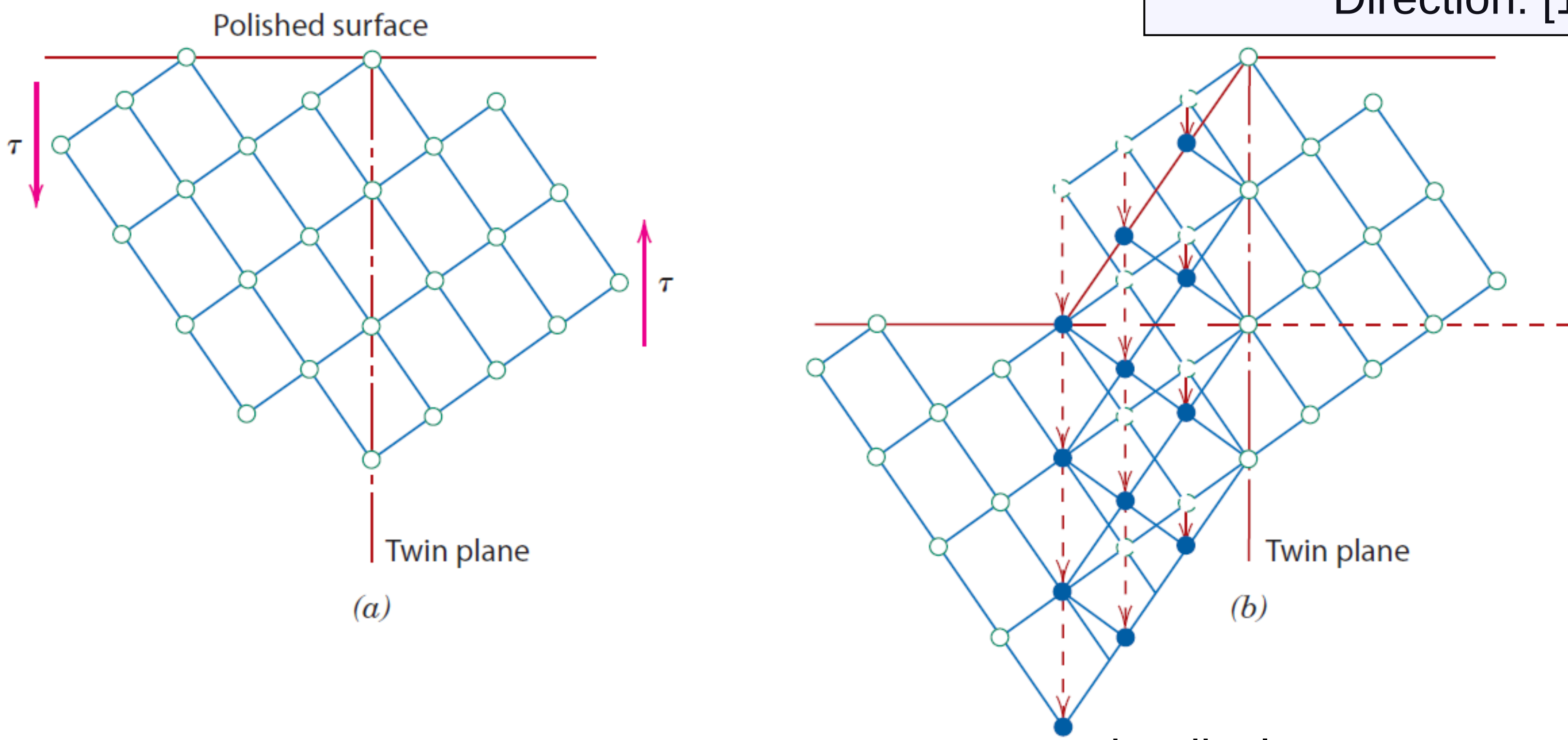


Figure 7.12 Schematic diagram showing how twinning results from an applied shear stress τ. In (*b*), open circles represent atoms that did not change position; dashed and solid circles represent original and final atom positions, respectively.

the displacement magnitude within the twin region (indicated by arrows) is proportional to the distance from the twin plane.

Dislocations & Plastic Deformation (PD)

Deformation by Twinning

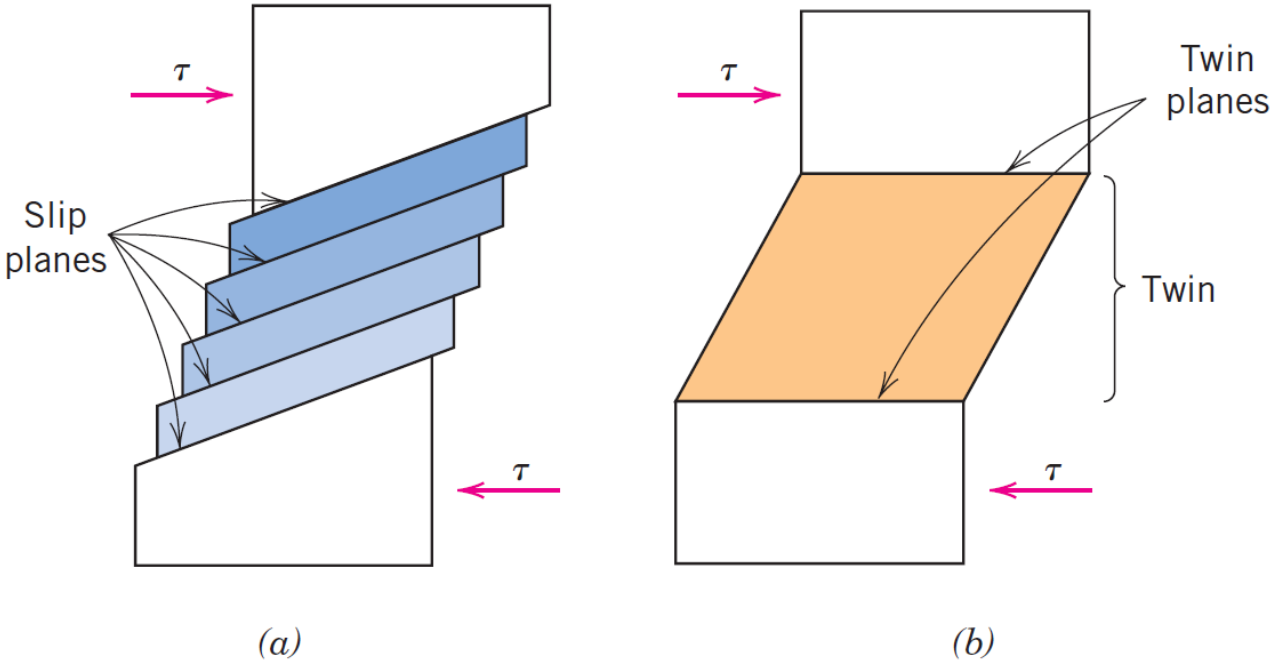


Figure 7.13 For a single crystal subjected to a shear stress τ, (*a*) deformation by slip; (*b*) deformation by twinning.

Slip: the crystallographic orientation above and below the slip plane is the same both before and after the deformation; for twinning, there will be a reorientation across the twin plane.

Slip occurs in distinct atomic spacing multiples, whereas the atomic displacement for twinning is less than the interatomic separation.

Twinning: in BCC & HCP metals at low temps & high loading rates (shock).

Mechanisms of Strengthening in Metals

- In alloy design: strengthening takes place on the expense of ductility.
- The ability of a metal to plastically deform depends on the ability of dislocations to move.
  - *Restricting or hindering dislocation motion renders a material harder and stronger*.

Mechanisms of Strengthening in Metals

Strengthening by Grain Size Reduction

- The size of the grains, or average grain diameter, in a polycrystalline metal influences the mechanical properties.
- Adjacent grains normally have different crystallographic orientations and, of course, a common grain boundary.

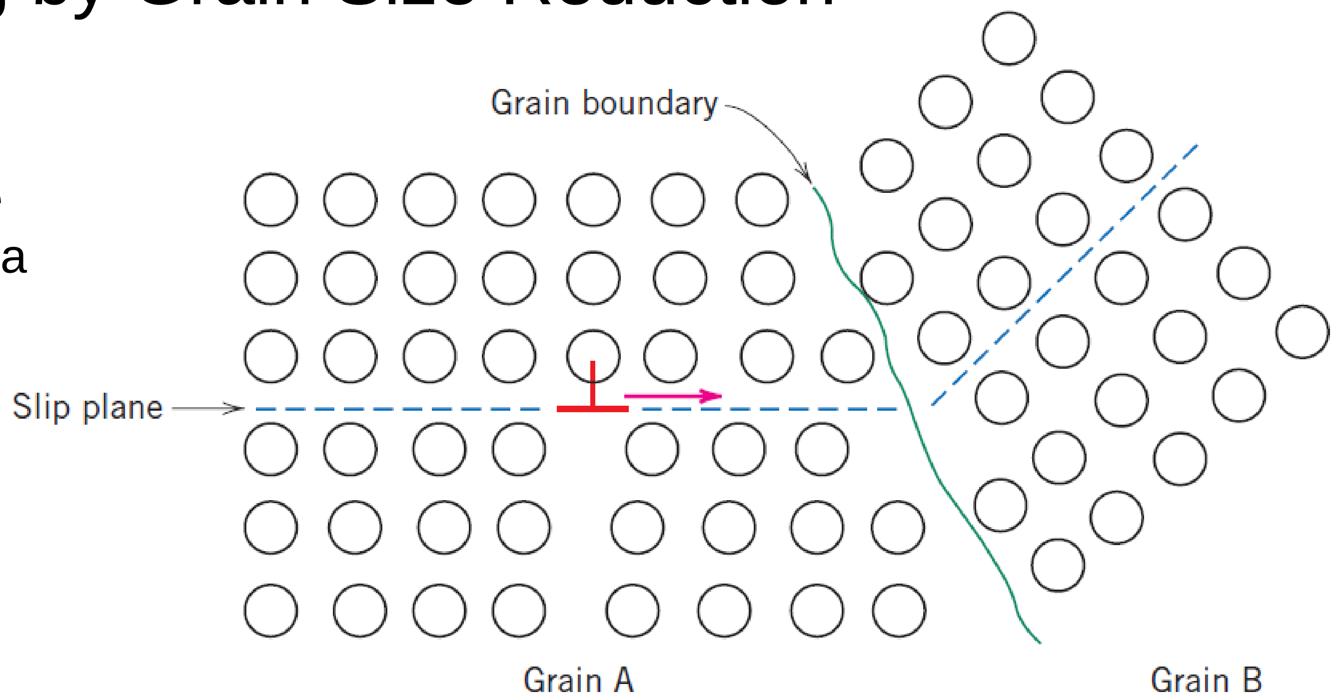


Figure 7.14 The motion of a dislocation as it encounters a grain boundary, illustrating how the boundary acts as a barrier to continued slip. Slip planes are discontinuous and change directions across the boundary.

Mechanisms of Strengthening in Metals
Strengthening by Grain Size Reduction

- The grain boundary acts as a barrier to dislocation motion for two reasons:
  - 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.
  - The atomic disorder within a grain boundary region will result in a discontinuity of slip planes from one grain into the other.

The smaller the grains, the greater the grain boundary area, the stronger the metal.

Mechanisms of Strengthening in Metals

Strengthening by Grain Size Reduction

Hall–Petch equation

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

Yield strength → σ_y

Constants → σ_0, k_y

Average grain size diameter → d

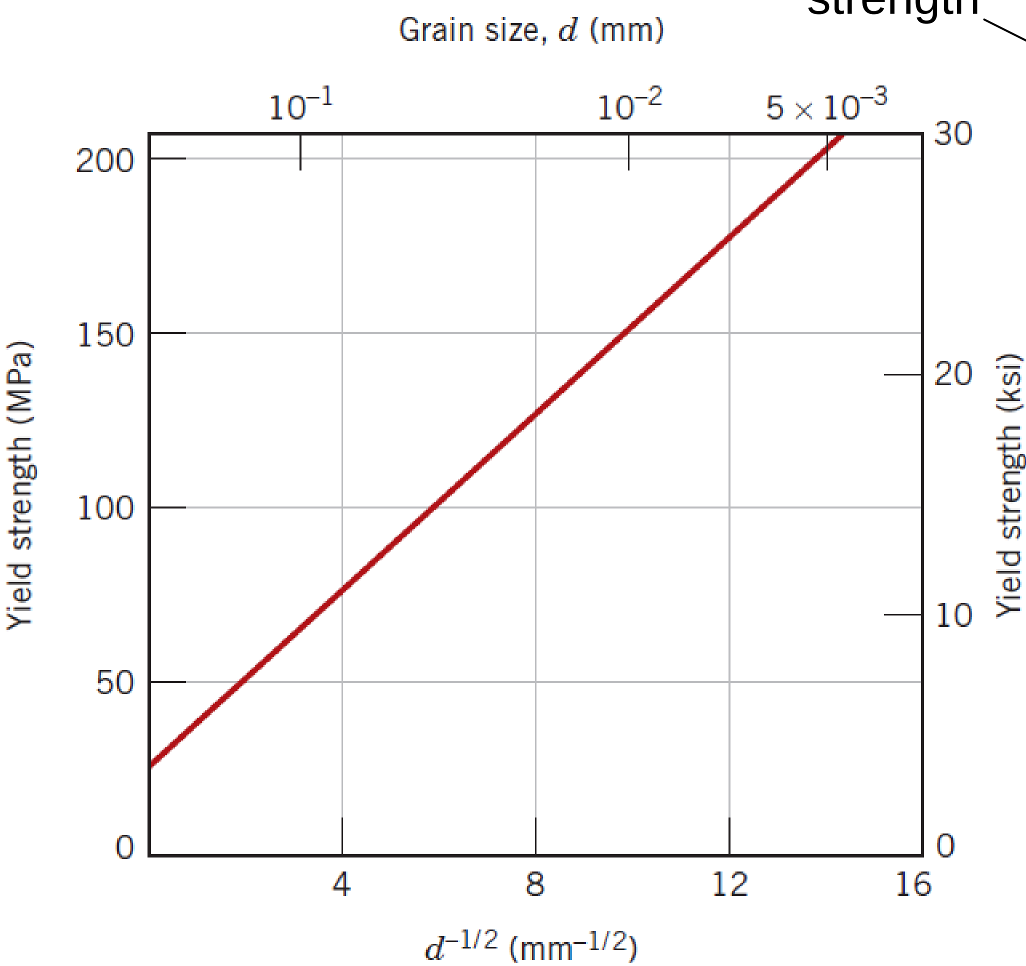


Figure 7.15 The influence of grain size on the yield strength of a 70 Cu–30 Zn brass alloy.

Mechanisms of Strengthening in Metals
Solid-Solution Strengthening

- **Solid-solution strengthening:** a technique to strengthen and harden metals by alloying with impurity atoms that go into either :
  - substitutional or interstitial solid solution.
- Alloys are stronger than pure metals because:
  - impurity atoms that go into solid solution ordinarily impose lattice strains on the surrounding host atoms.
- Lattice strain field interactions between dislocations and these impurity atoms result, and, consequently, dislocation movement is restricted.

Mechanisms of Strengthening in Metals
Solid-Solution Strengthening

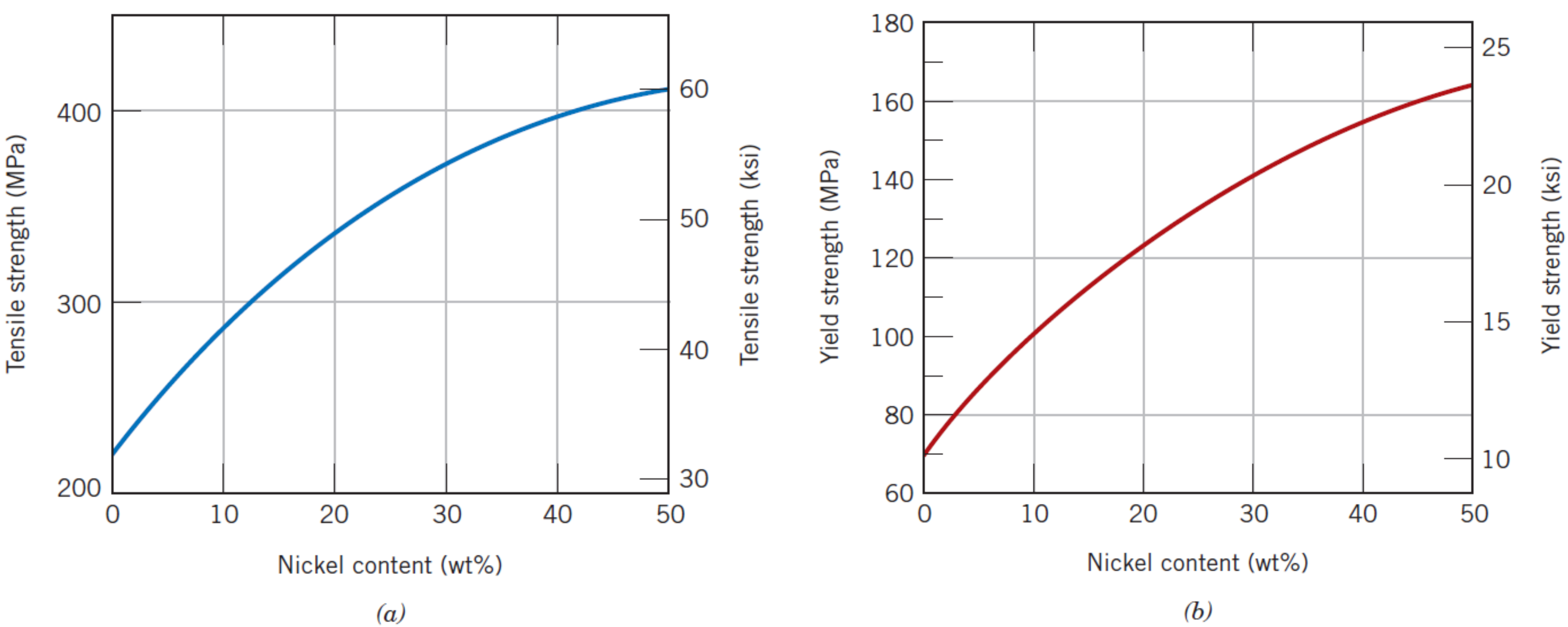
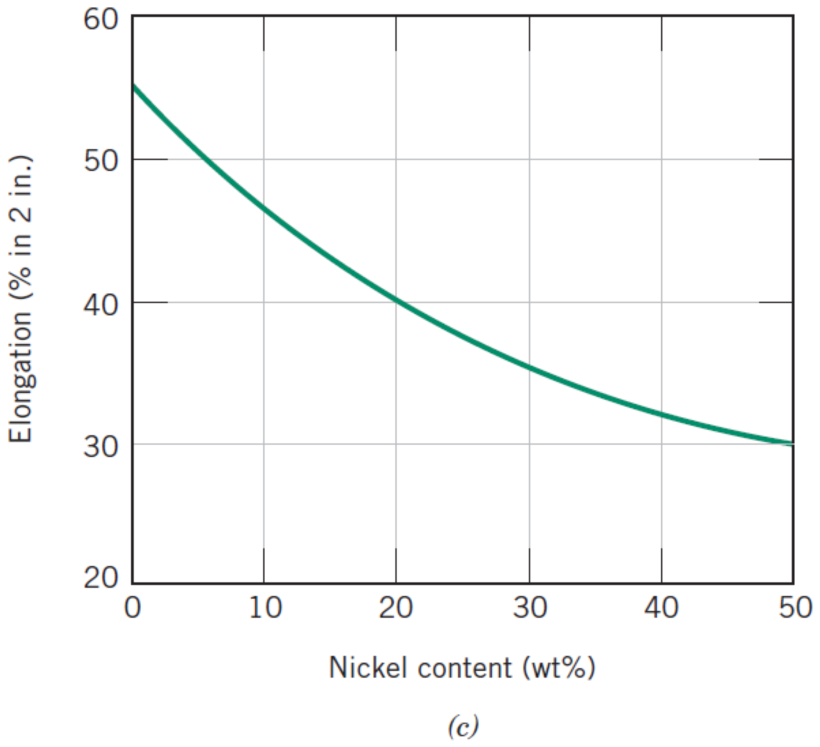


Figure 7.16 Variation with nickel content of (*a*) tensile strength, (*b*) yield strength, and (*c*) ductility (%EL) for copper–nickel alloys, showing strengthening.

Mechanisms of Strengthening in Metals
Solid-Solution Strengthening



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Mechanisms of Strengthening in Metals

Solid-Solution Strengthening

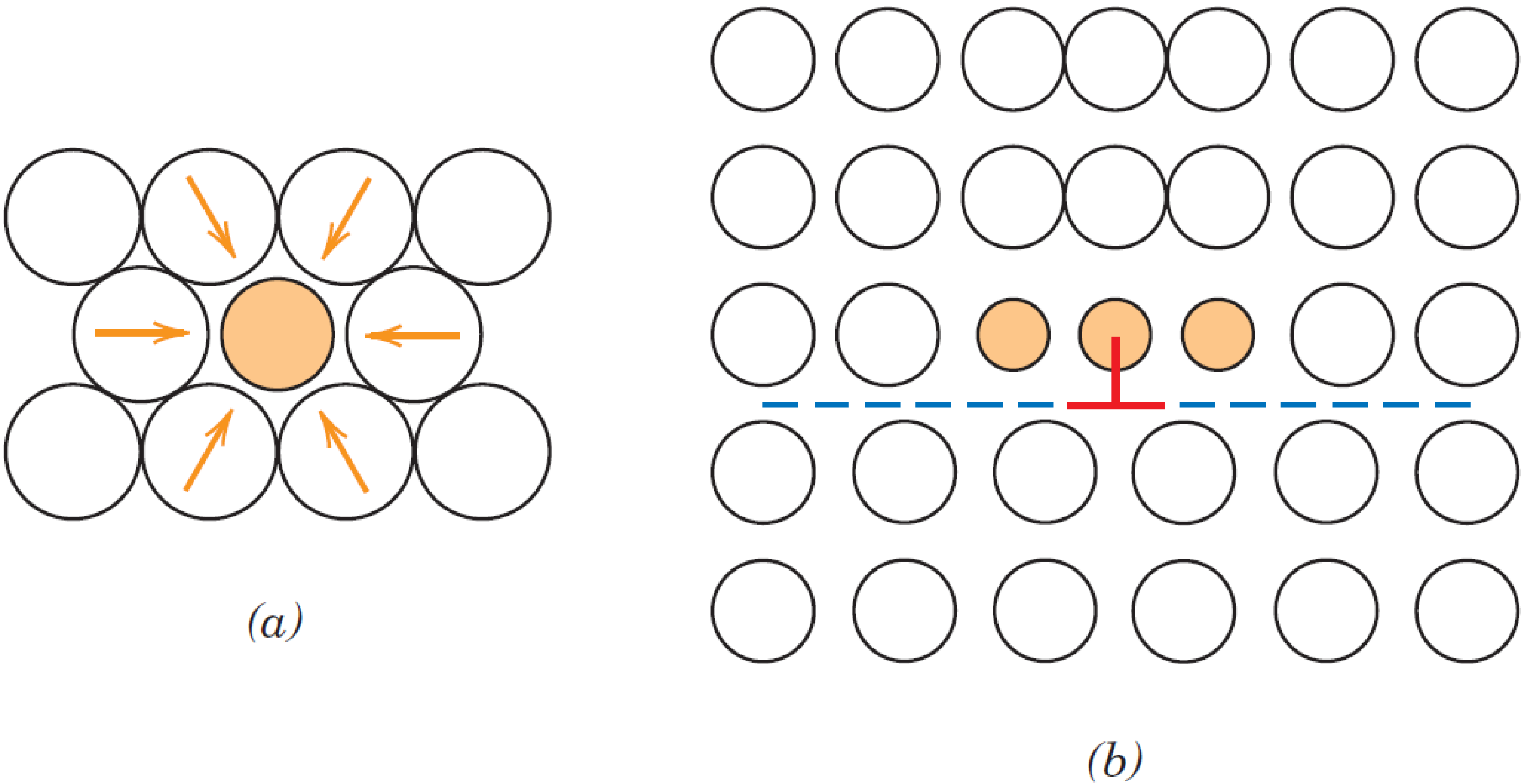


Figure 7.17 (*a*) Representation of tensile lattice strains imposed on host atoms by a smaller substitutional impurity atom. (*b*) Possible locations of smaller impurity atoms relative to an edge dislocation such that there is partial cancellation of impurity–dislocation lattice strains.

Mechanisms of Strengthening in Metals

Solid-Solution Strengthening

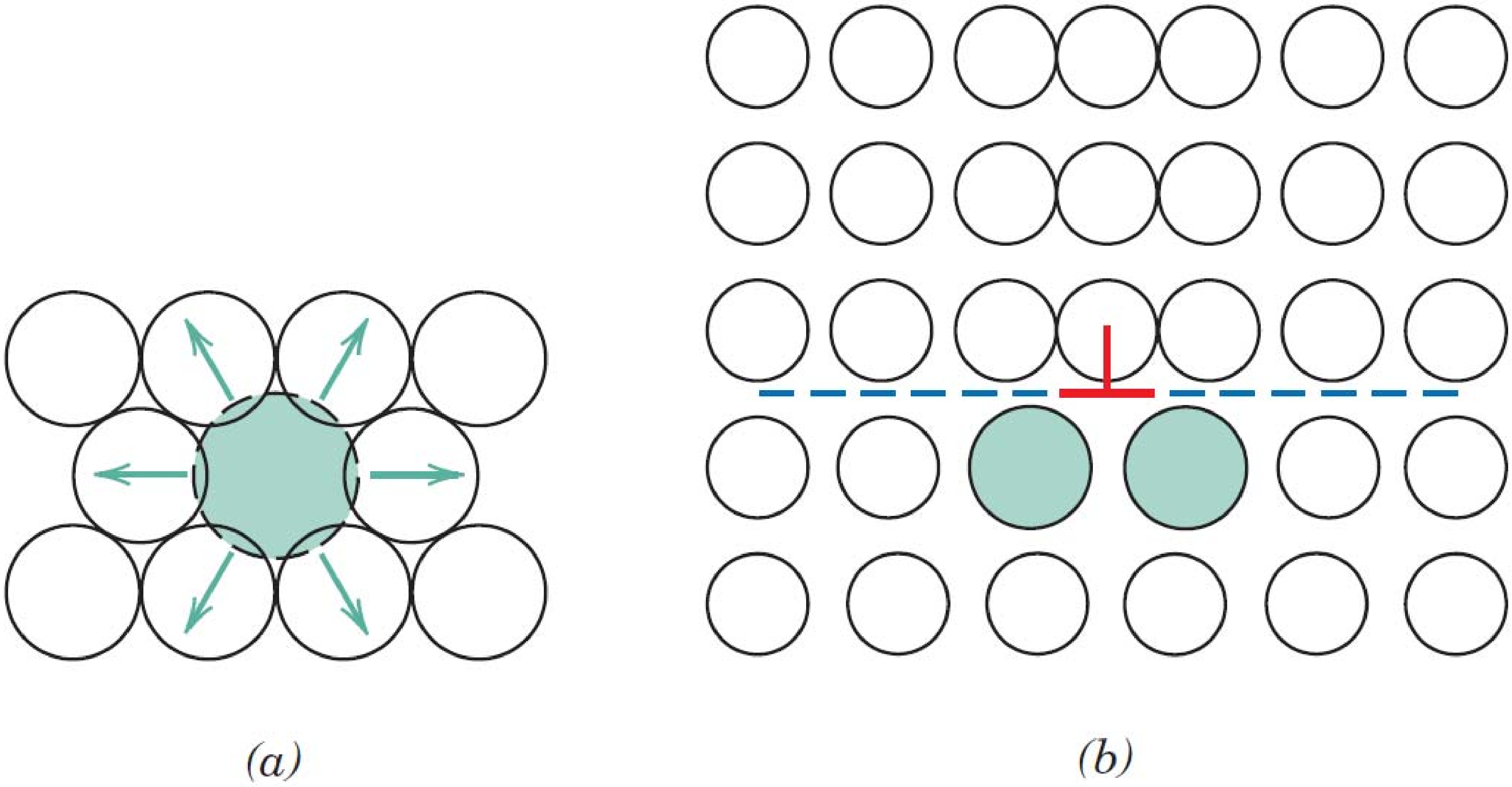


Figure 7.18 (*a*) Representation of compressive lattice strains imposed on host atoms by a larger substitutional impurity atom. (*b*) Possible locations of larger impurity atoms relative to an edge dislocation such that there is partial cancellation of impurity–dislocation lattice strains.

Mechanisms of Strengthening in Metals

Solid-Solution Strengthening

- solute atoms tend to diffuse to and segregate around dislocations in a way so as to reduce the overall strain energy—that is:
  - to cancel some of the strain in the lattice surrounding a dislocation.
- The resistance to slip is greater when impurity atoms are present because:
  - the overall lattice strain must increase if a dislocation is torn away from them.
- Furthermore, the same lattice strain interactions will exist between impurity atoms and dislocations that are in motion during plastic deformation. Thus, a greater applied stress is necessary to first initiate and then continue plastic deformation for solid-solution alloys

Mechanisms of Strengthening in Metals

Strain Hardening

- **Strain hardening** (or work hardening, or cold working): the phenomenon whereby a ductile metal becomes harder and stronger as it is plastically deformed.
  - Most metals strain harden at room temperature.

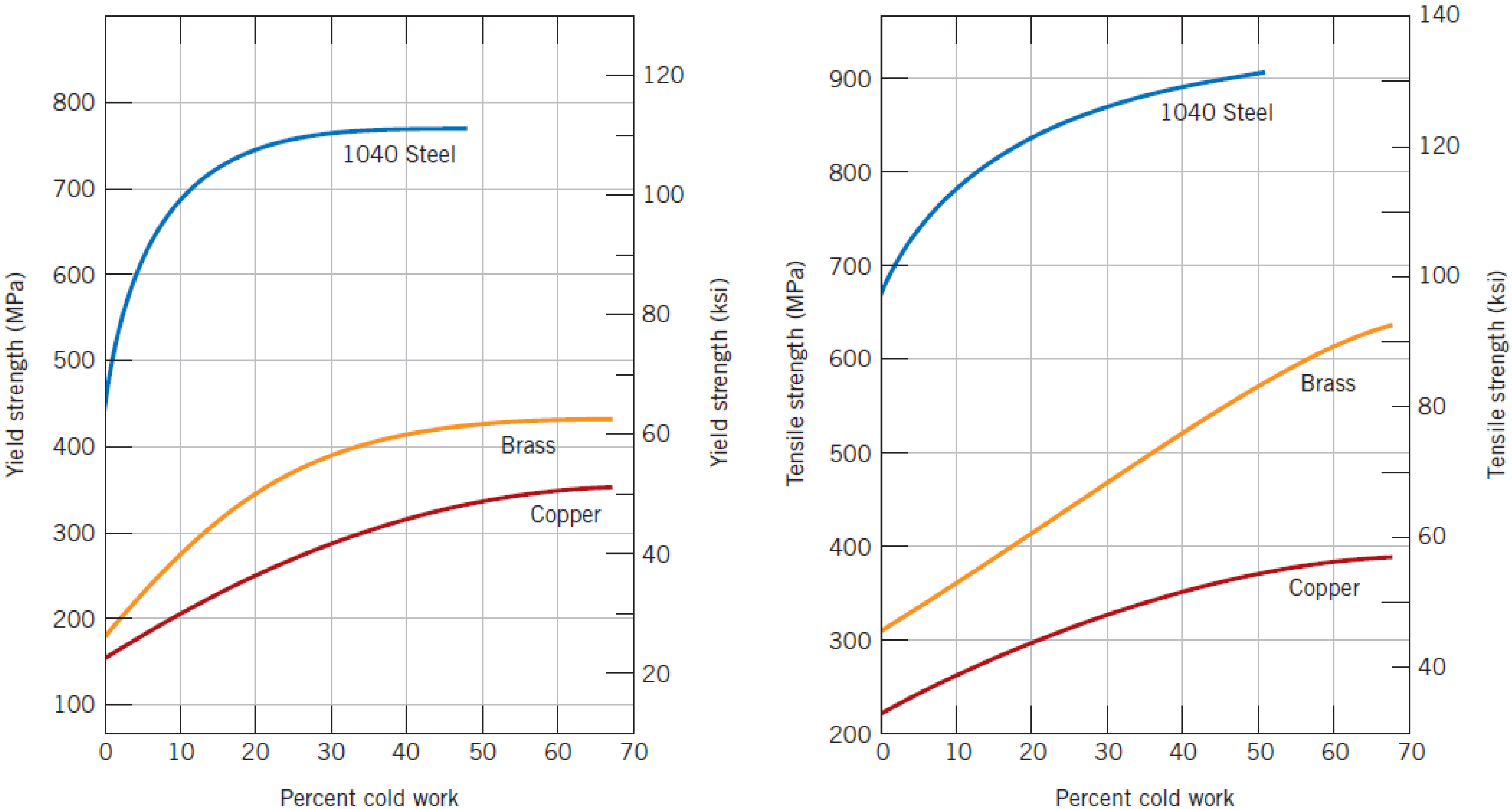
area after deformation

Degree of plastic deformation best expressed as *percent cold work*

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

Mechanisms of Strengthening in Metals

Strain Hardening

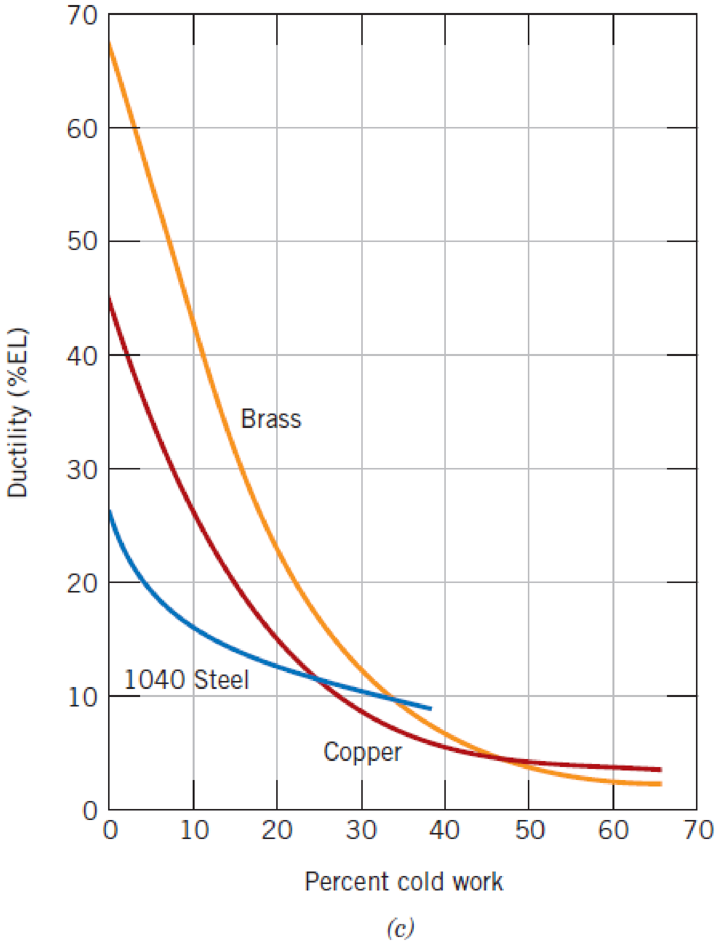


(a) (b)

Figure 7.19 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.

Mechanisms of Strengthening in Metals

Strain Hardening



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Mechanisms of Strengthening in Metals
Strain Hardening

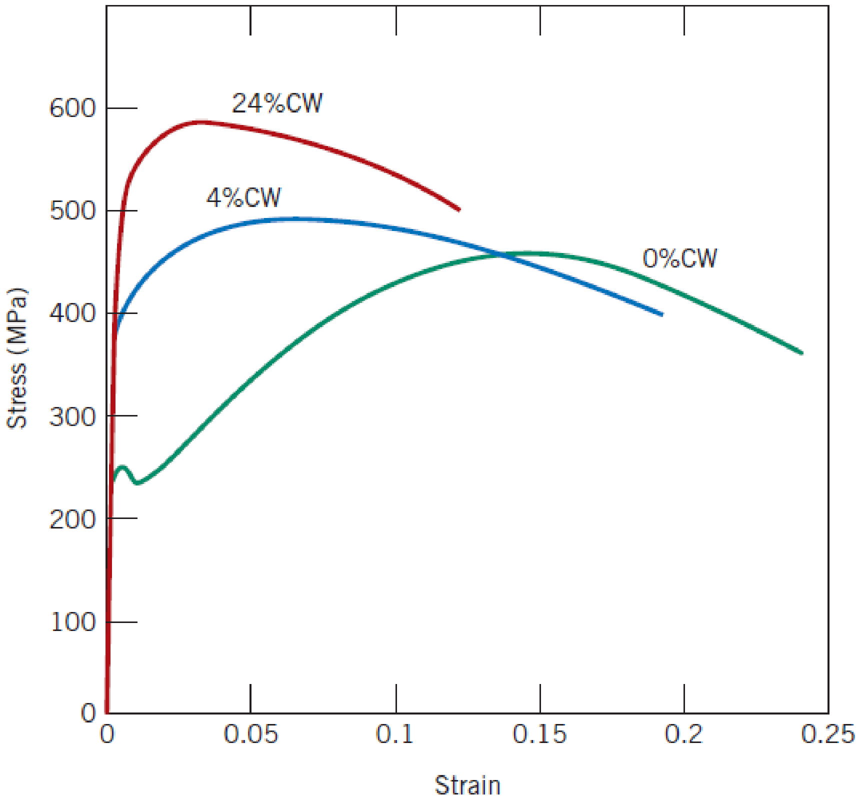

Figure 7.20 The influence of cold work on the stress–strain behavior of a low- carbon steel; curves are shown for 0%CW, 4%CW, and 24%CW.

Mechanisms of Strengthening in Metals
Strain Hardening

- By clod working: dislocations multiply or new dislocations form.
  - the average distance of separation between dislocations decreases.
  - On the average, dislocation–dislocation strain interactions are repulsive. The net result is that the motion of a dislocation is hindered by the presence of other dislocations.
  - As the dislocation density increases, this resistance to dislocation motion by other dislocations becomes more pronounced.
    - Thus, the imposed stress necessary to deform a metal increases with increasing cold work.

Mechanisms of Strengthening in Metals

Strain Hardening

- Example 7.2: 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

Mechanisms of Strengthening in Metals
Strain Hardening

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Recovery, Recrystallization, and Grain Growth

- Plastically deforming a polycrystalline metal specimen at temperatures that are low relative to its melting temperature produces microstructural and property changes that include:
  - (1) a change in grain shape.
  - (2) strain hardening.
  - (3) an increase in dislocation density.

- Some fraction of the energy expended in deformation is stored in the metal as strain energy, which is associated with tensile, compressive, and shear zones around the newly created dislocations.
  - Also electrical conductivity and corrosion resistance may be modified as a consequence of plastic deformation.

Recovery, Recrystallization, and Grain Growth

- ***Annealing Treatment***: a heat treating process in which the properties and structures may revert back to the precold-worked states.

- Restoration results from two different processes that occur at elevated temperatures:

  - *Recovery* and *Recrystallization,* which may be followed by *Grain Growth.*

Recovery, Recrystallization, and Grain Growth

Recovery

- During ***recovery*****,** some of the stored internal strain energy is relieved by virtue of dislocation motion (in the absence of an externally applied stress),
  - As a result of enhanced atomic diffusion at the elevated temperature.
- There is some reduction in the number of dislocations, and dislocation configurations are produced having low strain energies.
  - In addition, physical properties such as electrical and thermal conductivities are recovered to their precold-worked states.

Recovery, Recrystallization, and Grain Growth

Recrystallization

- ***Recrystallization***: formation of a new set of strain-free and equiaxed grains that have low dislocation densities and are characteristic of the precold-worked condition.

  - The driving force to produce this new grain structure is the difference in internal energy between the strained and unstrained material.

  - Recrystallization of cold-worked metals may be used to refine the grain structure.

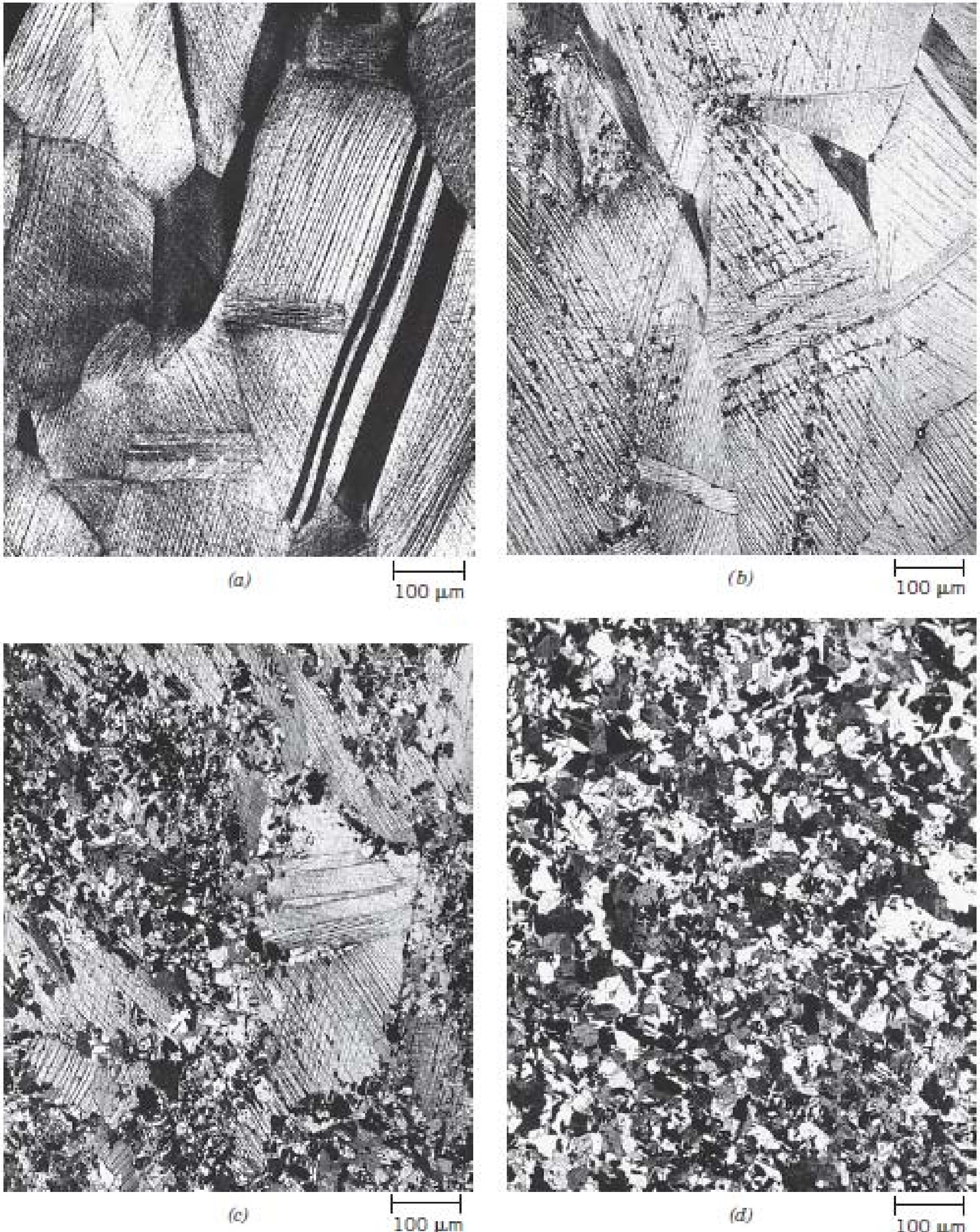

Figure 7.21
Photomicrographs showing several stages of the recrystallization and grain growth of brass. (*a*) Cold-worked (33%CW) grain structure. (*b*) Initial stage of recrystallization after heating 3 s at 580° C; the very small grains are those that have recrystallized. (*c*) Partial replacement of cold-worked grains by recrystallized ones (4 s at 580° C). (*d*) Complete recrystallization (8 s at 580° C). (*e*) Grain growth after 15 min at 580° C. (*f*) Grain growth after 10 min at 700° C.

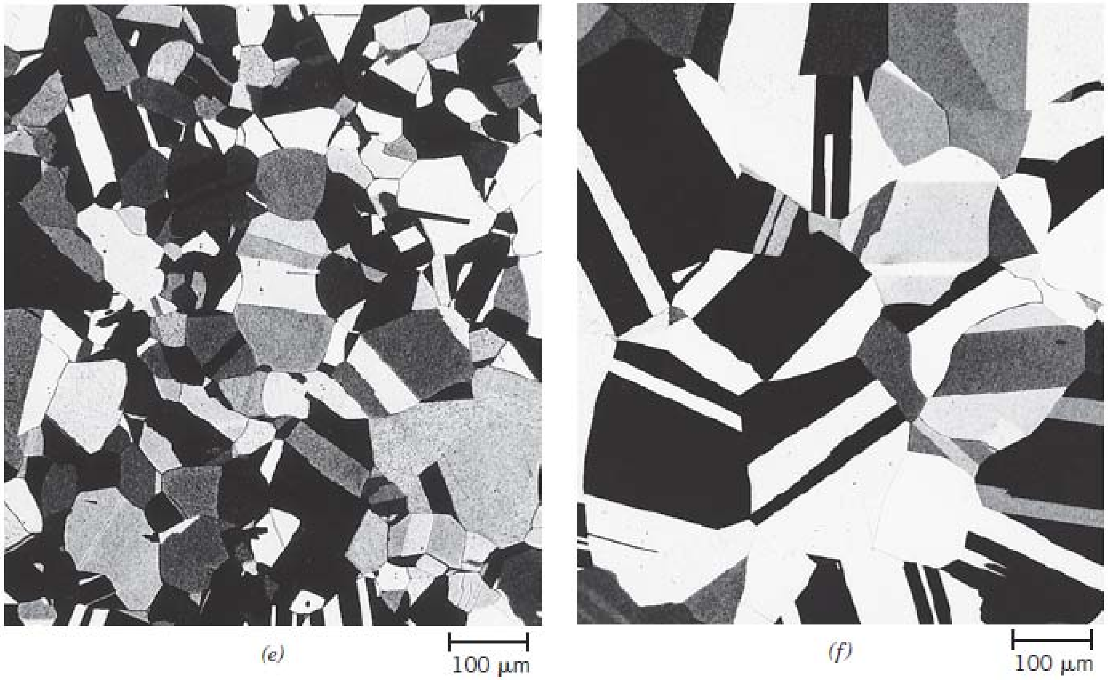

Figure 7.21 (*continued*)

Figure 7.21
Photomicrographs showing several stages of the recrystallization and grain growth of brass. (*a*) Cold-worked (33%CW) grain structure. (*b*) Initial stage of recrystallization after heating 3 s at 580° C; the very small grains are those that have recrystallized. (*c*) Partial replacement of cold-worked grains by recrystallized ones (4 s at 580° C). (*d*) Complete recrystallization (8 s at 580° C). (*e*) Grain growth after 15 min at 580° C. (*f*) Grain growth after 10 min at 700° C.

Recovery, Recrystallization, and Grain Growth

Recrystallization

- ***Recrystallization Temperature***: temperature at which recrystallization just reaches completion in 1 h.
  - Typically, it is between one-third and one-half of the absolute melting temperature of a metal or alloy (Figure 7.22).
  - Increasing the percentage of cold work enhances the rate of recrystallization, with the result that the recrystallization temperature is lowered, and approaches a constant or limiting value at high deformations (Figure 7.23).

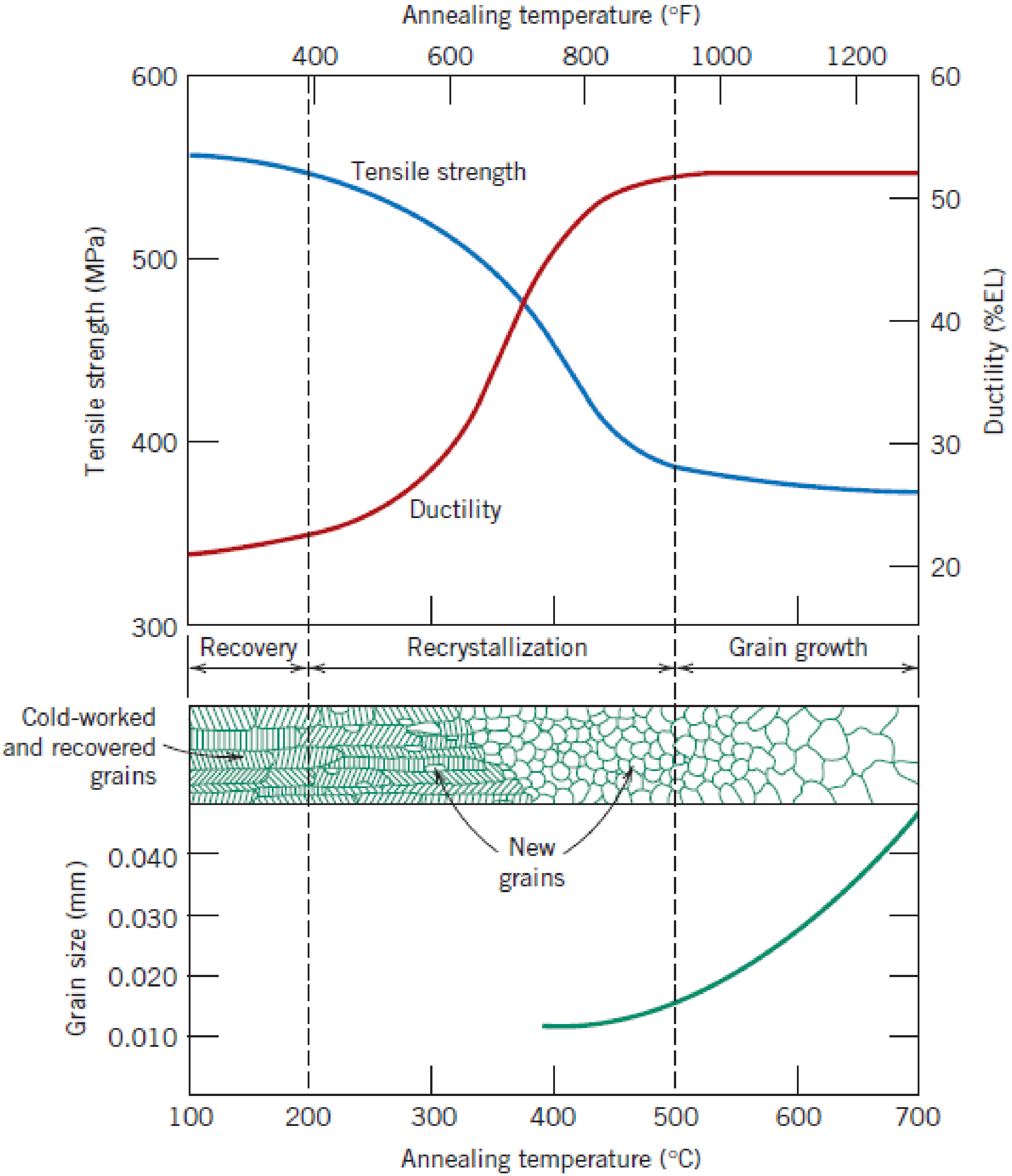

Figure 7.22 The influence of annealing temperature (for an annealing time of 1 h) on the tensile strength and ductility of a brass alloy. Grain size as a function of annealing temperature is indicated. Grain structures during recovery, recrystallization, and grain growth stages are shown schematically.

The recrystallization temperature for the brass alloy is about 450° C

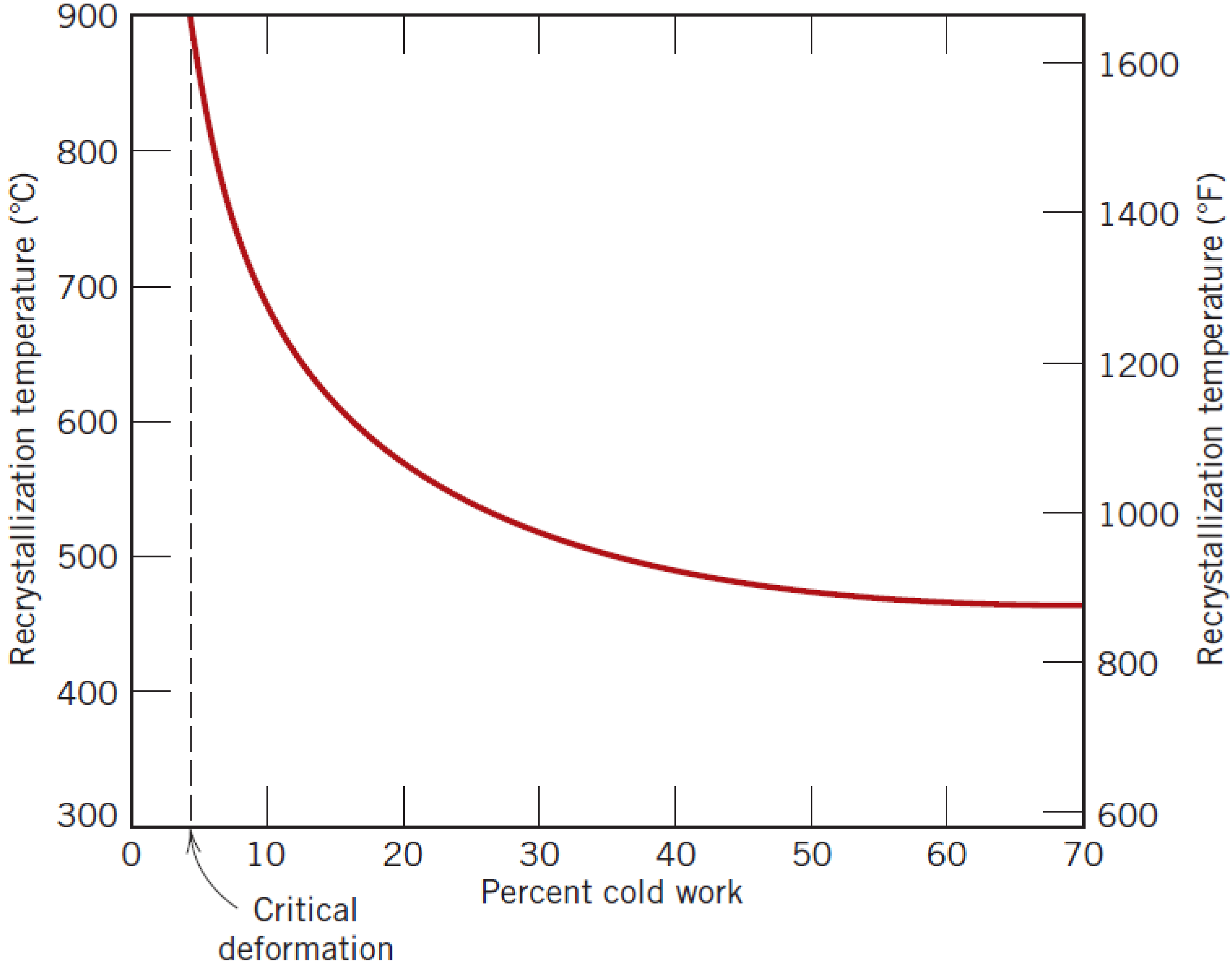

Figure 7.23 The variation of recrystallization temperature with percent cold work for iron. For deformations less than the critical (about 5%CW), recrystallization will not occur.

Recovery, Recrystallization, and Grain Growth

Recrystallization

- Recrystallization proceeds more rapidly in pure metals than in alloys.

- During recrystallization, grain-boundary motion occurs as the new grain nuclei form and then grow.

  - It is believed that impurity atoms preferentially segregate at and interact with these recrystallized grain boundaries so as to diminish their mobilities; this results in a decrease of the recrystallization rate and raises the recrystallization temperature.

  - For pure metals, the recrystallization temperature is normally $0.4T_m$, where T_m is the absolute melting temperature; for some commercial alloys it may run as high as $0.7T_m$.

Recovery, Recrystallization, and Grain Growth

Recrystallization

- Plastic deformation operations are often carried out at temperatures above the recrystallization temperature in a process termed *hot working*.
  - The material remains relatively soft and ductile during deformation because it does not strain harden, and thus large deformations are possible.

	Recrystallization Temperature		*Melting Temperature*	
Metal	*°C*	*°F*	*°C*	*°F*
Lead	−4	25	327	620
Tin	−4	25	232	450
Zinc	10	50	420	788
Aluminum (99.999 wt%)	80	176	660	1220
Copper (99.999 wt%)	120	250	1085	1985
Brass (60 Cu–40 Zn)	475	887	900	1652
Nickel (99.99 wt%)	370	700	1455	2651
Iron	450	840	1538	2800
Tungsten	1200	2200	3410	6170

Table 7.2 Recrystallization and Melting Temperatures for Various Metals and Alloys

Recovery, Recrystallization, and Grain Growth
Grain Growth

- ***Grain growth***: the continuous growth of the grains when a metallic specimen is left at elevated temperatures.
  - Grain growth does not need to be preceded by recovery and recrystallization.
- The driving force for grain growth: As grains increase in size, the total boundary area decreases, yielding an attendant reduction in the total energy.

Recovery, Recrystallization, and Grain Growth

Grain Growth

- For many polycrystalline materials, the grain diameter d varies with time t:

time-independent constants

$$d^n - d_0^n = Kt$$

initial grain diameter at $t = 0$

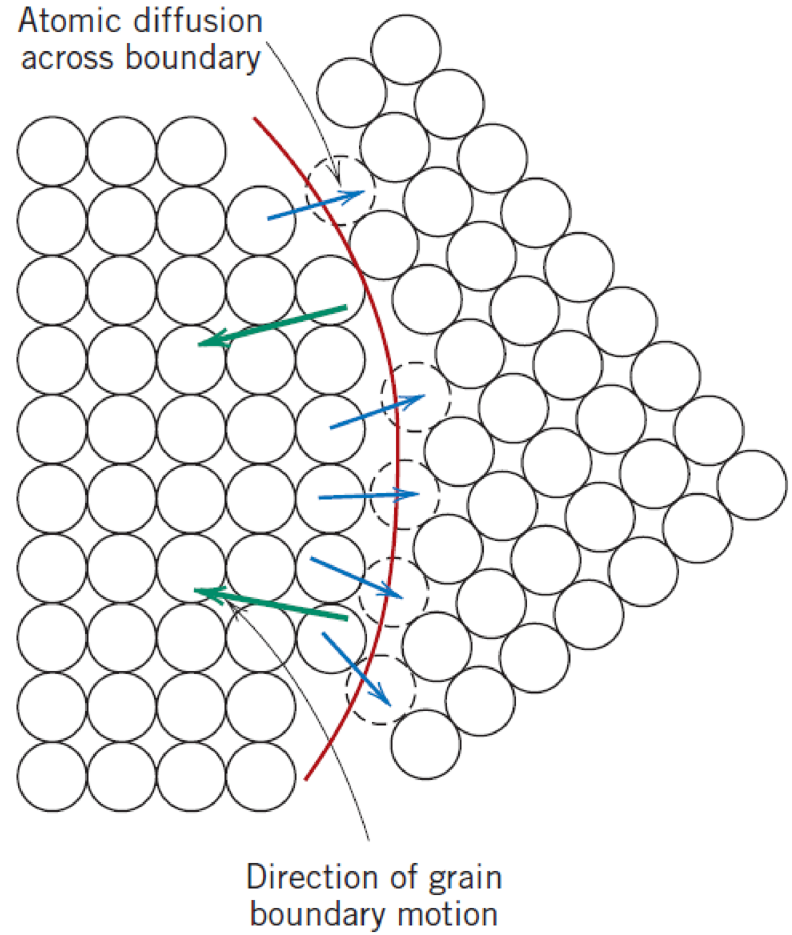

Figure 7.24 Schematic representation of grain growth via atomic diffusion.

Recovery, Recrystallization, and Grain Growth

Grain Growth

- The mechanical properties at room temperature of a fine-grained metal are usually superior (i.e., higher strength and toughness) to those of coarse-grained ones.
- If the grain structure of a single-phase alloy is coarser than that desired, refinement may be accomplished by plastically deforming the material, then subjecting it to a recrystallization heat treatment.

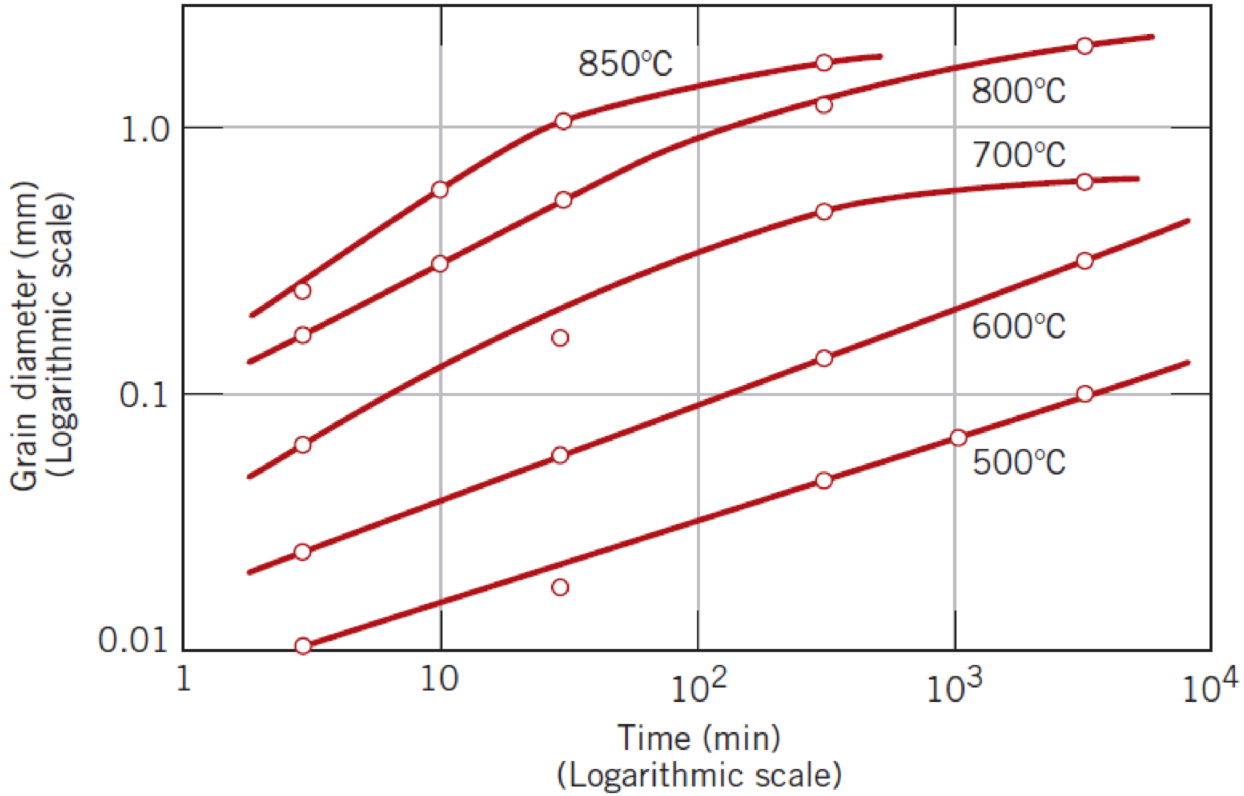

Figure 7.25 The logarithm of grain diameter versus the logarithm of time for grain growth in brass at several temperatures.