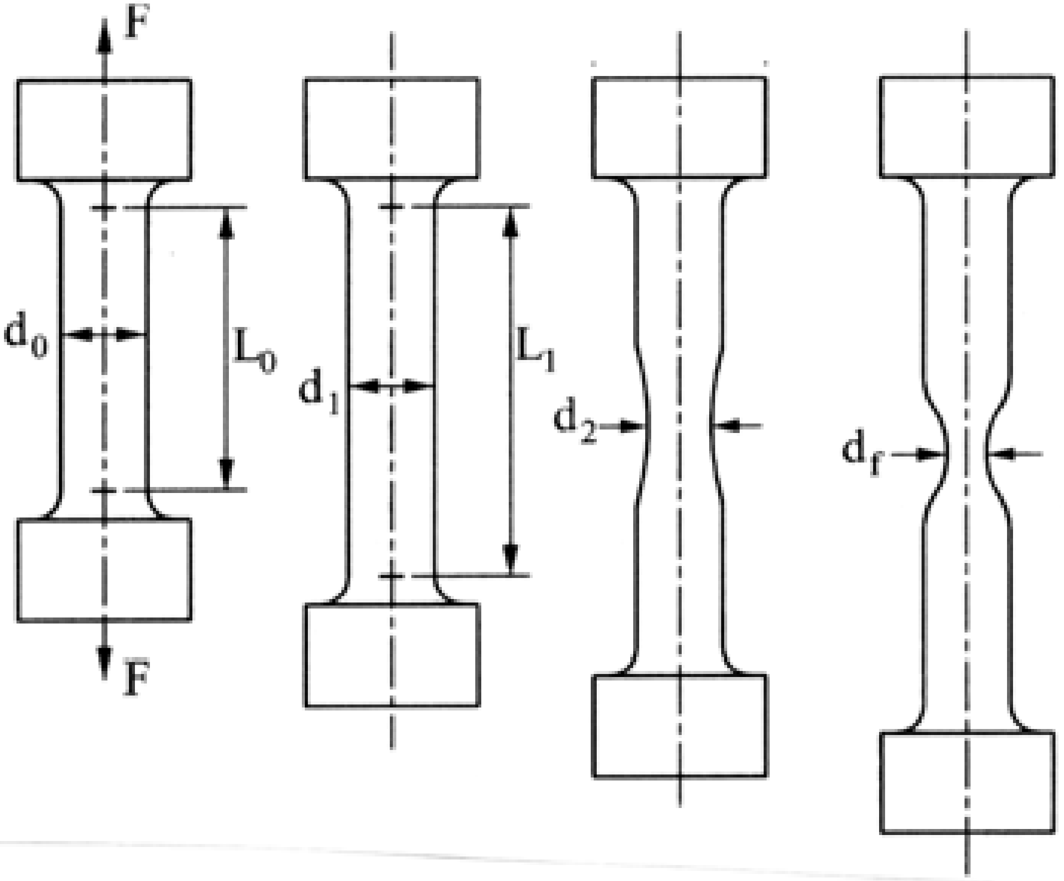
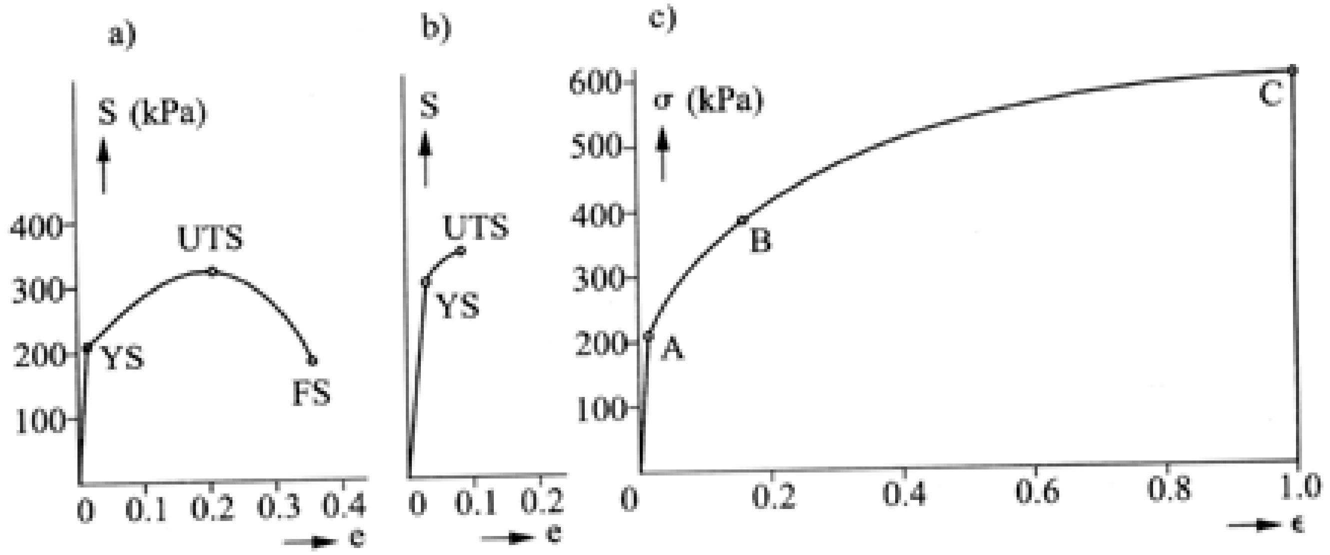
Engineering Materials and Their Properties

- Significance of:
  - the yield strength
  - specific heat
  - thermal conductivity
  - the wear rate
  - hardness
  - toughness
- Materials of interest
  - metals
  - plastics
  - ceramics
  - composites

The Tensile Test

The tensile test specimen.





The stress-strain diagrams: a) engineering stress S versus engineering strain e for a ductile material; b) brittle material; c) graph (a) replotted as the true stress σ–true strain ε diagram.

$$S = \frac{F}{A_0} = \frac{F}{\pi d_0^2/4}$$

$$e = \frac{L_1 - L_0}{L_0} = \frac{\Delta L}{L_0}$$

- It is more proper to evaluate true stress and true strain, and to relate these values to the neck only.
- Though the true stress - true strain diagram is more realistic, the majority of tensile test data is published in the form of engineering stress - strain.
- The three most important parameters characterizing metal:
  - yield strength (YS)
  - ultimate tensile strength (UTS)
  - elongation (e_f or e)
- Some example values for steels:
  - mild steel: UTS = 60,000 psi = 410 Mpa; e = 35%
  - medium-carbon steel: UTS = 85,000 psi = 590 MPa; e = 6%
  - high-strength alloy steel: UTS = 180,000 psi = 1,240 MPa; e = 6%

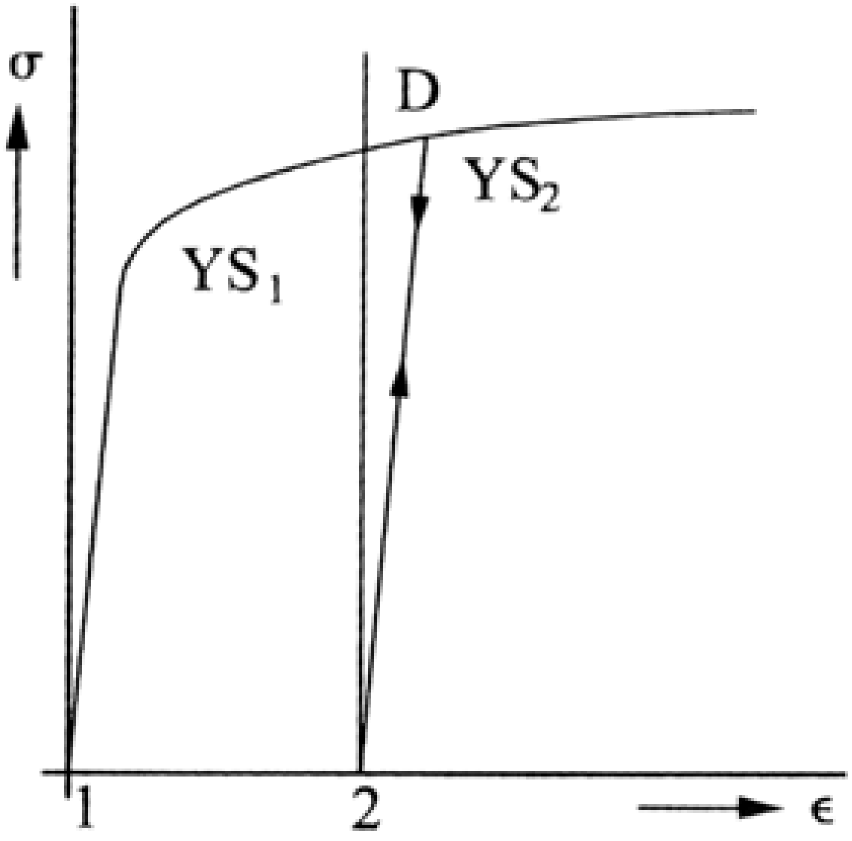
- The area under the true stress-strain curve is significant when expressing the increment of work related to volume:

$$dW = \frac{FdL}{AL} = \left(\frac{F}{A}\right)\left(\frac{dL}{L}\right) = \sigma d\varepsilon$$

$$W_s = \int_0^{\varepsilon} dW$$

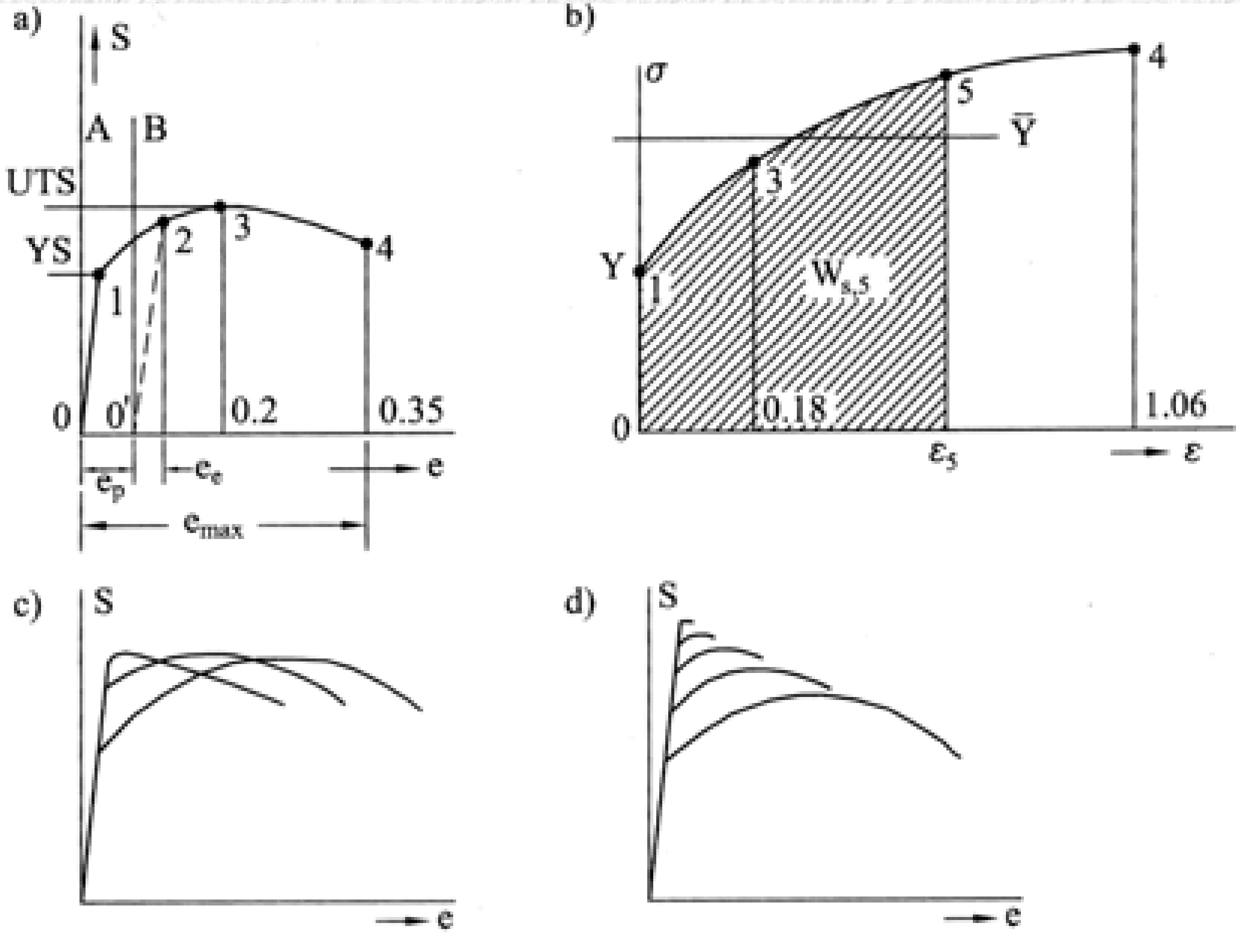
- which is the specific work to fracture and a measure of the toughness of the material.
- Toughness - the ability of a material to absorb impacts and to dissipate the corresponding kinetic energy in plastic deformation without failure.

- Important to the understanding of strengthening mechanisms is the relation between dislocation motion and mechanical behavior of metals. Because macroscopic plastic deformation corresponds to the motion of large numbers of dislocations, the ability of a metal to plastically deform depends on the ability of dislocations to move. Since hardness and strength are related to the ease with which plastic deformation can be made to occur, by reducing the mobility of dislocations, the mechanical strength may be enhanced; that is, greater mechanical forces will be required to initiate plastic deformation. In contrast, the more unconstrained the dislocation motion, the greater the facility with which a metal may deform, and the softer and weaker it becomes. Virtually all strengthening techniques rely on this simple principle: restricting or hindering dislocation motion renders a material harder and stronger.



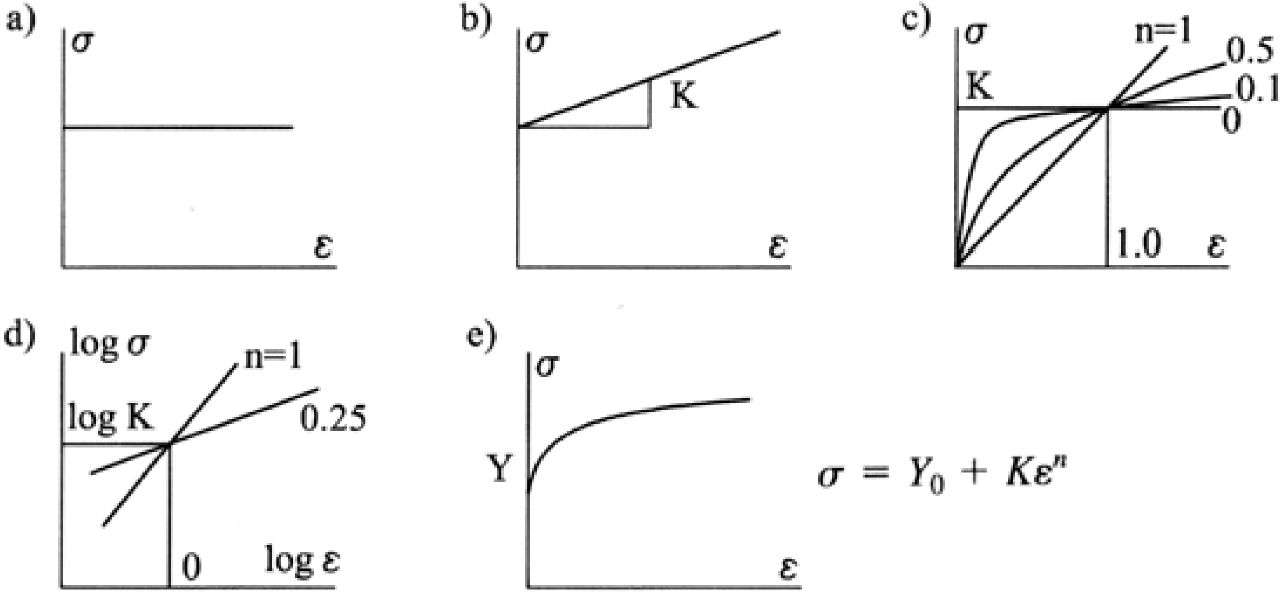
Strain-hardening in an interrupted and restarted tensile test.

- The area under the true-stress true-strain curve is the specific plastic deformation work per unit volume.



Stress-strain diagram of the tensile test: a) "engineering" stress and strain; b) "true" stress and strain; c) changes in (a) due to strain-hardening in the tensile test; d) changes due to strain-hardening in general cold work.

- The stress strain diagram can be approximated in various ways by mathematical expressions that are graphically indicated below.

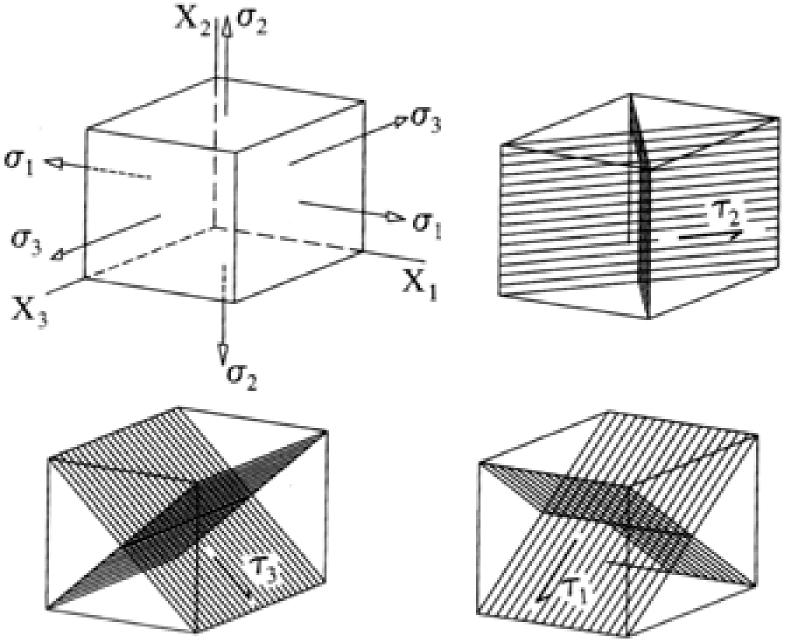


$$\sigma = Y_0 + K\varepsilon^n$$

Various models of the stress-strain diagram: a) rigid perfectly plastic; b)–e) various forms of the strain-hardening effect.

- Stress in three dimensions
  - There are no shear stresses on these planes:

Three-dimensional stress. Normal stresses in principal axes and principal shear stresses.



  - If two of the principle stresses are equal, the state is called cylindrical stress. If all three are equal, it is the state of hydrostatic, or spherical stress.

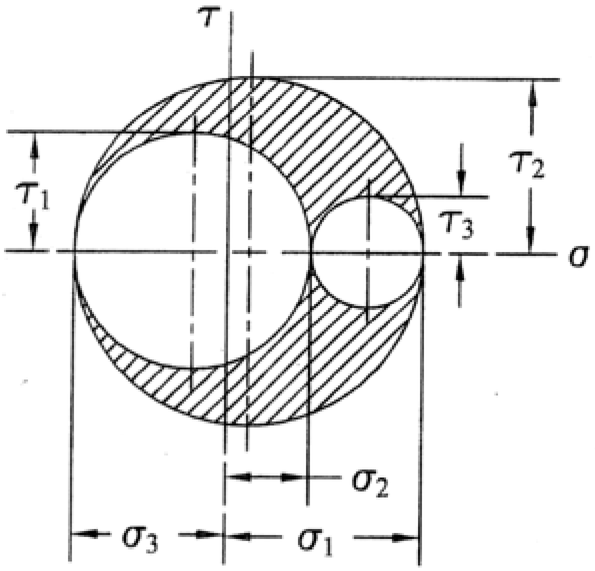
- All other planes than principle planes contain shear stresses. For all the planes passing through each of the principal axes, there are two orthogonal planes for which shear stresses are maximum. These are called principle shear stresses. They are located at 45º to the principle planes, and the stresses are:

$$\tau_1 = \frac{\sigma_2 - \sigma_3}{2}$$

$$\tau_{\max} = \tau_2 = \frac{\sigma_1 - \sigma_3}{2}$$

$$\tau_3 = \frac{\sigma_1 - \sigma_2}{2}$$

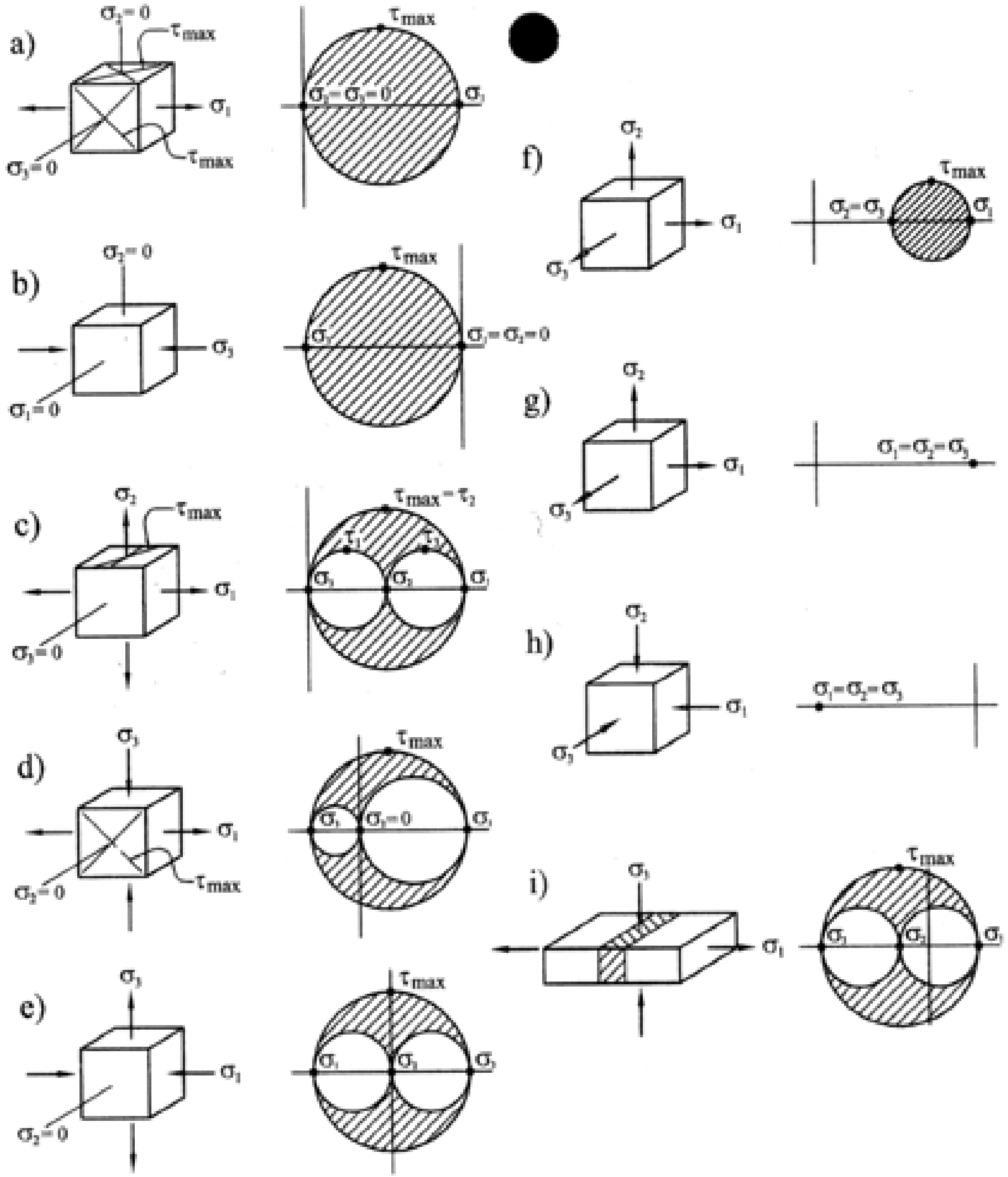
- The stresses on all planes of the system, as related to the principal stresses, are easily obtained using Mohr's circles. In the system of the graph, it's axes being those of normal stresses and shear stresses, three circles are drawn located diametrically between points 1, 2, 3, with centers on the σ axis. Each of the three circles represents stresses in planes passing through the X_1, X_2, X_3 axes respectively. Stresses on all other planes correspond to points in the shaded area between the circles.



Mohr's circles for three-dimensional stress. Normal stresses are measured on the horizontal axis, shear stresses on the vertical axis. Each circle represents stresses in planes passing through one of the principal axes.

Figure 5.5

Various co[illegible]nations of principal stresses: a) uniaxial tension; b) uniaxial compression; c) and d) plane-stress cases; e) special case of plane stress–pure shear; f) triaxial tension; g) uniform triaxial tension; h) hydrostatic compression; i) plane strain.



- Let's look at some special stress states and comment on them with respect to the ratio of maximum shear stress to maximum tensile stress. Shear stress, as noted in the subsequent paragraph, is associated with plastic deformation without material failure. Tensile stress is associated with cracks and fractures. The ratio shear/tensile then expresses the ability to deform without fracture.

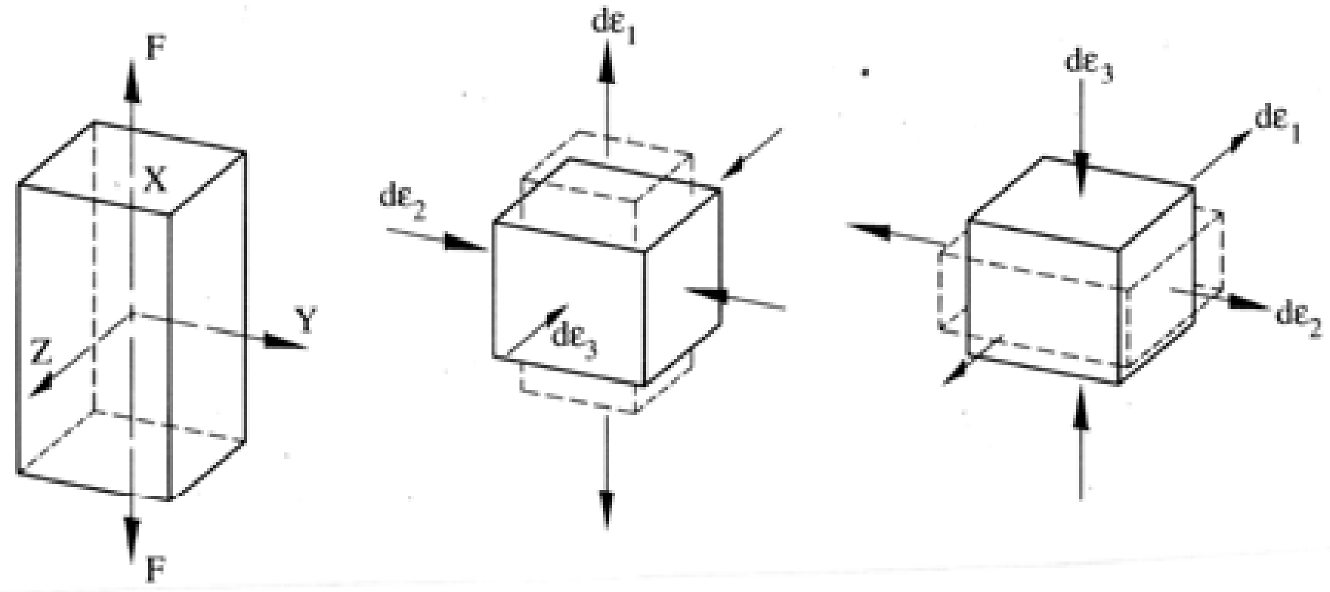
- Yielding: Plastic deformation
  - Yielding is only affected by deviatory stresses, that is, by the differences between a complex stress state, and the corresponding hydrostatic stress. The two most widely stated criteria that have been developed empirically are those established by Tresca and Von Mises.
    - The Tresca criterion is based on the maximum shear stress:

$$\tau_{\max} = \frac{\sigma_1 - \sigma_3}{2} = \frac{Y}{2} = k$$

    - Where Y is the yield stress, and k is the shear flow stress obtained in pure shear, where $\sigma_1 = -\sigma_3 = k$, and $\sigma_2 = 0$
    - Obviously this leads to $k = \dfrac{Y}{2}$

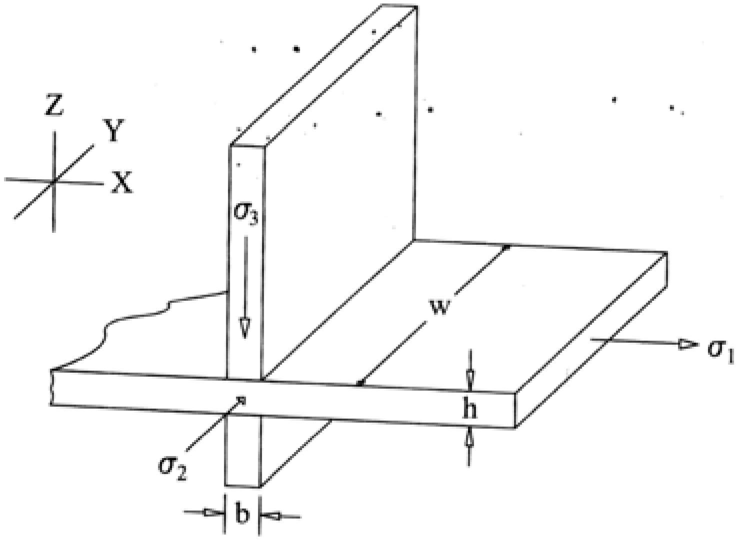
- The criterion is rather simple, and it is a good approximation to experimental observations. However, the Von Mises criterion was found to be still closer to reality, and we will use this criterion in most of our exercises. It is also called the criterion of maximum distortion theory, and it combines all three deviatoric stresses in what is called the effective stress. Yielding is obtained is the effective stress equals the yield stress.
- Now we need to discuss the relations between stress and strain in plastic deformation. As mentioned before, the strains are not determined by the stresses; they depend on the entire history of loading. It is necessary to follow the strain increments through the changing stress situation and integrate them along the loading path.
- It is established that strain increments be proportional to the effective stresses.

- Special cases of yielding
  - Uniaxial Tension or Compression
    - This situation is represented in the figure. A force F acts in direction X on an area A.



Strains in uniaxial tension and compression.

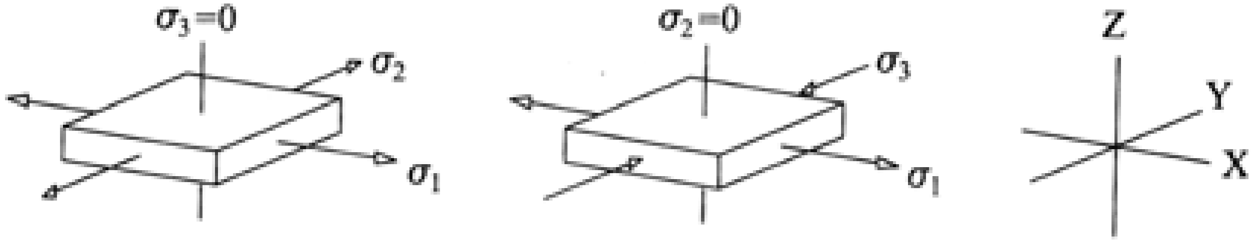
- Plane strain
  - In some situations, the material is prevented from defoeming in one of the principal axes. The most common such case arises in rolling and can be represented as shown in Fig. 5.7. A wide plate is compressed between anvils, the width b of which is much smaller than the width w of the plate. The material is prevented from spreading in direction Y by the material of the plate adhacent to the anvils. Correspondingly, the strain equals 0 and the material deforms in the directions X and Z only.



Plane-strain situation. In compressing over a long narrow strip across a wide sheet the surrounding material prevents sideways strain. Representative of rolling of wide sheet and plate.

- Plane stress
  - – In other situations, stresses may occur in two principal axes only. These cases were depicted in diagrams c, d, and e of Fir. 5.5. In proctive this applies often to sheet metal forming, and as shown in Fig. 5.8, the stress in x being tensile, the stress in y may be either tensile or compressive.

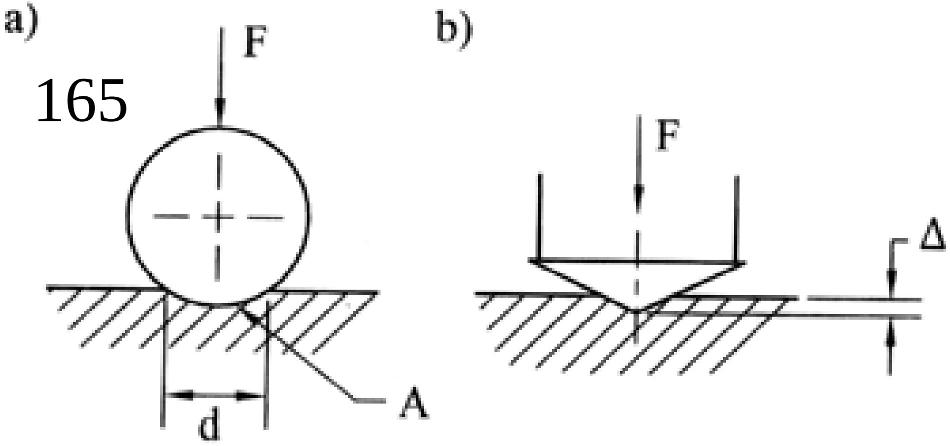
Figure 5.8
Plane-stress situation. Representative of sheet-metal forming.



- Hardness testing
  - hardness expresses the resistance of the material surface to indentation. This resistance is closely related to the yield strength of the material, and it is further affected by its susceptibility to strain hardening. There is a good relationship between the strength parameters of the tensile test and the results of hardness tests for most materials.

The *Brinell hardness*

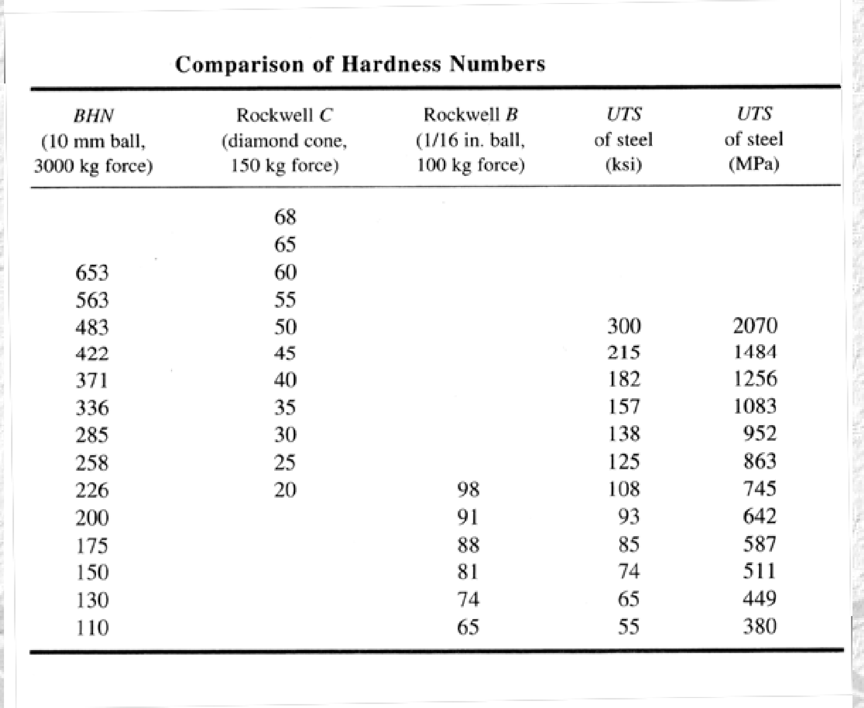
Mild steel: 120
Medium-carbon steel: 165
Cast iron: 150-200



Hardness testing: a) Brinell indenter; b) Rockwell C indenter.

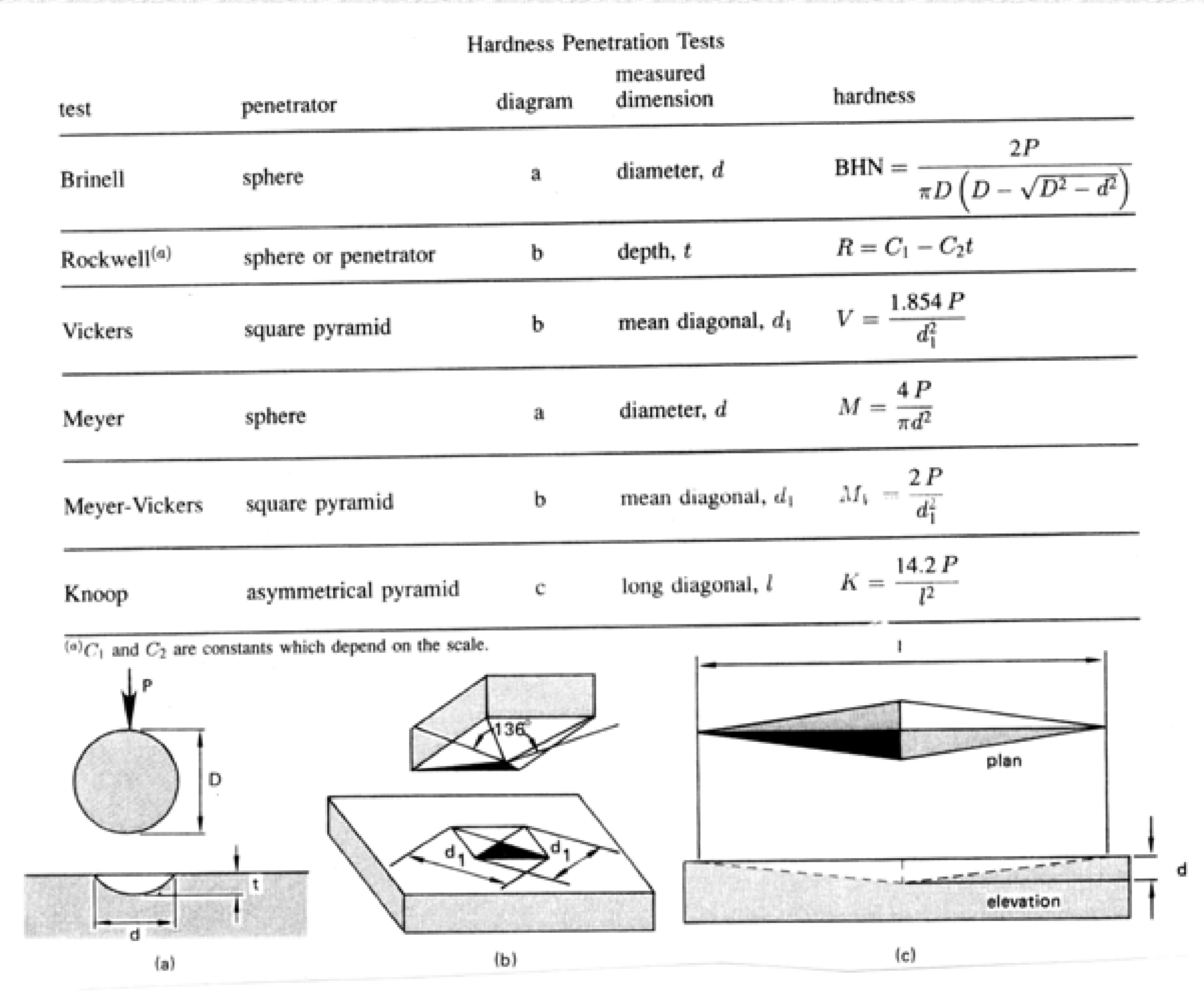
- The limitations of the brinell test are several. The first one is due to the use of a ball for the indenter; for very hard materials, the shallow imprint is inaccurate. The second limitation, for materials of lower hardness, is due to the rather large size of the indenter and of the force and, therefore, of the imprint. Correspondingly, the value obtained is the average of all the material grains involved. If a part with a thin surface hardened layer is to be tested, this layer will be deformed and the underlying material will be involved, which affects the result of the measurement.

- Harder materials are tested by means of several specifications of the Rockwell hardness test. The material of the indenter is diamond, and in the most popular Rockwell C scale it has the shape of a cone (see Fig. 2.4b). The tester is so designed that the vertical penetration between an initial small load and full load is the measure of hardness. For the C scale, the full load is 150 kg force. The B scale uses a ball of 1/16 in. diameter and 100 kg force, and it is intended for softer materials.



Comparison of Hardness Numbers

BHN (10 mm ball, 3000 kg force)	Rockwell *C* (diamond cone, 150 kg force)	Rockwell *B* (1/16 in. ball, 100 kg force)	*UTS* of steel (ksi)	*UTS* of steel (MPa)
	68			
	65			
653	60			
563	55			
483	50		300	2070
422	45		215	1484
371	40		182	1256
336	35		157	1083
285	30		138	952
258	25		125	863
226	20	98	108	745
200		91	93	642
175		88	85	587
150		81	74	511
130		74	65	449
110		65	55	380



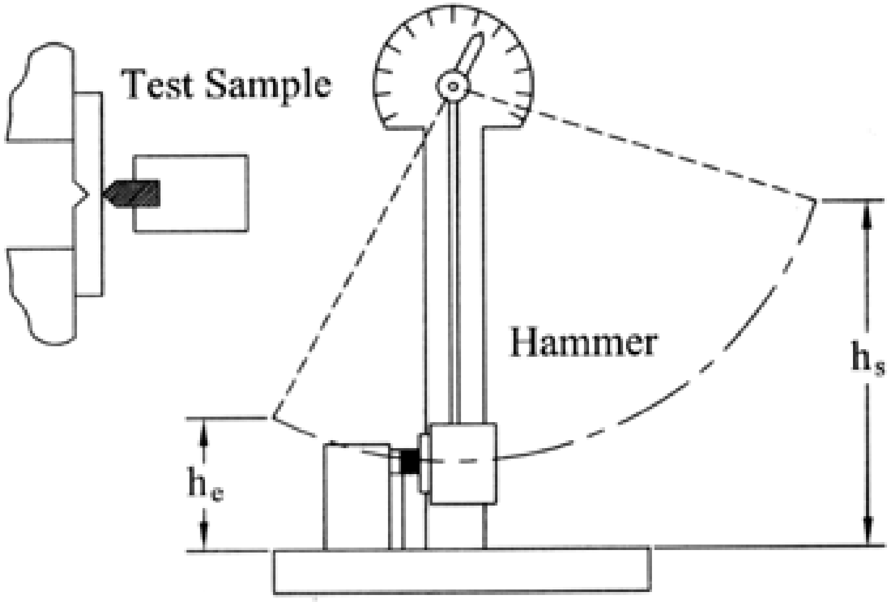
Hardness Penetration Tests

test	penetrator	diagram	measured dimension	hardness
Brinell	sphere	a	diameter, d	$\mathrm{BHN} = \dfrac{2P}{\pi D\left(D - \sqrt{D^2 - d^2}\right)}$
Rockwell[a]	sphere or penetrator	b	depth, t	$R = C_1 - C_2 t$
Vickers	square pyramid	b	mean diagonal, d_1	$V = \dfrac{1.854\,P}{d_1^2}$
Meyer	sphere	a	diameter, d	$M = \dfrac{4\,P}{\pi d^2}$
Meyer-Vickers	square pyramid	b	mean diagonal, d_1	$M_V = \dfrac{2\,P}{d_1^2}$
Knoop	asymmetrical pyramid	c	long diagonal, l	$K = \dfrac{14.2\,P}{l^2}$

[a] C_1 and C_2 are constants which depend on the scale.

- Notched bar impact tests
  - The difference in height of fall and of rise after the strike determines the energy spent on the fracturing of the specimen. This energy is not directly comparable to the specific energy to fracture in the tensile test because different materials are differently sensitive to the stress concentration around the notch. The test is mostly used for evaluating the effect of various heat treatments of steels on their toughness.

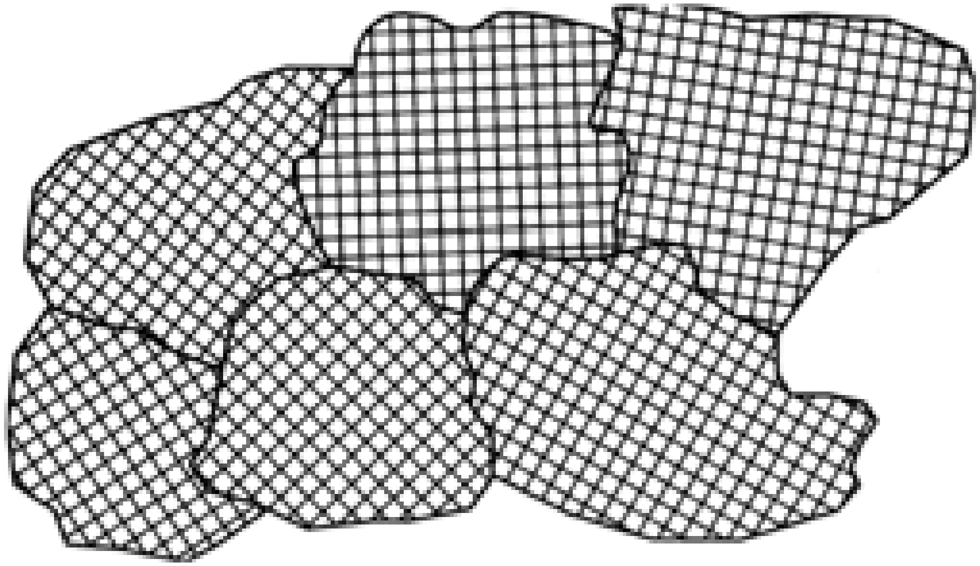
Charpy impact testing of toughness using a notched specimen. The difference in the initial and final potential energies defines the fracture energy.



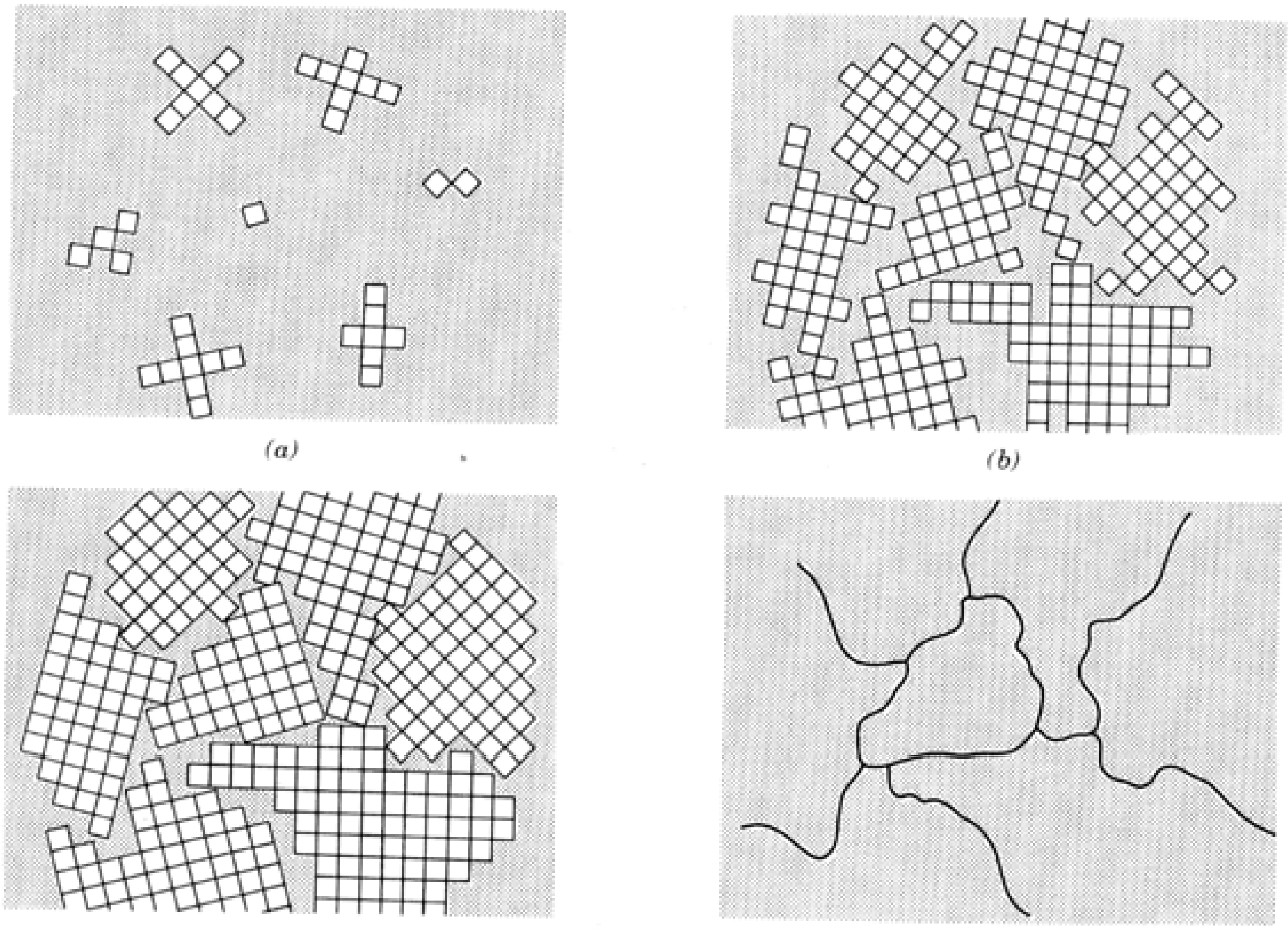
- High-temperature tests
  - Elevated temperature affects the properties of metals. These effects may be determined by carrying out tests like the tensile test at various temperatures while keeping the specimen inside of a furnace. In other instances upset hot forging of test workpieces is carried out. These kinds of tests deal with short-time plastic behavior of materials.
  - If long time periods are considered, the phenomenon of creep becomes significant. Materials yield at elevated temperatures very slowly under stresses considerably lower than those needed for a fast plastic deformation.

- Fatigue testing
  - Fatigue failure occurs as a result of cyclic loads at stress levels that, when applies statically, would not produce any yielding or failure. The level of stress at which fatigue failure happens decreases with the number of duty cycles. However, for ferrous alloys, an endurance limit is observed as a stress below which failure does not occur for any number of cycles. This limit is reached approximately after 10^6 to 10^7 cycles. Fatigue develops in ductile materials by propagation of cracks and by spreading of defects from highly stressed areas. Eventually the final fracture is one of a brittle type.

- Structures and Transformations in Metals and Alloys
  - Metals and their alloys are the most common engineering materials. Most are solid at room temperature and exhibit elastice behavior up to the yield stress. Their YS, UTS, and hardness are rather high, and they also mostly possess significant ductility. Their strength is retained often to elevated temperatures, and the melting points of most metals are in the 1000 to 2000 C range. They are good electrical and thermal conductors.
  - Their atoms are held strongly together by the metallic bond which involves loosely held valence electrons that are “free” to move throughout the structure as an “electron cloud” shared by adjacent atoms. The mobility of electrons is the reason for the good electrical and thermal conductivity. The atoms in solid metals are arranged in long-range order regular patterns of crystals.



Crystal grains of a metal.

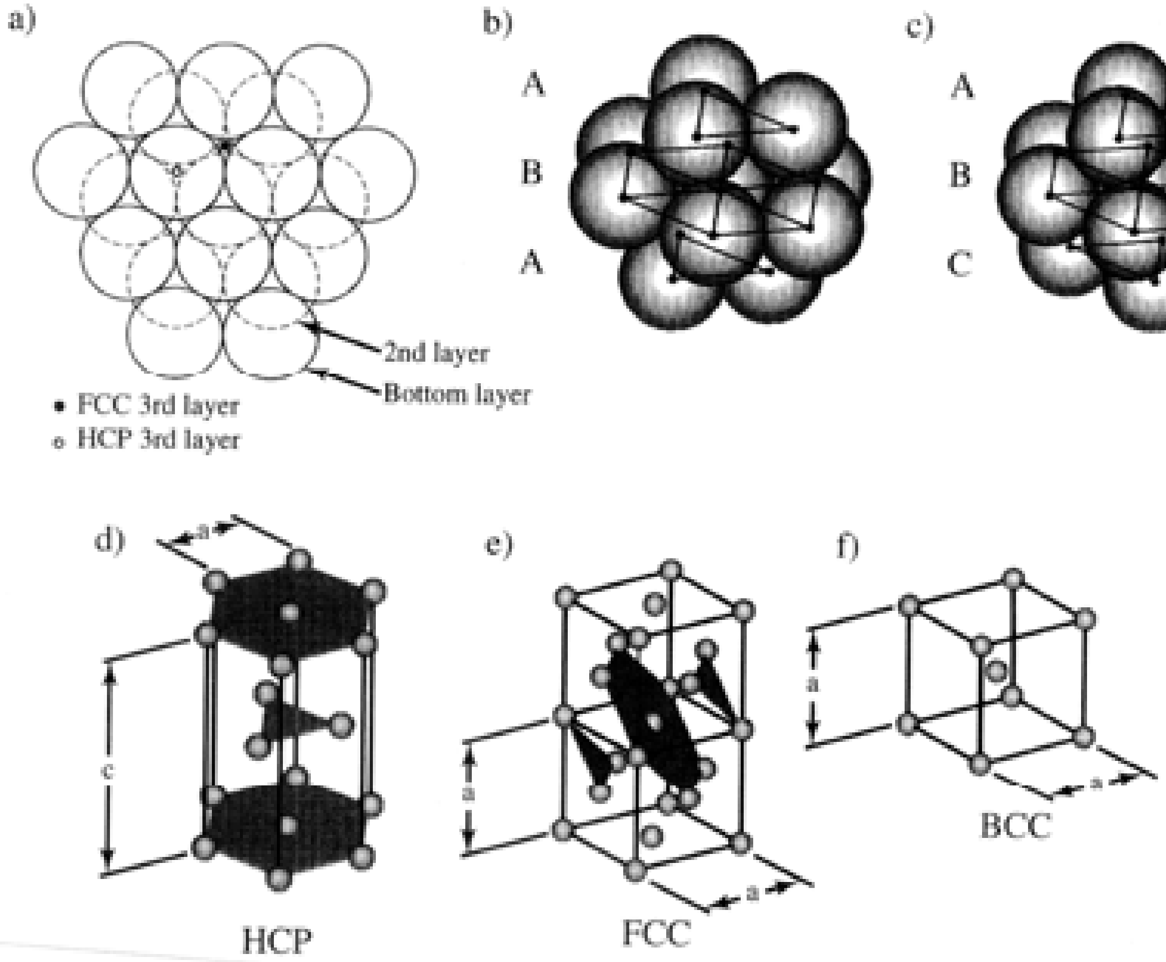


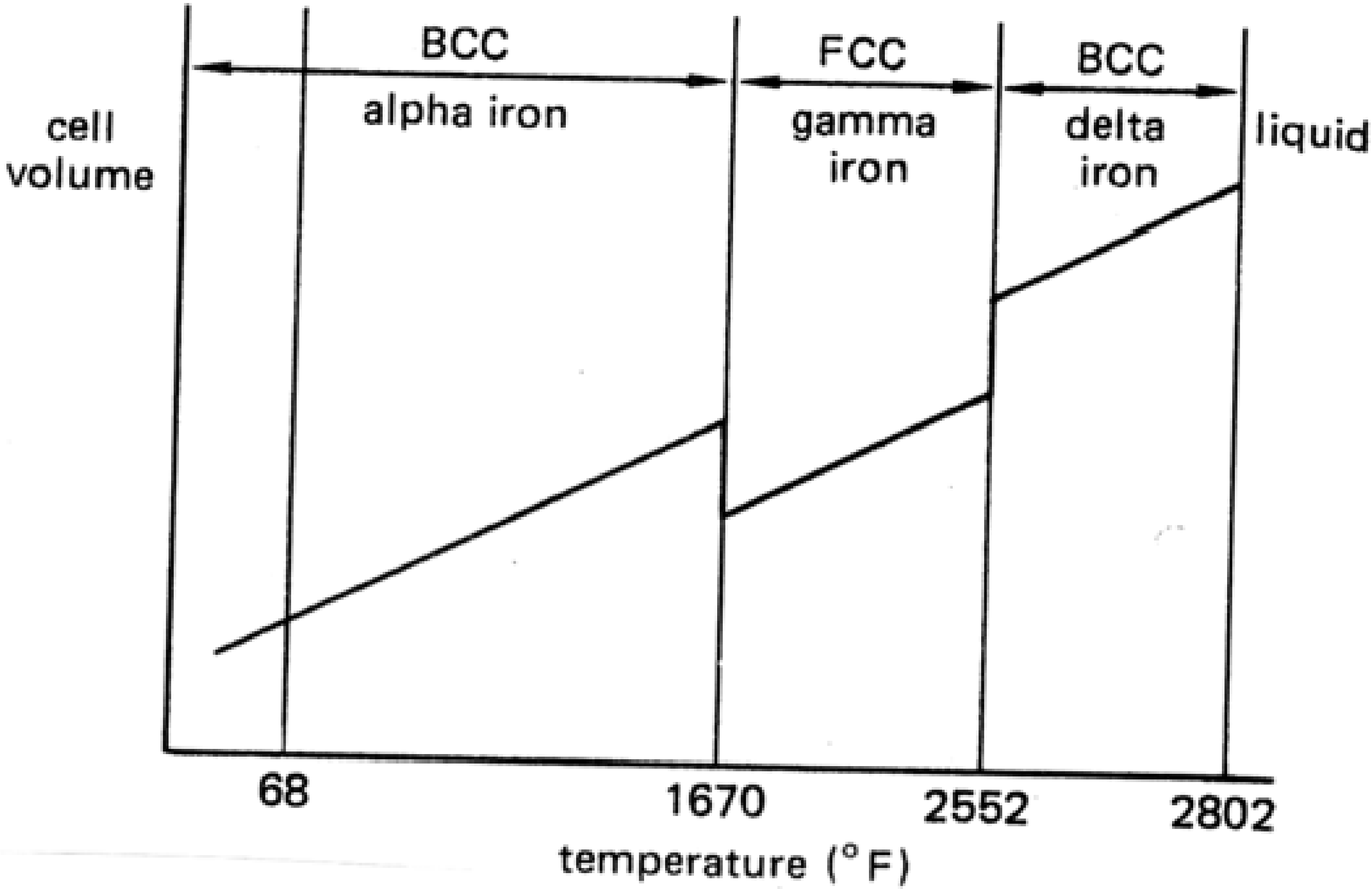
(a) (b) (c) (d)

Figure 3.15. Schematic diagrams of the various stages in the solidification of a polycrystalline material; the square grids depict unit cells. (*a*) Small crystallite nuclei. (*b*) Growth of the crystallites; the obstruction of some grains that are adjacent to one another is also shown. (*c*) Upon completion of solidification, grains having irregular shapes have formed. (*d*) The grain structure as it would appear under the microscope; dark lines are the grain boundaries. (Adapted from W. Rosenhain, *An Introduction to the Study of Physical Metallurgy*, 2nd edition, Constable & Company Ltd., London, 1915.)

- Crystal structures
  - The following have the HCP structure: Be, Mg, Co, Zn, Y, Zr, Ru, Hf, Re, Os. Because of the limited number of slip planes in this structure, these metals have limited ductility. The metals that crystallize in the FCC structure are, on the contrary, most ductile: Al, Ca, Sc, Ni, Cu, Sr, Rh, Pd, Ag, Ir, Pt, Au, Pb, Th. Metals of the BCC structure have medium ductility: Li, Na, K, V, Cr, Rb, Nb, Mo, Cs, Ba, Ta, W.
  - Two metals have a property called allotropy, which means that they can exist in two different structures, depending mainly on temperature. Thus, Fe is BCC at room temperature, and FCC above 723 C, and Ti has an HCP structure at room temperature and transforms to BCC at 880 C.

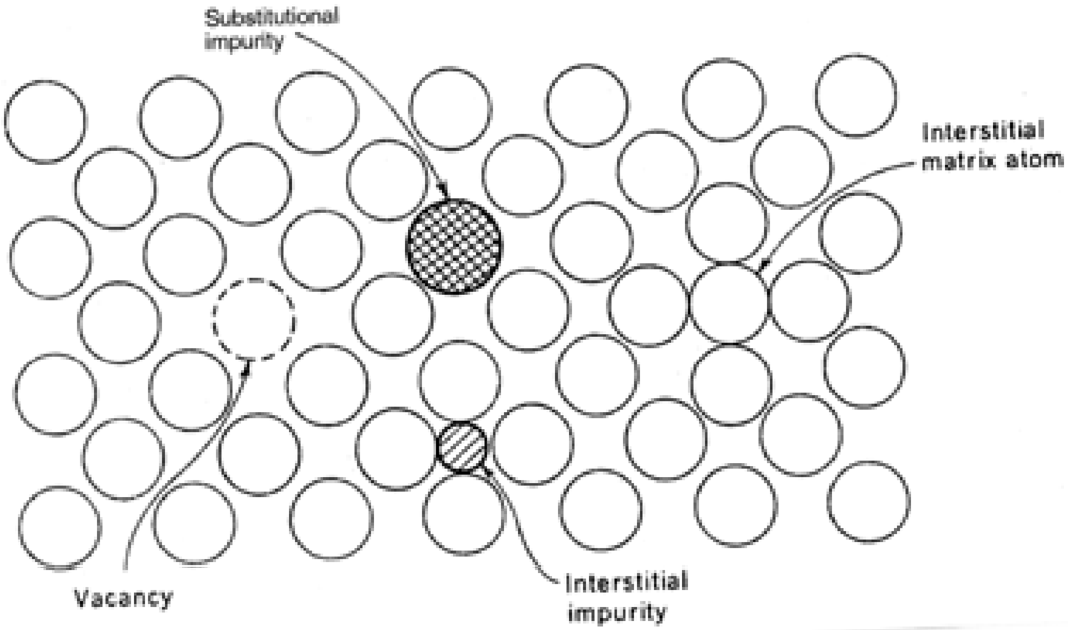
The HCP, FCC, and BCC unit cells. [Brick Gordon Phillips], [Van Vlack]





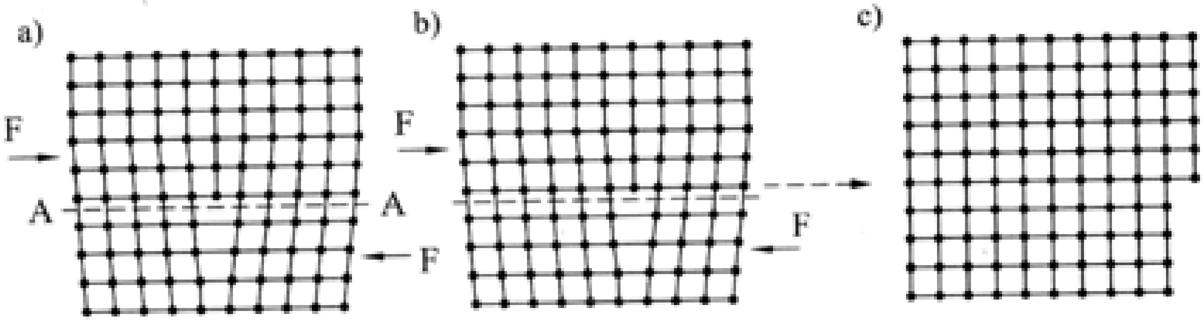
Allotropic Changes of Iron

- Crystal imperfections: dislocations
  - Crystals are practically never perfect. The material behavior actually depends mainly on the various kinds of imperfections, structural disorders, and impurities in the structures. Most importantly, plastic deformation of metals is entirely dependent on line imperfections called dislocations.
  - There are a great number of dislocations in a material, and any stress will encounter enough of them to carry out the plastic deformations. Dislocations can climb, cross-slip, expand, and multiply. During plastic deformation, their number grows; they interact with each other and with other barriers, especially with grain boundaries and with precipitate particles and foreign atoms, where they pile up and interlock. These are the mechanisms of strain hardening.



Point defects in crystals.
[SHEWMON]

- Dislocations exist in two basic types: the edge dislocation and the screw dislocation; and other types are combinations of these.



The edge dislocation and its movement.

- The process by which plastic deformation is produced by dislocation motion is termed slip; the plane along which the dislocation line traverses is the slip plane, as indicated in Figure 7.2. Macroscopic plastic deformation simply corresponds to permanent deformation that results from the movement of dislocations, or slip, in response to an applied shear stress.

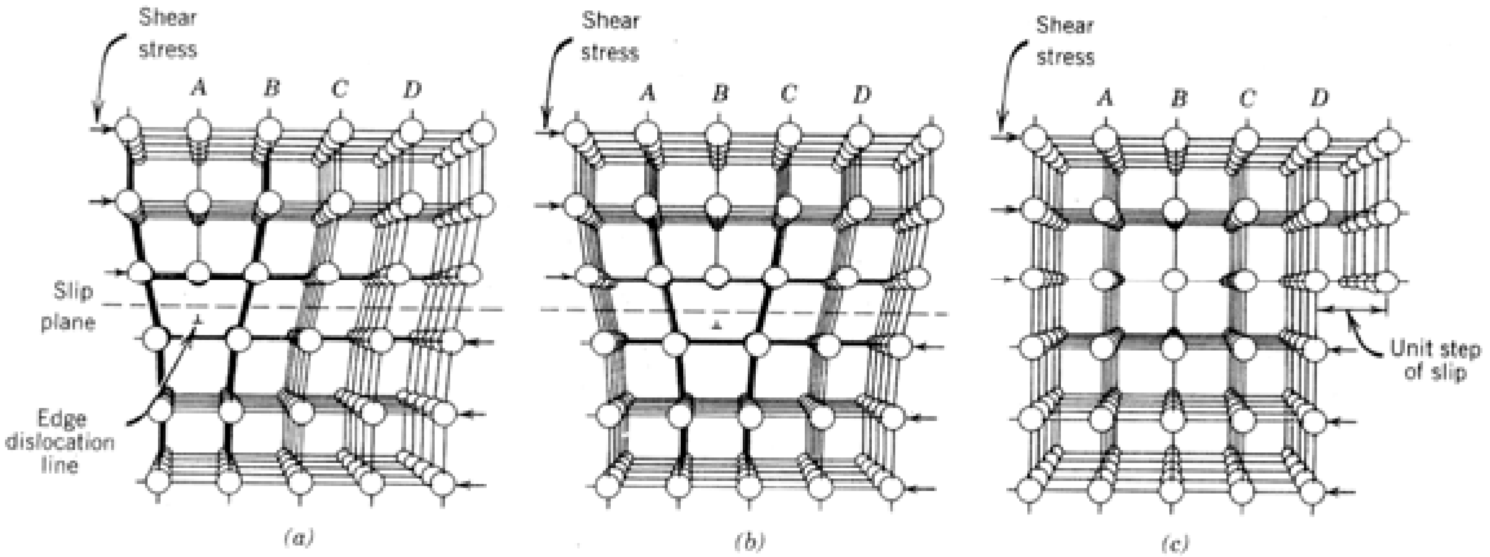


Figure 7.2. Atomic rearrangements that accompany the motion of an edge dislocation as it moves in response to an applied shear stress. (*a*) The extra half-plane of atoms is labeled as *A*. (*b*) The dislocation moves one atomic distance to the right as *A* links up to the lower portion of plane *B*; 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. (Adapted from A. G. Guy, *Essentials of Materials Science*, McGraw-Hill Book Company, New York, 1976, p. 153.)

- Dislocation motion is analogous to the mode of locomotion employed by a caterpillar (Figure 7.4). 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 repeating 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.

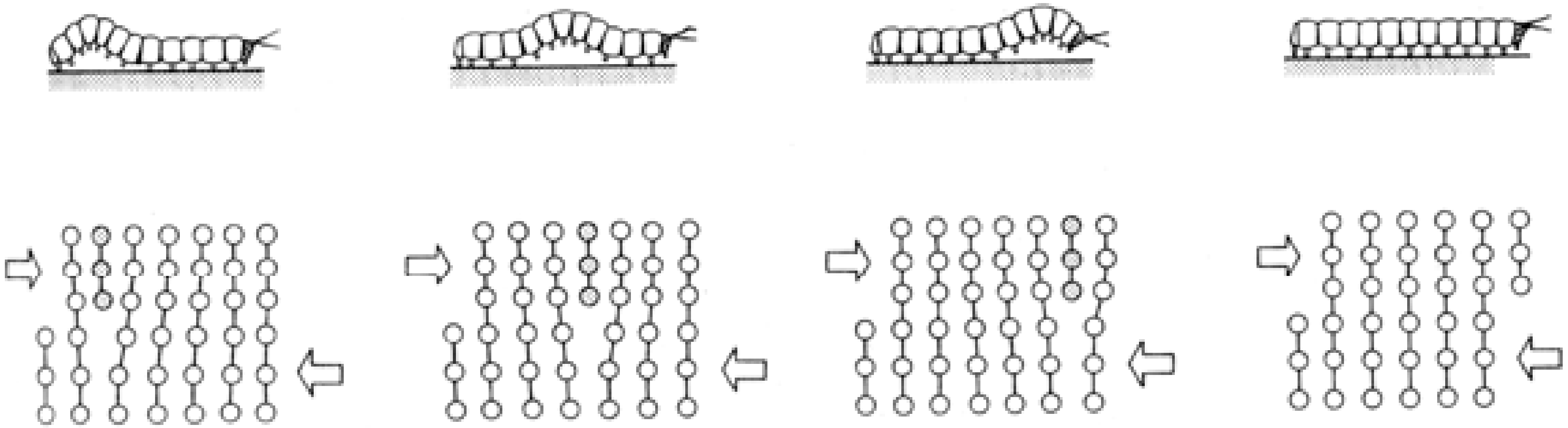


Figure 7.4. Representation of the analogy between caterpillar and dislocation motion.

- Grain boundaries and deformation
  - A grain boundary has a rather high surface energy and is thus the locality for preferential precipitation of foreign atoms. This is one more obstacle to dislocation movement at grain boundaries. The yield stress of a material increases with the decrease of grain size mainly because for finer grains, the grain boundary surface area per volume increases. The Hall-Petch relationship states that the tensile yield stress is related to grain size as follows:

$$Y = \sigma_i + k'D^{0.5}$$

  - where σ_i is friction stress opposing the motion of dislocations, k is the "unpinning constant" expressing the extent to which dislocations are piled up at barriers, and D is grain diameter.

- Mechanisms of strengthening in metals
  - Metallurgical and materials engineers are often called on to design alloys having high strengths yet some ductility and toughness; ordinarily ductility is sacrificed when an alloy is strengthened. Several hardening techniques are at the disposal of an engineer, and frequently alloy selection depends on the capacity of a material to be tailored with the mechanical characteristics required for a particular application
  - Important to the understanding of strengthening mechanisms is the relation between dislocation motion and mechanical behavior of metals. Because macroscopic plastic deformation corresponds to the motion of large numbers of dislocations, the ability of a metal to plastically deform depends on the ability of dislocations to move. Since hardness and strength are related to the ease with which plastic deformation can be made to occur, by reducing the mobility of dislocations, the mechanical strength may be enhanced; that is, greater mechanical forces will be required to initiate plastic deformation. In contrast, the more unconstrained the dislocation motion, the greater the facility with which a metal may deform, and the softer and weaker it becomes. Virtually all strengthening techniques rely on this simple principle: restricting or hindering dislocation motion renders a material harder and stronger.

- 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, as indicated in Figure 7.16. During plastic deformation, slip or dislocation motion must take place across this common boundary, say from grain A to grain B in Figure 7.16. The grain boundary acts as a barrier to dislocation motion for two reasons:
    - Since the two grains are of different orientations, a dislocation passing into grain B will have to change its direction of motion; this becomes mote 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.

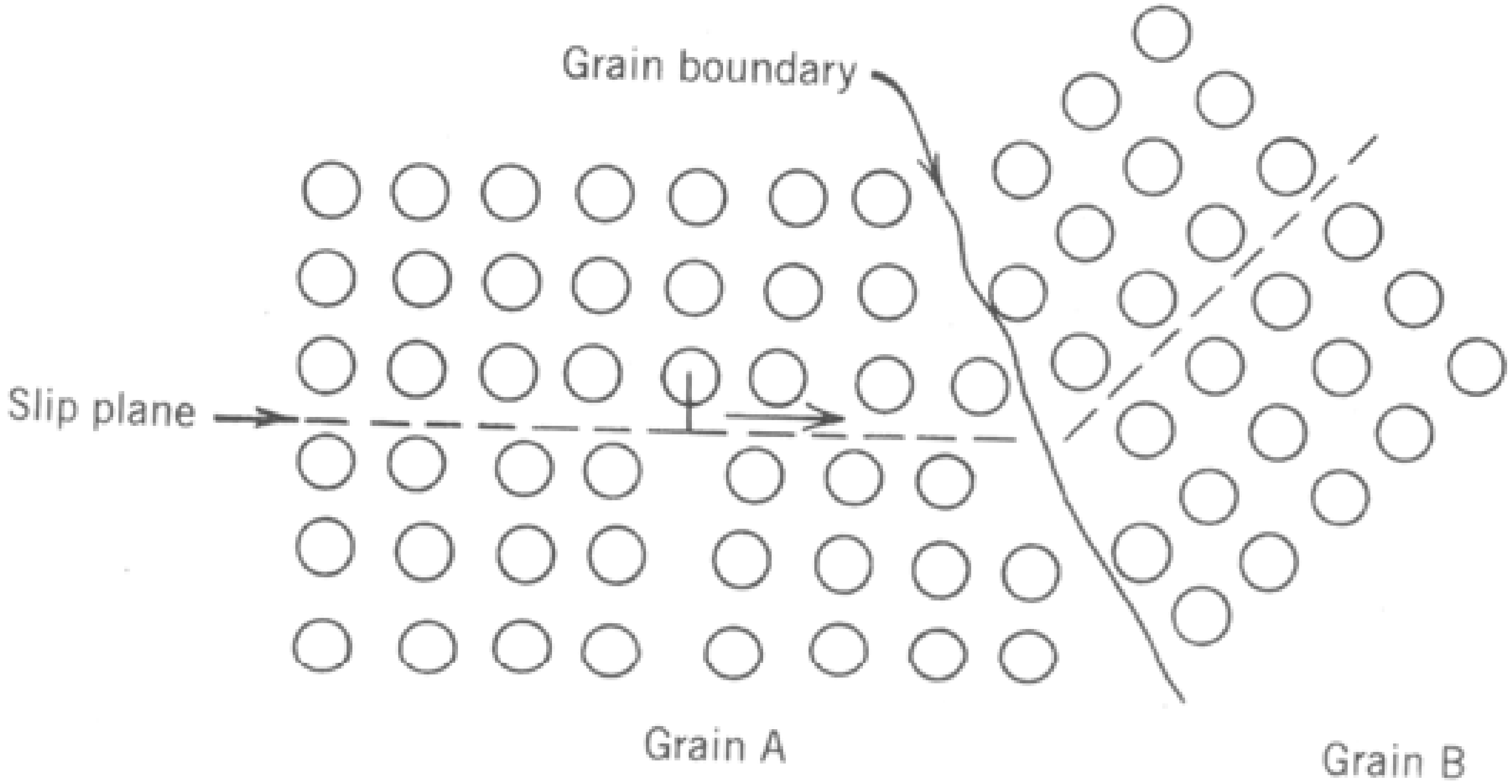


Figure 7.16. The motion of a dislocation as it encounters a grain boundary, illustrating how the boundary acts as a barrier to continued slip. Slip planes are discontinuous and change directions across the boundary

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

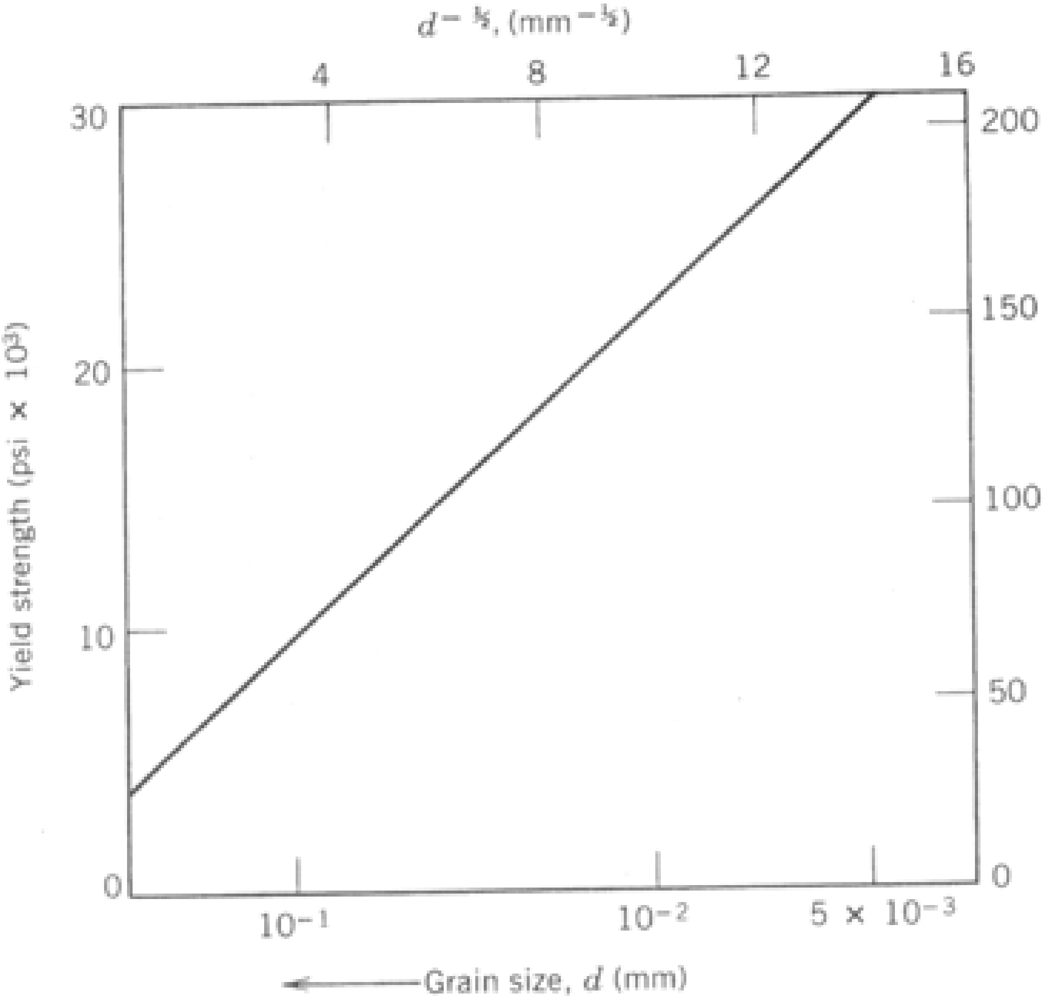
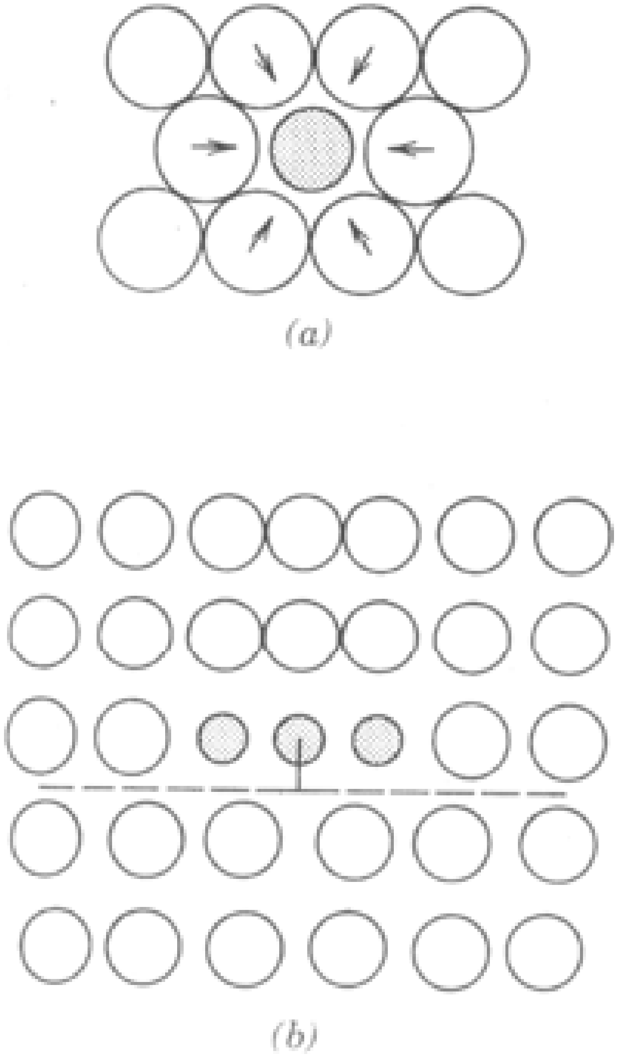


Figure 7.17. The influence of grain size on the yield strength of a 70 Cu–30 Zn brass alloy. Note that the grain diameter increases from right to left and is not linear. (Adapted from H. Suzuki, "The Relation Between the Structure and Mechanical Properties of Metals," Vol. II, *National Physical Laboratory, Symposium No. 15*, p. 524.)

- Solid solution hardening
  - another technique to strengthen and harden metals is alloying with impurity atoms that go into either substitutional or interstitial solid solution. Accordingly, this is called solid solution hardening. High purity metals are almost always softer and weaker than alloys composed of the same base metal. Increasing the concentration of the impurity results in an attendant increate in tensile strength and hardness, as indicated in Figures 7.18a and 7.18b for zinc in copper; the dependence of ductility on zinc concentration in presented in Figure 7.18c.
  - 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.



(a)

(b)

Figure 7.19. (*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.

- Strain hardening
  - Strain hardening is the phenomenon whereby a ductile metal becomes harder and stronger as it is plastically deformed. Sometimes it is also called work hardening or, because the temperature at which deformation takes place is “cold” relative to the absolute melting temperature of the metal, cold working. Most metals strain harden at room temperature.
  - It is sometimes convenient to express the degree of plastic deformation as percent cold work rather than as strain. Percent cold work (%CW) is defined as:

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

  - in which A_0 is the original area of the cross section that experiences deformation and A_d is the area after deformation.

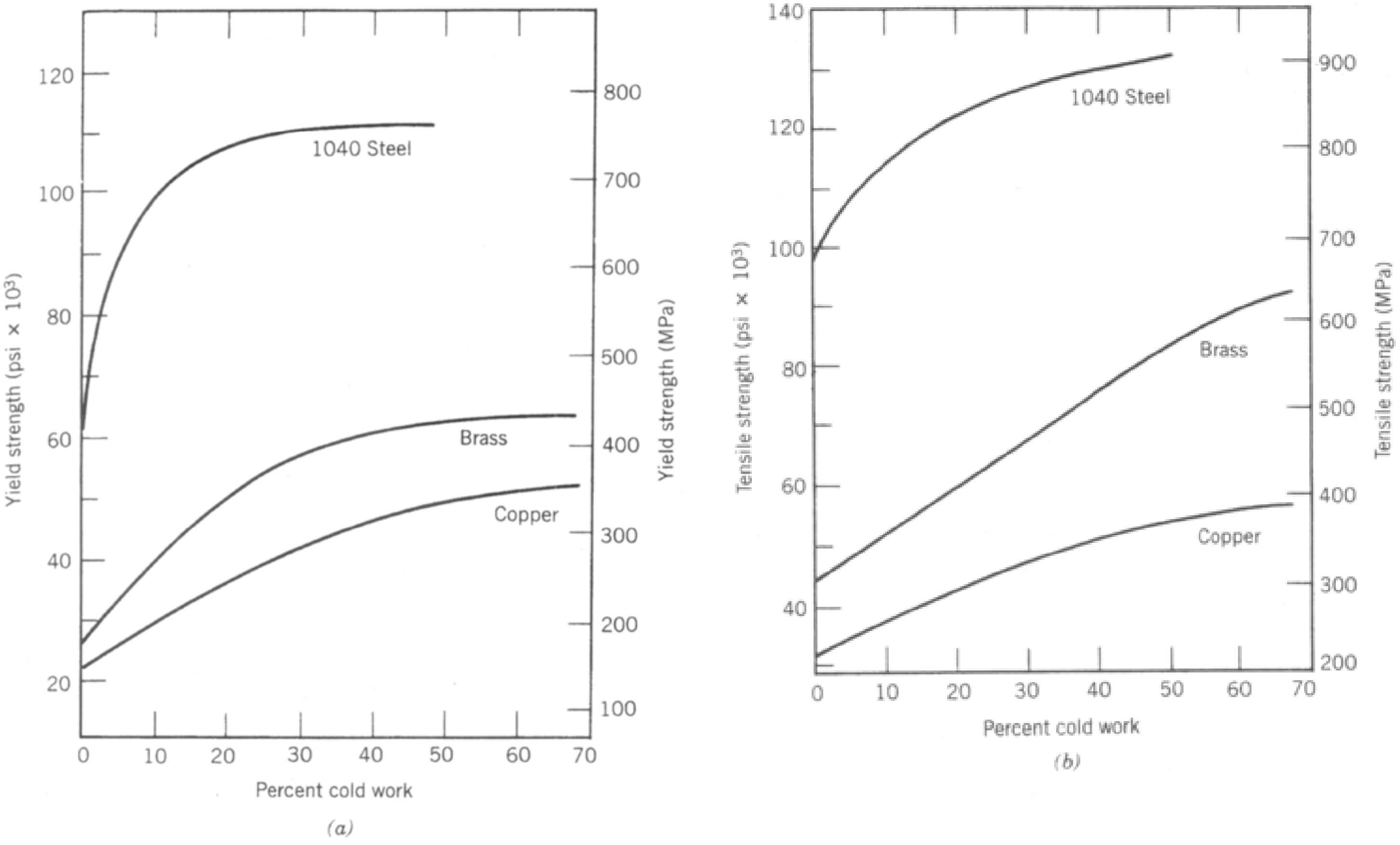


Figure 7.21. For 1040 steel, brass, and copper: (*a*) the increase in yield strength, (*b*) the increase in tensile strength, and (*c*) the decrease in ductility (%EL) with percent cold work. (Adapted from *Metals Handbook: Properties and Selection, Irons and Steels*, Vol. 1, 9th edition, B. Bardes, Editor, American Society for Metals, 1978, p. 226, and *Metals Handbook: Properties and Selection: Nonferrous Alloys and Pure Metals*, Vol. 2, 9th edition, H. Baker, Managing Editor, American Society for Metals, 1979, pp. 276 and 327.)

- The dislocation density in a metal increases with deformation or cold work, as already mentioned. Consequently, the average distance of separation between dislocations decreases - the dislocations are positioned close together. 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.
- Strain hardening is often utilized commercially to enhance the mechanical properties of metals during fabrication procedures.

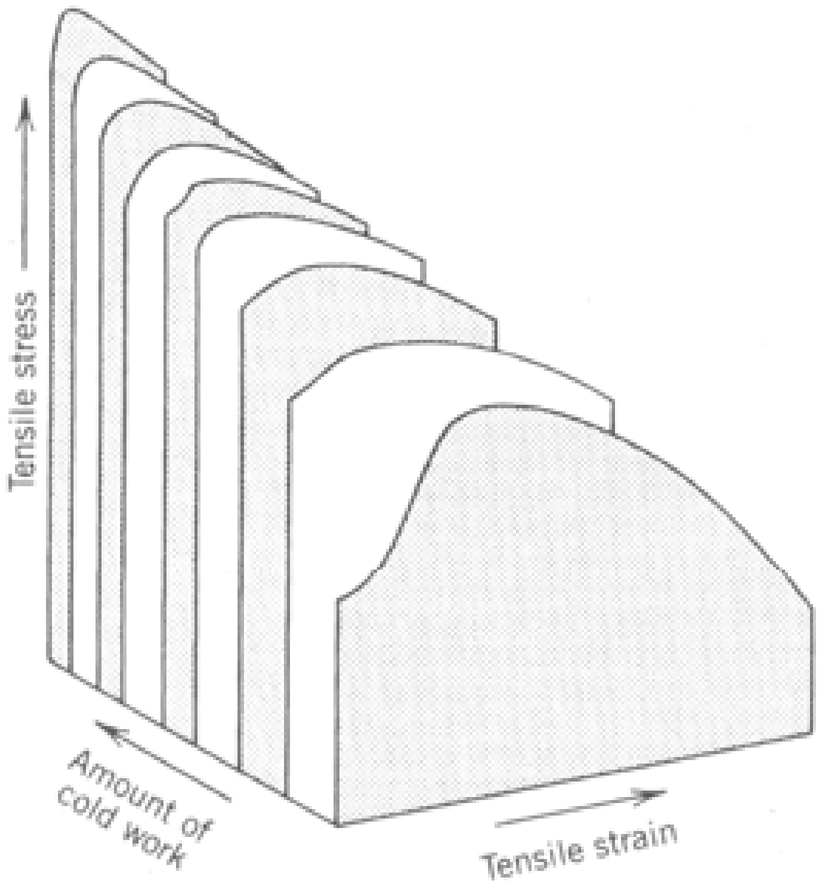
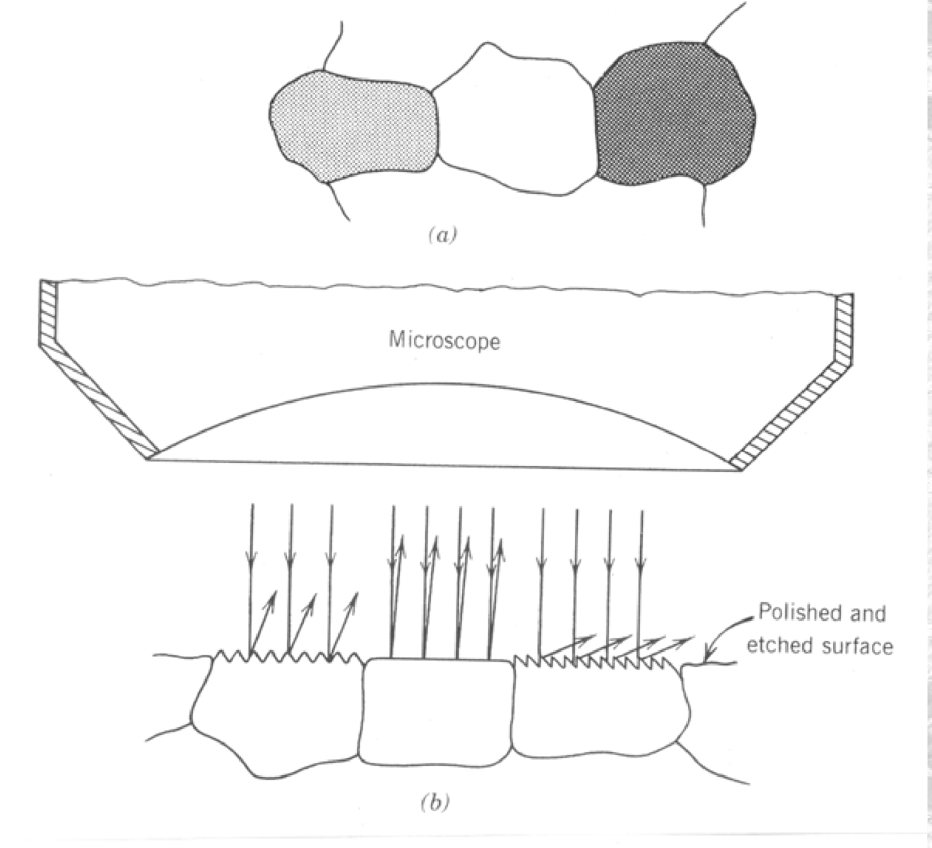
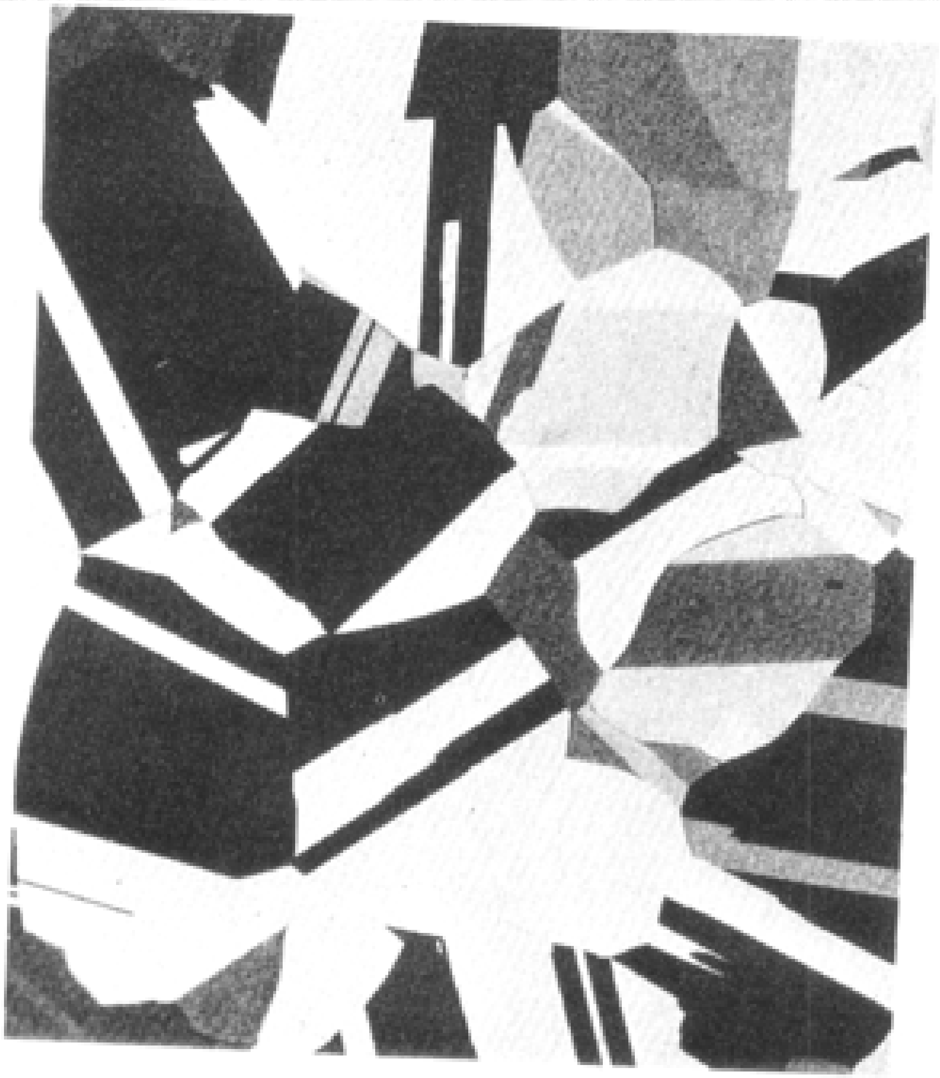


Figure 7.22. The influence of cold work on the stress–strain behavior for a low carbon steel. (From *Metals Handbook: Properties and Selection, Irons and Steels,* Vol. 1, 9th edition, B. Bardes, Editor, American Society for Metals, 1978, p. 221.)

- Microscopic inspection
  - General
    - On occasion it is necessary or desirable to examine the structural elements and defects that influence the properties of materials. The capacity to perform such examinations is important, first to ensure that the associations between the properties and structure (and defects) are properly understood, and second to predict the properties of materials once these relationships have been established. Several of the techniques hat are commonly used in such investigations are discussed next.

- Microscopy
    - both optical and electron microscopes are commonly used in microscopy. These instruments aid in investigations of the microstructural features of all three material types (metals, ceramics, and polymers). Most of these techniques employ photographic equipment in conjunction with the microscope; the photograph on which the image is recorded is called a photomicrograph.





(*c*)

Figure 4.5. (*a*) Polished and etched grains as they might appear when viewed with an optical microscope. (*b*) Section taken through these grains showing how the etching characteristics and resulting surface texture vary from grain to grain because of differences in crystallographic orientation. (*c*) Photomicrograph of a polycrystalline brass specimen. 60×. (Photomicrograph courtesy of J. E. Burke, General Electric Co.)

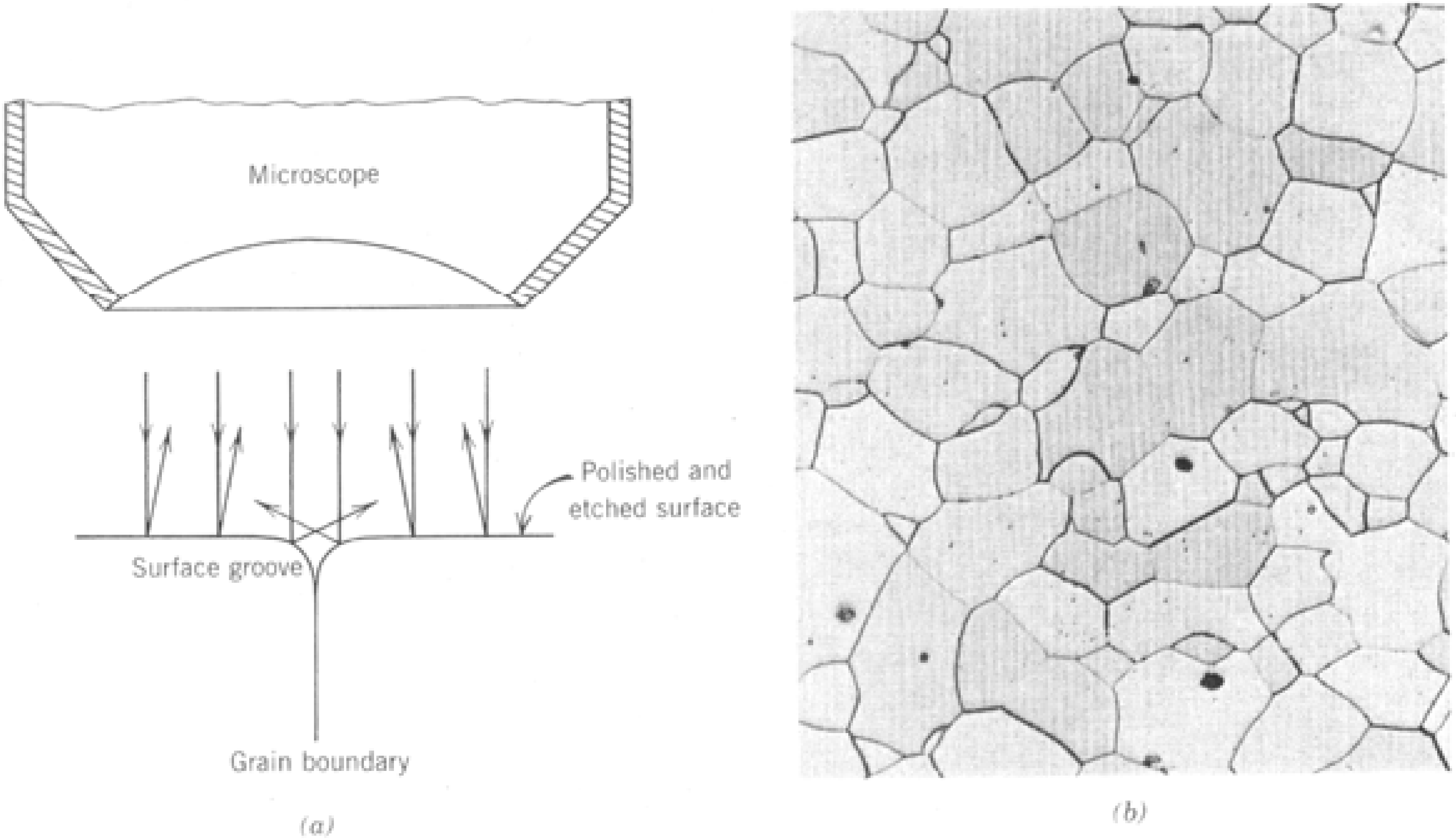


Figure 4.6. (*a*) Section of a grain boundary and its surface groove produced by etching; the light reflection characteristics in the vicinity of the groove are also shown. (*b*) Photomicrograph of the surface of a polished and etched polycrystalline specimen of an iron–chromium alloy in which the grain boundaries appear dark. 100×. (Photomicrograph courtesy of L. C. Smith and C. Brady, the National Bureau of Standards, Washington, DC.)

- Electron microscopy
  - The upper limit to the magnification possible with an optical microscope is approximately 2000 diameters. Consequently, some structural elements are too fine or small to permit observation using optical microscopy. Under such circumstances the electron microscope, which is capable of much higher magnifications, may be employed.
  - An image of the structure under investigation is formed using beams of electrons instead of light radiation. According to quantum mechanics, a high velocity electron will become wavelike, having a wavelength that is inversely proportional to its velocity. When accelerated across large voltages, electrons can be made to have wavelengths on the order of 0.003 nm. High magnifications and resolving powers of these microscopes are consequences of the short wavelengths of electron beams; in fact, structures as small as 2nm may be observed. The electron beam is focused and the image formed with magnetic lenses; otherwise the geometry of the microscope components is essentially the same as with optical systems. Both transmission and reflection beam modes of operation are possible for electron microscopes.

- Transmission electron microscopy
  - The image seen with a transmission electron microscope is formed by an electron beam that passes through the specimen. Details of internal microstructural features are accessible to observation; contrasts in the image are produced by differences in beam scattering or diffraction produced between various elements of the microstructure or defect. Since solid materials are highly absorptive to electron beams, a specimen to be examined must be prepared in the form of a very thin foil; this ensures transmission through the specimen of an appreciable fraction of the incident beam. The transmitted beam is projected onto a fluorescent screen or a photographic film so that the image may be viewed. Magnifications as high as 500,000x are possible with transmission electron microscopy, which is frequently utilized in the study of dislocations.

- Scanning electron microscopy
  - A more recent innovation, having proved to be an extremely useful investigative tool, is the scanning electron microscope. The surface of a specimen to be examined is scanned with an electron beam and the reflected beam of electrons is collected, then displayed at the same scanning rate on a cathode ray tube. The image that appears on the screen, which may be photographed, represents the surface features of the specimen. The surface may or may not be polished and etched, but it must be electrically conductive; a very thin metallic surface coating must be applied to nonconductive materials. Magnifications ranging from 10 to in excess of 50,000 diameters are possible, as are also very great depths of focus. Accessory equipment permits qualitative and semiquantitative analysis of the elemental composition of very localized surface areas.