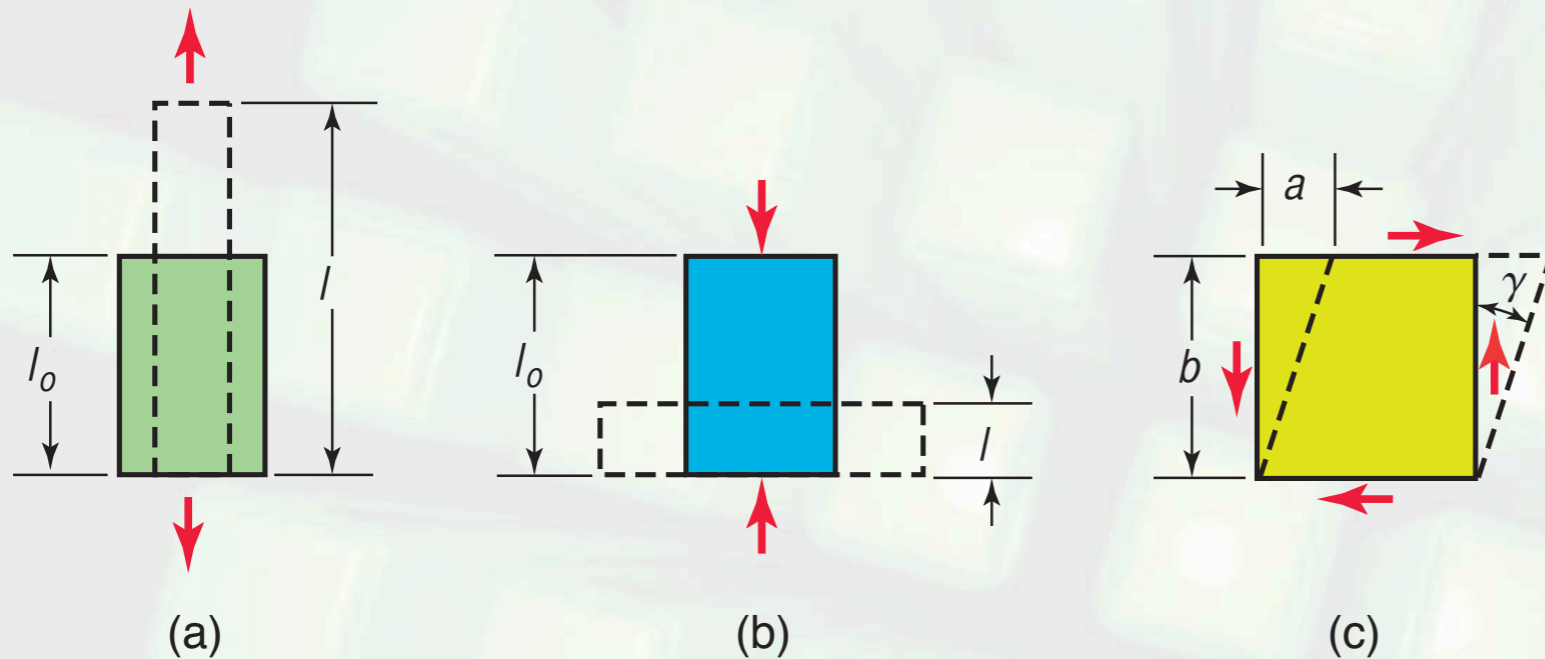


Types of Strain



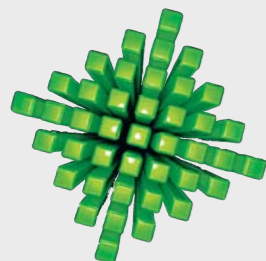
Engineering Strain:

$$e = \frac{l - l_0}{l_0}$$

Shear Strain:

$$\gamma = \frac{a}{b}$$

FIGURE 2.1 Types of strain. (a) Tensile. (b) Compressive. (c) Shear. All deformation processes in manufacturing involve strains of these types. Tensile strains are involved in stretching sheet metal to make car bodies, compressive strains in forging metals to make turbine disks, and shear strains in making holes by punching.



Tensile-Test

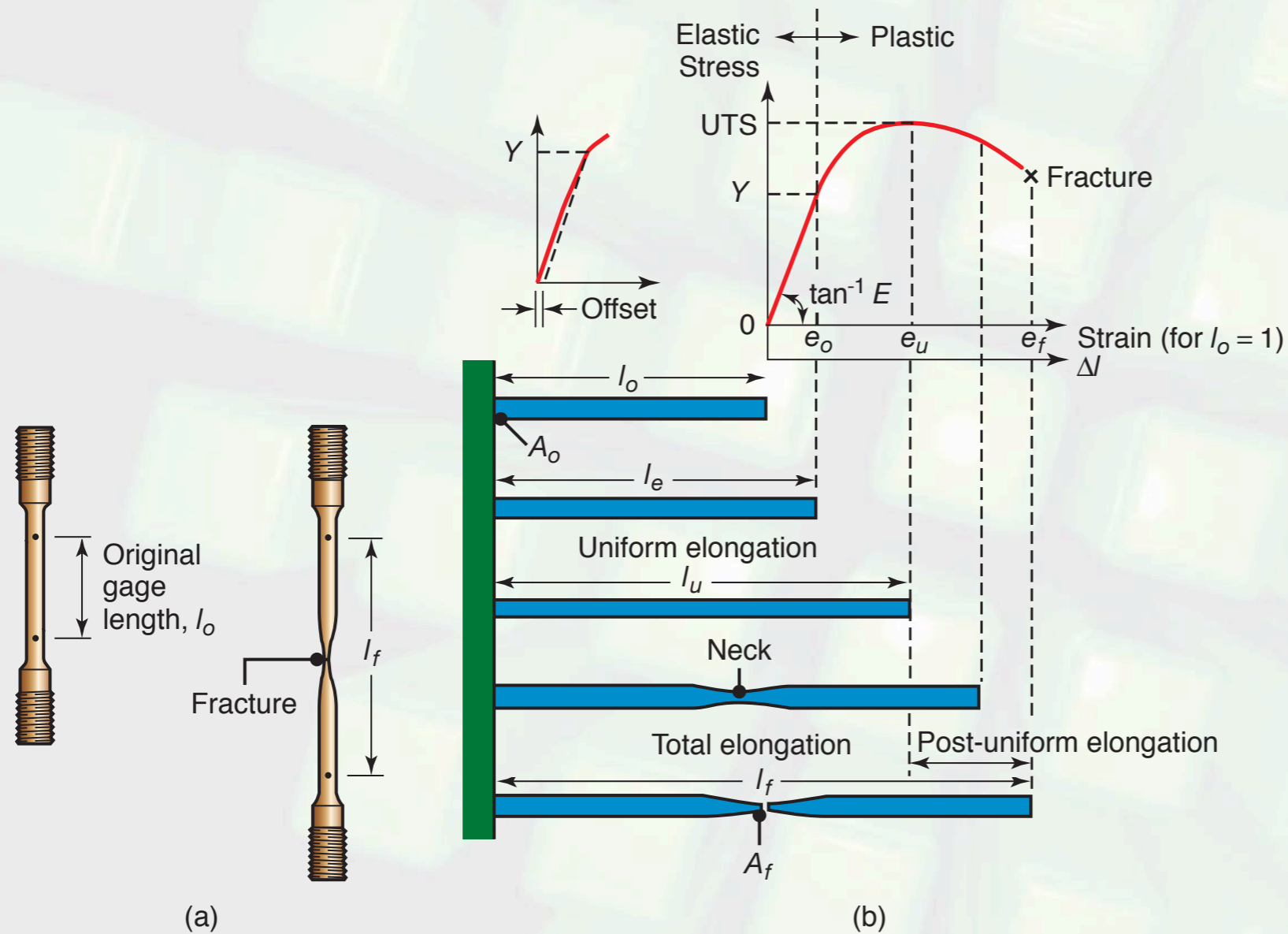
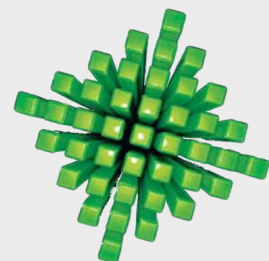


FIGURE 2.2 (a) Original and final shape of a standard tensile-test specimen. (b) Outline of a tensile-test sequence showing different stages in the elongation of the specimen.

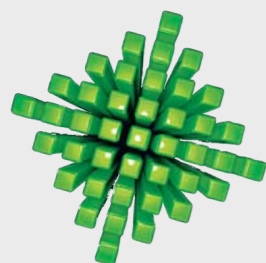


Mechanical Properties

	E (GPa)	Y (MPa)	UTS (MPa)	Elongation in 50 mm (%)	Poisson's Ratio (ν)
METALS (WROUGHT)					
Aluminum and its alloys	69-79	35-550	90-600	45-5	0.31-0.34
Copper and its alloys	105-150	76-1100	140-1310	65-3	0.33-0.35
Lead and its alloys	14	14	20-55	50-9	0.43
Magnesium and its alloys	41-45	130-305	240-380	21-5	0.29-0.35
Molybdenum and its alloys	330-360	80-2070	90-2340	40-30	0.32
Nickel and its alloys	180-214	105-1200	345-1450	60-5	0.31
Steels	190-200	205-1725	415-1750	65-2	0.28-0.33
Stainless steels	190-200	240-480	480-760	60-20	0.28-0.30
Titanium and its alloys	80-130	344-1380	415-1450	25-7	0.31-0.34
Tungsten and its alloys	350-400	550-690	620-760	0	0.27
NONMETALLIC MATERIALS					
Ceramics	70-1000	—	140-2600	0	0.2
Diamond	820-1050	—	—	—	—
Glass and porcelain	70-80	—	140	0	0.24
Rubbers	0.01-0.1	—	—	—	0.5
Thermoplastics	1.4-3.4	—	7-80	1000-5	0.32-0.40
Thermoplastics, reinforced	2-50	—	20-120	10-1	—
Thermosets	3.5-17	—	35-170	0	0.34
Boron fibers	380	—	3500	0	—
Carbon fibers	275-415	—	2000-5300	1-2	—
Glass fibers (S, E)	73-85	—	3500-4600	5	—
Kevlar fibers (29, 49, 129)	70-113	—	3000-3400	3-4	—
Spectra fibers (900, 1000)	73-100	—	2400-2800	3	—

Note: In the upper table, the lowest values for E , Y , and UTS and the highest values for elongation are for the pure metals. Multiply GPa by 145,000 to obtain psi, and MPa by 145 to obtain psi. For example 100 GPa = 14,500 ksi, and 100 MPa = 14,500 psi.

TABLE 2.1 Typical mechanical properties of various materials at room temperature. See also Tables 10.1, 10.4, 10.8, 11.3 and 11.7.



Loading & Unloading; Elongation

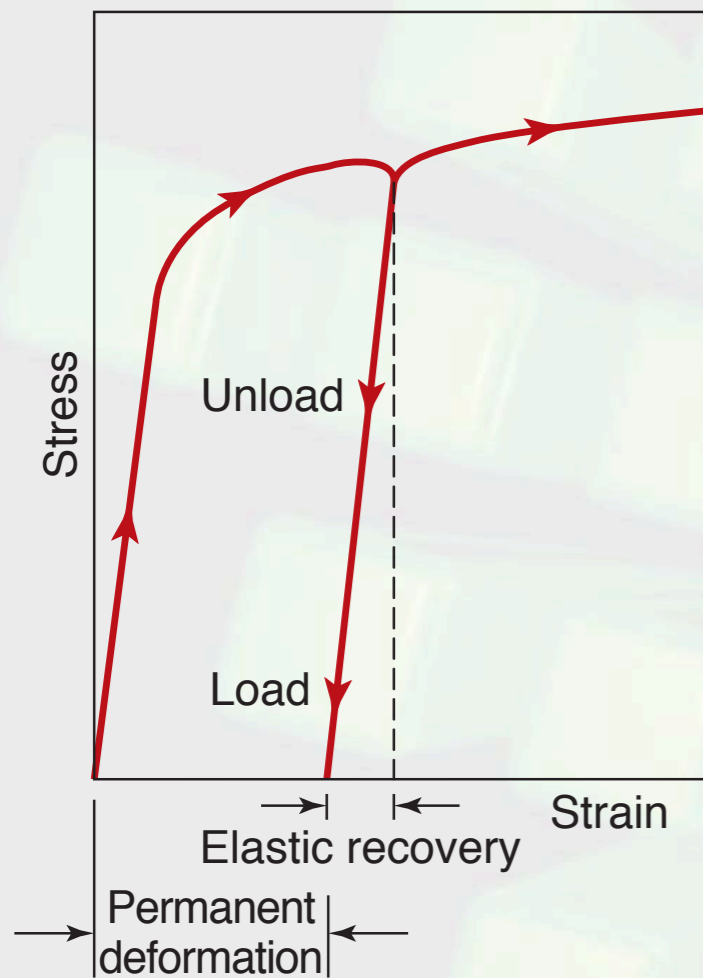


FIGURE 2.3 Schematic illustration of loading and unloading of a tensile-test specimen. Note that during unloading the curve follows a path parallel to the original elastic slope.

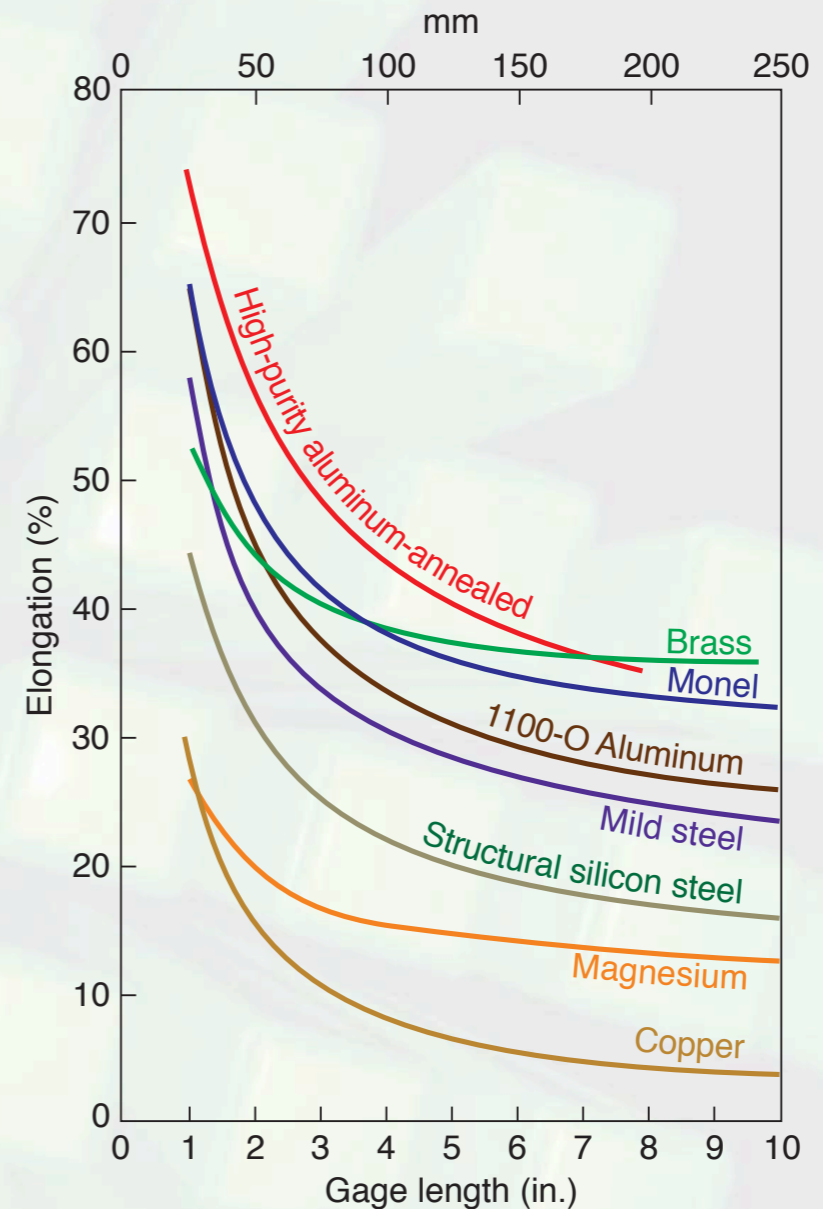
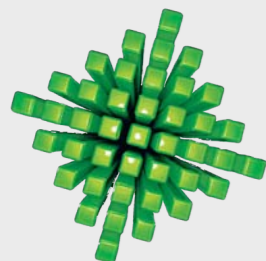


FIGURE 2.4 Total elongation in a tensile test as a function of original gage length for various metals. Because necking is a local phenomenon, elongation decreases with gage length. Standard gage length is usually 2 in. (50 mm), although shorter ones can be used if larger specimens are not available.



True Stress and True Strain

True stress

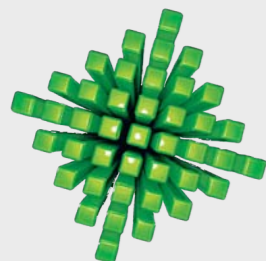
$$\sigma = \frac{P}{A}$$

True strain

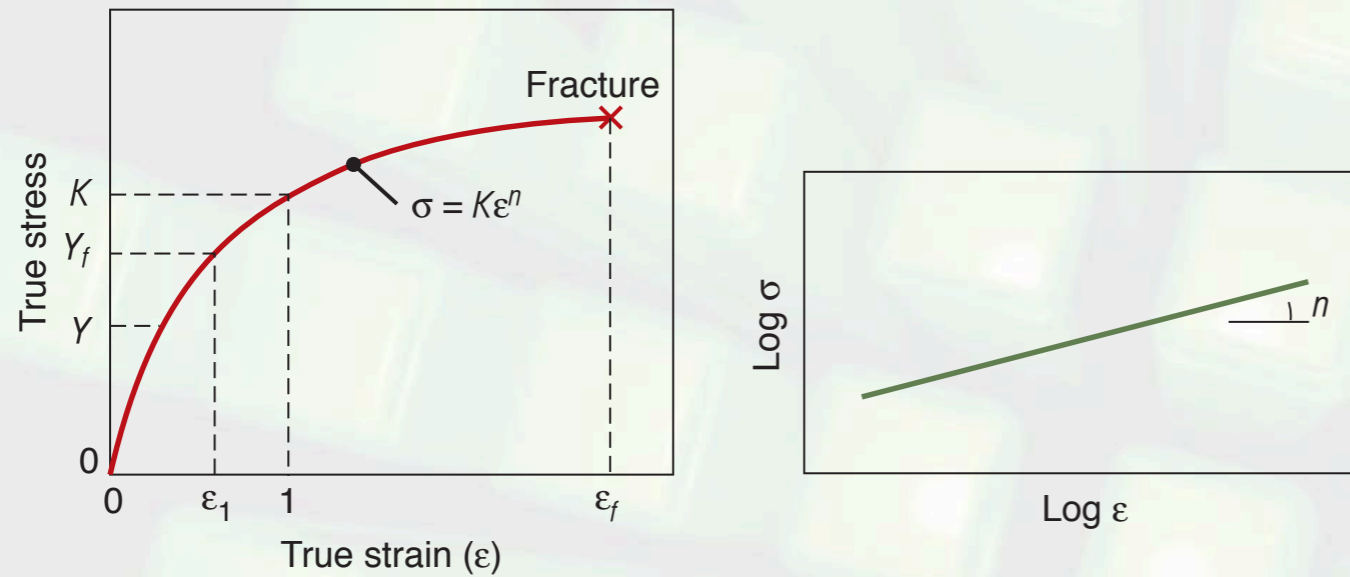
$$\epsilon = \ln \left(\frac{l}{l_o} \right) = \ln \left(\frac{A_o}{A} \right) = \ln \left(\frac{D_o}{D} \right)^2 = 2 \ln \left(\frac{D_o}{D} \right)$$

TABLE 2.2 Comparison of engineering and true strains in tension

e	0.01	0.05	0.1	0.2	0.5	1	2	5	10
ϵ	0.01	0.049	0.095	0.18	0.4	0.69	1.1	1.8	2.4

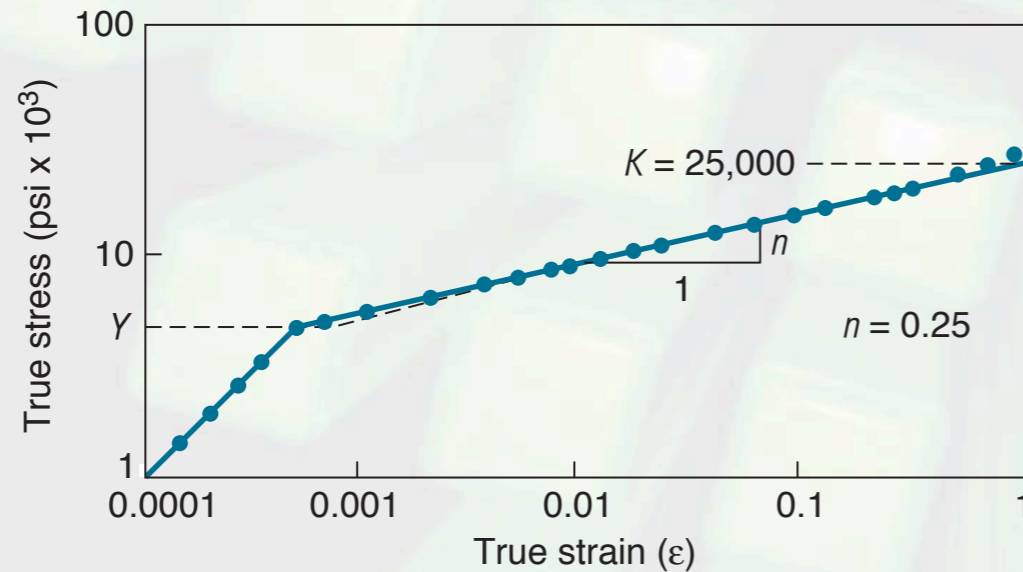


True Stress - True Strain Curve



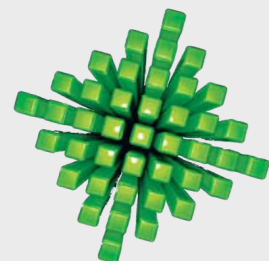
(a)

(b)



(c)

FIGURE 2.5 (a) True stress--true strain curve in tension. Note that, unlike in an engineering stress-strain curve, the slope is always positive and that the slope decreases with increasing strain. Although in the elastic range stress and strain are proportional, the total curve can be approximated by the power expression shown. On this curve, Y is the yield stress and Y_f is the flow stress. (b) True stress-true strain curve plotted on a log-log scale. (c) True stress-true strain curve in tension for 1100-O aluminum plotted on a log-log scale. Note the large difference in the slopes in the elastic and plastic ranges. Source: After R. M. Caddell and R. Sowerby.



Power Law Flow Rule

Material	K (MPa)	n
Aluminum, 1100-O	180	0.20
2024-T4	690	0.16
5052-O	210	0.13
6061-O	205	0.20
6061-T6	410	0.05
7075-O	400	0.17
Brass, 7030, annealed	895	0.49
85-15, cold rolled	580	0.34
Bronze (phosphor), annealed	720	0.46
Cobalt-base alloy, heat treated	2070	0.50
Copper, annealed	315	0.54
Molybdenum, annealed	725	0.13
Steel, low carbon, annealed	530	0.26
1045 hot rolled	965	0.14
1112 annealed	760	0.19
1112 cold rolled	760	0.08
4135 annealed	1015	0.17
4135 cold rolled	1100	0.14
4340 annealed	640	0.15
17-4 P-H, annealed	1200	0.05
52100, annealed	1450	0.07
304 stainless, annealed	1275	0.45
410 stainless, annealed	960	0.10

Note: 100 MPa = 14,500 psi.

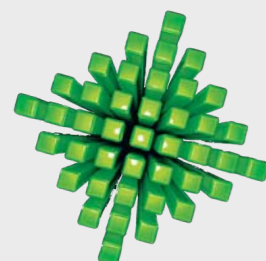
TABLE 2.3 Typical values for K and n in Eq. 2.11 at room temperature.

Flow rule:

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

K = Strength coefficient

n = Strain hardening exponent



True Stress-True Strain for Various Materials

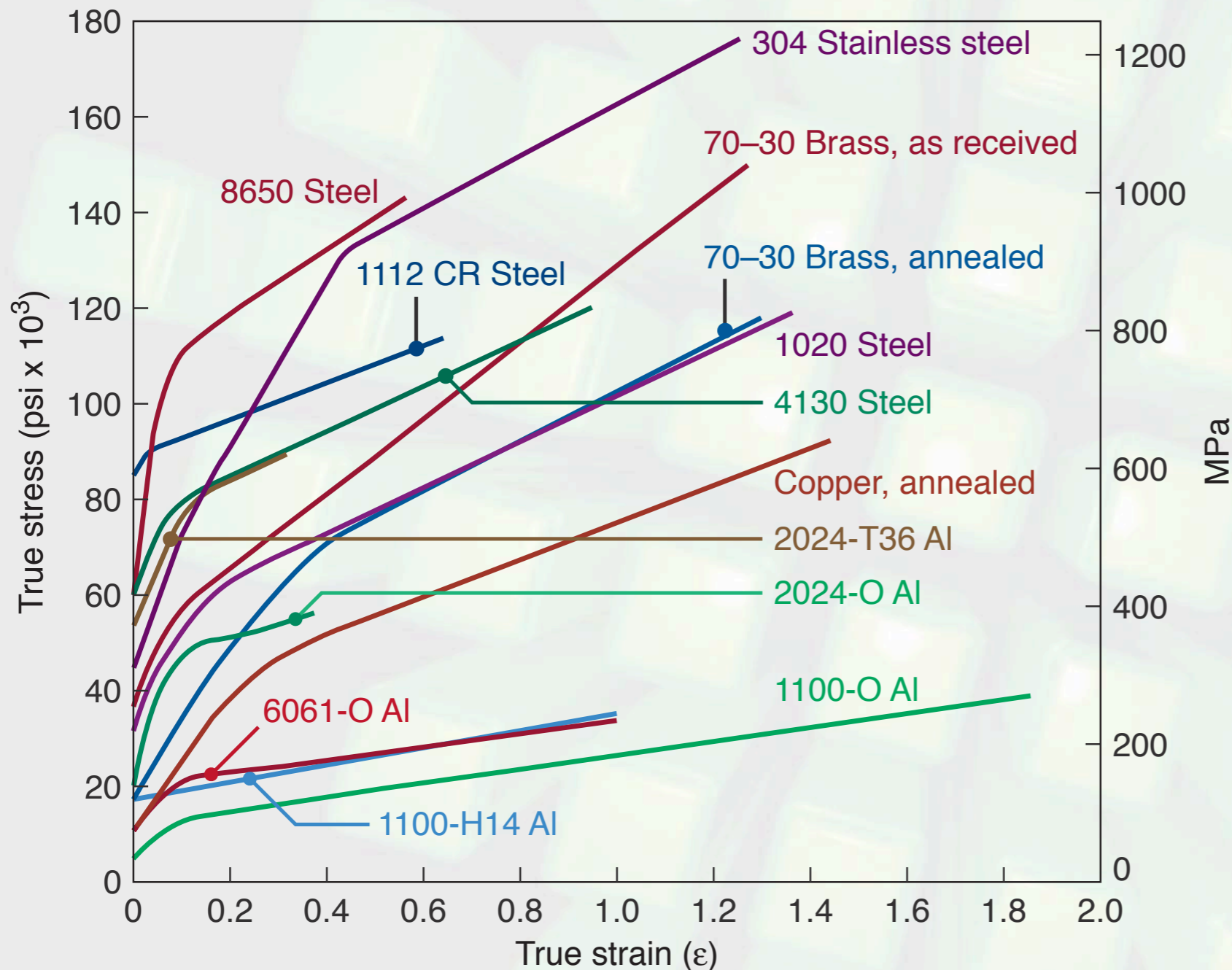
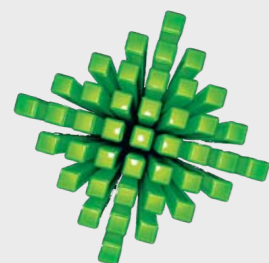


FIGURE 2.6 True stress-true strain curves in tension at room temperature for various metals. The point of intersection of each curve at the ordinate is the yield stress Y ; thus, the elastic portions of the curves are not indicated. When the K and n values are determined from these curves, they may not agree with those given in Table 2.3 because of the different sources from which they were collected. Source: S. Kalpakjian.



Idealized Stress-Strain Curves

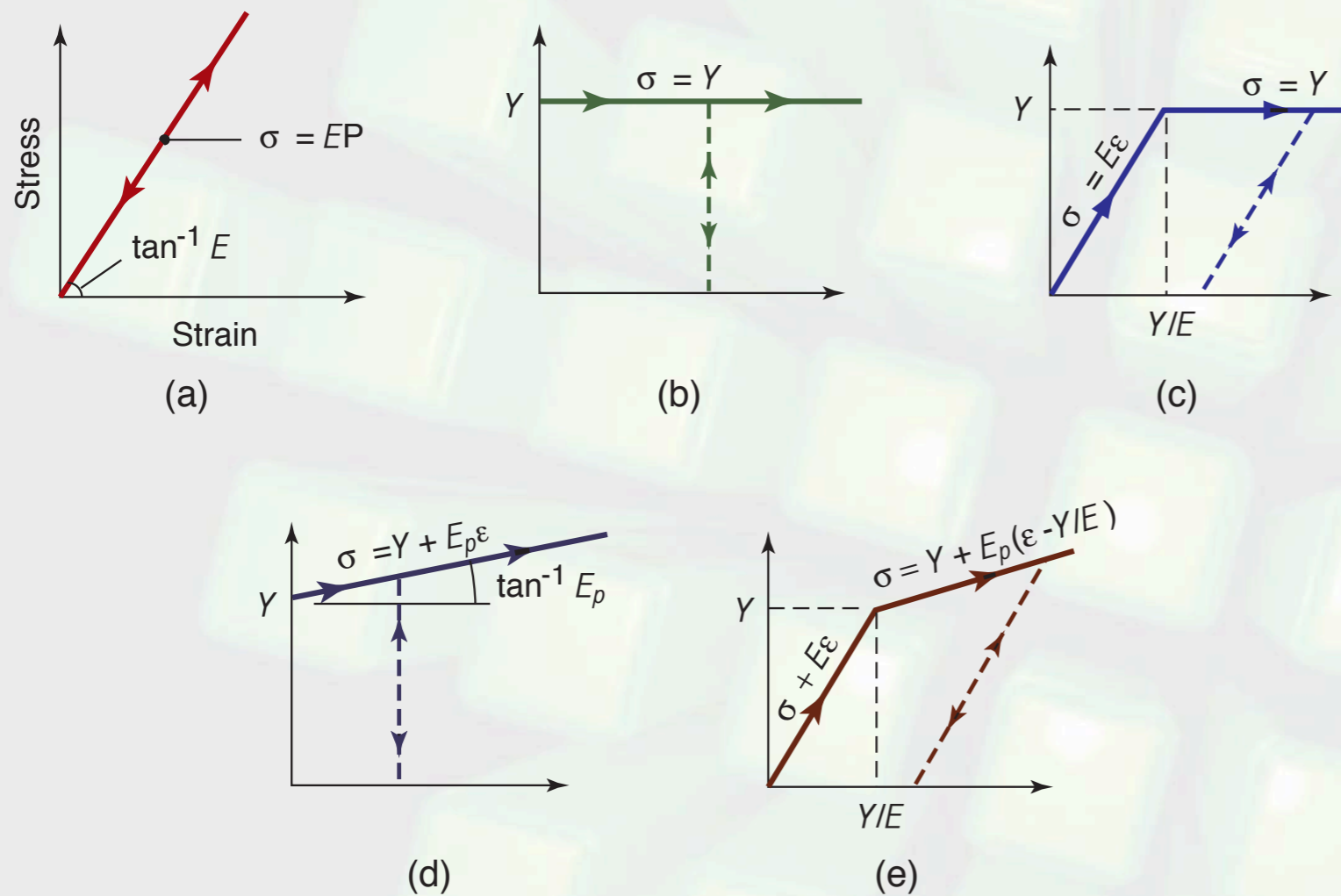


FIGURE 2.7 Schematic illustration of various types of idealized stress-strain curves. (a) Perfectly elastic. (b) Rigid, perfectly plastic. (c) Elastic, perfectly plastic. (d) Rigid, linearly strain hardening. (e) Elastic, linearly strain hardening. The broken lines and arrows indicate unloading and reloading during the test.

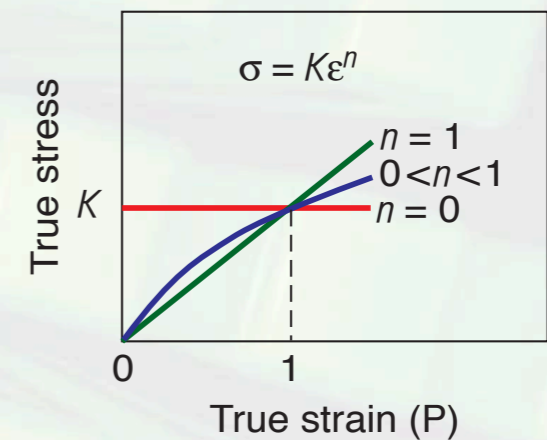
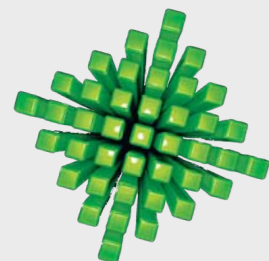


FIGURE 2.8 The effect of strain-hardening exponent n on the shape of true stress-true strain curves. When $n = 1$, the material is elastic, and when $n = 0$, it is rigid and perfectly plastic.



Temperature and Strain Rate Effects

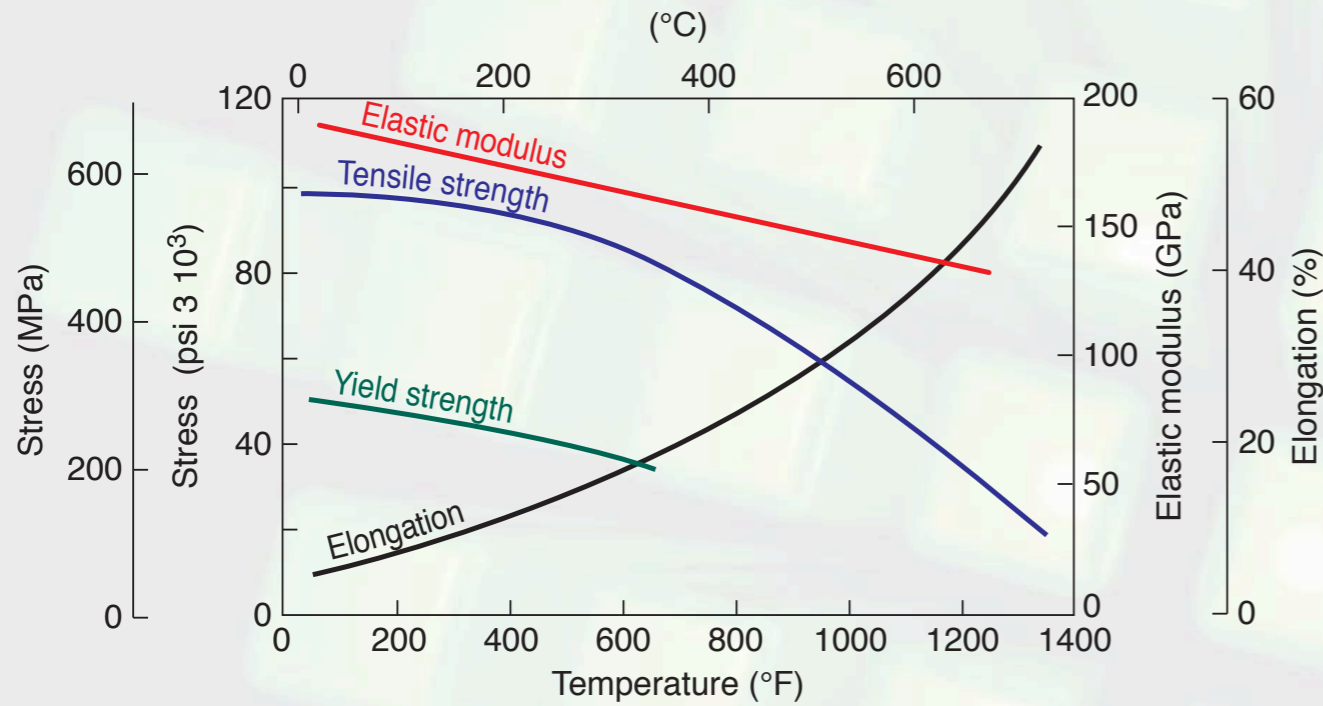


FIGURE 2.9 Effect of temperature on mechanical properties of a carbon steel. Most materials display similar temperature sensitivity for elastic modulus, yield strength, ultimate strength, and ductility.

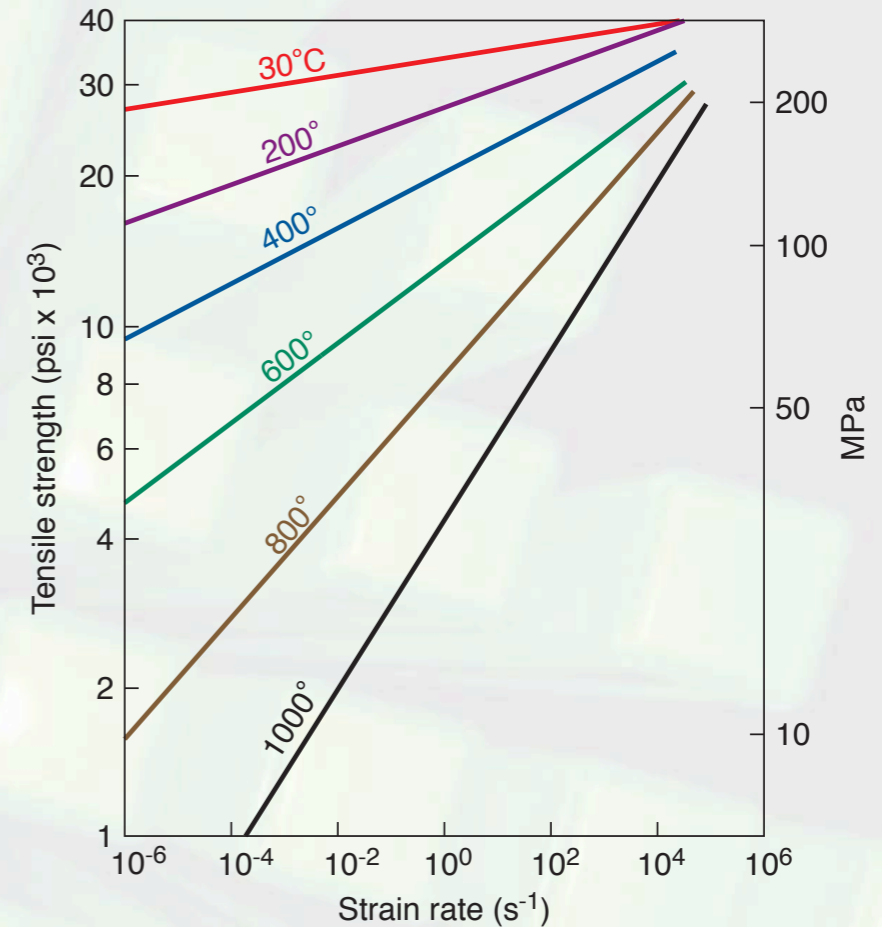
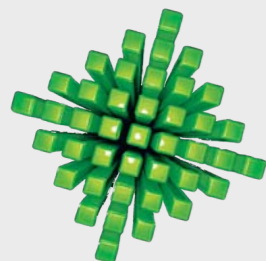


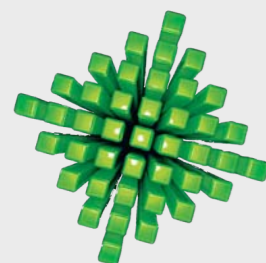
FIGURE 2.10 The effect of strain rate on the ultimate tensile strength of aluminum. Note that as temperature increases, the slope increases. Thus, tensile strength becomes more and more sensitive to strain rate as temperature increases. *Source:* After J. H. Hollomon.



Typical Strain Rates in Metalworking

Process	True Strain	Deformation Speed (m/s)	Strain Rate (s^{-1})
Cold Working			
Forging, rolling	0.1-0.5	0.1-100	$1 - 10^3$
Wire and tube drawing	0.05-0.5	0.1-100	$1 - 10^4$
Explosive forming	0.05-0.2	10-100	$10 - 10^5$
Hot working and warm working			
Forging, rolling	0.1-0.5	0.1-30	$1 - 10^3$
Extrusion	2-5	0.1-1	$10^{-1} - 10^2$
Machining	1-10	0.1-100	$10^3 - 10^6$
Sheet-metal forming	0.1-0.5	0.05-2	$1 - 10^2$
Superplastic forming	0.2-3	$10^{-4} - 10^{-2}$	$10^{-4} - 10^{-2}$

TABLE 2.4 Typical ranges of strain, deformation speed, and strain rates in metalworking processes.



Effect on Homologous Temperature

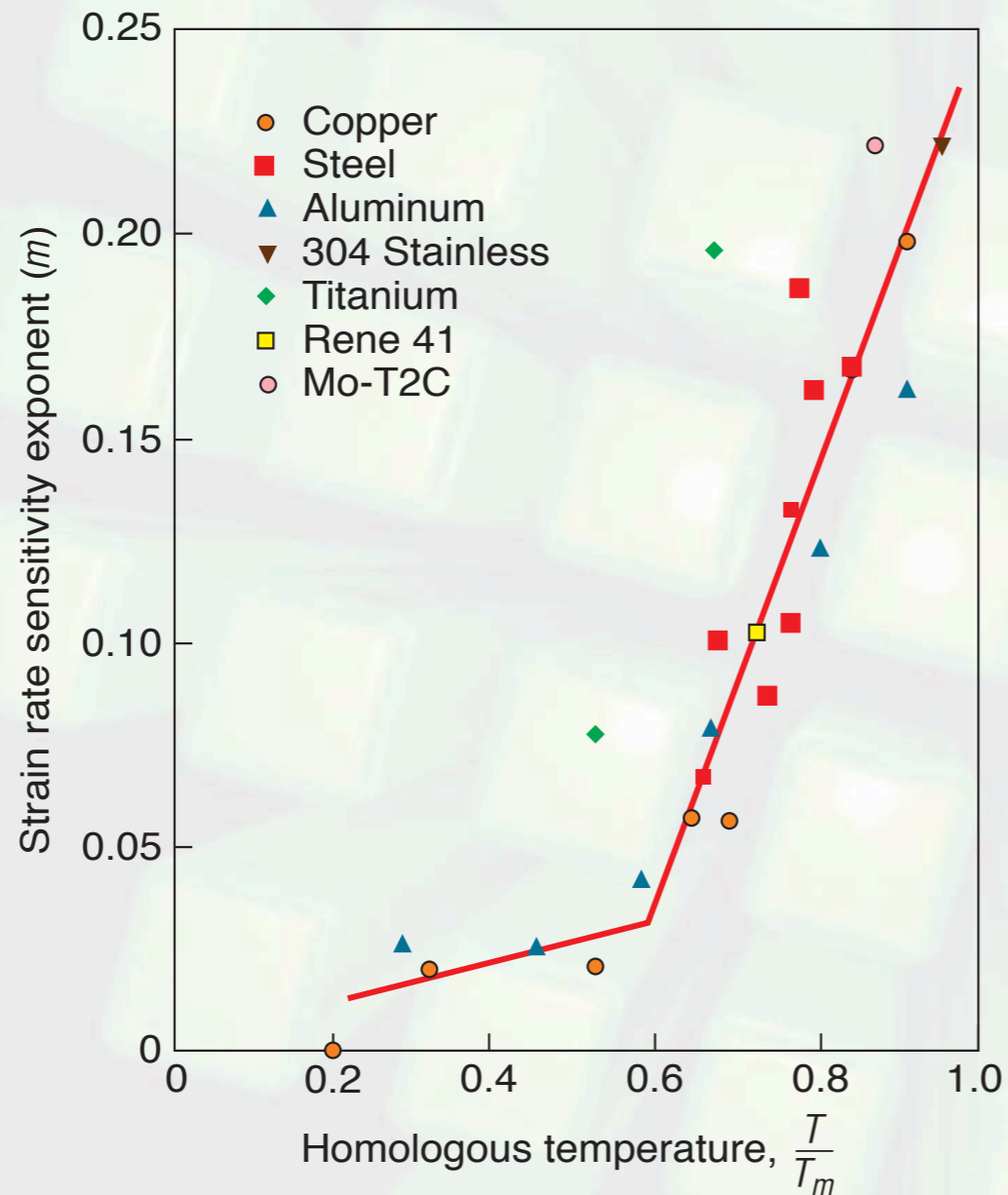
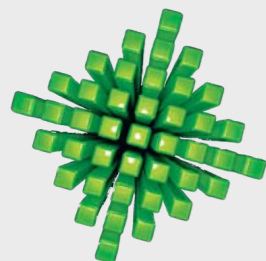


FIGURE 2.11 Dependence of the strain-rate sensitivity exponent m on the homologous temperature T/T_m for various materials. T is the testing temperature and T_m is the melting point of the metal, both on the absolute scale. The transition in the slopes of the curve occurs at about the recrystallization temperature of the metals. Source: After F.W. Boulger.



Strain Rate Effects

Material	Temperature, °C	C		m
		psi $\times 10^3$	MPa	
Aluminum	200-500	12-2	82-14	0.07-0.23
Aluminum alloys	200-500	45-5	310-35	0-0.20
Copper	300-900	35-3	240-20	0.06-0.17
Copper alloys (brasses)	200-800	60-2	415-14	0.02-0.3
Lead	100-300	1.6-0.3	11-2	0.1-0.2
Magnesium	200-400	20-2	140-14	0.07-0.43
Steel				
Low carbon	900-1200	24-7	165-48	0.08-0.22
Medium carbon	900-1200	23-7	160-48	0.07-0.24
Stainless	600-1200	60-5	415-35	0.02-0.4
Titanium	200-1000	135-2	930-14	0.04-0.3
Titanium alloys	200-1000	130-5	900-35	0.02-0.3
Ti-6Al-4V*	815-930	9.5-1.6	65-11	0.50-0.80
Zirconium	200-1000	120-4	830-27	0.04-0.4

* at a strain rate of $2 \times 10^{-4} \text{ s}^{-1}$.

Note: As temperature increases, C decreases and m increases. As strain increases, C increases and m may increase or decrease, or it may become negative within certain ranges of temperature and strain.

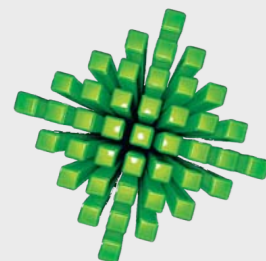
Source: After T. Altan and F.W. Boulger.

$$\sigma = C\dot{\epsilon}^m$$

C = Strength coefficient

m = Strain-rate sensitivity exponent

TABLE 2.5 Approximate range of values for C and m in Eq. (2.16) for various annealed metals at true strains ranging from 0.2 to 1.0.



Effect of Strain Rate Sensitivity on Elongation

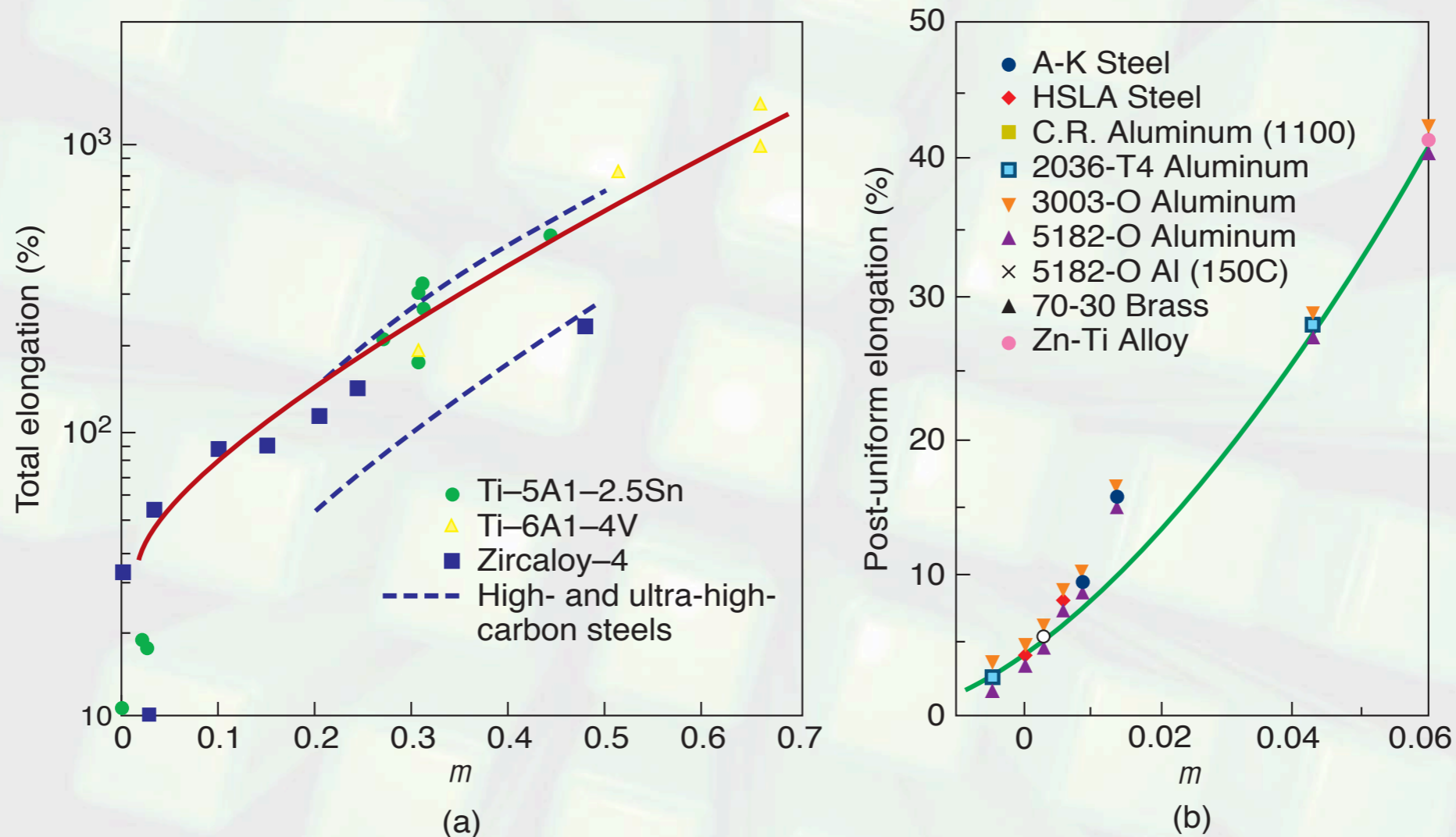
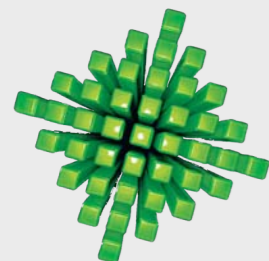


FIGURE 2.12 (a) The effect of strain-rate sensitivity exponent m on the total elongation for various metals. Note that elongation at high values of m approaches 1000%. Source: After D. Lee and W.A. Backofen. (b) The effect of strain-rate sensitivity exponent m on the post uniform (after necking) elongation for various metals. Source: After A.K. Ghosh.



Hydrostatic Pressure & Barreling

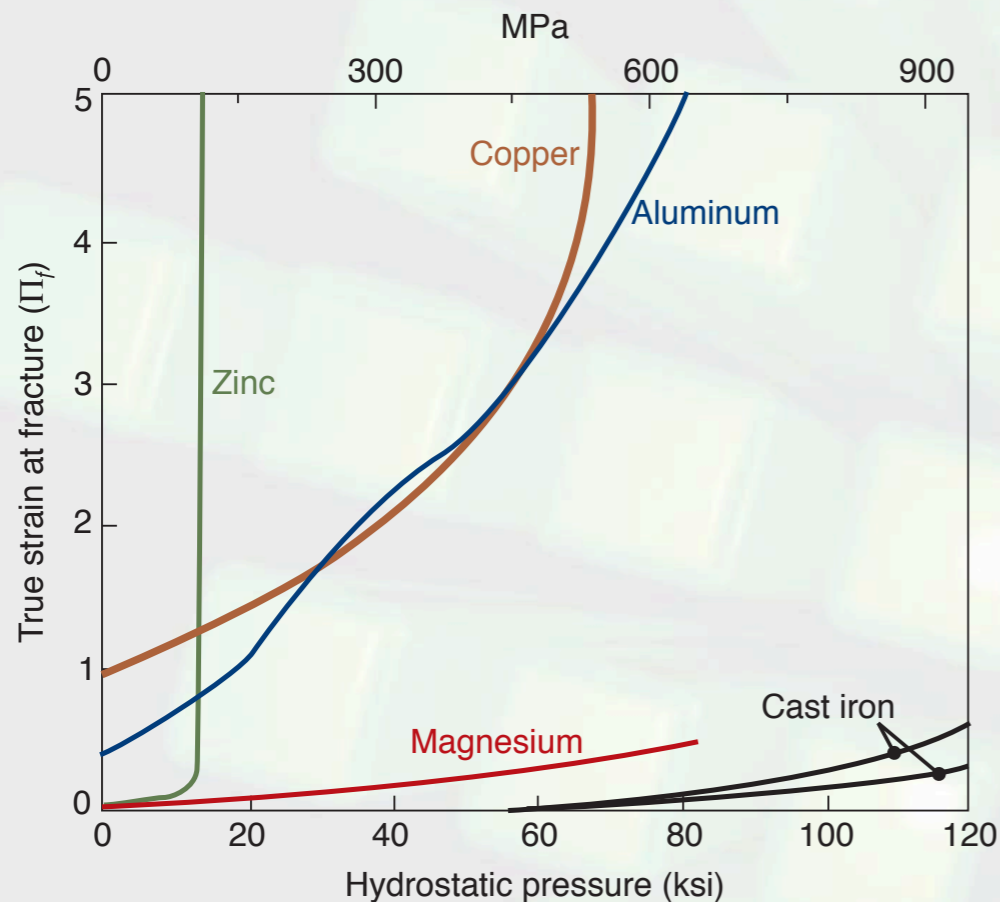
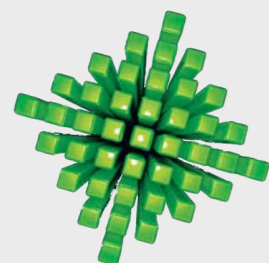


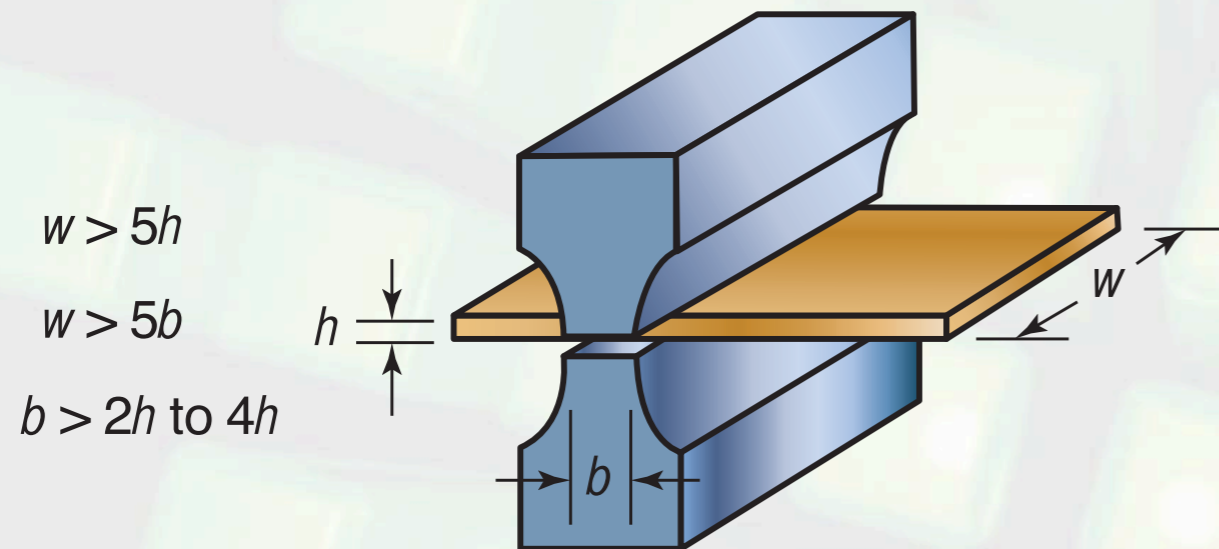
FIGURE 2.13 The effect of hydrostatic pressure on true strain at fracture in tension for various metals. Even cast iron becomes ductile under high pressure. *Source:* After H.L.D. Pugh and D. Green.



FIGURE 2.14 Barreling in compressing a round solid cylindrical specimen (7075-O aluminum) between flat dies. Barreling is caused by friction at the die-specimen interfaces, which retards the free flow of the material. See also Figs.6.1 and 6.2. *Source:* K.M. Kulkarni and S. Kalpakjian.



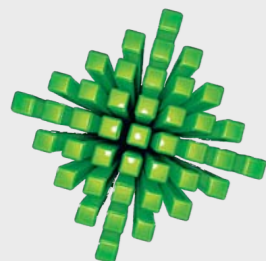
Plane-Strain Compression Test



Yield stress in plane strain:

$$Y' = \frac{2}{\sqrt{3}}Y = 1.15Y$$

FIGURE 2.15 Schematic illustration of the plane-strain compression test. The dimensional relationships shown should be satisfied for this test to be useful and reproducible. This test gives the yield stress of the material in plane strain, Y' . Source: After A. Nadai and H. Ford.



Tension & Compression; Baushinger Effect

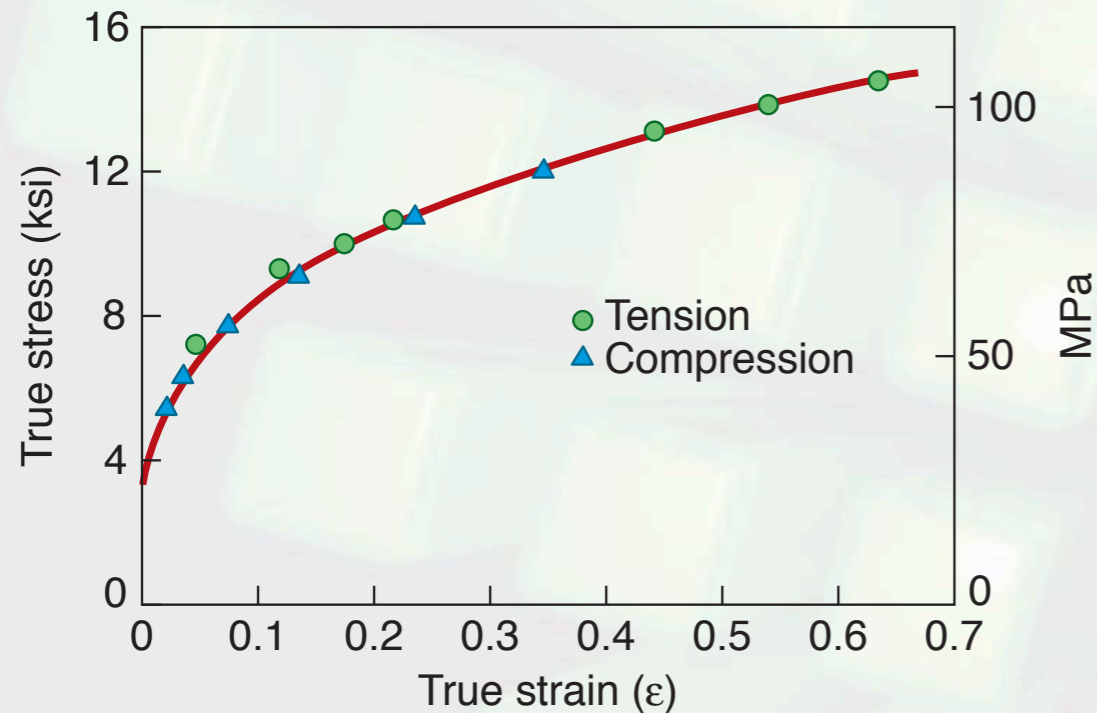


FIGURE 2.16 True stress-true strain curve in tension and compression for aluminum. For ductile metals, the curves for tension and compression are identical. *Source:* After A.H. Cottrell.

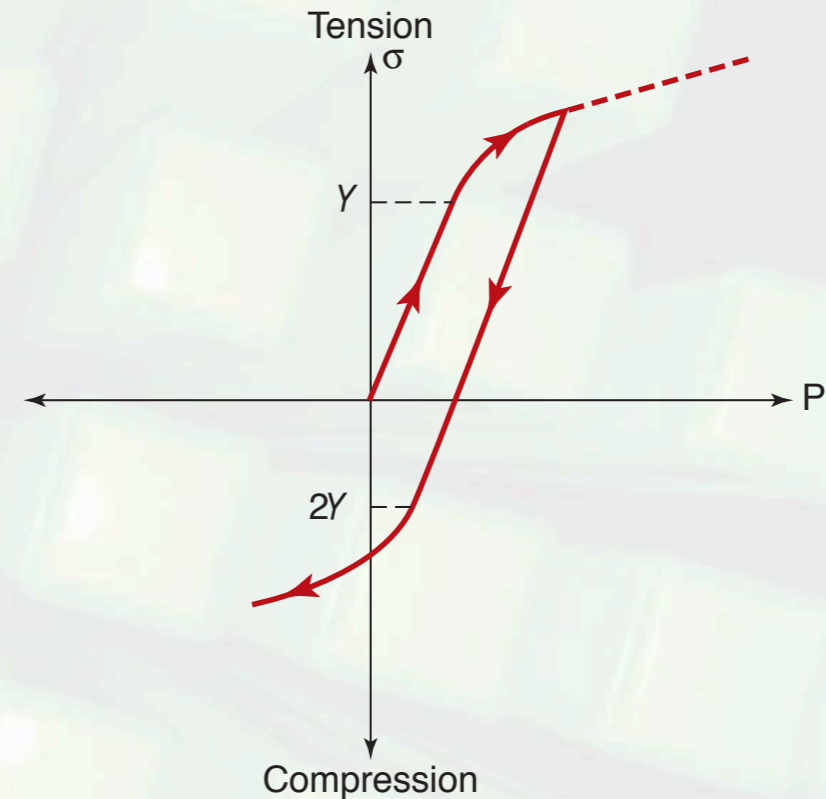
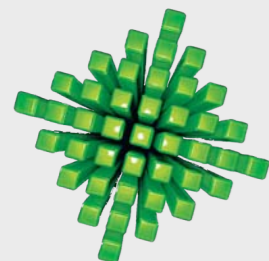
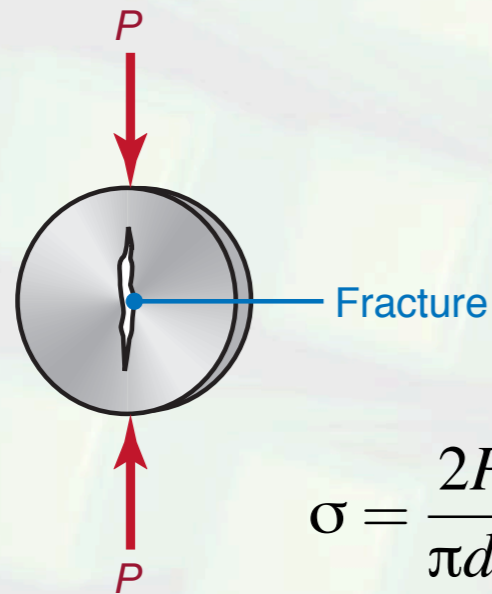


FIGURE 2.17 Schematic illustration of the Bauschinger effect. Arrows show loading and unloading paths. Note the decrease in the yield stress in compression after the specimen has been subjected to tension. The same result is obtained if compression is applied first, followed by tension, whereby the yield stress in tension decreases.

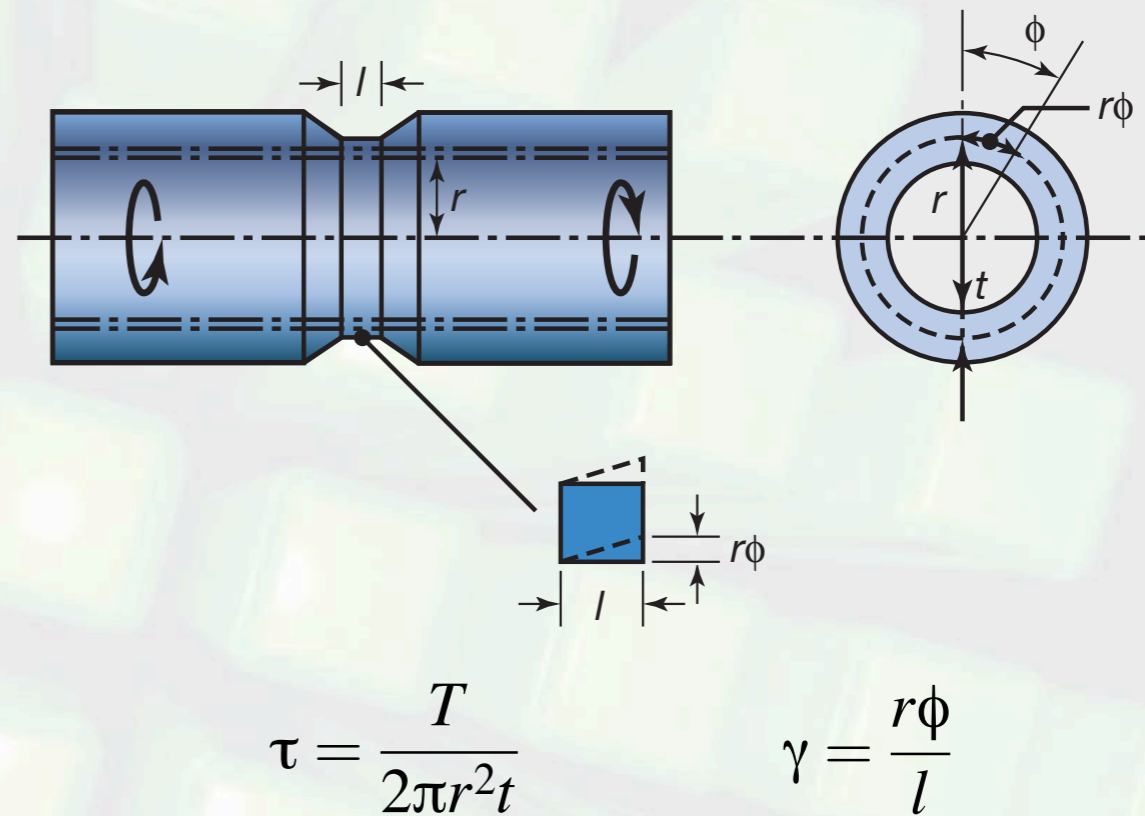


Disk & Torsion Tests



$$\sigma = \frac{2P}{\pi dt}$$

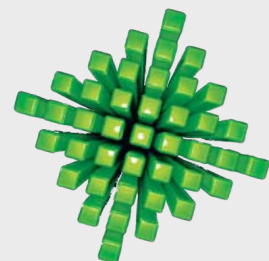
FIGURE 2.18 Disk test on a brittle material, showing the direction of loading and the fracture path. This test is useful for brittle materials, such as ceramics and carbides.



$$\tau = \frac{T}{2\pi r^2 t}$$

$$\gamma = \frac{r\phi}{l}$$

FIGURE 2.19 A typical torsion-test specimen. It is mounted between the two heads of a machine and is twisted. Note the shear deformation of an element in the reduced section.



Simple vs. Pure Shear

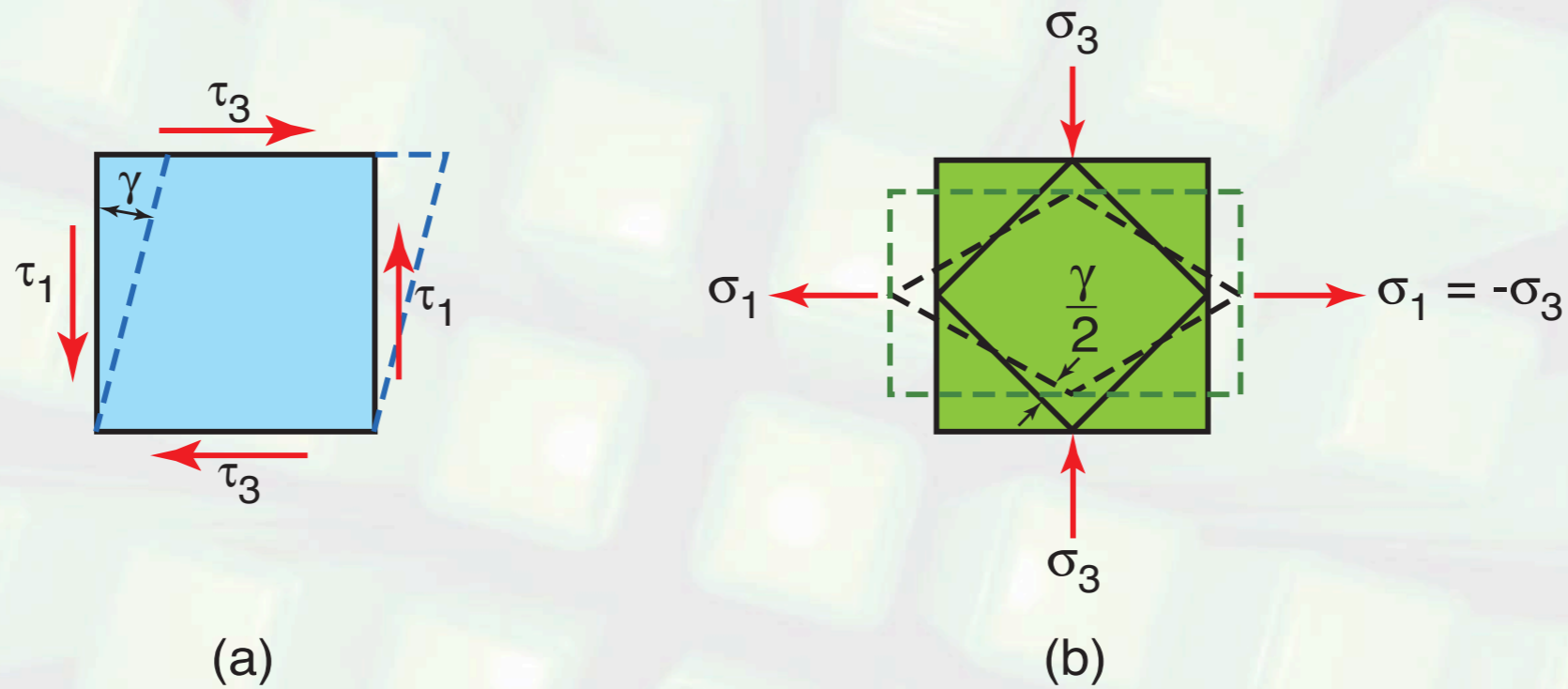
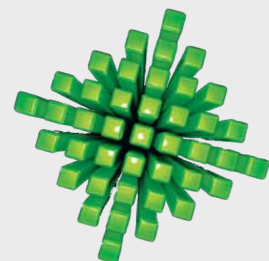
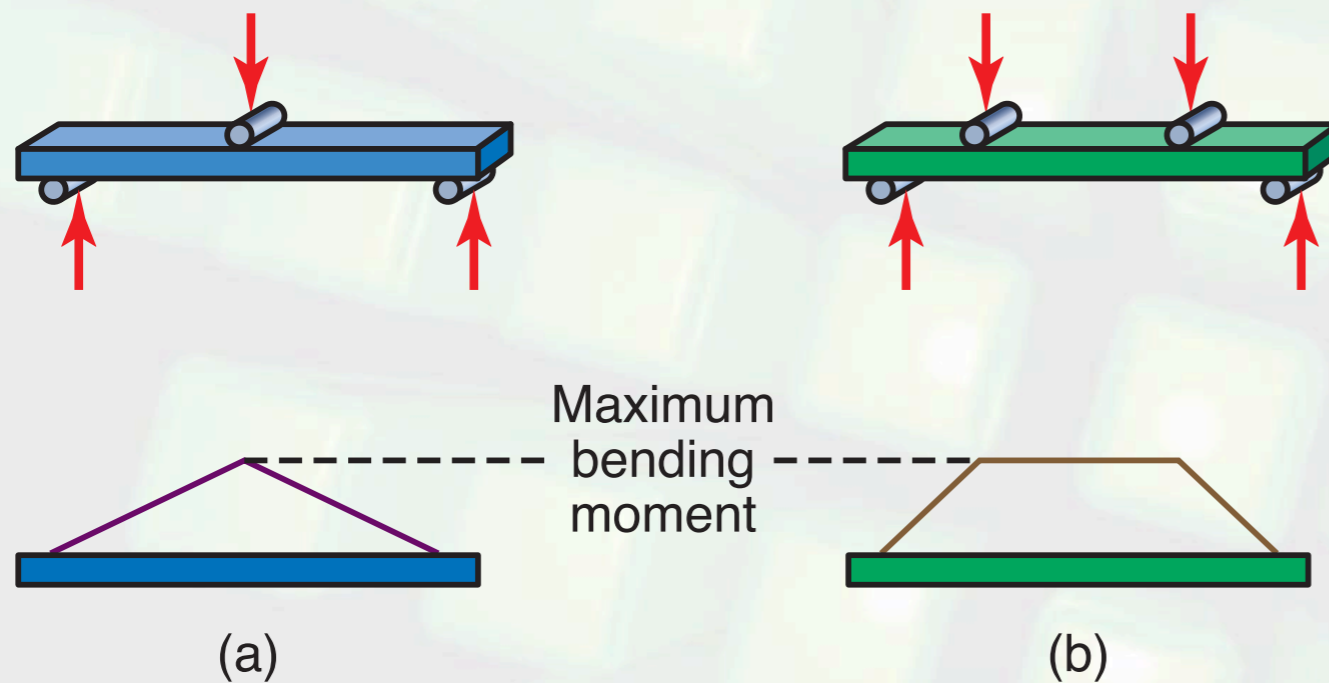


FIGURE 2.20 Comparison of (a) simple shear and (b) pure shear. Note that simple shear is equivalent to pure shear plus a rotation.

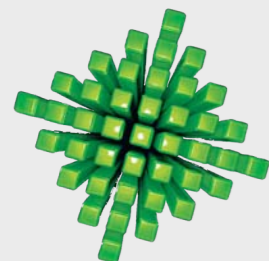


Three- and Four-Point Bend-Tests



$$\sigma = \frac{Mc}{I}$$

FIGURE 2.21 Two bend-test methods for brittle materials: (a) three-point bending; (b) four-point bending. The shaded areas on the beams represent the bending-moment diagrams, described in texts on the mechanics of solids. Note the region of constant maximum bending moment in (b), whereas the maximum bending moment occurs only at the center of the specimen in (a).



Hardness Tests

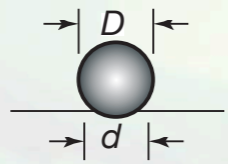
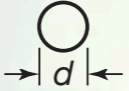
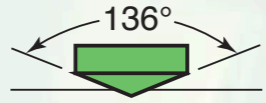

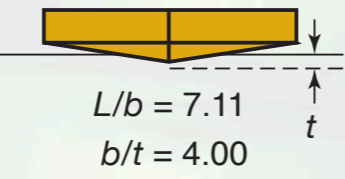
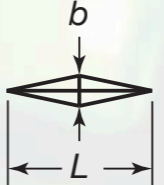
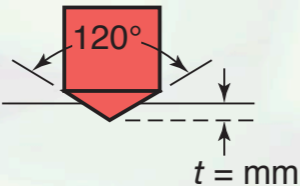

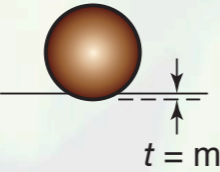

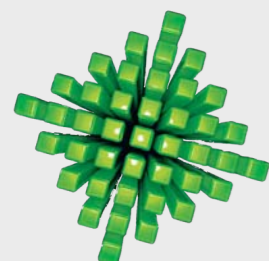
Test	Indenter	Shape of indentation		Load, P	Hardness number
		Side view	Top view		
Brinell	10-mm steel or tungsten carbide ball			500 kg 1500 kg 3000 kg	$HB = \frac{2P}{(\pi D)(D - \sqrt{D^2 - d^2})}$
Vickers	Diamond pyramid			1-120 kg	$HV = \frac{1.854P}{L^2}$
Knoop	Diamond pyramid			25 g-5 kg	$HK = \frac{14.2P}{L^2}$
Rockwell					
A } C } D }	Diamond cone			60 kg 150 kg 100 kg	HRA } HRC } = 100 - 500t HRD }
B } F } G }	$\frac{1}{16}$ - in. diameter steel ball			100 kg 60 kg 150 kg	HRB } HRF } = 130 - 500t HRG }
E	$\frac{1}{8}$ - in. diameter steel ball			100 kg	HRE }

FIGURE 2.22 General characteristics of hardness testing methods. The Knoop test is known as a microhardness test because of the light load and small impressions. *Source:* After H.W. Hayden, W.G. Moffatt, and V. Wulff.



Hardness Test Considerations

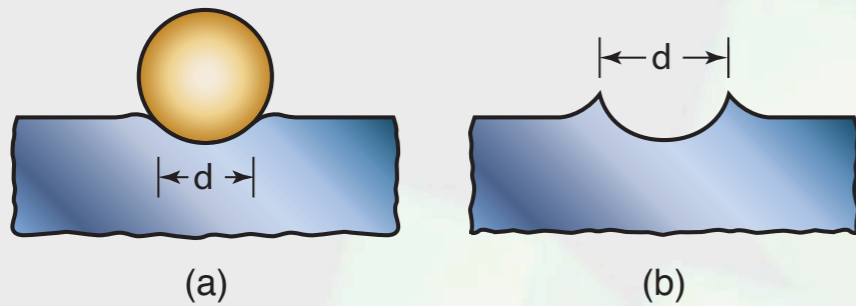


FIGURE 2.23 Indentation geometry for Brinell hardness testing: (a) annealed metal; (b) work-hardened metal. Note the difference in metal flow at the periphery of the impressions.

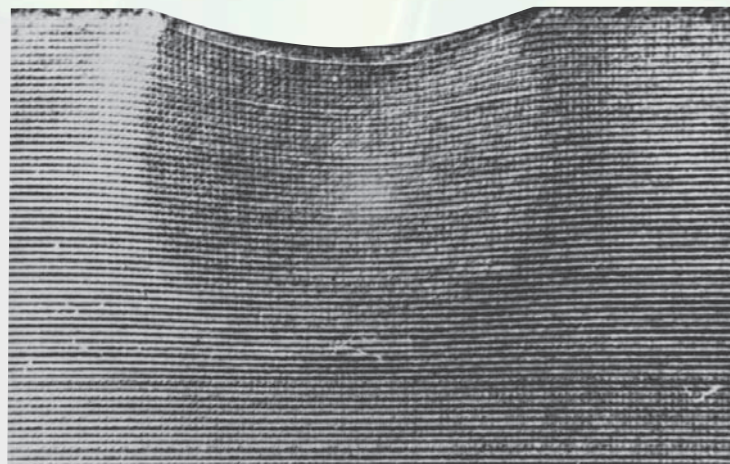


FIGURE 2.25 Bulk deformation in mild steel under a spherical indenter. Note that the depth of the deformed zone is about one order of magnitude larger than the depth of indentation. For a hardness test to be valid, the material should be allowed to fully develop this zone. This is why thinner specimens require smaller indentations. *Source:* Courtesy of M.C. Shaw and C.T. Yang.

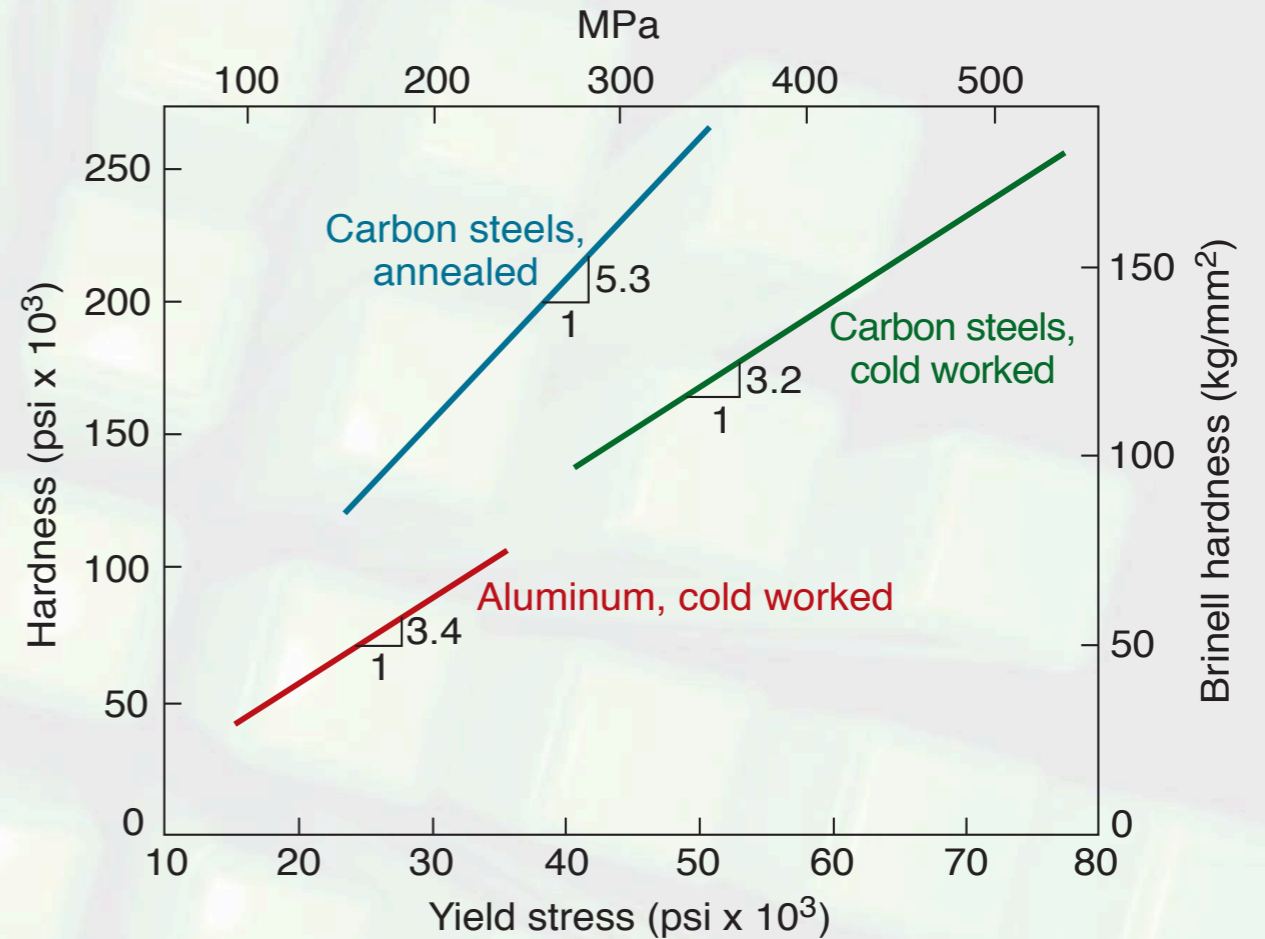
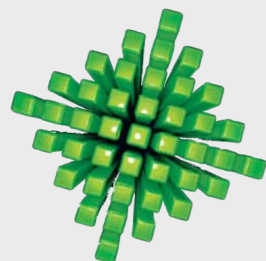
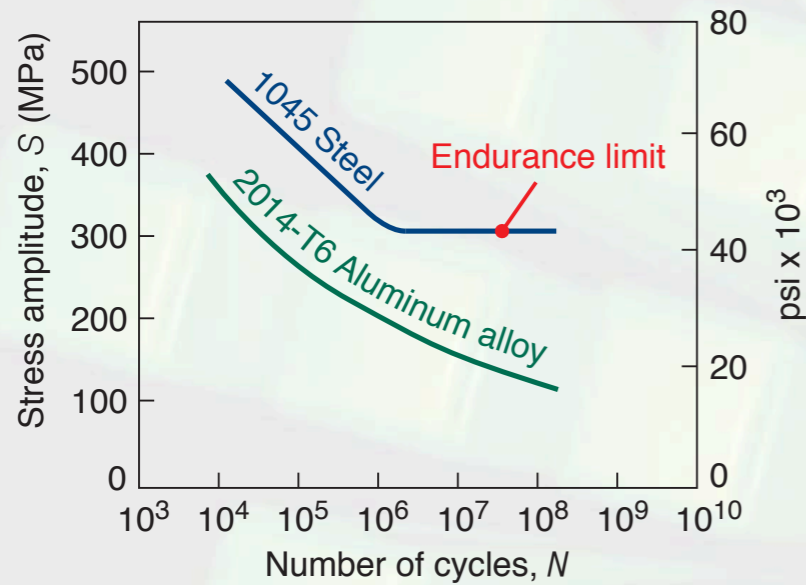


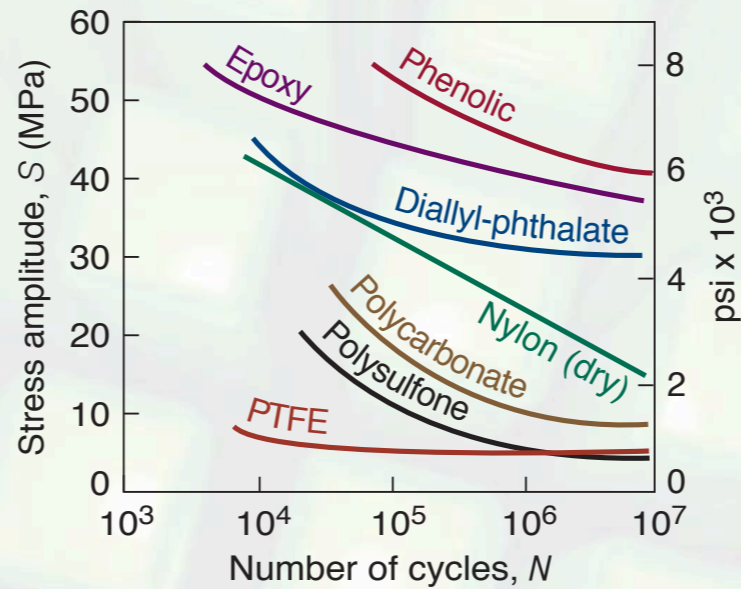
FIGURE 2.24 Relation between Brinell hardness and yield stress for aluminum and steels. For comparison, the Brinell hardness (which is always measured in kg/mm^2) is converted to psi units on the left scale.



Fatigue



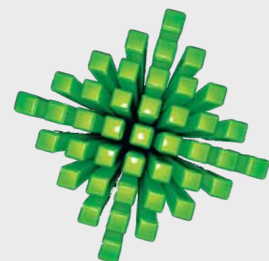
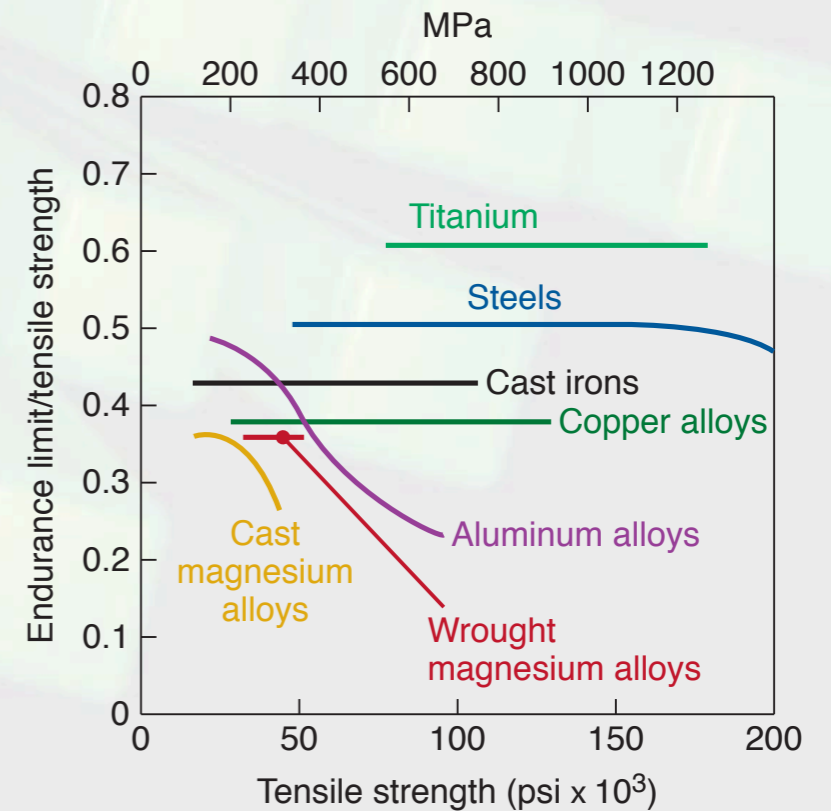
(a)



(b)

FIGURE 2.26 Typical S-N curves for two metals. Note that, unlike steel, aluminum does not have an endurance limit.

FIGURE 2.27 Ratio of fatigue strength to tensile strength for various metals, as a function of tensile strength.



Creep & Impact

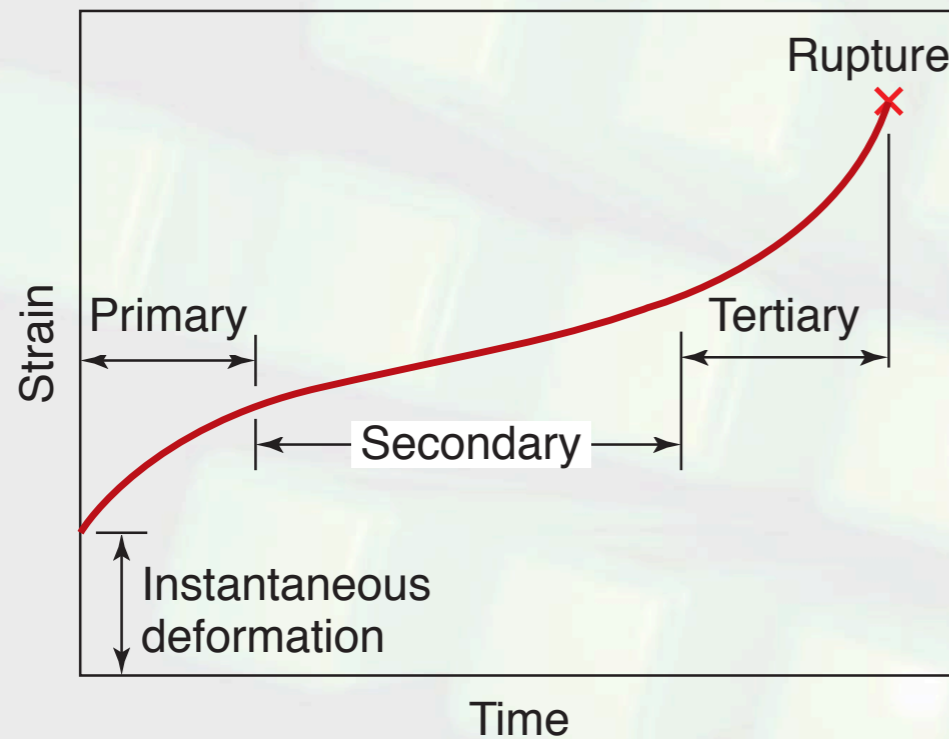


FIGURE 2.28 Schematic illustration of a typical creep curve. The linear segment of the curve (constant slope) is useful in designing components for a specific creep life.

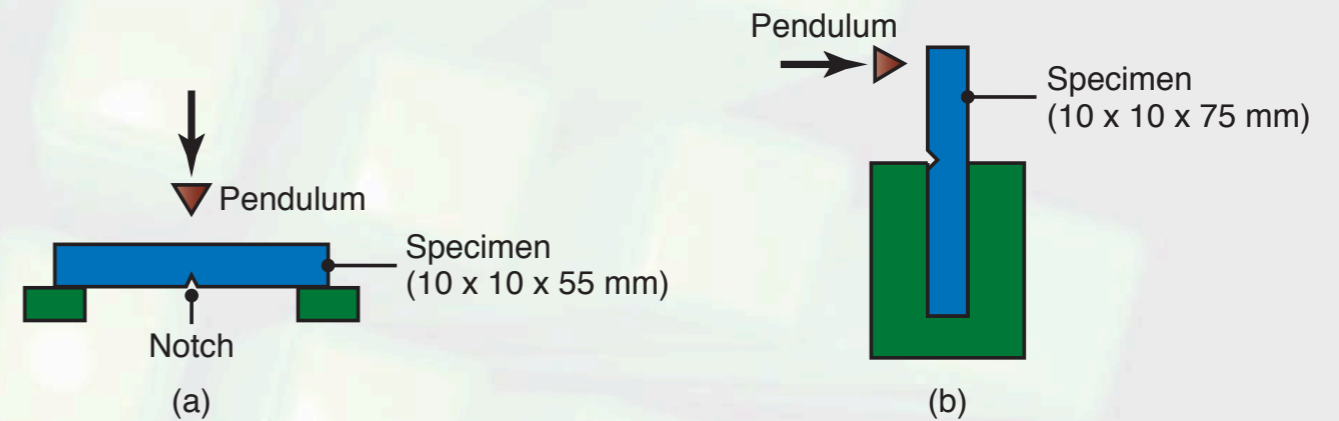
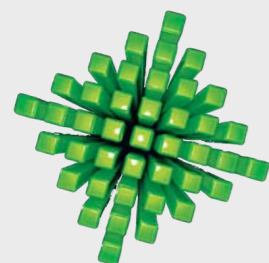


FIGURE 2.29 Impact test specimens: (a) Charpy; (b) Izod.



Residual Stresses

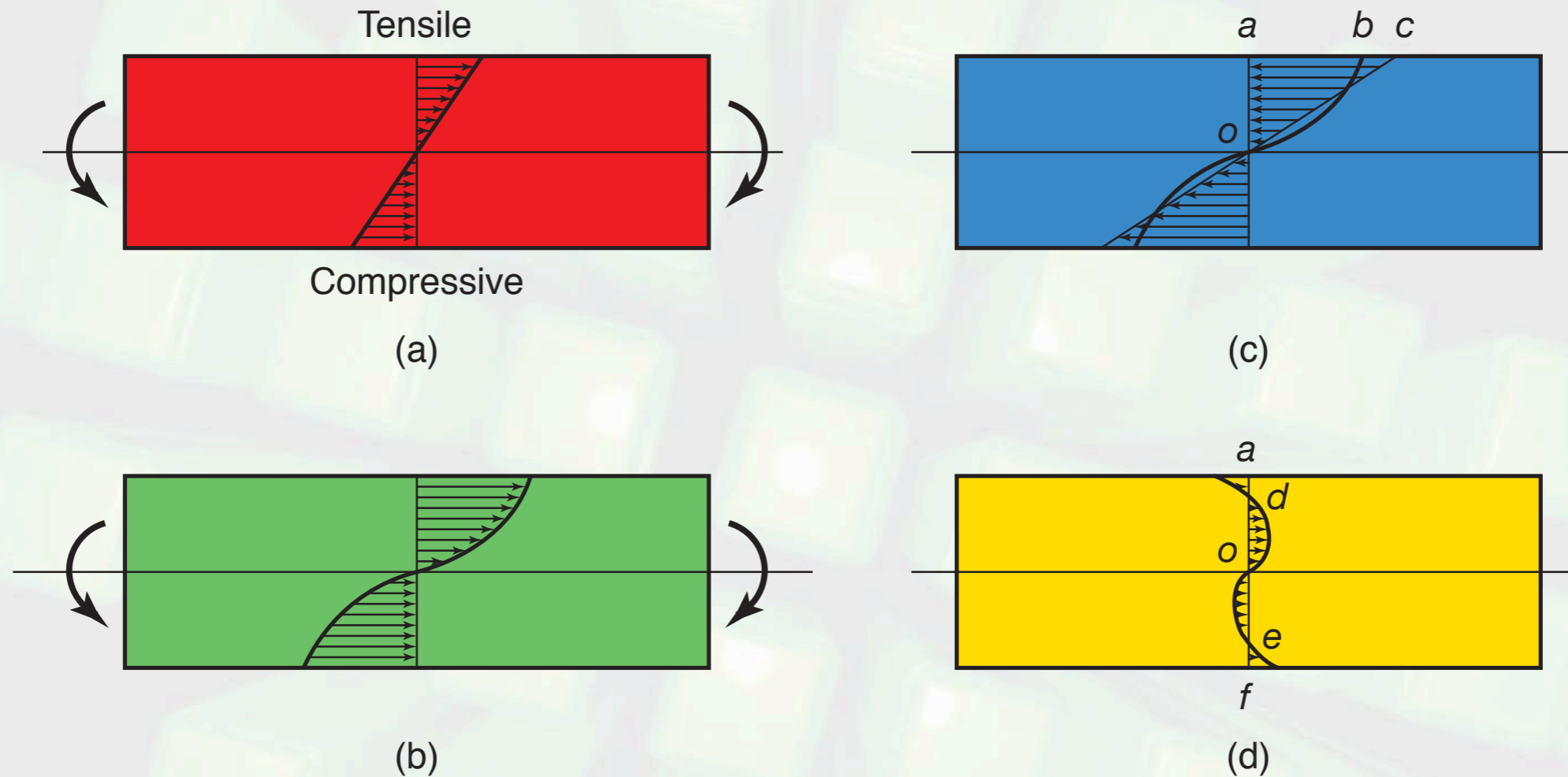
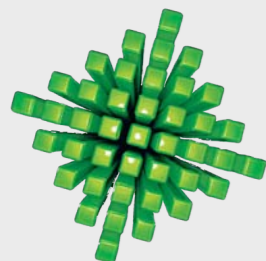


FIGURE 2.30 Residual stresses developed in bending a beam made of an elastic, strain-hardening material. Note that unloading is equivalent to applying an equal and opposite moment to the part, as shown in (b). Because of nonuniform deformation, most parts made by plastic deformation processes contain residual stresses. Note that the forces and moments due to residual stresses must be internally balanced.



Distortion due to Residual Stress

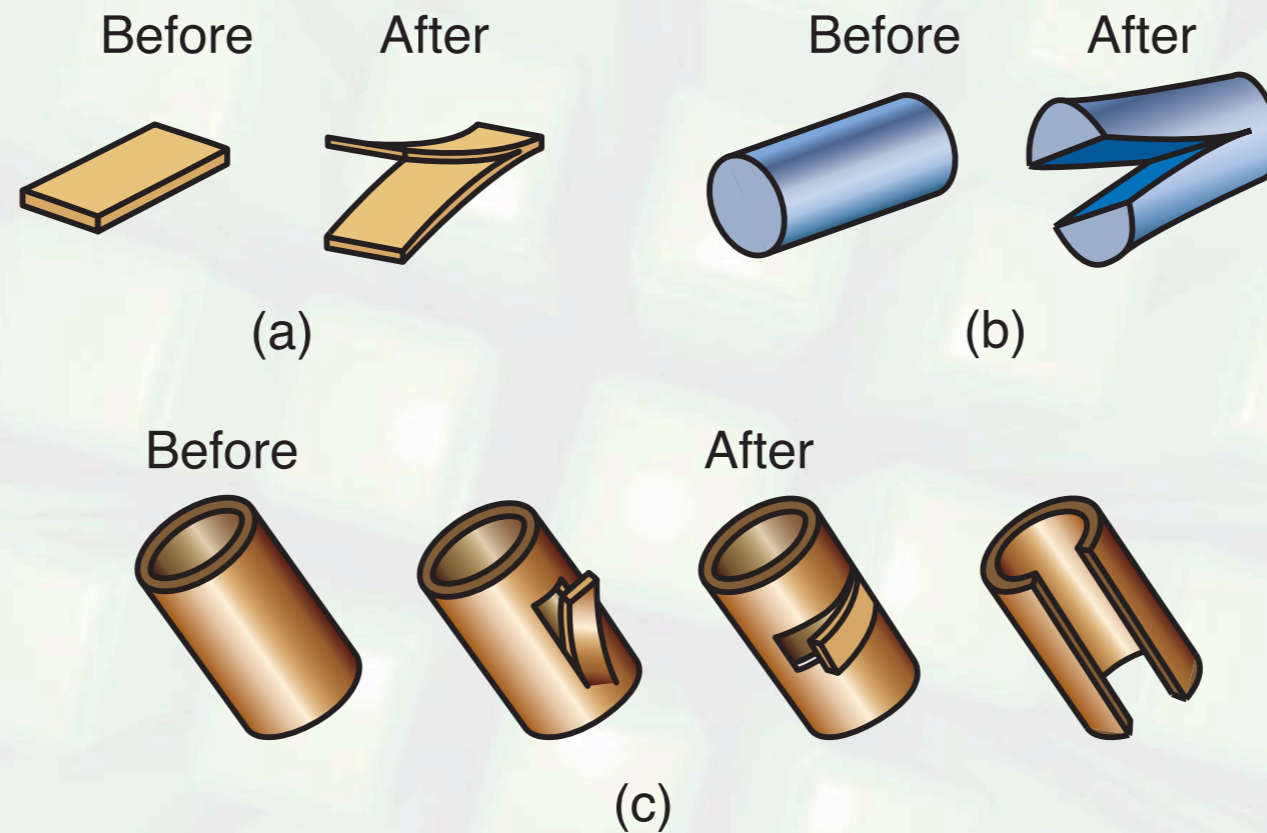
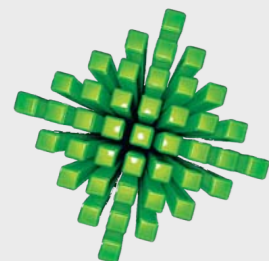


FIGURE 2.31 Distortion of parts with residual stresses after cutting or slitting: (a) rolled sheet or plate; (b) drawn rod; (c) thin-walled tubing. Because of the presence of residual stresses on the surfaces of parts, a round drill may produce an oval-shaped hole because of relaxation of stresses when a portion is removed.



Elimination of Residual Stresses

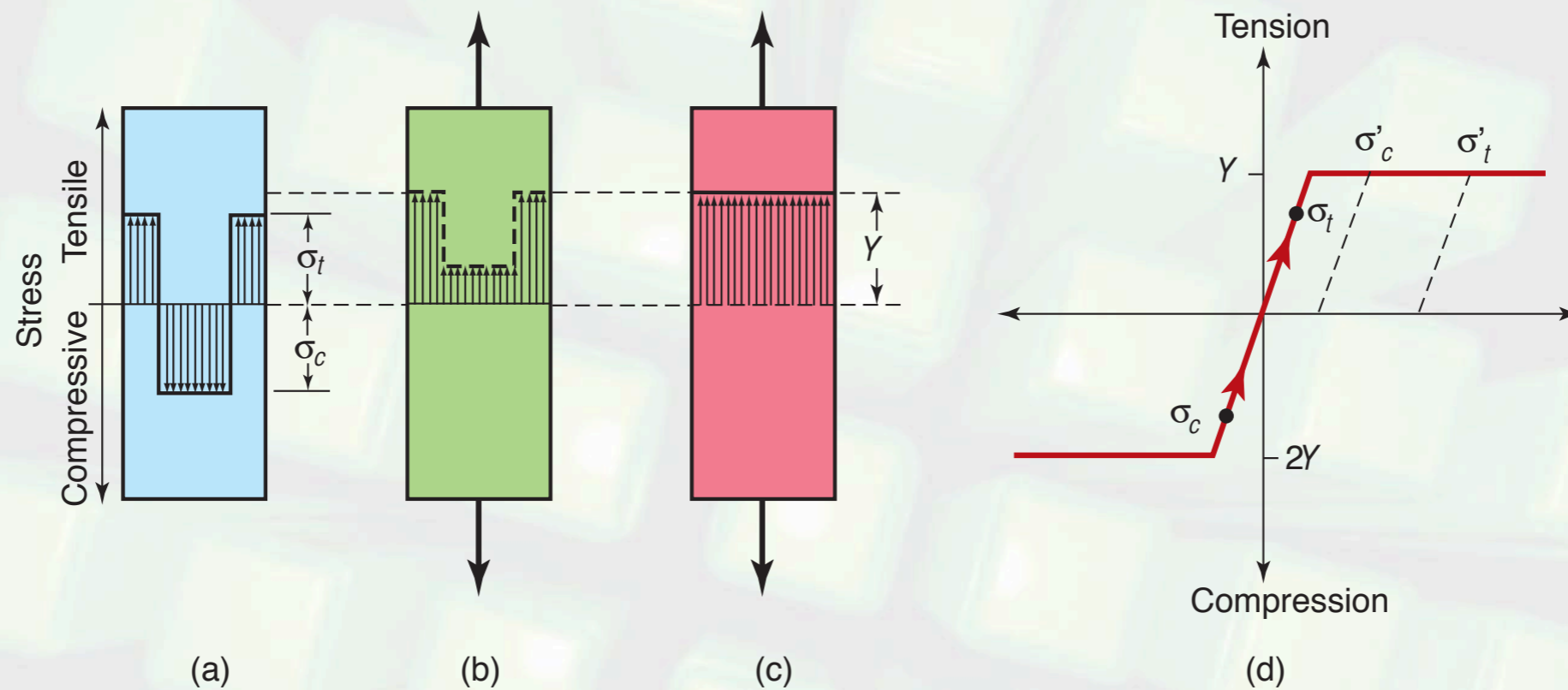
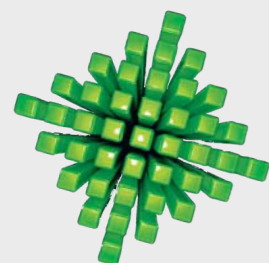


FIGURE 2.32 Elimination of residual stresses by stretching. Residual stresses can be also reduced or eliminated by thermal treatments, such as stress relieving or annealing.



State of Stress in Metalworking

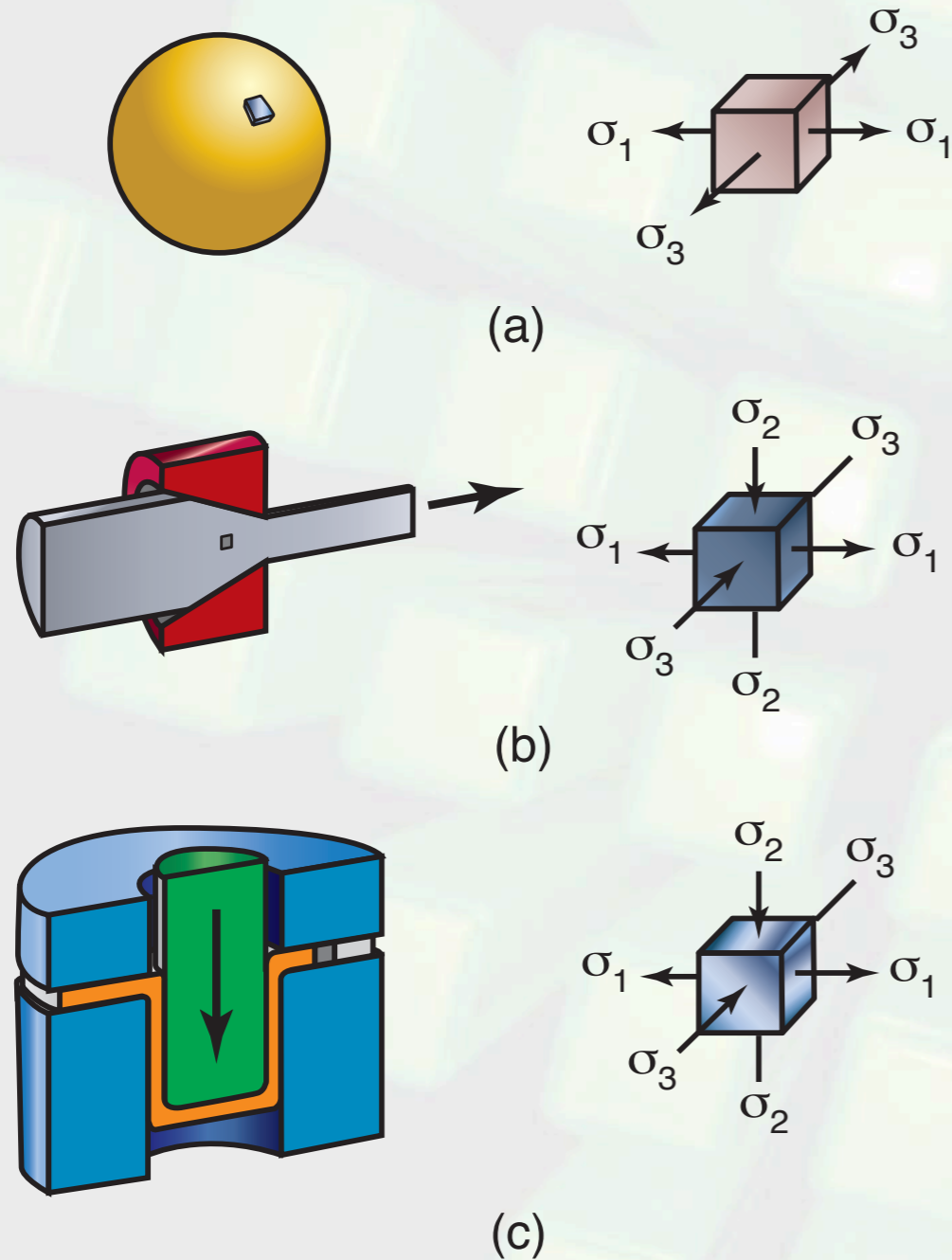
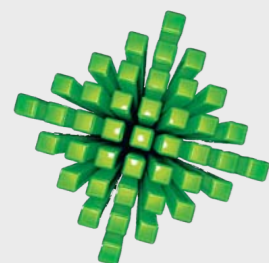
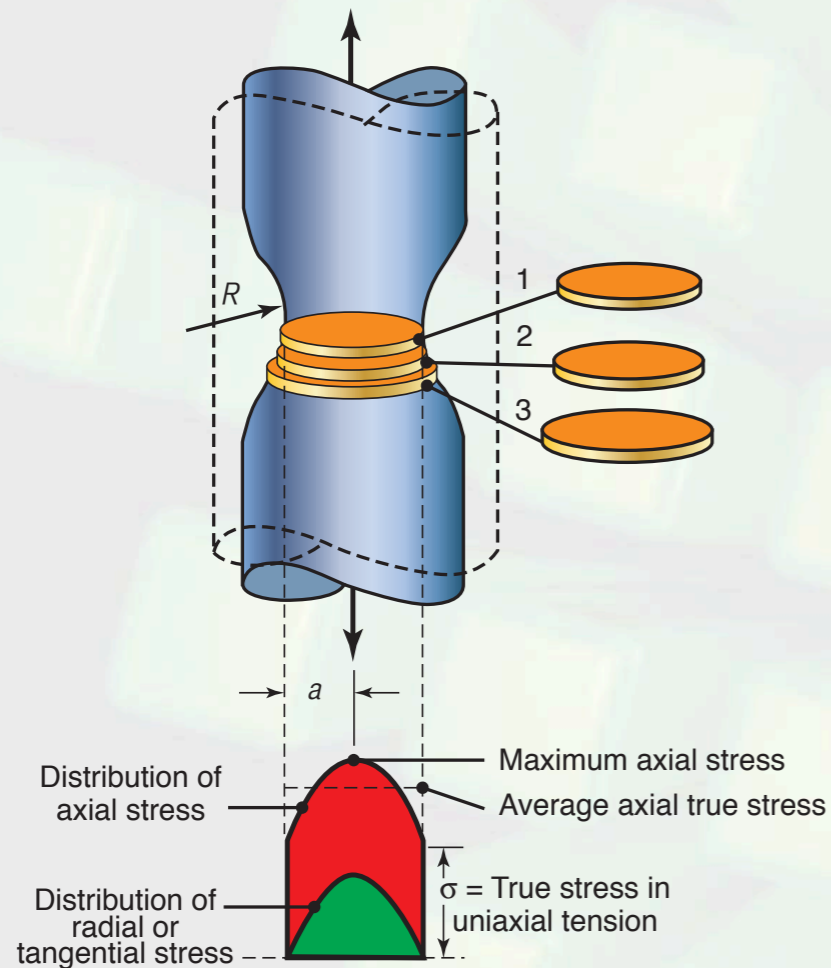


FIGURE 2.33 The state of stress in various metalworking operations. (a) Expansion of a thin-walled spherical shell under internal pressure. (b) Drawing of round rod or wire through a conical die to reduce its diameter; see Section 6.5 (c) Deep drawing of sheet metal with a punch and die to make a cup; see Section 7.6.



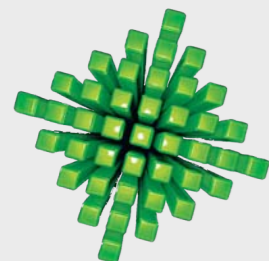
Strain State in Necking



Correction factor due to Bridgman:

$$\frac{\sigma}{\sigma_{av}} = \frac{1}{\left(1 + \frac{2R}{a}\right) \left[1 + \frac{a}{2R}\right]}$$

FIGURE 2.34 Stress distribution in the necked region of a tension-test specimen.



States of Stress

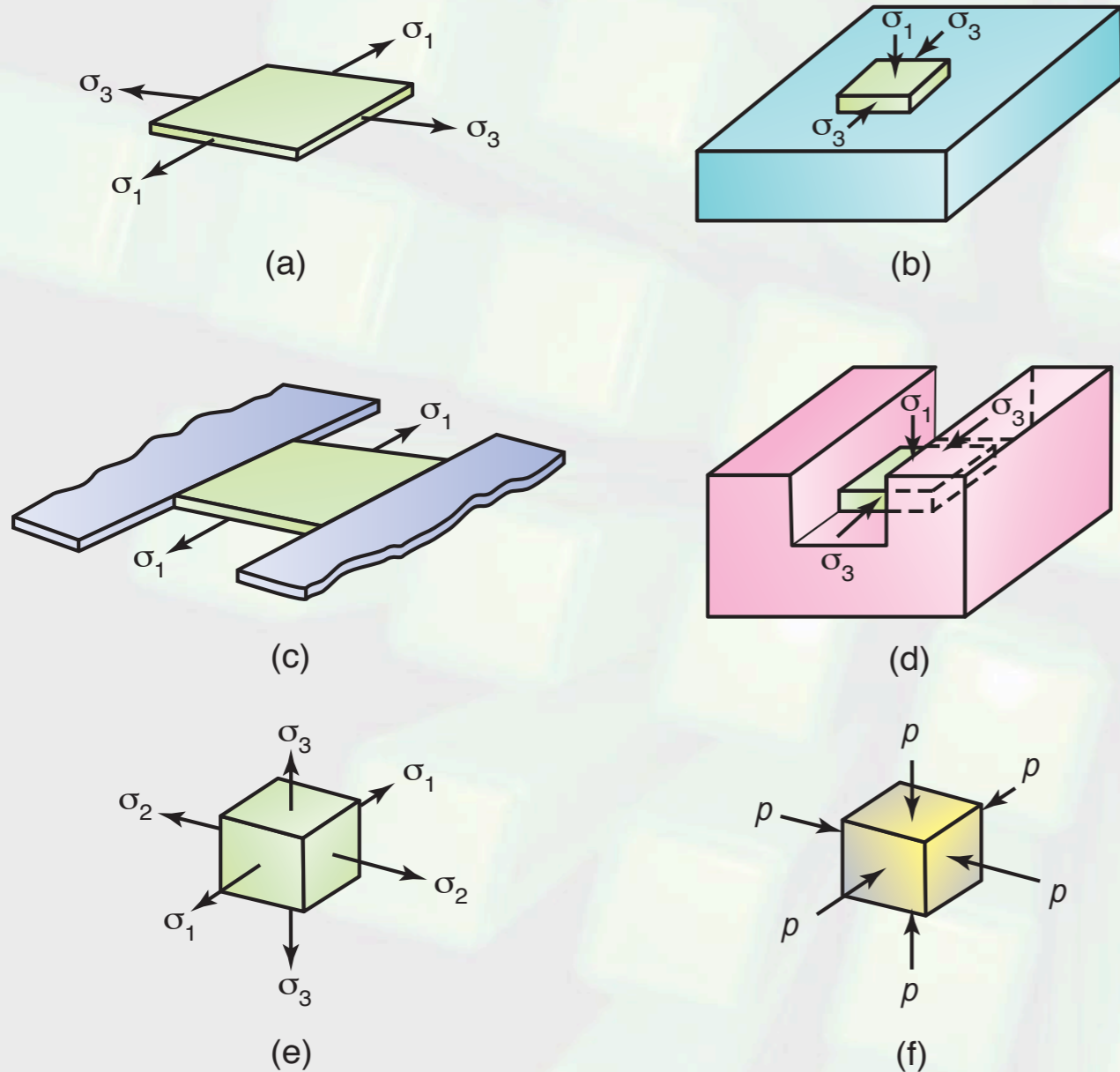
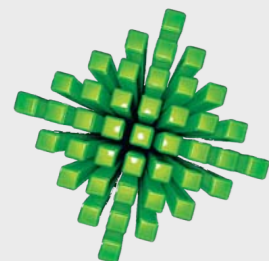
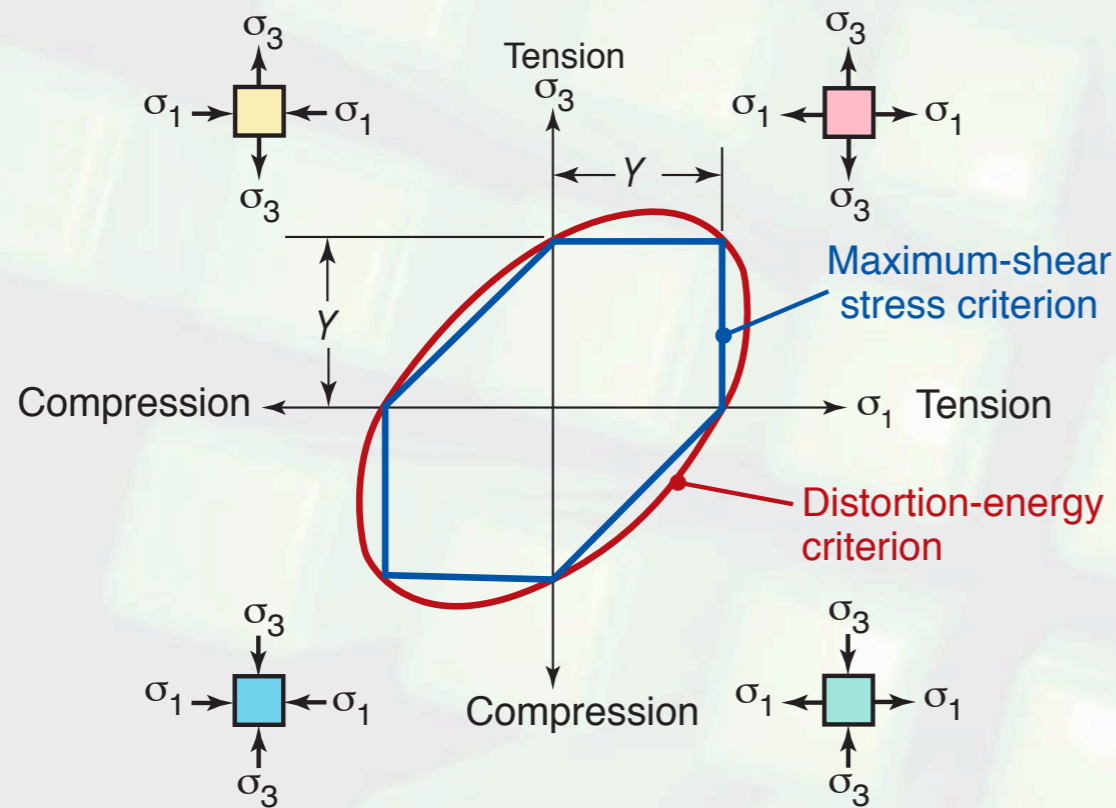


FIGURE 2.35 Examples of states of stress: (a) plane stress in sheet stretching; there are no stresses acting on the surfaces of the sheet. (b) plane stress in compression; there are no stresses acting on the sides of the specimen being compressed. (c) plane strain in tension; the width of the sheet remains constant while being stretched. (d) plane strain in compression (see also Fig. 2.15); the width of the specimen remains constant due to the restraint by the groove. (e) Triaxial tensile stresses acting on an element. (f) Hydrostatic compression of an element. Note also that an element on the cylindrical portion of a thin-walled tube in torsion is in the condition of both plane stress and plane strain (see also Section 2.11.7).



Yield Criteria



Maximum-shear-stress criterion:

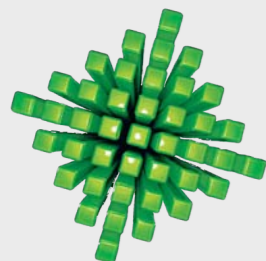
$$\sigma_{max} - \sigma_{min} = Y$$

Distortion-energy criterion:

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = 2Y^2$$

FIGURE 2.36 Plane-stress diagrams for maximum-shear-stress and distortion-energy criteria.

Note that $\sigma_2 = 0$.



Flow Stress and Work of Deformation

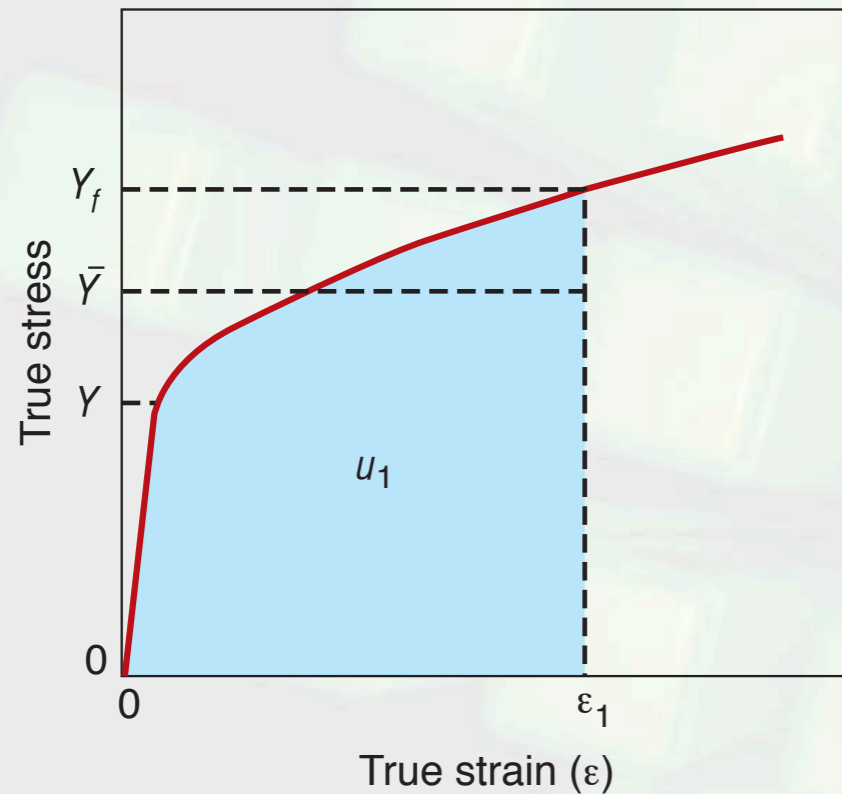


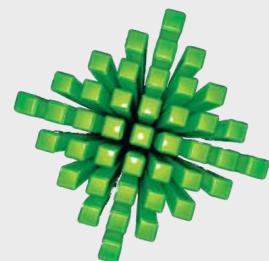
FIGURE 2.37 Schematic illustration of true stress-true strain curve showing yield stress Y , average flow stress, specific energy u_1 and flow stress Y_f .

Flow stress:

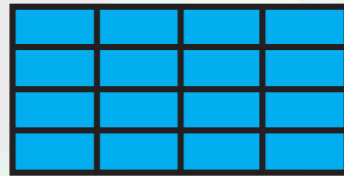
$$\bar{Y} = \frac{K\epsilon_1^n}{n+1}$$

Specific energy

$$u = \int_0^{\epsilon} \bar{\sigma} d\bar{\epsilon}$$



Ideal & Redundant Work



(a)



(b)



(c)

Total specific energy:

$$u_{total} = u_{ideal} + u_{friction} + u_{redundant}$$

Efficiency:

$$\eta = \frac{u_{ideal}}{u_{total}}$$

FIGURE 2.38 Deformation of grid patterns in a workpiece: (a) original pattern; (b) after ideal deformation; (c) after inhomogeneous deformation, requiring redundant work of deformation. Note that (c) is basically (b) with additional shearing, especially at the outer layers. Thus (c) requires greater work of deformation than (b). See also Figs. 6.3 and 6.49.

