Mechanical properties are discussed individually in the sections that follow. Several new quantitative relationships for the properties are presented here which make it possible to understand the mechanical properties to a depth that is not possible by means of the conventional tabular listings, where the properties of each material are listed separately.

7.8 HARDNESS

Hardness is used more frequently than any other of the mechanical properties by the design engineer to specify the final condition of a structural part. This is due in part to the fact that hardness tests are the least expensive in time and money to conduct. The test can be performed on a finished part without the need to machine a special test specimen. In other words, a hardness test may be a nondestructive test in that it can be performed on the actual part without affecting its service function.

Hardness is frequently defined as a measure of the ability of a material to resist plastic deformation or penetration by an indenter having a spherical or conical end. At the present time, hardness is more a technological property of a material than it is a scientific or engineering property. In a sense, hardness tests are practical shop tests rather than basic scientific tests. All the hardness scales in use today give relative values rather than absolute ones. Even though some hardness scales, such as the Brinell, have units of stress (kg/mm^2) associated with them, they are not absolute scales because a given piece of material (such as a 2-in cube of brass) will have significantly different Brinell hardness numbers depending on whether a 500-kg or a 3000-kg load is applied to the indenter.

7.8.1 Rockwell Hardness

The *Rockwell hardnesses* are hardness numbers obtained by an indentation type of test based on the depth of the indentation due to an increment of load. The Rockwell scales are by far the most frequently used hardness scales in industry even though they are completely relative. The reasons for their large acceptance are the simplicity of the testing apparatus, the short time necessary to obtain a reading, and the ease with which reproducible readings can be obtained, the last of these being due in part to the fact that the testing machine has a "direct-reading" dial; that is, a needle points directly to the actual hardness value without the need for referring to a conversion table or chart, as is true with the Brinell, Vickers, or Knoop hardnesses. Table 7.2 lists the most common Rockwell hardness scales.

TABLE 7.2 Rockwell Hardness Scales

	Scale								
	A	B	C	D	E	F	G	H	K
Indenter	1	2	1	1	3	2	2	3	3
Load, kg	60	100	150	100	100	60	150	60	150

Indenter 1 is a diamond cone having an included angle of 120° and a spherical end radius of 0.008 in. Indenters 2 and 3 are $\frac{1}{16}$-in-diameter and $\frac{1}{8}$-in-diameter balls, respectively. In addition to the preceding scales, there are several others for testing very soft bearing materials, such as babbit, that use $\frac{1}{4}$-in-diameter and $\frac{1}{2}$-in-diameter balls. Also, there are several "superficial" scales that use a special diamond cone with loads less than 50 kg to test the hardness of surface-hardened layers.

The particular materials that each scale is used on are as follows: the A scale on the extremely hard materials, such as carbides or thin case-hardened layers on steel; the B scale on soft steels, copper and aluminum alloys, and soft-case irons; the C scale on medium and hard steels, hard-case irons, and all hard nonferrous alloys; the E and F scales on soft copper and aluminum alloys. The remaining scales are used on even softer alloys.

Several precautions must be observed in the proper use of the Rockwell scales. The ball indenter should not be used on any material having a hardness greater than 50 R_C; otherwise the steel ball will be plastically deformed or flattened and thus give erroneous readings. Readings taken on the sides of cylinders or spheres should be corrected for the curvature of the surface. Readings on the C scale of less than 20 should not be recorded or specified because they are unreliable and subject to much variation.

The hardness numbers for all the Rockwell scales are an inverse measure of the depth of the indentation. Each division on the dial gauge of the Rockwell machine corresponds to an 80×10^6 in depth of penetration. The penetration with the C scale varies between 0.0005 in for hard steel and 0.0015 in for very soft steel when only the minor load is applied. The total depth of penetration with both the major and minor loads applied varies from 0.003 in for the hardest steel to 0.008 in for soft steel (20 R_C). Since these indentations are relatively shallow, the Rockwell C hardness test is considered a nondestructive test and it can be used on fairly thin parts.

Although negative hardness readings can be obtained on the Rockwell scales (akin to negative Fahrenheit temperature readings), they are usually not recorded as such, but rather a different scale is used that gives readings greater than zero. The only exception to this is when one wants to show a continuous trend in the change in hardness of a material due to some treatment. A good example of this is the case of the effect of cold work on the hardness of a fully annealed brass. Here the annealed hardness may be –20 R_B and increase to 95 R_B with severe cold work.

7.8.2 Brinell Hardness

The *Brinell hardness* H_B is the hardness number obtained by dividing the load that is applied to a spherical indenter by the surface area of the spherical indentation produced; it has units of kilograms per square millimeter. Most readings are taken with a 10-mm ball of either hardened steel or tungsten carbide. The loads that are applied vary from 500 kg for soft materials to 3000 kg for hard materials. The steel ball should not be used on materials having a hardness greater than about 525 H_B (52 R_C) because of the possibility of putting a flat spot on the ball and making it inaccurate for further use.

The Brinell hardness machine is as simple as, though more massive than, the Rockwell hardness machine, but the standard model is not direct-reading and takes a longer time to obtain a reading than the Rockwell machine. In addition, the indentation is much larger than that produced by the Rockwell machine, and the machine cannot be used on hard steel. The method of operation, however, is simple. The prescribed load is applied to the 10-mm-diameter ball for approximately 10 s. The part is then withdrawn from the machine and the operator measures the diameter of the indentation by means of a millimeter scale etched on the eyepiece of a special Brinell microscope. The Brinell hardness number is then obtained from the equation

$$H_B = \frac{L}{(\pi D/2)[D - (D^2 - d^2)^{1/2}]} \tag{7.2}$$

where L = load, kg
D = diameter of indenter, mm
d = diameter of indentation, mm

The denominator in this equation is the spherical area of the indentation.

The Brinell hardness test has proved to be very successful, partly due to the fact that for some materials it can be directly correlated to the tensile strength. For example, the tensile strengths of all the steels, if stress-relieved, are very close to being 0.5 times the Brinell hardness number when expressed in kilopounds per square inch (kpsi). This is true for both annealed and heat-treated steel. Even though the Brinell hardness test is a technological one, it can be used with considerable success in engineering research on the mechanical properties of materials and is a much better test for this purpose than the Rockwell test.

The Brinell hardness number of a given material increases as the applied load is increased, the increase being somewhat proportional to the strain-hardening rate of the material. This is due to the fact that the material beneath the indentation is plastically deformed, and the greater the penetration, the greater is the amount of cold work, with a resulting high hardness. For example, the cobalt base alloy HS-25 has a hardness of 150 H_B with a 500-kg load and a hardness of 201 H_B with an applied load of 3000 kg.

7.8.3 Meyer Hardness

The *Meyer hardness* H_M is the hardness number obtained by dividing the load applied to a spherical indenter by the projected area of the indentation. The Meyer hardness test itself is identical to the Brinell test and is usually performed on a Brinell hardness-testing machine. The difference between these two hardness scales is simply the area that is divided into the applied load—the projected area being used for the Meyer hardness and the spherical surface area for the Brinell hardness. Both are based on the diameter of the indentation. The units of the Meyer hardness are also kilograms per square millimeter, and hardness is calculated from the equation

$$H_M = \frac{4L}{\pi d^2} \tag{7.3}$$

Because the Meyer hardness is determined from the projected area rather than the contact area, it is a more valid concept of stress and therefore is considered a more basic or scientific hardness scale. Although this is true, it has been used very little since it was first proposed in 1908, and then only in research studies. Its lack of acceptance is probably due to the fact that it does not directly relate to the tensile strength the way the Brinell hardness does.

Meyer is much better known for the original strain-hardening equation that bears his name than he is for the hardness scale that bears his name. The strain-hardening equation for a given diameter of ball is

$$L = Ad^p \tag{7.4}$$

where L = load on spherical indenter
d = diameter of indentation
p = Meyer strain-hardening exponent

The values of the strain-hardening exponent for a variety of materials are available in many handbooks. They vary from a minimum value of 2.0 for low-work-hardening materials, such as the PH stainless steels and all cold-rolled metals, to a maximum of about 2.6 for dead soft brass. The value of p is about 2.25 for both annealed pure aluminum and annealed 1020 steel.

Experimental data for some metals show that the exponent p in Eq. (7.4) is related to the strain-strengthening exponent m in the tensile stress-strain equation $\sigma = \sigma_0 \varepsilon^m$, which is to be presented later. The relation is

$$p - 2 = m \tag{7.5}$$

In the case of 70-30 brass, which had an experimentally determined value of $p = 2.53$, a separately run tensile test gave a value of $m = 0.53$. However, such good agreement does not always occur, partly because of the difficulty of accurately measuring the diameter d. Nevertheless, this approximate relationship between the strain-hardening and the strain-strengthening exponents can be very useful in the practical evaluation of the mechanical properties of a material.

7.8.4 Vickers or Diamond-Pyramid Hardness

The *diamond-pyramid hardness* H_p, or the *Vickers hardness* H_V, as it is frequently called, is the hardness number obtained by dividing the load applied to a square-based pyramid indenter by the surface area of the indentation. It is similar to the Brinell hardness test except for the indenter used. The indenter is made of industrial diamond, and the area of the two pairs of opposite faces is accurately ground to an included angle of 136°. The load applied varies from as low as 100 g for microhardness readings to as high as 120 kg for the standard macrohardness readings. The indentation at the surface of the workpiece is square-shaped. The diamond pyramid hardness number is determined by measuring the length of the two diagonals of the indentation and using the average value in the equation

$$H_p = \frac{2L \sin(\alpha/2)}{d^2} = \frac{1.8544L}{d^2} \tag{7.6}$$

where L = applied load, kg
d = diagonal of the indentation, mm
α = face angle of the pyramid, 136°

The main advantage of a cone or pyramid indenter is that it produces indentations that are geometrically similar regardless of depth. In order to be geometrically similar, the angle subtended by the indentation must be constant regardless of the depth of the indentation. This is not true of a ball indenter. It is believed that if geometrically similar deformations are produced, the material being tested is stressed to the same amount regardless of the depth of the penetration. On this basis, it would be expected that conical or pyramidal indenters would give the same hardness number regardless of the load applied. Experimental data show that the pyramid hardness number is independent of the load if loads greater than 3 kg are applied. However, for loads less than 3 kg, the hardness is affected by the load, depending on the strain-hardening exponent of the material being tested.

7.8.5 Knoop Hardness

The *Knoop hardness* H_K is the hardness number obtained by dividing the load applied to a special rhombic-based pyramid indenter by the projected area of the indentation. The indenter is made of industrial diamond, and the four pyramid faces are ground so that one of the angles between the intersections of the four faces is 172.5° and the other angle is 130°. A pyramid of this shape makes an indentation that has the projected shape of a parallelogram having a long diagonal that is 7 times as large as the short diagonal and 30 times as large as the maximum depth of the indentation.

The greatest application of Knoop hardness is in the microhardness area. As such, the indenter is mounted on an axis parallel to the barrel of a microscope having magnifications of 100× to 500×. A metallurgically polished flat specimen is used. The place at which the hardness is to be determined is located and positioned under the hairlines of the microscope eyepiece. The specimen is then positioned under the indenter and the load is applied for 10 to 20 s. The specimen is then located under the microscope again and the length of the long diagonal is measured. The Knoop hardness number is then determined by means of the equation

$$H_K = \frac{L}{0.070\,28d^2} \tag{7.7}$$

where L = applied load, kg
d = length of long diagonal, mm

The indenter constant 0.070 28 corresponds to the standard angles mentioned above.

7.8.6 Scleroscope Hardness

The *scleroscope hardness* is the hardness number obtained from the height to which a special indenter bounces. The indenter has a rounded end and falls freely a distance of 10 in in a glass tube. The rebound height is measured by visually observing the maximum height the indenter reaches. The measuring scale is divided into 140 equal divisions and numbered beginning with zero. The scale was selected so that the rebound height from a fully hardened high-carbon steel gives a maximum reading of 100.

All the previously described hardness scales are called *static hardnesses* because the load is slowly applied and maintained for several seconds. The scleroscope hardness, however, is a *dynamic hardness.* As such, it is greatly influenced by the elastic modulus of the material being tested.

7.9 THE TENSILE TEST

The tensile test is conducted on a machine that can apply uniaxial tensile or compressive loads to the test specimen, and the machine also has provisions for accurately registering the value of the load and the amount of deformation that occurs to the specimen. The tensile specimen may be a round cylinder or a flat strip with a reduced cross section, called the *gauge section,* at its midlength to ensure that the fracture does not occur at the holding grips. The minimum length of the reduced section for a standard specimen is four times its diameter. The most commonly used specimen has a 0.505-in-diameter gauge section (0.2 in^2 cross-sectional area) that is 2¼ in long to accommodate a 2-in-long gauge section. The overall length of the specimen is 5½ in, with a 1-in length of size ¾-10NC screw threads on each end. The ASTM specifications list several other standard sizes, including flat specimens.

In addition to the tensile properties of strength, rigidity, and ductility, the tensile test also gives information regarding the stress-strain behavior of the material. It is very important to distinguish between *strength* and *stress* as they relate to material properties and mechanical design, but it is also somewhat awkward, since they have the same units and many books use the same symbol for both.

Strength is a property of a material—it is a measure of the ability of a material to withstand stress or it is the load-carrying capacity of a material. The numerical value of strength is determined by dividing the appropriate load (yield, maximum, fracture, shear, cyclic, creep, etc.) by the original cross-sectional area of the specimen and is designated as S. Thus

$$S = \frac{L}{A_0} \tag{7.8}$$

The subscripts y, u, f, and s are appended to S to denote yield, ultimate, fracture, and shear strength, respectively. Although the strength values obtained from a tensile test have the units of stress [psi (Pa) or equivalent], they are not really values of stress.

Stress is a condition of a material due to an applied load. If there are no loads on a part, then there are no stresses in it. (Residual stresses may be considered as being caused by unseen loads.) The numerical value of the stress is determined by dividing the actual load or force on the part by the actual cross section that is supporting the load. Normal stresses are almost universally designated by the symbol σ, and the stresses due to tensile loads are determined from the expression

$$\sigma = \frac{L}{A_i} \tag{7.9}$$

where A_i = instantaneous cross-sectional area corresponding to that particular load. The units of stress are pounds per square inch (pascals) or an equivalent.

During a tensile test, the stress varies from zero at the very beginning to a maximum value that is equal to the true fracture stress, with an infinite number of stresses in between. However, the tensile test gives only three values of strength: yield, ultimate, and fracture. An appreciation of the real differences between strength and stress will be achieved after reading the material that follows on the use of tensile-test data.

7.9.1 Engineering Stress-Strain

Traditionally, the tensile test has been used to determine the so-called engineering stress-strain data that are needed to plot the engineering stress-strain curve for a given material. However, since engineering stress is not really a stress but is a measure of the strength of a material, it is more appropriate to call such data either *strength–nominal strain* or *nominal stress–strain data.* Table 7.3 illustrates the data that are normally collected during a tensile test, and Fig. 7.14 shows the condition of a standard tensile specimen at the time the specific data in the table are recorded. The load-versus-gauge-length data, or an elastic stress-strain curve drawn by the machine, are needed to determine Young's modulus of elasticity of the material as well as the proportional limit. They are also needed to determine the yield strength if the offset method is used. All the definitions associated with engineering stress-strain, or, more appropriately, with the strength–nominal strain properties, are presented in the section which follows and are discussed in conjunction with the experimental data for commercially pure titanium listed in Table 7.3 and Fig. 7.14.

The elastic and elastic-plastic data listed in Table 7.3 are plotted in Fig. 7.15 with an expanded strain axis, which is necessary for the determination of the yield strength. The nominal (approximate) stress or the strength S which is calculated by means of Eq. (7.8) is plotted as the ordinate.

The abscissa of the engineering stress-strain plot is the *nominal strain,* which is defined as the unit elongation obtained when the change in length is divided by the original length and has the units of inch per inch and is designated as n. Thus, for tension,

$$n = \frac{\Delta \ell}{\ell} = \frac{\ell_f - \ell_0}{\ell_0} \tag{7.10}$$

where ℓ = gauge length and the subscripts 0 and f designate the original and final state, respectively. This equation is valid for deformation strains that do not exceed the strain at the maximum load of a tensile specimen.

It is customary to plot the data obtained from a tensile test as a stress-strain curve such as that illustrated in Fig. 7.16, but without including the word *nominal.* The reader then considers such a curve as an actual stress-strain curve, which it obviously is not. The curve plotted in Fig. 7.16 is in reality a load-deformation curve. If the ordinate axis were labeled load (lb) rather than stress (psi), the distinction between

TABLE 7.3 Tensile Test Data

Material: A40 titanium; condition: annealed; specimen size: 0.505-in diameter by 2-in gauge length; A_0 = 0.200 in^2

Yield load	9 040 lb	Yield strength	45.2 kpsi
Maximum load	14 950 lb	Tensile strength	74.75 kpsi
Fracture load	11 500 lb	Fracture strength	57.5 kpsi
Final length	2.480 in	Elongation	24%
Final diameter	0.352 in	Reduction of area	51.15%

Load, lb	Gauge length, in	Load, lb	Gauge length, in
1 000	2.0006	6 000	2.0044
2 000	2.0012	7 000	2.0057
3 000	2.0018	8 000	2.0070
4 000	2.0024	9 000	2.0094
5 000	2.0035	10 000	2.0140

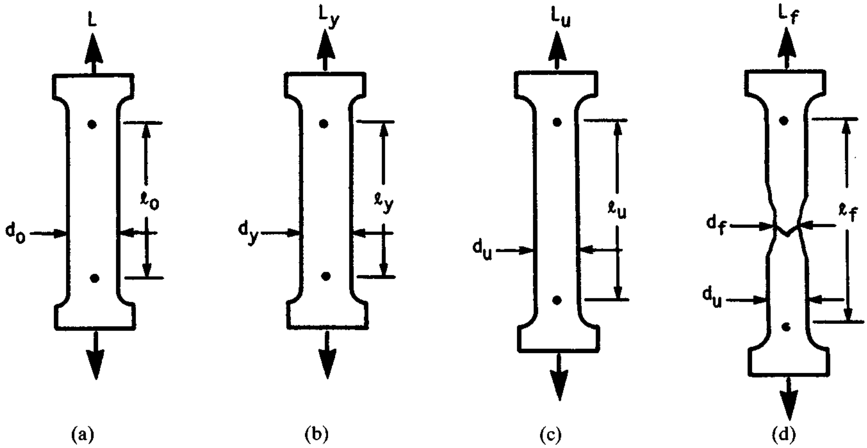

FIGURE 7.14 A standard tensile specimen of A40 titanium at various stages of loading. (*a*) Unloaded, $L = 0$ lb, $d_0 = 0.505$ in, $\ell_0 = 2.000$ in, $A_0 = 0.200$ in^2; (*b*) yield load $L_y = 9040$ lb, $d_y = 0.504$ in, $\ell_y = 2.009$ in, $A_y = 0.1995$ in^2; (*c*) maximum load $L_u = 14\,950$ lb, $d_u = 0.470$ in, $\ell_u = 2.310$ in, $A_u = 0.173$ in^2; (*d*) fracture load $L_f = 11\,500$ lb, $d_f = 0.352$ in, $\ell_f = 2.480$ in, $A_f = 0.097$ in^2, $d_u = 0.470$ in.

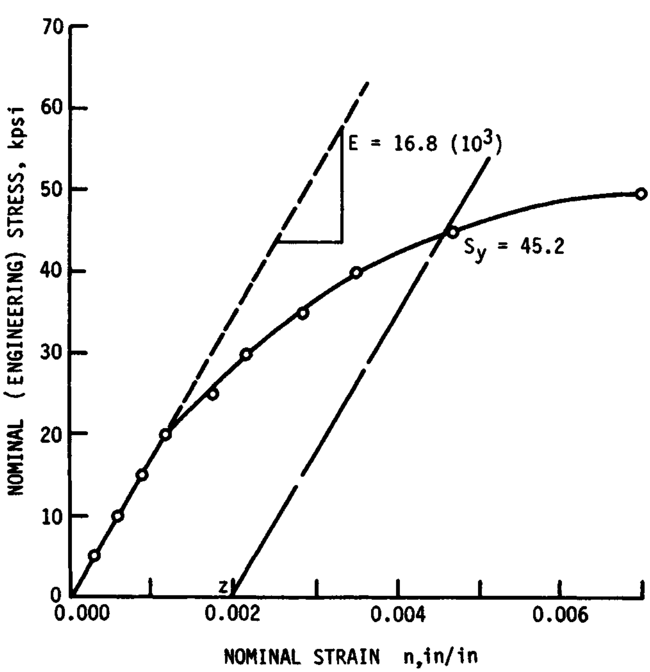

FIGURE 7.15 The elastic-plastic portion of the engineering stress-strain curve for annealed A40 titanium.

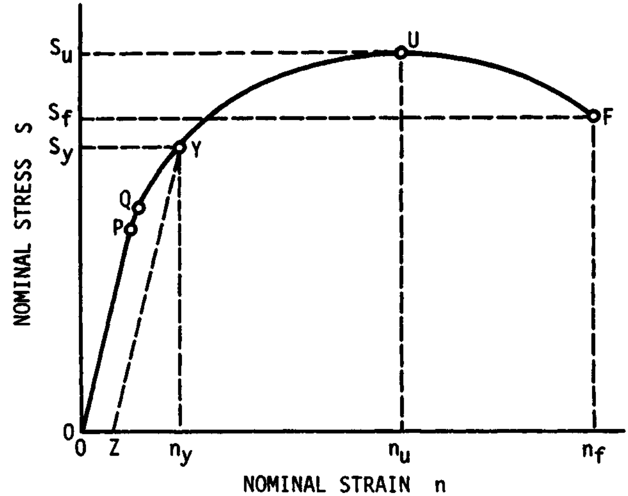

FIGURE 7.16 The engineering stress-strain curve. P = proportional limit, Q = elastic limit, Y = yield load, U = ultimate (maximum) load, and F = fracture load.

strength and stress would be easier to make. Although the fracture load is lower than the ultimate load, the stress in the material just prior to fracture is much greater than the stress at the time the ultimate load is on the specimen.

7.9.2 True Stress-Strain

The tensile test is also used to obtain true stress-strain or true stress–natural strain data to define the plastic stress-strain characteristics of a material. In this case it is necessary to record simultaneously the cross-sectional area of the specimen and the load on it. For round sections it is sufficient to measure the diameter for each load recorded. The load-deformation data in the plastic region of the tensile test of an annealed titanium are listed in Table 7.4. These data are a continuation of the tensile test in which the elastic data are given in Table 7.3.

The load-diameter data in Table 7.4 are recorded during the test and the remainder of the table is completed afterwards. The values of stress are calculated by means of Eq. (7.9). The strain in this case is the *natural strain* or *logarithmic strain,* which is the sum of all the infinitesimal nominal strains, that is,

$$\varepsilon = \frac{\Delta\ell_1}{\ell_0} + \frac{\Delta\ell_2}{\ell_0 + \Delta\ell_1} + \frac{\Delta\ell_3}{\ell_0 + \Delta\ell_1 + \Delta\ell_2} + \cdots$$

$$= \ln \frac{\ell_f}{\ell_0} \tag{7.11}$$

The volume of material remains constant during plastic deformation. That is,

$$V_0 = V_f \qquad \text{or} \qquad A_0\ell_0 = A_f\ell_f$$

TABLE 7.4 Tensile Test Data†

Load, lb	Diameter, in	Area, in^2	Area ratio	Stress, kpsi	Strain, in/in
12 000	0.501	0.197	1.015	60.9	0.0149
14 000	0.493	0.191	1.048	73.5	0.0473
14 500	0.486	0.186	1.075	78.0	0.0724
14 950	0.470	0.173	1.155	86.5	0.144
14 500	0.442	0.153	1.308	94.8	0.268
14 000	0.425	0.142	1.410	99.4	0.344
11 500	0.352	0.097	2.06	119.0	0.729

†This table is a continuation of Table 7-3.

Thus, for tensile deformation, Eq. (7.11) can be expressed as

$$\varepsilon = \ln \frac{A_0}{A_f} \tag{7.12}$$

Quite frequently, in calculating the strength or the ductility of a cold-worked material, it is necessary to determine the value of the strain ε that is equivalent to the amount of the cold work. The *amount of cold work* is defined as the percent reduction of cross-sectional area (or simply the percent reduction of area) that is given the material by a plastic-deformation process. It is designated by the symbol W and is determined from the expression

$$W = \frac{A_0 - A_f}{A_0}(100) \tag{7.13}$$

where the subscripts 0 and f refer to the original and the final area, respectively. By solving for the A_0/A_f ratio and substituting into Eq. (7.12), the appropriate relationship between strain and cold work is found to be

$$\varepsilon_W = \ln \frac{100}{100 - W} \tag{7.14}$$

The stress-strain data of Table 7.4 are plotted in Fig. 7.17 on cartesian coordinates. The most significant difference between the shape of this stress-strain curve and that of the load-deformation curve in Fig. 7.16 is the fact that the stress continues to rise until fracture occurs and does not reach a maximum value as the load-deformation curve does. As can be seen in Table 7.4 and Fig. 7.17, the stress at the time of the maximum load is 86 kpsi, and it increases to 119 kpsi at the instant that fracture occurs. A smooth curve can be drawn through the experimental data, but it is not a straight line, and consequently many experimental points are necessary to accurately determine the shape and position of the curve.

The stress-strain data obtained from the tensile test of the annealed A40 titanium listed in Tables 7.3 and 7.4 are plotted on logarithmic coordinates in Fig. 7.18. The elastic portion of the stress-strain curve is also a straight line on logarithmic coordinates as it is on cartesian coordinates. When plotted on cartesian coordinates, the slope of the elastic modulus is different for the different materials. However, when

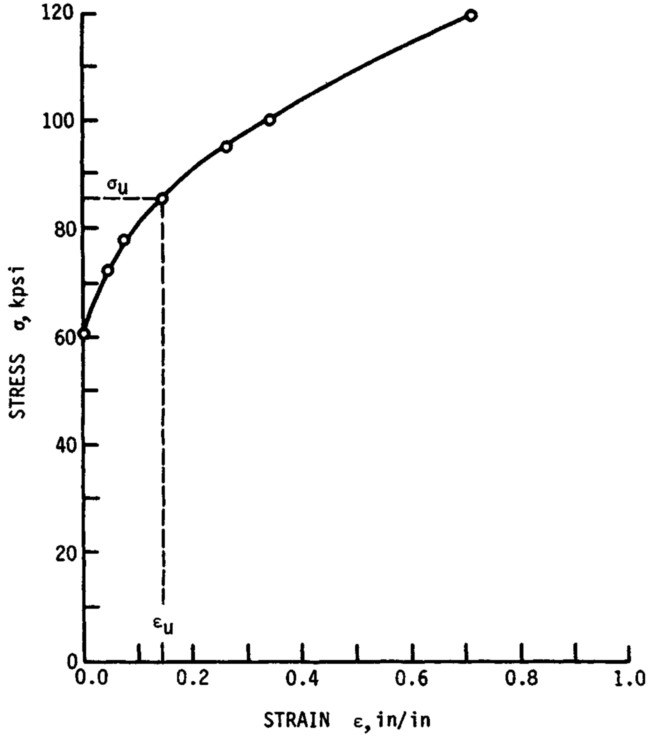

FIGURE 7.17 Stress-strain curve for annealed A40 titanium. The strain is the natural or logarithmic strain and the data of Tables 7.3 and 7.4 are plotted on cartesian coordinates.

plotted on logarithmic coordinates, the slope of the elastic modulus is 1 (unity) for all materials—it is only the height, or position, of the line that is different for different materials. In other words, the elastic moduli for all the materials are parallel lines making an angle of 45° with the ordinate axis.

The experimental points in Fig. 7.18 for strains greater than 0.01 (1 percent plastic deformation) also fall on a straight line having a slope of 0.14. The slope of the stress-strain curve in logarithmic coordinates is called the *strain-strengthening exponent* because it indicates the increase in strength that results from plastic strain. It is sometimes referred to as the *strain-hardening exponent,* which is somewhat misleading because the real strain-hardening exponent is the Meyer exponent p, discussed previously under the subject of strain hardening. The strain-strengthening exponent is represented by the symbol m.

The equation for the plastic stress-strain line is

$$\sigma = \sigma_0 \varepsilon^m \tag{7.15}$$

and is known as the *strain-strengthening equation* because it is directly related to the yield strength. The proportionality constant σ_0 is called the *strength coefficient.* The strength coefficient σ_0 is related to the plastic behavior of a material in exactly

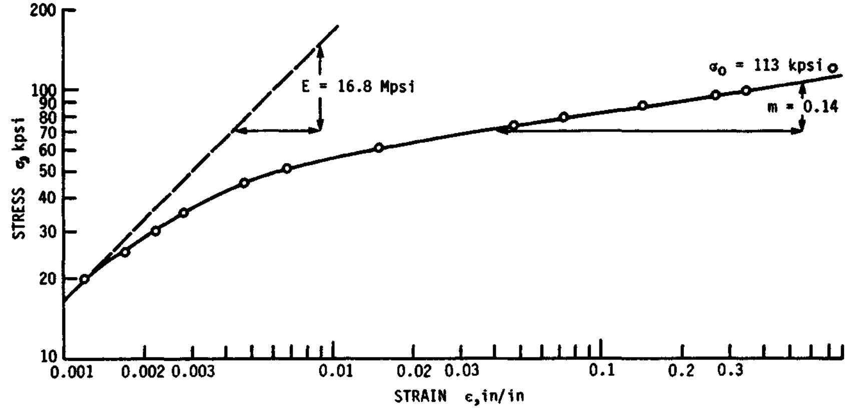

FIGURE 7.18 Stress-strain curve for annealed A40 titanium plotted on logarithmic coordinates. The data are the same as in Fig. 7.17.

the same manner in which Young's modulus E is related to elastic behavior. Young's modulus E is the value of stress associated with an elastic strain of unity; the strength coefficient σ_0 is the value of stress associated with a plastic strain of unity. The amount of cold work necessary to give a strain of unity is determined from Eq. (7.14) to be 63.3 percent.

For most materials there is an elastic-plastic region between the two straight lines of the fully elastic and fully plastic portions of the stress-strain curve. A material that has no elastic-plastic region may be considered an "ideal" material because the study and analysis of its tensile properties are simpler. Such a material has a complete stress-strain relationship that can be characterized by two intersecting straight lines, one for the elastic region and one for the plastic region. Such a material would have a stress-strain curve similar to the one labeled *I* in Fig. 7.19. A few real materials have a stress-strain curve that approximates the "ideal" curve. However, most engineering materials have a stress-strain curve that resembles curve *O* in Fig. 7.19. These materials appear to "overyield"; that is, they have a higher yield strength than the "ideal" value, followed by a region of low or no strain strengthening before the fully plastic region begins. Among the materials that have this type of curve are steel, stainless steel, copper, brass alloys, nickel alloys, and cobalt alloys.

Only a few materials have a stress-strain curve similar to that labeled *U* in Fig. 7.19. The characteristic feature of this type of material is that it appears to "underyield"; that is, it has a yield strength that is lower than the "ideal" value. Some of the fully annealed aluminum alloys have this type of curve.

7.10 TENSILE PROPERTIES

Tensile properties are those mechanical properties obtained from the tension test; they are used as the basis of mechanical design of structural components more frequently than any other of the mechanical properties. More tensile data are available for materials than any other type of material property data. Frequently the design engineer must base his or her calculations on the tensile properties even under

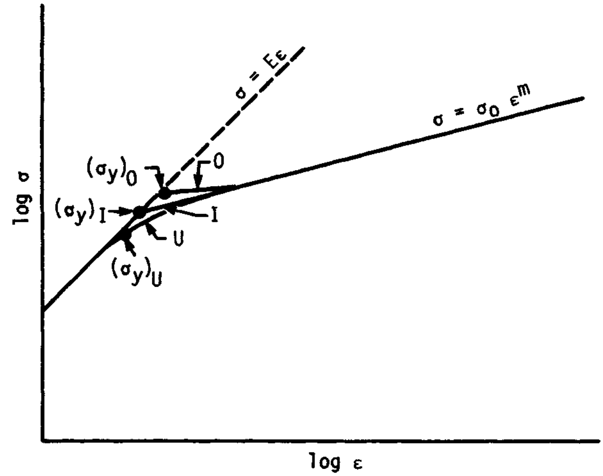

FIGURE 7.19 Schematic representation of three types of stress-strain curves. *I* is an "ideal" curve, and *O* and *U* are two types of real curve.

cyclic, shear, or impact loading simply because the more appropriate mechanical property data are not available for the material he or she may be considering for a specific part. All the tensile properties are defined in this section and are briefly discussed on the basis of the tensile test described in the preceding section.

7.10.1 Modulus of Elasticity

The *modulus of elasticity,* or *Young's modulus,* is the ratio of stress to the corresponding strain during elastic deformation. It is the slope of the straight-line (elastic) portion of the stress-strain curve when drawn on cartesian coordinates. It is also known, as indicated previously, as Young's modulus, or the proportionality constant in Hooke's law, and is commonly designated as E with units of pounds per square inch (pascals) or the equivalent. The modulus of elasticity of the titanium alloy whose tensile data are reported in Table 7.3 is shown in Fig. 7.15, where the first four experimental data points fall on a straight line having a slope of 16.8 Mpsi.

7.10.2 Proportional Limit

The *proportional limit* is the greatest stress which a material is capable of developing without any deviation from a linear proportionality of stress to strain. It is the point where a straight line drawn through the experimental data points in the elastic region first departs from the actual stress-strain curve. Point P in Fig. 7.16 is the proportional limit (20 kpsi) for this titanium alloy. The proportional limit is very seldom used in engineering specifications because it depends so much on the sensitivity and accuracy of the testing equipment and the person plotting the data.

7.10.3 Elastic Limit

The *elastic limit* is the greatest stress which a material is capable of withstanding without any permanent deformation after removal of the load. It is designated as point Q in Fig. 7.16. The elastic limit is also very seldom used in engineering specifications because of the complex testing procedure of many successive loadings and unloadings that is necessary for its determination.

7.10.4 Yield Strength

The *yield strength* is the nominal stress at which a material undergoes a specified permanent deformation. There are several methods to determine the yield strength, but the most reliable and consistent method is called the *offset method.* This approach requires that the nominal stress-strain diagram be first drawn on cartesian coordinates. A point z is placed along the strain axis at a specified distance from the origin, as shown in Figs. 7.15 and 7.16. A line parallel to the elastic modulus is drawn from Z until it intersects the nominal stress-strain curve. The value of stress corresponding to this intersection is called the *yield strength* by the offset method. The distance $0Z$ is called the *offset* and is expressed as percent. The most common offset is 0.2 percent, which corresponds to a nominal strain of 0.002 in/in. This is the value of offset used in Fig. 7.15 to determine the yield strength of the A40 titanium. An offset of 0.01 percent is sometimes used, and the corresponding nominal stress is called the *proof strength,* which is a value very close to the proportional limit. For some nonferrous materials an offset of 0.5 percent is used to determine the yield strength.

Inasmuch as all methods of determining the yield strength give somewhat different values for the same material, it is important to specify what method, or what offset, was used in conducting the test.

7.10.5 Tensile Strength

The *tensile strength* is the value of nominal stress obtained when the maximum (or ultimate) load that the tensile specimen supports is divided by the original cross-sectional area of the specimen. It is shown as S_u in Fig. 7.16 and is sometimes called the *ultimate strength.* The tensile strength is a commonly used property in engineering calculations even though the yield strength is a measure of when plastic deformation begins for a given material. The real significance of the tensile strength as a material property is that it indicates what maximum load a given part can carry in uniaxial tension without breaking. It determines the absolute maximum limit of load that a part can support.

7.10.6 Fracture Strength

The *fracture strength,* or *breaking strength,* is the value of nominal stress obtained when the load carried by a tensile specimen at the time of fracture is divided by its original cross-sectional area. The breaking strength is not used as a material property in mechanical design.

7.10.7 Reduction of Area

The *reduction of area* is the maximum change in area of a tensile specimen divided by the original area and is usually expressed as a percent. It is designated as A_r and is calculated as follows:

$$A_r = \frac{A_0 - A_f}{A_0}(100) \tag{7.16}$$

where the subscripts 0 and f refer to the original area and area after fracture, respectively. The percent reduction of area and the strain at ultimate load ε_u are the best measure of the ductility of a material.

7.10.8 Fracture Strain

The *fracture strain* is the true strain at fracture of the tensile specimen. It is represented by the symbol ε_f and is calculated from the definition of strain as given in Eq. (7.12). If the percent reduction of area A_r is known for a material, the fracture strain can be calculated from the expression

$$\varepsilon_f = \ln \frac{100}{100 - A_r} \tag{7.17}$$

7.10.9 Percentage Elongation

The *percentage elongation* is a crude measure of the ductility of a material and is obtained when the change in gauge length of a fractured tensile specimen is divided by the original gauge length and expressed as percent. Because of the ductility relationship, we express it here as

$$D_e = \frac{\ell_f - \ell_0}{\ell_0}(100) \tag{7.18}$$

Since most materials exhibit nonuniform deformation before fracture occurs on a tensile test, the percentage elongation is some kind of an average value and as such cannot be used in meaningful engineering calculations.

The percentage elongation is not really a material propety, but rather it is a combination of a material property and a test condition. A true material property is not significantly affected by the size of the specimen. Thus a ¼-in-diameter and a ½-in-diameter tensile specimen of the same material give the same values for yield strength, tensile strength, reduction of area or fracture strain, modulus of elasticity, strain-strengthening exponent, and strength coefficient, but a 1-in gauge-length specimen and a 2-in gauge-length specimen of the same material do not give the same percentage elongation. In fact, the percentage elongation for a 1-in gauge-length specimen may actually be 100 percent greater than that for the 2-in gauge-length specimen even when they are of the same diameter.

7.11 STRENGTH, STRESS, AND STRAIN RELATIONS

The following relationships between strength, stress, and strain are very helpful to a complete understanding of tensile properties and also to an understanding of their use in specifying the optimum material for a structural part. These relationships also help in solving manufacturing problems where difficulty is encountered in the fabrication of a given part because they enable one to have a better concept of what can be expected of a material during a manufacturing process. A further advantage of these relations is that they enable an engineer to more readily determine the mechanical properties of a fabricated part on the basis of the original properties of the material and the mechanisms involved with the particular process used.

7.11.1 Natural and Nominal Strain

The relationship between these two strains is determined from their definitions. The expression for the natural strain is $\varepsilon = \ln (\ell_f/\ell_0)$. The expression for the nominal strain can be rewritten as $\ell_f/\ell_0 = n + 1$. When the latter is substituted into the former, the relationship between the two strains can be expressed in the two forms

$$\varepsilon = \ln (n+1) \qquad \exp (\varepsilon) = n+1 \tag{7.19}$$

7.11.2 True and Nominal Stress

The definition of true stress is $\sigma = L/A_i$. From constancy of volume it is found that $A_i = A_0(\ell_0/\ell_i)$, so that

$$\sigma = \frac{L}{A_0}\left(\frac{\ell_i}{\ell_0}\right)$$

which is the same as

$$\sigma = \begin{cases} S(n+1) \\ S \exp (\varepsilon) \end{cases} \tag{7.20}$$

7.11.3 Strain-Strengthening Exponent and Maximum-Load Strain

One of the more useful of the strength-stress-strain relationships is the one between the strain-strengthening exponent and the strain at maximum load. It is also the simplest, since the two are numerically equal, that is, $m = \varepsilon_u$. This relation is derived on the basis of the load-deformation curve shown in Fig. 7.20. The load at any point along this curve is equal to the product of the true stress on the specimen and the corresponding area. Thus

$$L = \sigma A$$

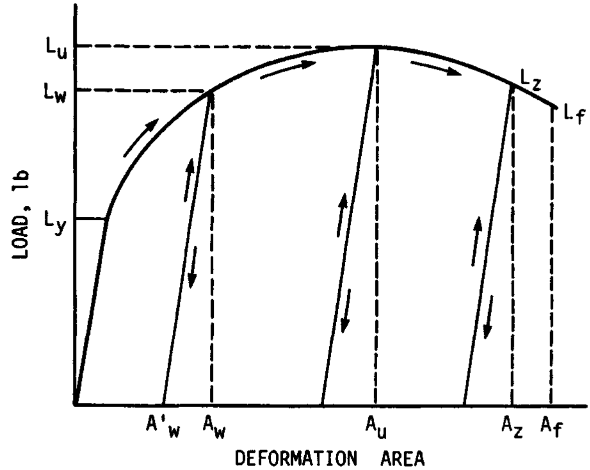

FIGURE 7.20 A typical load-deformation curve showing unloading and reloading cycles.

Now, since

$$\sigma = \sigma_0 \varepsilon^m$$

and

$$\varepsilon = \ln \frac{A_0}{A} \qquad \text{or} \qquad A = \frac{A_0}{\exp(\varepsilon)}$$

the load-strain relationship can be written as

$$L = \sigma_0 A_0 \varepsilon^m \exp(-\varepsilon)$$

The load-deformation curve shown in Fig. 7.20 has a maximum, or zero-slope, point on it. Differentiating the last equation and equating the result to zero gives the simple expression $\varepsilon = m$. Since this is the strain at the ultimate load, the expression can be written as

$$\varepsilon_u = m \tag{7.21}$$

7.11.4 Yield Strength and Percent Cold Work

The stress-strain characteristics of a material obtained from a tensile test are shown in Fig. 7.18. In the region of plastic deformation, the relationship between stress and strain for most materials can be approximated by the equation $\sigma = \sigma_0 \varepsilon^m$. When a load is applied to a tensile specimen that causes a given amount of cold work W (which is a plastic strain of ε_W), the stress on the specimen at the time is σ_W and is defined as

$$\sigma_W = \sigma_0(\varepsilon_W)^m \tag{7.22}$$

Of course, σ_W is also equal to the applied load L_W divided by the actual cross-sectional area of the specimen A_W.

If the preceding tensile specimen were immediately unloaded after reading L_W, the cross-sectional area would increase to A'_W from A_W because of the elastic recovery or springback that occurs when the load is removed. This elastic recovery is insignificant for engineering calculations with regard to the strength or stresses on a part.

If the tensile specimen that has been stretched to a cross-sectional area of A'_W is now reloaded, it will deform elastically until the load L_W is approached. As the load is increased above L_W, the specimen will again deform plastically. This unloading-reloading cycle is shown graphically in Fig. 7.20. The yield load for this previously cold-worked specimen before the reloading is A'_W. Therefore, the yield strength of the previously cold-worked (stretched) specimen is approximately

$$(S_y)_W = \frac{L_W}{A'_W}$$

But since $A'_W = A_W$, then

$$(S_y)_W = \frac{L_W}{A_W}$$

By comparing the preceding equations, it is apparent that

$$(S_y)_W \cong \sigma_W$$

And by substituting this last relationship into Eq. (7.22), we get

$$(S_y)_W = \sigma_0(\varepsilon_W)^m \tag{7.23}$$

Thus it is apparent that *the plastic portion of the $\sigma - \varepsilon$ curve is approximately the locus of yield strengths for a material as a function of the amount of cold work.* This relationship is valid only for the axial tensile yield strength after tensile deformation or for the axial compressive yield strength after axial deformation.

7.11.5 Tensile Strength and Cold Work

It is believed by materials and mechanical-design engineers that the only relationships between the tensile strength of a cold-worked material and the amount of cold work given it are the experimentally determined tables and graphs that are provided by the material manufacturers and that the results are different for each family of materials. However, on the basis of the concepts of the tensile test presented here, two relations are derived in Ref. [7.1] between tensile strength and percent cold work that are valid when the prior cold work is tensile. These relations are derived on the basis of the load-deformation characteristics of a material as represented in Fig. 7.20. This model is valid for all metals that do not strain age.

Here we designate the tensile strength of a cold-worked material as $(S_u)_W$, and we are interested in obtaining the relationship to the percent cold work W. For any specimen that is given a tensile deformation such that A_W is equal to or less than A_u, we have, by definition, that

$$(S_u)_W = \frac{L_u}{A'_W}$$

And also, by definition,

$$L_u = A_0(S_u)_0$$

where $(S_u)_0$ = tensile strength of the original non-cold-worked specimen and A_0 = its original area.

The percent cold work associated with the deformation of the specimen from A_0 to A'_W is

$$W = \frac{A_0 - A'_W}{A_0}(100) \qquad \text{or} \qquad w = \frac{A_0 - A'_W}{A_0}$$

where $w = W/100$. Thus

$$A'_W = A_0(1 - w)$$

By substitution into the first equation,

$$(S_u)_W = \frac{A_0(S_u)_0}{A_0(1 - w)} = \frac{(S_u)_0}{1 - w} \tag{7.24}$$

Of course, this expression can also be expressed in the form

$$(S_u)_W = (S_u)_0 \exp(\varepsilon) \tag{7.25}$$

Thus *the tensile strength of a material that is prestrained in tension to a strain less than its ultimate load strain is equal to its original tensile strength divided by one minus the fraction of cold work.* This relationship is valid for deformations less than the deformation associated with the ultimate load. That is, for

$$A_W \le A_u \qquad \text{or} \qquad \varepsilon_W \le \varepsilon_u$$

Another relationship can be derived for the tensile strength of a material that has been previously cold-worked in tension by an amount greater than the deformation associated with the ultimate load. This analysis is again made on the basis of Fig. 7.20. Consider another standard tensile specimen of 1020 steel that is loaded beyond L_u (12 000 lb) to some load L_z, say, 10 000 lb. If dead weights were placed on the end of the specimen, it would break catastrophically when the 12 000-lb load was applied. But if the load had been applied by means of a mechanical screw or a hydraulic pump, then the load would drop off slowly as the specimen is stretched. For this particular example the load is considered to be removed instantly when it drops to L_z or 10 000 lb. The unloaded specimen is not broken, although it may have a "necked" region, and it has a minimum cross-sectional area A_z = 0.100 in^2 and a diameter of 0.358 in. Now when this same specimen is again loaded in tension, it deforms elastically until the load reaches L_z (10 000 lb) and then it deforms plastically. But L_z is also the maximum value of load that this specimen reaches on reloading. It never again will support a load of L_u = 12 000 lb. On this basis, the yield strength of this specimen is

$$(S_y)_W = \frac{L_z}{A_z'} = \frac{10\,000}{0.101} = 99\,200 \text{ psi}$$

And the tensile strength of this previously deformed specimen is

$$(S_u)_W = \frac{L_z}{A_z} = \frac{10\,000}{0.101} = 99\,200 \text{ psi}$$

7.11.6 Ratio of Tensile Strength to Brinell Hardness

It is commonly known by mechanical-design engineers that the tensile strength of a steel can be estimated by multiplying its Brinell hardness number by 500. As stated earlier, this fact led to the wide acceptance of the Brinell hardness scale. However, this ratio is not 500 for all materials—it varies from as low as 450 to as high as 1000 for the commonly used metals. The ratio of the tensile strength of a material to its Brinell hardness number is identified by the symbol K_B, and it is a function of both the load used to determine the hardness and the strain-strengthening exponent of the material.

Since the Brinell hardness number of a given material is not a constant but varies in proportion to the applied load, it then follows that the proportionality coefficient K_B is not a constant for a given material, but it too varies in proportion to the load used in determining the hardness. For example, a 50 percent cobalt alloy (L605 or HS25) has a Brinell hardness number of 201 when tested with a 3000-kg load and a hardness of only 150 when tested with a 500-kg load. Since the tensile strength is about 145 000 psi for this annealed alloy, the value for K_B is about 970 for the low load and about 730 for the high load.

Since the material is subjected to considerable plastic deformation when both the tensile strength and the Brinell hardness are measured, these two values are influenced by the strain-strengthening exponent m for the material. Therefore, K_B must also be a function of m.

Figure 7.21 is a plot of experimental data obtained by this author over a number of years that shows the relationships between the ratio K_B and the two variables strain-strengthening exponent m and diameter of the indentation, which is a function of the applied load. From these curves it is apparent that K_B varies directly with m and inversely with the load or diameter of the indentation d. The following examples will illustrate the applicability of these curves.

A test was conducted on a heat of alpha brass to see how accurately the tensile strength of a material could be predicted from a hardness test when the strain-strengthening exponent of the material is not known. Loads varying from 200 to 2000 kg were applied to a 10-mm ball, with the following results:

Load, kg	200	500	1000	1500	2000
Diameter, mm	2.53	3.65	4.82	5.68	6.30

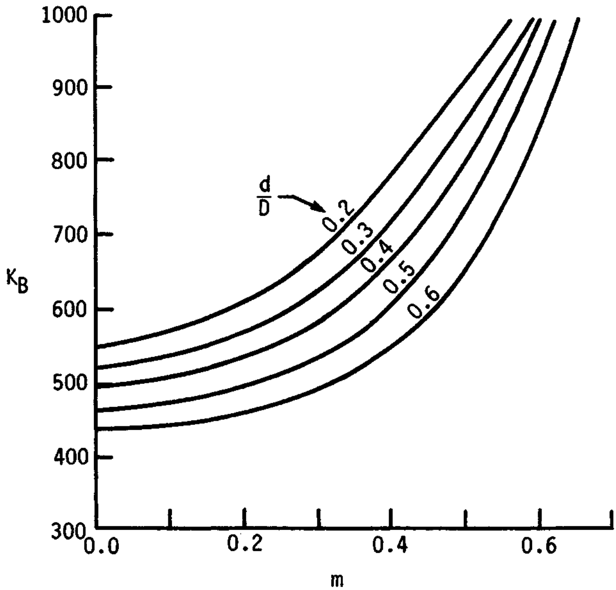

FIGURE 7.21 Relationships between the S_u/H_B ratio (K_B) and the strain-strengthening exponent m. D = diameter of the ball, and d = diameter of the indentation. Data are based on experimental results obtained by the author.

When plotted on log-log paper, these data fall on a straight line having a slope of 2.53, which is the Meyer strain-hardening exponent n. The equation for this straight line is

$$L = 18.8d^{2.53}$$

Since, for some metals, $m = n - 2$, the value of m is 0.53.

For ease in interpreting Fig. 7.21, the load corresponding to an indentation of 3 mm is calculated from Eq. (7.2) as 43. K_B can now be determined from Fig. 7.21 as 890. Thus the tensile strength is $S_u = K_B H_B = 890(43) = 38\ 300$ psi. In a similar fashion, the load for a 5-mm diameter is 110 kg, and the corresponding Brinell hardness number is 53. From Fig. 7.21, the value of K_B is found to be 780, and the tensile strength is estimated as $S_u = K_B H_B = 780(53) = 41\ 300$ psi. The average value of these two calculated tensile strengths is 39 800 psi. The experimentally determined value of the tensile strength for this brass was 40 500 psi, which is just 2 percent lower than the predicted value.

As another example, consider the estimation of tensile strength for a material when its typical strain-strengthening exponent is known. Annealed 3003 aluminum has an average m value of 0.28. What is the tensile strength of a heat that has a Brinell hardness number of 28 when measured with a 500-kg load? The diameter of the indentation for this hardness number is 4.65. Then from Fig. 7.21 the value of K_B is determined as 535. The tensile strength can then be calculated as $S_u = K_B H_B = 535(28) = 15\ 000$ psi.

7.12 IMPACT STRENGTH

In some cases a structural part is subject to a single, large, suddenly applied load. A standard test has been devised to evaluate the ability of a material to absorb the impact energy through plastic deformation. The test can be described as a technological one, like the Rockwell hardness test, rather than as a scientific one. The values obtained by the impact test are relative rather than absolute. They serve as a basis of comparison and specification of the toughness of a material.

The *impact strength* is the energy, expressed in footpounds, required to fracture a standard specimen with a single-impact blow. The impact strength of a material is frequently referred to as being a measure of the toughness of the material, that is, its ability to absorb energy. The area under the tensile stress–strain curve is also a measure of the ability of a material to absorb energy (its toughness). Unfortunately, there is only a very general relationship between these two different measures of toughness; namely, if the material has a large area under its tensile stress–strain curve, it also has a relatively high impact strength.

Most impact-strength data are obtained with the two types of notched specimens shown in Fig. 7.22. Figure 7.22*a* illustrates the Charpy V-notch specimen as well as how the impact load is applied. Figure 7.22*b* does the same for the Izod V-notch specimen, and the details of the notch are shown in Fig. 7.22*c*. There are several modifications of the standard V-notch specimen. One is called the *keyhole notch* and another the *U-notch*. Both have a 1-mm radius at the bottom rather than the 0.25-mm radius of the V-notch. There is no correlation between the various types of notch-bar impact-strength values. However, the Charpy V-notch impact-strength value is considerably greater than the Izod V-notch value, particularly in the high toughness range.

The impact-testing machine consists of a special base mounted on the floor to support the specimen and a striking hammer that swings through an arc of about 32-in radius, much like a pendulum. When the hammer is "cocked" (raised to a locked elevation), it has a potential energy that varies between 25 and 250 ft · lb, depending on the mass of the hammer and the height to which it is raised. When the hammer is released and allowed to strike the specimen, a dial registers the energy that was absorbed by the specimen. The standards specify that the striking velocity must be in the range of 10 to 20 ft/s because velocities outside this range have an effect on the impact strength.

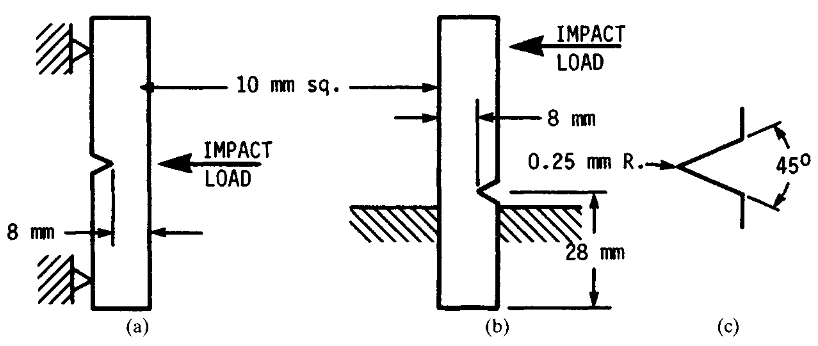

FIGURE 7.22 Impact tests and specimens. (*a*) Charpy $L = 55$ mm; (*b*) Izod $L = 75$ mm; (*c*) details of the notch.

The impact strengths of some materials, particularly steel, vary significantly with the testing temperature. Figure 7.23 shows this variation for a normalized AISI 1030 steel. At the low testing temperature the fracture is of the cleavage type, which has a bright, faceted appearance. At the higher temperatures the fractures are of the shear type, which has a fibrous appearance. The *transition temperature* is that temperature that results in 50 percent cleavage fracture and 50 percent shear fracture, or it may be defined as the temperature at which the impact strength shows a marked drop. The *nil-ductility temperature* is the highest temperature at which the impact strength starts to increase above its minimum value. These two temperatures are shown in Fig. 7.23.

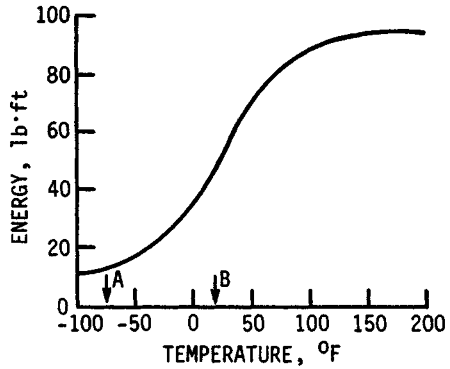

FIGURE 7.23 Charpy V-notch impact strength of 1030 steel versus temperature. A = nil-ductility temperature; B = transition temperature.

7.13 CREEP STRENGTH

A part may fail with a load that induced stresses in it that lie between the yield strength and the tensile strength of the material even if the load is steady and constant rather than alternating and repeating as in a fatigue failure. This type of constant loading causes the part to elongate or creep. The failure point may be when the part stretches to some specified length, or it may be when the part completely fractures.

The *creep strength* of a material is the value of nominal stress that will result in a specified amount of elongation at a specific temperature in a given length of time. It is also defined as the value of nominal stress that induces a specified creep rate at a specific temperature. The creep strength is sometimes called the *creep limit.* The *creep rate* is the slope of the strain-time creep curve in the steady-creep region, referred to as a *stage 2 creep.* It is illustrated in Fig. 7.24.

Most creep failures occur in parts that are exposed to high temperatures rather than room temperature. The stress necessary to cause creep at room temperature is considerably higher than the yield strength of a material. In fact, it is just slightly less than the tensile strength of a material. The stress necessary to induce creep at a temperature that is higher than the recrystallization temperature of a material, however, is very low.

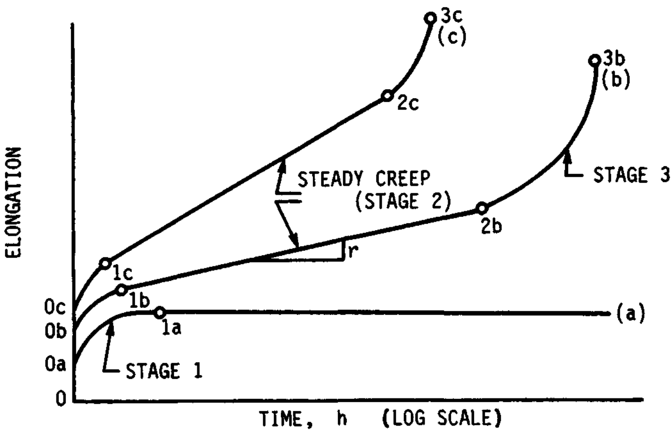

FIGURE 7.24 Creep data plotted on semilog coordinates. (*a*) Low stress (slightly above S_y) or low temperature (well below recrystallization); (*b*) moderate stress (midway between S_y and S_u) or moderate temperature (at recrystallization); (*c*) high stress (slightly below S_u) or high temperature (well above recrystallization). The elastic elongations are designated as 0*a*, 0*b*, and 0*c*.

The specimens used for creep testing are quite similar to round tensile specimens. During the creep test the specimen is loaded with a dead weight that induces the required nominal stress applied throughout the entire test. The specimen is enclosed in a small round tube-type furnace to maintain a constant temperature throughout the test, and the gauge length is measured after various time intervals. Thus the three variables that affect the creep rate of the specimen are (1) nominal stress, (2) temperature, and (3) time.

Figure 7.24 illustrates the most common method of presenting creep-test data. Three different curves are shown. Curve (*a*) is typical of a creep test conducted at a temperature well below the recrystallization temperature of the material (room temperature for steel) and at a fairly high stress level, slightly above the yield strength. Curve (*a*) is also typical of a creep test conducted at a temperature near the recrystallization temperature of a material but at a low stress level. Curve (*c*) is typical of either a high stress level, such as one slightly below S_u, at a low temperature, or else a low stress level at a temperature significantly higher than the recrystallization temperature of the material. Curve (*b*) illustrates the creep rate at some intermediate combination of stress and temperature.

A creep curve consists of four separate parts, as illustrated with curve (*b*) in Fig. 7.24. These are explained as follows:

1. An initial elastic extension from the origin 0 to point 0*b*.
2. A region of primary creep, frequently referred to as *stage 1 creep*. The extension occurs at a decreasing rate in this portion of the creep curve.
3. A region of secondary creep, frequently called *stage 2 creep*. The extension occurs at a constant rate in this region. Most creep design is based on this portion of the creep curve, since the creep rate is constant and the total extension for a given number of hours of service can be easily calculated.
4. A region of tertiary creep or *stage 3 creep*. The extension occurs at an increasing rate in this region until the material fractures.

Another practical way of presenting creep data is illustrated in Fig. 7.25, which is a log-log plot of nominal stress versus the second-stage creep rate expressed as percent per hour with the temperature as a parameter. Figure 7.26 illustrates still another type of plot that is used to present creep data where both the stress and temperature are drawn on cartesian coordinates.

The mechanism of creep is very complex inasmuch as it involves the movements of vacancies and dislocations, strain hardening, and recrystallization, as well as grain-boundary movements. At low temperatures, creep is restricted by the pile-up of dislocations at the grain boundaries and the resulting strain hardening. But at higher temperatures, the dislocations can climb out of the original slip plane and thus permit further creep. In addition, recrystallization, with its resulting lower strength, permits creep to occur readily at high temperatures.

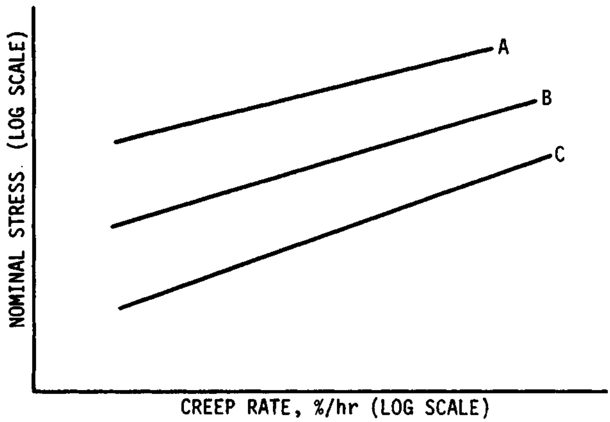

FIGURE 7.25 Second-stage creep rate versus nominal stress. *A*, *B*, and *C* are for low, medium, and high temperatures, respectively.

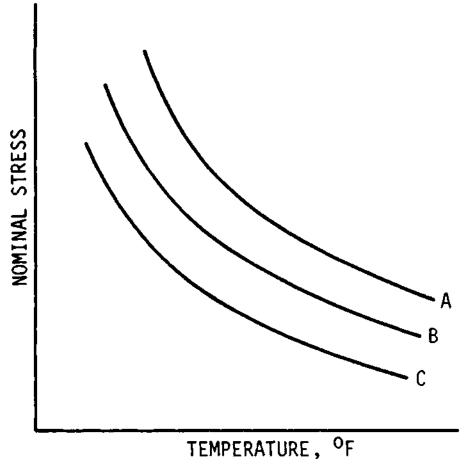

FIGURE 7.26 Second-stage creep rate versus temperature and nominal stress. *A*, 1%/h creep rate; *B*, 0.1%/h creep rate; *C*, 0.001%/h creep rate.

As explained in an earlier section, the grain-boundary material is stronger than the material at the interior portions at low temperatures, but the opposite is true at high temperatures. The temperature where these two portions of the grains are equal is called the *equicohesive temperature*. Consequently, parts that are exposed to high temperatures have lower creep rates if they are originally heat-treated to form coarse grains.

7.14 MECHANICAL-PROPERTY DATA

The number of different combinations of thermal and mechanical treatments for each family of materials plus the large number of individual material compositions within one family makes it impossible to compile a complete listing in one handbook. For more information on the typical values of the mechanical properties of a specific material, you should consult the engineering manuals published by the various material manufacturers as well as the references at the end of this chapter. The total number of pages of mechanical-property data listed in all the sources cited at the end of this chapter runs into the thousands, making it impossible to include it all in one handbook. The mechanical properties are simply listed as the experimentally obtained values for each of the many conditions of a given metal.

This section includes some select mechanical-property data in tabular form for a variety of materials in Table 7.5. Both the format of the data and the actual mechanical properties listed are different from the traditional handbook presentations. There are several advantages to presenting the data in this manner. One of the main advantages is that it requires much less space. For example, as shown in Table 7.5, only five numbers have to be recorded for each metal in its original non-cold-worked condition. These numbers refer to the five primary mechanical properties. From these original values it is very easy to calculate the new strengths of the metal after any specific amount of cold work or to construct tables or graphs of strength versus percent cold work. This is in sharp contrast to the large amount of space required to store the tables or graphs in any handbook or manual of properties.

A second advantage of presenting the data in this manner is that it is possible to make use of the rules and relationships included in Chap. 8 to calculate both the compressive and tensile properties in all directions in a cold-worked part. This is extremely important because for some materials (those having a high strain-strengthening exponent m) it is possible to have a compressive yield strength for a given amount of cold work that is one-half the tensile yield strength that may be tabulated in a materials handbook.

Table 7.6 includes some of the properties of very-high-strength steels. To illustrate the versatility of documenting mechanical properties in the format of Table 7.5, consider the annealed 303 stainless steel listed in the table. In the annealed condition it has the following listed properties: $S_y = 35$ kpsi, $S_u = 87.3$ kpsi, strength coefficient $\sigma_0 = 205$ kpsi, strain-strengthening exponent $m = 0.51$, and fracture strain $\varepsilon_f = 1.16$. In an upsetting operation, a 2-in-diameter bar is upset to a diameter of 2½ in for a length of 1½ in prior to having splines machined on the end. Since the splines are cantilevered beams subject to bending stresses in the circumferential or transverse direction, the strength of the material in this direction rather than in the axial or longitudinal direction is required. Also, the stresses are compressive on one side of the splines and tensile on the other. Therefore, the designer should know both the tensile and compressive strengths in the transverse direction. The following sample calculations will demonstrate how this can be done.

TABLE 7.5 Tensile Properties of Some Metals[a]

Material	Condition	Strength: Yield S_y, kpsi	Strength: Ultimate S_u, kpsi	Strength: Coefficient σ_0, kpsi	Strain-strengthening exponent m	Fracture strain ε_f
Carbon and alloy steels						
1002	1500°F @ 1 h, A 0.032 in	22.0	39.5	76.0	0.29	1.25
1002[a]	1800°F @ 1 h, A	19.0	42.0	78.0	0.27	1.25
1008 DQ	As rec'd 0.024 in	25.0	39.0	70.0	0.24	1.20
1008 DQ	As above—trans	27.0	43.0	70.0	0.24	1.10
1008 DQ	1600°F @ 1 h A	26.5	40.0			
1010	0.024-in CD strip	33.2	47.5	84.0	0.23	1.20
1010	As above—trans	36.8	48.5	88.0	0.26	1.00
1010	1600°F @ 1 h A	28.6	44.2	82.0	0.23	1.20
1010	As above—trans	29.1	43.8	82.0	0.23	1.20
1018	A	32.0	49.5	90.0	0.25	1.05
1020	HR	42.0	66.2	115.0	0.22	0.90
1045	HR	60.0	92.5	140.0	0.14	0.58
1144	A	52.0	93.7	144.0	0.14	0.49
1144[b]	A	50.0	93.7	144.0	0.14	0.05
1212	HR	28.0	61.5	110.0	0.24	0.85
4340	HR	132.0	151.0	210.0	0.09	0.45
52100	Spher. A	80.0	101.0	165.0	0.18	0.58
52100	1500°F A	131.0	167.0	210.0	0.07	0.40
Stainless steels						
18-8	1600°F @ 1 h A	37.0	89.5	210.0	0.51	1.08
18-8	1800°F @ 1 h A	37.5	96.5	230.0	0.53	1.38
302	1800°F @ 1 h A	34.0	92.4	210.0	0.48	1.20
303	A	35.0	87.3	205.0	0.51	1.16
304	A	40.0	82.4	185.0	0.45	1.67
202	1900°F @ 1 h A	55.0	105.0	195.0	0.30	1.00
17-4 PH	1100°F aged	240.0	246.0	260.0	0.01	0.65
17-4 PH	A	135.0	142.0	173.0	0.05	1.20
17-7 PH	1050°F aged	155.0	185.0	225.0	0.05	0.90
17-7 PH	900°F aged	245.0	255.0	300.0	0.04	0.50
440 C	Solution H T	63.5	107.0	153.0	0.11	0.36
440 C	A 1600°F–50°F/h	67.6	117.0	180.0	0.14	0.12
Aluminum alloys						
1100	900°F @ 1 h A	4.5	12.1	22.0	0.25	2.30
3003	800°F @ 1 h A	6.0	15.0	29.0	0.30	1.50
2024[c]	T-351	52.0	68.8	115.0	0.20	0.37
2024	T-4	43.0	64.8	100.0	0.15	0.18
7075	800°F A	14.3	33.9	61.0	0.22	0.53
7075	T-6	78.6	86.0	128.0	0.13	0.18
2011	800°F @ 1 h A	7.0	25.2	41	0.18	0.35
2011	T-6	24.5	47.0	90	0.28	0.10

TABLE 7.5 Tensile Properties of Some Metals[a] (*Continued*)

Material	Condition	Strength: Yield S_y, kpsi	Strength: Ultimate S_u, kpsi	Strength: Coefficient σ_0, kpsi	Strain-strengthening exponent m	Fracture strain ε_f
Magnesium alloys						
HK31 XA	800°F @ 1 h A	19.0	25.5	49.5	0.22	0.33
HK31 XA	H-24	31.0	36.2	48.0	0.08	0.20
Copper alloys						
ETP Cu	100°F @ 1 h A	4.7	31.0	78.0	0.55	1.19
ETP Cu	1250°F @ 1 h A	4.6	30.6	72.0	0.50	1.21
ETP Cu	1500°F @ 1 h A	4.2	30.0	68.0	0.48	1.26
OFHC Cu	1250°F @ 1 h A	5.3	33.1	67.0	0.35	1.00
90-10 brass	As rec'd[c]	12.8	38.0	85.0	0.43	
90-10 brass	1200°F @ 1 h A	8.4	36.4	83.0	0.46	
90-10 brass	As above, 10% CW, 1200°F A	6.9	35.0	87.0	1.83	
80-20 brass	1200°F @ 1 h A	7.2	35.8	84.0	0.48	
80-20 brass	As above, 10% CW, 1200°F A	6.4	34.6	85.0	0.51	1.83
70-30 brass	1200°F @ 1 h A	12.1	44.8	112.0	0.59	
70-30 brass	As above, 10% CW, 1200°F A	10.7	43.4	107.0	0.59	1.62
70-30 brass[b]	1000°F @ 1 h A	11.5	45.4	110.0	0.56	1.50
70-30 brass[b]	1200°F @ 1 h A	10.5	44.0	105.0	0.52	1.55
70-30 brass[b]	1400°F @ 1 h A	8.8	42.3	105.0	0.60	1.60
70-30 leaded brass	1250°F @ 1 h A	11.0	45.0	105.0	0.50	1.10
Naval brass[d]	1350°F @ $\frac{1}{2}$ h A	17.0	54.5	125.0	0.48	1.00
Naval brass[d]	1350°F @ $\frac{1}{2}$ h WQ	27.0	66.2	135.0	0.37	0.50
Naval brass[d]	850°F @ $\frac{1}{2}$ h A	17.5	56.0	125.0	0.48	0.90
Naval brass[d]	850°F @ $\frac{1}{2}$ h WQ	31.5	64.5	135.0	0.37	0.80
Naval brass[d]	1500°F @ 3 h A	11.0	48.0			0.74
Nickel alloys						
Ni 200	1700°F @ $\frac{1}{4}$ h WQ	16.2	72.1	150.0	0.375	1.805
99.44% Ni	CD, A	20.5	73.7	160.0	0.40	1.47
Monel 400	1700°F @ $\frac{1}{4}$ h WQ	26.5	77.7	157.0	0.337	1.184
Monel K500	1700°F @ $\frac{1}{4}$ h WQ	34.4	92.6	182.0	0.32	1.305
Inconel 600	1700°F @ $\frac{1}{4}$ h WQ	46.6	102.5	201.0	0.315	1.14
Inconel 625	1700°F @ $\frac{1}{2}$ h WQ	77.1	139.7	297.0	0.395	0.75
Inconel 718	1750°F @ 20 min AC	43.6	99.4	205.0	0.363	1.337
Inconel X750	2050°F @ 45 min WQ	36.4	106.4	230.0	0.415	1.27
Incoloy 800	2050°F @ 2 h AC	22.2	77.1	169.0	0.420	1.262
Incoloy 825	1700°F @ 20 min WQ	66.7	138.0	283.0	0.353	0.715
Ni, 2% Be	1800°F sol. T WQ	41.0	104.0	222.0	0.39	1.00

TABLE 7.5 Tensile Properties of Some Metals[a] (*Continued*)

Material	Condition	Strength: Yield S_y, kpsi	Strength: Ultimate S_u, kpsi	Strength: Coefficient σ_0, kpsi	Strain-strengthening exponent m	Fracture strain ε_f
			Nickel alloys (*Continued*)			
Ni, 2% Be	As above + 1070°F @ 2 h aged	140.0	195.0	300.0	0.15	0.18
Ni, 15.8% Cr, 7.2% Fe	A	36.0	90.0	203.0	0.45	0.92
			Special alloys			
Cobalt alloy[f]	2250°F solution HT	65.0	129.0	300.0	0.50	0.51
Cobalt alloy[f]	As above—trans[c]	65.0	129.0	300.0	0.50	0.40
Cobalt alloy[e,g]	As rec'd, annealed	62.8	119.5	283.0	0.52	0.75
Cobalt alloy[e,g]	Machined, 2250°F sol. HT	48.0	112.5	283.0	0.62	0.70
Cobalt alloy[e,g]	2250°F sol. HT, 925°F aged	48.0	107.5	270.0	0.63	1.00
Molybdenum	Extr'd A	49.5	70.7	106.0	0.12	0.38
Vanadium	A	45.0	63.0	97.0	0.17	1.10

[a]All values are for longitudinal specimens except as noted. These are values obtained from only one or two heats. The values will vary from heat to heat because of the differences in composition and annealing temperatures. The fracture strain may vary as much as 100 percent.
[b]$\frac{3}{4}$-in-diameter bar.
[c]Tensile specimen machined from a 4-in-diameter bar transverse to rolling direction.
[d]Specimens cut from $\frac{1}{2}$-in hot-rolled plate.
[e]$\frac{1}{2}$-in-diameter bar.
[f]HS 25 or L 605 alloy; 50 Co, 20 Cr, 15 W, 10 Ni, 3 Fe.
[g]Eligiloy; 50 Co, 20 Cr, 15 Ni, 7 Mo, 15 Fe.
SOURCE: From Datsko [7-1].

The strain associated with upsetting a 2-in-diameter bar to a 2½-in-diameter can be calculated by means of Eq. (7.12). Thus

$$\varepsilon = -\ln\left(\frac{2}{2.5}\right)^2 = 0.45$$

The negative sign in front of the function is needed because Eq. (7.12) is for tensile deformation, whereas in this problem the deformation is axial compression. The equivalent amount of cold work can be calculated from Eq. (7.14) as 36.2 percent.

The axial compressive yield strength can be approximated by means of Eq. (7.23). Thus

$$(S_y)_c = \sigma_0(\varepsilon_W)^m = 205(0.45)^{0.51} = 136 \text{ kpsi}$$

If one were to interpolate in a table of yield strength versus cold work in a handbook, this value of 136 kpsi would be approximately the value that would be

TABLE 7.6 Properties of Some High-Strength Steels

AISI number	Processing[a]	Brinell hardness H_B	Modulus of elasticity E, Mpsi	Yield strength[b] S_y, kpsi	Ultimate strength S_u, kpsi	Reduction in area, %	True fracture strength σ_F, kpsi	True fracture ductility[c] ε_F	Strain-strengthening exponent m
1045	Q & T 80°F	705	29	265T[d] 300C[d]	300	2	310T 420C	0.02	0.186
1045	Q & T 360°F	595	30	270	325	41	430/ 395	0.52	0.071
1045	Q & T 500°F	500	30	245	265	51	370/ 330	0.71	0.047
1045	Q & T 600°F	450	30	220	230	55	345/ 305	0.81	0.041
1045	Q & T 720°F	390	30	185	195	59	315/ 270	0.89	0.044
4142	Q & T 80°F	670	29	235T 275C	355	6	375	0.06	0.136
4142	Q & T 400°F	560	30	245	325	27	405/ 385	0.31	0.091
4142	Q & T 600°F	475	30	250	280	35	340/ 315	0.43	0.048
4142	Q & T 700°F	450	30	230	255	42	320/ 290	0.54	0.043
4142	Q & T 840°F	380	30	200	205	48	295/ 265	0.66	0.051
4142[e]	Q & D 550°F	475	29	275T 225C	295	20	310/ 300	0.22	0.101T 0.060C
4142	Q & D 650°F	450	29	270T 205C	280	37	330/ 305	0.46	0.016T 0.070C
4142	Q & D 800°F	400	29	210T[f] 175C	225	47	305/ 275	0.63	0.032T 0.085C

[a]AISI 1045: Cold drawn to $\frac{9}{16}$-in rounds from hot-rolled rod. Austenized 1500°F (oxidizing atmosphere) 20 min, water quenched at 70°F. AISI 4142: Cold-drawn to $\frac{9}{16}$-in rounds from annealed rod. Austenized at 1500°F (neutral atmosphere), quenched in agitated oil at 180°F. AISI 4142 Def: Austenized at 1500°F, oil quenched. Reheated in molten lead, drawn 14 percent through die at reheating temperature to $\frac{5}{8}$-in rods.

[b]0.2 percent offset method.

[c]Bridgman's correction for necking.

[d]T, tension; C, compression.

[e]Deformed 14 percent.

[f]Proportional limit in tension.

SOURCE: Data from R. W. Landgraf, *Cyclic Deformation and Fatigue Behavior of Hardened Steels,* Report no. 320, Dept. of Theoretical and Applied Mechanics, University of Illinois, Urbana, 1968.

obtained for 36 percent cold work. And the handbook would not indicate whether it was a compressive or tensile yield strength, nor in what direction it was applied.

However, for this problem, the designer really needs both the tensile and compressive yield strengths in the transverse, i.e., circumferential, direction. These values can be closely approximated by means of Table 8.1. The tensile yield strength in the transverse direction is designated by the code $(S_y)_{tTt}$, which is in group 2 of Table 8.1. Since the bar was given only one cycle of deformation (a single upset), ε_{qus} is 0.45 and the tensile yield strength is calculated to be 123 kpsi. The compressive yield strength in the transverse direction is designated by the code $(S_y)_{cTt}$, which is in group 4 of Table 8.1. The compressive yield strength is then calculated to be $0.95(S_y)_{tTt}$ = 0.95(123) = 117 kpsi; this is 14 percent lower than the 136 kpsi that would normally be listed in a materials handbook.

In some design situations, the actual value of the yield strength in a given part for a specific amount of cold work may be 50 percent less than the value that would be listed in the materials handbook. In order to have a reliable design, the designer must be able to determine the strength of the material in a part in the direction and sense of the induced stresses. The information in this chapter and in Chap. 8 makes it possible for the design engineer to make a reasonable prediction of the mechanical properties of a fabricated part. However, it must be recognized that the original non-cold-worked properties of a given metal vary from heat to heat, and that the calculations are valid only for a part having the original properties that are used in the calculations.

7.15 NUMBERING SYSTEMS†

7.15.1 AISI and SAE Designation of Steel

Carbon and alloy steels are specified by a code consisting of a four-digit (sometimes five) number, as illustrated below with the substitution of the letters X, Y, and Z for the numbers. A steel specification of XYZZ (or XYZZZ) has the following meaning:

X indicates the type of alloy or alloys present.

Y indicates the total percent of the alloys present.

ZZ (or ZZZ) indicates the "points" of carbon in the steel (points of carbon equals the percent carbon times 100). For example, if ZZ is 40, then the steel has 0.40 percent carbon (C). If ZZZ is 120, then the steel has 1.20 percent carbon.

Table 7.7 identifies the number X corresponding to the alloy or alloys present. In addition, the following two special classes are included. A resulfurized free-machining steel is identified as 11ZZ and 12ZZ. These steels have a high sulfur content, which combines with the manganese to form the compound manganese sulfide. It is the presence of this compound that makes the steel more machinable. The 13ZZ and 15ZZ groups are plain carbon steels that have high and moderate amounts of manganese, respectively.

† This section presents the numbering systems now in general use in order to correspond with those used in other sections of this handbook. See Ref. [7.2] for details of the unified numbering system (UNS).

TABLE 7.7 Alloy Designations for Steels

Number X	Alloying elements
1	None (plain carbon)
2	Nickel
3	Nickel-chromium
4	Molybdenum-nickel-chromium
5	Chromium
6	Chromium-vanadium
8	Nickel-chromium-molybdenum
9	Silicon-manganese

Some examples:

2130 is a steel with 1 percent nickel and 0.3 percent carbon.

4340 is a steel with a total of 3 percent Mo, Ni, and Cr and 0.4 percent C.

52100 is a steel with 2 percent Cr and 1 percent C.

7.15.2 Designation System for Aluminum Alloys

Wrought aluminum alloys are specified by a code consisting of four-digit numbers such as 1100, 2024, or 7075. To explain this code, the letters XYZZ are substituted for the four digits. The types of alloys present in the aluminum are identified by the letter X from Table 7.8.

The second digit in the code, Y, indicates alloy modifications. When Y is zero, it indicates the original alloy, or in the 1YZZ series it indicates that the alloy is made to the standard impurity limits. When Y is any digit from 1 to 9, it indicates that a modification has been made to the original alloy and then designates which of the sequential changes were made. For example, 7075 refers to the original zinc alloy, whereas 7175 and 7475 refer to the first and fourth modifications made to it.

The third and fourth digits (ZZ in the code) have no numerical significance but simply relate to the chemical composition of the alloys.

TABLE 7.8 Alloy Designations for Wrought Aluminum Alloys

Number X	Alloying elements
1	None (99.00% Al min.)
2	Copper
3	Manganese
4	Silicon
5	Magnesium
6	Magnesium-silicon
7	Zinc

Temper Designation. The temper designation for aluminum alloys consists of a suffix which is a letter that may be followed by several digits. The suffix is separated from the alloy designation by a hyphen or dash. For example, 7075-T4 identifies both the alloy composition and its temper. The T in this suffix identifies the tempering treatment as a heat-treating process. Table 7.9 shows the letters used to identify the type of process used in the tempering treatment.

In addition to the T temper designations, other two- or three-digit numbers have been assigned to some specific treatments to certain special alloys or types of products.

7.15.3 Designation System for Copper Alloys

The designation system for copper alloys is not based on a coded system as those for steel and aluminum alloys are. It is simply a means of defining the chemical composition of the specific alloys. Table 7.10 identifies the principal alloying elements for the common classes of copper alloys.

Temper Designation. The temper designation for copper alloys refers to the amount of cold work given to the metal. Table 7.11 defines the amount of cold work associated with each temper designation.

TABLE 7.9 Tempering Processes and Designations for Aluminum Alloys

Designation	Process
F	As fabricated
O	Annealed
H	Strain hardened; the H is followed by two or more digits to indicate the amount of strain hardening
H1	Strain hardened only
H2	Strain hardened and partially annealed
H3	Strain hardened and stabilized
W	Solution heat treated
T	Heat treated; the T is always followed by one or more digits to specify the particular process used
T1	Cooled from a high-temperature forming process and naturally aged
T2	Cooled from a high-temperature forming process, cold worked, and naturally aged
T3	Solution heat treated, cold worked, and naturally aged
T4	Solution heat treated and naturally aged
T5	Cooled from a high-temperature forming process and artificially aged
T6	Solution heat treated and artifically aged
T7	Solution heat treated
T8	Solution heat treated, cold worked, and artifically aged
T9	Solution heat treated, artifically aged, and cold worked
T10	Cooled from a high-temperature forming process, cold worked, and artifically aged

TABLE 7.10 Designation of Copper Alloys

UNS Number	Alloy	Class or name
C10000-C13000	None	Commercially pure (ETP or OFHC)
C21000	Zn	Gilding brass (95% Cu)
C22000	Zn	Commercial bronze (90% Cu)
C23000	Zn	Red brass (85% Cu)
C24000	Zn	Low brass (80% Cu)
C26000	Zn	Cartridge brass (70% Cu)
C28000	Zn	Muntz metal (60% Cu)
C50000	Sn	Phosphor bronze
C60600-C64200	Al	Aluminum bronze
C64700-C66100	Li	Silicon bronze
C70000	Ni	Copper-nickel

TABLE 7.11 Temper Designation of Copper Alloys

	Percent cold work	
Temper	Rolled sheet	Drawn wire
¼ hard	10.9	20.7
½ hard	20.7	37.1
¾ hard	29.4	50.1
Hard	37.1	60.5
Extra hard	50.1	75.1
Spring	60.5	84.4
Extra spring	68.6	90.2
Special spring	75.1	93.8

7.15.4 Designation System for Magnesium Alloys

The designation system for magnesium alloys consists of four parts that include a combination of letters and digits. A typical example is AZ31B-H24.

The first part of the designation consists of two letters representing the two main alloying elements in order of decreasing amounts. The 10 principal alloying elements are given the following letters: A, aluminum; E, rare earth; H, thorium; K, zirconium; L, lithium; M, manganese; Q, silver; S, silicon; T, tin; and Z, zinc. Thus, in the preceding alloy, the main element is aluminum and the second one is zinc.

The second part consists of two digits corresponding to rounded-off percentages of the two main alloying elements. In the preceding example the alloy contains 3 percent aluminum and 1 percent zinc.

The third part of the designation consists of a letter that indicates the chronologic order of when that particular composition became a standard one. In the preceding example the letter B indicates that this particular alloy is the second one, having 3 percent aluminum and 1 percent zinc, that became an industry standard.

The fourth part consists of a letter preceded by a hyphen and followed by a number. It indicates the specific condition or temper that the alloy is in. Table 7.12 specifies the symbols that are used for each temper.

TABLE 7.12 Temper Designation of Magnesium Alloys

Designation	Process
F	As fabricated
O	Annealed
H10, H11	Slightly strain hardened
H23, H24, H26	Strain hardened and partially annealed
T4	Solution heat treated
T5	Solution heat treated and artificially aged
T8	Solution heated treated, cold worked, and artificially aged

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