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MECHANICAL TESTING OF STRUCTURAL MATERIALS

Vladislav Demenko

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Mechanical Testing of Structural Materials

Any designer must know the methods of controlling the microstructure and macrostructure of structural materials, because, by controlling the structure we in turn can control the mechanical properties to select the most advanced material for structure.

As has been considered earlier there are six important mechanisms used to control structure and properties – grain size strengthening, solid solution strengthening, strain hardening, dispersion strengthening, age hardening, and phase transformations (see Figure 1.87). All introduce barriers to slip. In the first three methods, we rely on the three types of lattice imperfections. By controlling surface defects such as grain boundaries, we obtain *grain size strengthening.* Controlling point defects such as substitutional atoms gives *solid solution strengthening.* Increasing the number of line defects, or dislocations, provides *strain hardening.*

We obtain strengthening in the other three mechanisms by introducing multiple phases, where each phase has a different composition or crystal structure. The boundaries between the phases can provide strengthening by interfering with the deformation mechanisms. *Dispersion strengthening* is a general term indicating strengthening by multiple phases. *Age hardening* is a special technique that provides an optimum, fine dispersion of phases. *Phase transformations* include more sophisticated treatments, often relying on allotropic transformations.

In technical university courses the strengthening mechanisms are discussed from the point of view of *processing* of the material. That is why *solidification*, *alloying*, *deformation* and *heat treatment* are examined. *Solidification* helps to determine grain size, grain shape, and the fineness and distribution of phases in many multiple-phase alloys. *Alloying* produces solid solution strengthening and provides the basis for dispersion strengthening. *Deformation processing* produces strain hardening and helps to control grain size and shape. *Heat treatment* permits us to perform the dispersion strengthening, age hardening, and phase transformation strengthening techniques.

After looking in Chapter 1 the strengthening mechanisms and the processes used to control these mechanisms, we can briefly examine the mechanical testing of materials and understand the results of these tests, which are the mechanical properties of a material.

We select materials for many components and applications by matching the mechanical properties of the material to the service conditions required of the component. The first step in the selection process requires that we analyze the application to determine the most important characteristics that the material must possess. Should the material be strong, or stiff, or ductile? Will it be subjected to repeated application of a high force, a sudden (impact) force, a high stress at elevated tempera-

ture, or abrasive conditions? Once we have determined the required properties, we can select the appropriate material using data listed in handbooks. However, we must know how the properties listed in the hand book are obtained, know what the properties mean, and realize that the properties listed are obtained from idealized tests that may not apply exactly to real-life engineering applications.

In this chapter we will study several tests that are used to measure how a material withstands an applied mechanical force. They are: tensile tests, impact tests, hardness tests, fatigue tests, fracture tests.

These tests will be referred to throughout this text, and materials will be compared on data developed from these tests. It is imperative that the designer understands how these tests are run and how to interpret the test information.

3.1 Tensile Tests

These tests are used to apply statically or slowly a stress to a material and record the material's response to this stress. As you remember the mathematical definition of stress (s) is the load (F) on a body distributed over the cross-sectional area of the body (A)*:*

$$s = \frac{F}{A}. \tag{3.1}$$

As you know from applied mechanics a tensile stress tends to pull a member apart; a compressive stress tends to crush or collapse a body; a shear stress tends to cleave a structural member; a bending stress tends to deflect a member. Handbooks on material properties invariably list the properties of materials subjected to tensile loading. Data on a material's response to compression and shear are sometimes given, but often are not. The allowable torsional stress that a material can tolerate is measured by shear strength, and the allowable bending stress that a material can tolerate is based on the tensile properties. This is because bending puts the outer fibers of a member in tension.

A material's response to the three major forms of stress – tension, compression, and shear, can be measured on a universal testing machine, more commonly referred to as a *tensile tester*. These machines, one of which is shown in Figure 3.1, can pull axially on a test sample (tensile load) or push on a test sample to measure response to compression loading. Shear tests are run by loading a pin in a special fixture. A test setup is shown in Figure 3.2.

These machines apply a tensile load when one end of the test sample (specimen) is attached to a *movable crosshead* with the other end fixed to a *stationary member*. The crosshead is then driven in such a manner as to pull the sample apart. Compressive loading is achieved by driving the crosshead against short *stubby cylinders* placed on the *stationary* machine *platen*. Attachments are used to hold various shaped specimens, but tensile specimens are usually made in a “dog-bone” shape

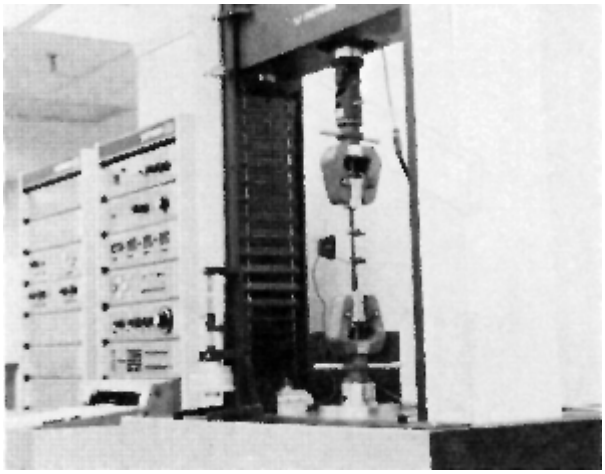


Figure 3.1 Typical universal test machine

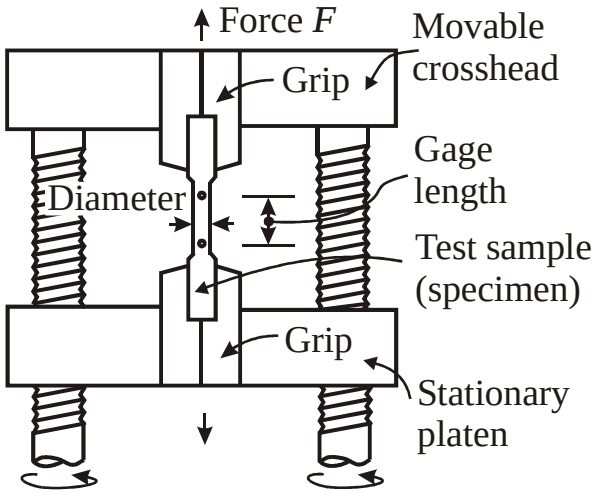


Figure 3.2 A unidirectional force is applied to a specimen in the tensile test by means of the movable crosshead

(Figure 3.3). The “dog-bone” shape ensures that the sample will break in the center and not in the grip area.

A typical specimen has a diameter of 0.505 in. and gage length of 2 in. (in national machinery 10 mm and 100 mm respectively).

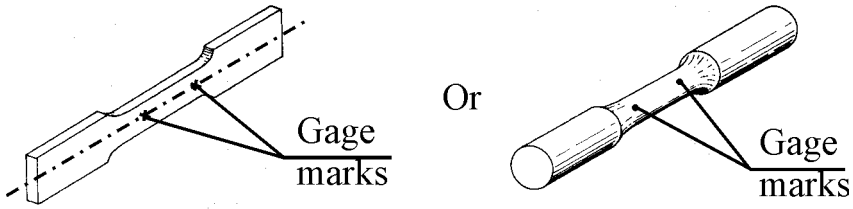


Figure 3.3 Tensile samples (specimens)

3.1.1 Stress–Strain Diagram

The specimen is placed in the testing machine and a force *F* is applied. A mechanical or electrical device – *strain gage* or *extensometer* is used to measure the amount that the specimen stretches between the *gage marks* when the force is applied until the specimen fails. The stretch, both elastic (recoverable) and plastic (permanent), is converted into *strain* by division of the change in length (extension or elongation) by the *original length*. Using the *original cross-sectional area* of the sample, the load *F* is converted into *stress*, and an *engineering stress-strain diagram* is obtained (Figure 3.4).

Table 3.1 includes the effect of the load on the gage length of an aluminum alloy test specimen and illustrates the concept of stress and strain.

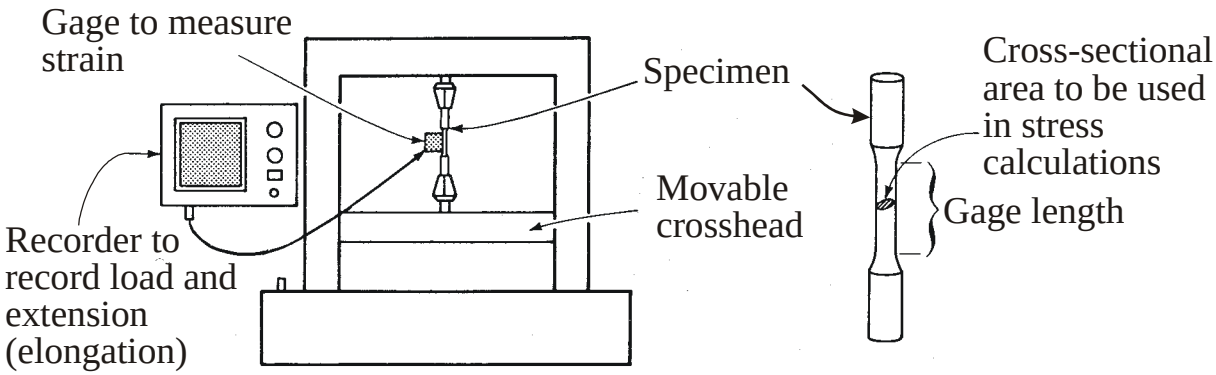


Figure 3.4 Concept of stress and strain

Table 3.1 The results of a tensile test of a 0.505-in. diameter aluminum alloy test specimen

Load, lb	Load, N	Stress, psi	Stress, MPa	Gage Length, in.	Gage Length, $\times 10^{-3}$ m	Strain, m/m
0	0	0	0	2.000	50.80	0
1,000	4,450	5,000	34.5	2.001	50.83	0.0005
3,000	13,350	15,000	103.4	2.003	50.88	0.0015
5,000	22,250	25,000	172.4	2.005	50.93	0.0025
7,000	31,150	35,000	241.3	2.007	50.98	0.0035
7,500	33,375	37,500	258.6	2.030	51.56	0.0500
7,900	35,155	39,500	272.3	2.080	52.83	0.0400
8,000	35,600	40,000	275.8	2.120	53.85	0.0600
8,000 (max.)	35,600 (max.)	40,000	275.8	2.160	54.86	0.0800
7,600 (fracture)	33,820 (fracture)	38,000	262.0	2.205	56.01	0.1025

Figure 3.5 shows the load versus gage length for our test. Displaying the results of the test in this manner describes the behavior of this material when the diameter is 0.505 in. Unfortunately, this figure does not tell us the force required to produce a given amount of stretching if the diameter is larger or smaller.

3.1.2 Engineering Stress and Strain

The results of a single test apply to all sizes and shapes of specimens for a given material if we convert the force to stress and the distance between gage marks to strain. *Engineering stress* and *engineering strain* are defined by the following equations:

$$\text{Engineering stress} = s = \frac{F}{A_0}, \quad (3.2)$$

$$\text{Engineering strain} = e = \frac{l - l_0}{l_0} \quad (3.3)$$

where A_0 is the original cross-sectional area of the specimen before the test begins, l_0 is the original distance between the gage marks, and l is the distance between the gage marks after force F is applied. The conversions from load-gage length to stress-strain are also included in Table 3.1. The stress-strain curve (diagram) (Figure 3.6) is usually used to record the results of a tensile test.

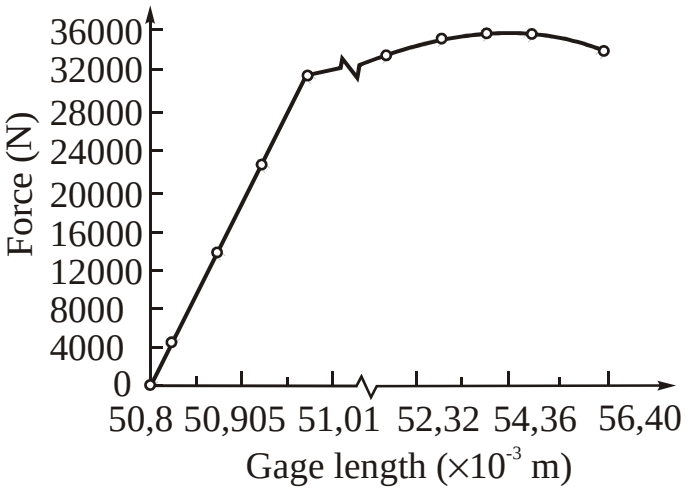


Figure 3.5 Graph of the load–gage length data from Table 3.1 for an aluminum alloy test specimen

Example 3.1

Convert the load-gage length data in Table 3.1 to engineering stress and strain and plot a stress-strain curve (diagram).

For the 1000-lb load (4,450 N)

$$s = \frac{F}{A_0} = \frac{1000}{(p/4)\cdot(0.505)^2} = \frac{1000}{0.2} = 5000 \text{ psi} = 34.474 \text{ MPa},$$

$$e = \frac{l - l_0}{l_0} = \frac{2.001 - 2.000}{2.000} = 0.0005 \text{ in./in=0.0005 (dimensionless)}.$$

The results of similar calculations for each of the remaining loads are given in Table 3.1 and are plotted in Figure 3.6.

It is important to note, that a 0.505-in. diameter is specified for the standard cylindrical test specimen in USA because the original cross-sectional area is 0.20 in^2 (1.29×10^{-5} m^2). We can convert force to stress simply by multiplying by five.

Example 3.2

Compare the force required to produce a stress of 25,000 psi (172,4 MPa) in a 1-in (0.0254 m) diameter bar and in a 2-in (0.051 m) diameter bar:

$$F = sA_0 = (25{,}000)\left(\frac{p}{4}\right)(1)^2 = 19{,}635\text{-lb force (87,341 N)} - \text{for a 1-in. bar},$$

$$F = sA_0 = (25{,}000)\left(\frac{p}{4}\right)(2)^2 = 78{,}540\text{-lb force (349,363 N)} - \text{for a 2-in. bar}.$$

The engineering strain tells us how much each inch of the metal will stretch for a given applied stress. If the metal part is 10in. long, we can multiply the strain

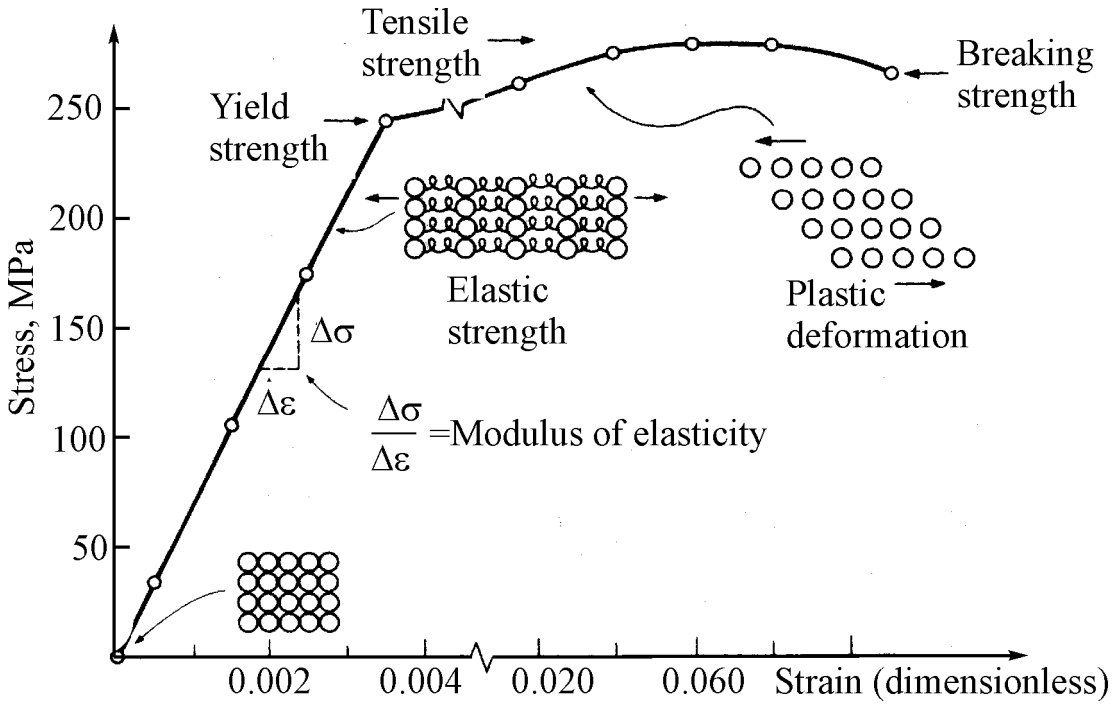


Figure 3.6 The stress–strain curve for an aluminum alloy from Table 3.1

by 10 to determine the total amount that the part will stretch, assuming that the part stretches uniformly.

Elastic versus Plastic Deformation

When a force is first applied to the specimen, the bonds between the atoms are stretched and the specimen elongates. When we remove the force, the bonds return to their original length and the specimen returns to its initial size. Stretching of the metal in this *elastic* portion of the stress-strain curve is recoverable.

Example 3.3

Suppose a 5000-lb force (22,241 N) is applied to a 0.505-in. (0.013 m) diameter bar that is 50 in. (1.27 m) long. The bar is made from the same aluminum alloy we have discussed previously. Determine the length of the bar when the force is applied.

Answer

$$s = \frac{F}{A_0} = \frac{5000}{(p/4)(0.505)^2} = 25{,}000 \text{ psi} = 172.37 \text{ MPa}.$$

From Figure 3.6, $e = 0.0025$ in./in.

$$\frac{l - l_0}{l_0} = 0.0025;$$

$$\frac{l-50}{50}=0.0025;$$

$$l=50+(0.0025)(50)=50.125 \text{ in}=1.273 \text{ m}.$$

The results of tensile tests are measured using many different *units*. The most common units for stress are *pounds per square inch* (psi) and *megapascals* (MPa). The units for strain include inch/inch, centimeter/centimeter, and meter/meter. The conversion factors for stress are summarized in Table 3.2. Because strain is really dimensionless, no conversion factors are required to change the system of units.

Table 3.2 Units and conversion factors for stress

1 psi = pounds per square inch
1 MPa = megapascal
1 MN/m^2 = 1 MPa = meganewton per square meter
= newton per square millimeter
1 GPa = 1000 MPa = gigapascal
1 ksi = 1000 psi
1 ksi = 6.895 MPa
1 psi = 0.006895 MPa
1 MPa = 0.145 ksi = 145 psi

Example 3.4

Determine the stress in megapascals when a 5000-lb force is applied to a 0.505-in. diameter bar.

Answer

$$s=\frac{F}{A_0}=\frac{5000}{(p/4)(0{,}505)^2}=25{,}000 \text{ psi};$$

$$s=(25{,}000 \text{ psi})(0.006895 \text{ MPa/psi})=172.4 \text{ MPa}.$$

3.1.3 Properties Obtained from the Tensile Test

Four very important mechanical properties are determined from the stress-strain diagrams.

1. Yield strength.
2. Tensile strength.
3. Modulus of elasticity.
4. Poisson's ratio.

3.1.3.1 Yield Strength

If we are designing a structure component that must support a force applied during use, we must be sure that the component does not plastically deform. For this we must know the stress at which *slip* becomes significant, so called *yield strength.* It is the stress that divides the elastic and plastic behavior of the material. At this stress level the material permanently stretched. In most design situations this property is more important than the *tensile strength*, the stress at which the sample pulls apart. Most designers do not want a structure part to permanently deform under service stresses. Thus, design stresses should be significantly lower, than the *yield strength*.

We must select a material that has high yield strength, or we must make the structure component large so that the applied force produces a stress that is bellow the yield strength. On the other hand, if we are manufacturing shapes or components by some deformation process, the applied stress must produce the stress that exceeds the yield strength of the material to develop a permanent change in the shape of the material.

Example 3.5

You are to design a cable that must support an elevator cab that weighs 10,000 1b (44,482 N). The cable is made from the aluminum alloy in Example 2.1. Calculate the minimum diameter of the cable required to support the cab without permanent deformation.

Answer

We must not exceed the yield strength of 35,000 psi (241.32 MPa).

$$A_0 = \frac{F}{s} = \frac{10{,}000}{35{,}000} = 0.286 \text{ in}^2,$$

$$d = \sqrt{\frac{4}{p} \cdot A_0} = \sqrt{\frac{4}{p} \cdot 0.286} = 0.603 \text{ in}=0{,}015 \text{ m}.$$

Example 3.6

You wish to bend an aluminum bar which is 1/2 in. (0,013 m) × 6 in. (0,152 m) in cross section into a bracket by applying a tensile force. What is the minimum force that must be exerted by your forming equipment?

Answer

We must exceed the yield strength of 35,000 psi (241.3 MPa).

$$F = s \cdot A_0 = (35{,}000)\left(\frac{1}{2}\right)(6) = 105{,}000 \text{ lb force} = 467{,}063 \text{ N}.$$

In some materials, the stress at which the material changes from elastic to plastic behavior is not easily detected and the stress-strain curve often has a different shape from that shown in Figure 3.6. In this case, we may determine an *offset yield*

strength (Figure 3.7). We decide that a small amount of permanent deformation, such as 0.2% or 0.002 in./in., might be allowable without damaging the performance of our component. We can construct a line parallel to the initial portion of the stress-strain curve but offset by 0.002 in./in. from the origin. The 0.2% offset yield strength is the stress at which our constructed line intersects the stress-strain curve.

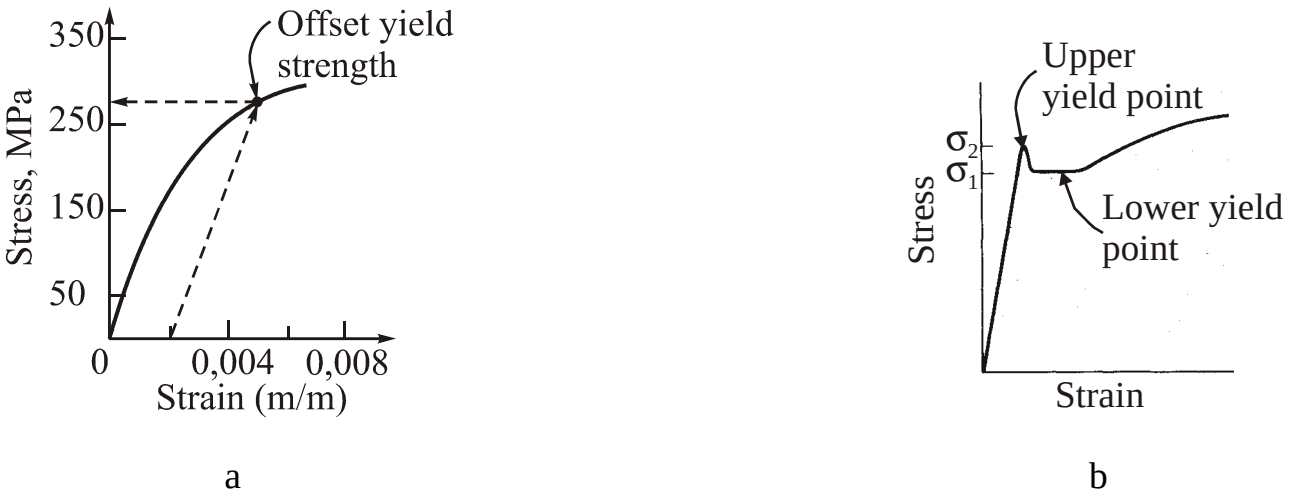


Figure 3.7 (a) Determing the 0.2 % offset yield strength in gray cast iron and (b) upper and lower yield point behavior in a low–carbon steel

Example 3.7

Determine the 0.2% offset yield strength for gray cast iron (Figure 3.7).

Answer

By constructing a line starting at 0.002 in./in. strain, which is parallel to the elastic portion of the stress-strain curve, we find that the 0.2% offset yield strength is 40,000 psi (275.8 MPa).

On the other hand, the stress-strain curve for certain low-carbon steels displays a *double yield point* (Figure 3.7 (b)). The material is expected to plastically deform at stress s_1. However, small interstitial atoms clustered around the dislocations interfere with slip and raise the yield point to s_2. Only after we apply the higher stress s_2 does the dislocation slip. After slip begins at s_2, the dislocation moves away from the clusters of small atoms and continues to move very rapidly at the lower stress s_1. We can easily determine the lower (s_1) yield strength for materials having this type of stress-strain behavior.

3.1.3.2 Tensile Strength

The *tensile strength* is the stress obtained at the highest applied force and thus is the maximum stress on the engineering stress-strain curve. In many ductile materials, deformation does not remain uniform. At some point, one region deforms more

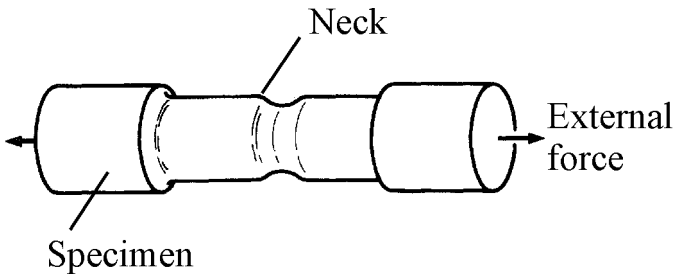


Figure 3.8 Localized deformation of a ductile material during a tensile test produces a necked region

than other areas and a large local decrease in the cross-sectional area occurs (Figure 3.8). This locally deformed region is called a *neck*. Because the cross-sectional area becomes smaller at this point, a lower force is required to continue its deformation, and the engineering stress, calculated from the *original* area A_0, will decrease. The tensile strength is the stress at which *necking* begins in ductile materials.

Tensile strengths are easy to measure. They are useful in comparing the behaviors of materials, and they permit us to estimate other properties which are more difficult to measure. However, the tensile strength is relatively unimportant for materials selection or materials fabrication – the yield strength determines whether the material will or will not deform.

3.1.3.3 Modulus of Elasticity

The *modulus of elasticity*, or *Young's modulus*, is the slope of the stress-strain curve in the elastic region. This relationship is *Hooke's law* (R. Hook, 1756):

$$E = \frac{s}{e} = \text{modulus of elasticity.} \qquad (3.4)$$

The modulus of elasticity is closely related to the forces bonding the atoms in the material. A steep slope in the force-distance graph at the equilibrium spacing indicates that high forces are required to separate the atoms and cause the metal to stretch elastically. Thus, the metal has a high modulus of elasticity. Binding forces, and consequently the modulus of elasticity, are higher for high melting point metals (Table 3.3).

The modulus of elasticity is a measure of the *stiffness* or *rigidity* of the material. The units are *pounds per square inch* (psi) or *pascals* (Pa) in SI.

The modulus of elasticity is of crucial importance in material selection. It determines the elastic deflection of a structural member under load. It is also used in many stress and deflection calculations. Polymers have very low stiffness compared to metals, and this must be considered in selection (Figure 3.9).

If we are designing a shaft and bearing, we may need very close tolerances. But if the shaft deforms elastically, those close tolerances may cause excessive *rubbing*, *wear*, or *seizing*. Figure 3.10 shows the elastic behavior of iron and aluminum. If a stress of 30,000 psi (206.8 MPa) is applied to the shaft, the steel deforms elastically 0.001 in./in. while, at the same stress, aluminum deforms 0.003 in./in. Iron has a modulus of elasticity three times greater than that of aluminum.

Table 3.3 Relationship between the modulus of elasticity and the melting temperature of metals

Metal	Melting Temperature, °C	Modulus of elasticity, psi	Modulus of elasticity, MPa
Pb	327	2.0×10^6	13.8×10^3
Mg	650	6.5×10^6	44.9×10^3
Al	660	10.0×10^6	69.0×10^3
Ag	962	10.3×10^6	71.1×10^3
Au	1064	11.3×10^6	78.0×10^3
Cu	1085	18.1×10^6	124.9×10^3
Ni	1453	29.9×10^6	206.3×10^3
Fe	1538	30.0×10^6	207.0×10^3
Mo	2610	43.4×10^6	299.5×10^3
W	3410	59.2×10^6	408.5×10^3

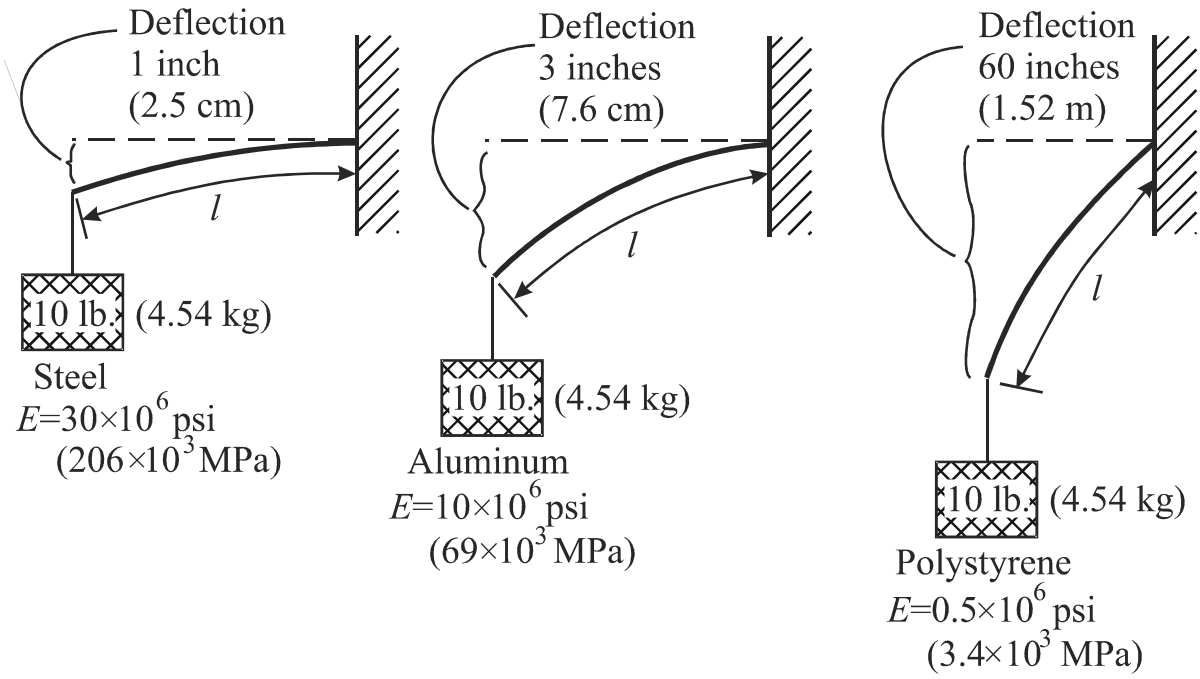


Figure 3.9 Effect of modulus of elasticity on elastic deflection. All beams have the same length and cross section

Example 3.8

From the data in Example 3.1, calculate the modulus of elasticity of the aluminum alloy. Use the modulus to determine the length of a 50-in. (1.27 m) bar to which a stress of 35,000 psi is applied.

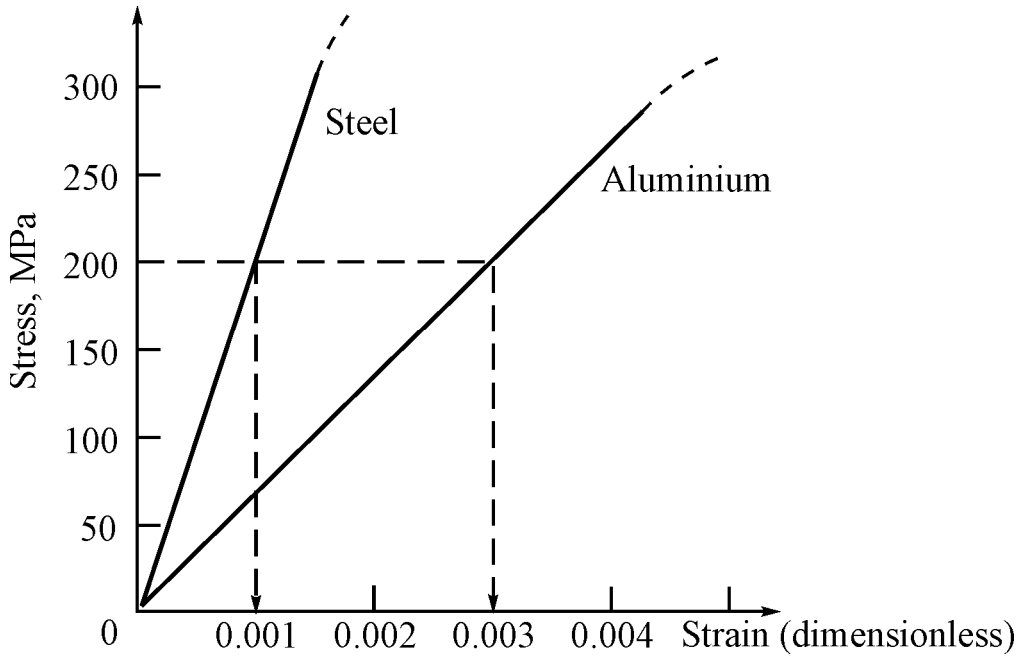


Figure 3.10 Comparison of the elastic behavior of steel and aluminum

Answer

When a stress of 35,000 psi (241.32 MPa) is applied, a strain of 0.0035 is produced. Thus

$$\text{Modulus of elasticity} = E = \frac{s}{e} = \frac{35{,}000}{0.0035} = 10 \times 10^6 \text{ psi} = 0.68948 \cdot 10^{11} \text{ Pa}.$$

From Hooke's law

$$e = \frac{l - l_0}{l_0} = 0.0035,$$

and total length $l = l_0 + el_0 = 1.27 + (0.0035) \cdot (1.27) = 1.2744$ m.

3.1.3.4 Poisson's Ratio

It relates the *longitudinal* elastic deformation produced by a uniaxial tensile or compressive stress to the *lateral* deformation that must simultaneously occur:

$$m = -\frac{e_{lateral}}{e_{longitudinal}}. \qquad (3.5)$$

For ideal materials, we can show that Poisson's ratio is $m = 0{,}5$. However, in real materials we find that less lateral strain develops than it would be predicted based on conservation of volume; typically, Poisson's ratios of $m = 0{,}3$ are measured for metals and alloys.

There are other important mechanical properties that can be obtained as the re-

sult of the tensile test: ***percent elongation*** (amount of sample stretch in the original gage section) and ***percent reduction in area*** (amount of necking in the gage section). These two properties are measures of the ***ductility*** of materials. Percent elongation is obtained by putting the two halves of a fractured tensile specimen back together and measuring the total stretch in the gage length:

$$\text{percent elongation} = \frac{l_f - l_0}{l_0} \cdot 100, \tag{3.6}$$

where l_f is the distance between gage marks after the specimen ***breaks***.

A second approach is to measure the percent change in cross-sectional area at the point of fracture ***before*** and ***after*** the test. This percent reduction in area describes the amount of thinning that the specimen undergoes during the test:

$$\text{percent reduction in area} = \frac{A_0 - A_f}{A_0} \cdot 100, \tag{3.7}$$

where A_f is the final cross–sectional area at the fracture surface, and A_0 – original area.

Ductility is important to both designers and manufacturers. The designer of a component would prefer a material that displays at least some ductility so that, if the applied stress is too high, the component deforms before it breaks. Fabricators want a ductile material so they can form complicated shapes without breaking the material in the process.

Example 3.9

The aluminum alloy in Example 3.1 has a final gage length after failure of 2.195 in. (0.056 m) and a final diameter of 0.398 in. (0.010 m) at the fractured surface. Calculate the ductility of this alloy.

Answer

a) $$\text{percent elongation} = \frac{l_f - l_0}{l_0} \cdot 100 = \frac{2.195 - 2.000}{2.000} \cdot 100 = 9.75\,\%.$$

b) $$\begin{matrix}\text{percent} \\ \text{reduction} \\ \text{in area}\end{matrix} = \frac{A_0 - A_f}{A_0} \cdot 100 = \frac{(p/4)(0.505)^2 - (p/4)\cdot(0.398)^2}{(p/4)\cdot(0.505)^2} \cdot 100 = 37.8\,\%.$$

The final gage length is less than 2.205 in. (0.056 m) (see Table 3.1) since, after fracture, the elastic strain is recovered.

3.1.4 True stress–true strain

The decrease in engineering stress beyond the tensile point occurs because of our definition of engineering stress. We used the original area A_0 in our calculations, which is not precise because the area continually changes (decreases). We define

true stress and *true strain* by the following equations:

$$\text{True stress} = s_{tr} = \frac{F}{A}, \tag{3.8}$$

$$\text{True strain} = e_{tr} = \int \frac{dl}{l_0} = \ln\left(\frac{l}{l_0}\right) = \ln\left(\frac{A_0}{A}\right), \tag{3.9}$$

where A is the *actual area* at which the force F is applied. The expression $\ln(A_0/A)$ must be used after necking begins. The true stress-strain curve is compared with the engineering stress-strain curve in Figure 3.11. The true stress continues to increase after necking because, although the load required decreases, the area decreases even more.

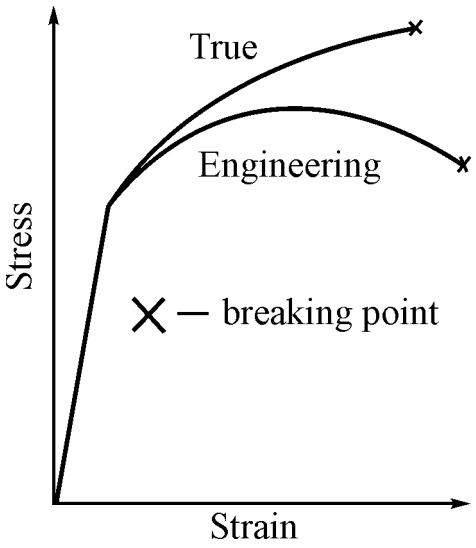


Figure 3.11 The relationship between the true stress-true strain diagram and the engineering stress-strain diagram

We seldom require true stress and true strain. As soon as we exceed the yield strength, the metal begins to deform. Our component has failed because it no longer has the original intended shape. Furthermore, a significant difference develops between the two curves only when necking begins. But when necking begins, our component is grossly deformed and no longer satisfies its intended use.

Example 3.10

Compare the engineering stress and strain with the true stress and strain for the aluminum alloy in Example 3.6 at (a) the maximum load and (b) fracture. The diameter at maximum load is 0.497 in. (0.013 m) and at fracture is 0.398 in. (0.010 m).

Answer

(a) At the tensile or maximum load

$$\text{Engineering stress} = \frac{F}{A_0} = \frac{8000}{(p/4)(0.505)^2} = 40{,}000 \text{ psi} = 275.8 \text{ MPa}.$$

$$\text{True stress} = \frac{F}{A} = \frac{8000}{(p/4)\cdot(0.497)^2} = 41{,}237 \text{ psi} = 284.3 \text{ MPa}.$$

$$\text{Engineering strain} = \frac{l - l_0}{l_0} = \frac{2.120 - 2.000}{2.000} = 0.060.$$

$$\text{True strain} = \ln\left(\frac{l}{l_0}\right) = \ln\left(\frac{2{,}120}{2{,}000}\right) = 0.058.$$

(b) At fracture

$$\text{Engineering stress} = \frac{F}{A_0} = \frac{7600}{(p/4)\cdot(0.505)^2} = 38{,}000 \text{ psi} = 262 \text{ MPa}.$$

$$\text{True stress} = \frac{F}{A} = \frac{7600}{(p/4)\cdot(0.398)^2} = 61{,}090 \text{ psi} = 421.2 \text{ MPa}.$$

$$\text{Engineering stress} = \frac{l - l_0}{l_0} = \frac{2.205 - 2.000}{2.000} = 0.1025 \text{ in./in.}$$

$$\text{True strain} = \ln\left(\frac{A_0}{A}\right) = \ln\left[\frac{(p/4)\cdot(0.505)^2}{(p/4)\cdot(0.398)^2}\right] = \ln(1.610) = 0.476.$$

The true stress becomes much greater than the engineering stress only after necking begins.

3.1.5 Shear Strength

A common application of metals in engineering design is in shear loading. Bolts, rivets, and drive keys are loaded in such a manner as to cleave the material in half. The shear strength of a material is the stress at which a shear-loaded member will fail. A shear test can be performed in a tensile machine with special grips replacing the tensile specimen (Figure 3.12).

It is not common to use polymers or ceramics as shear-loaded devices in machines, and thus their shear properties are seldom reported in handbooks. The application of the property of shear strength in machine design is obvious. It is this property that must be considered on shear–loaded fasteners and the like. Unfortunately, it is often difficult to find good tabulations in the literature on shear strength. A useful and conservative relationship to use if this is the case is shear strength $\approx 40\%$ of the tensile strength.

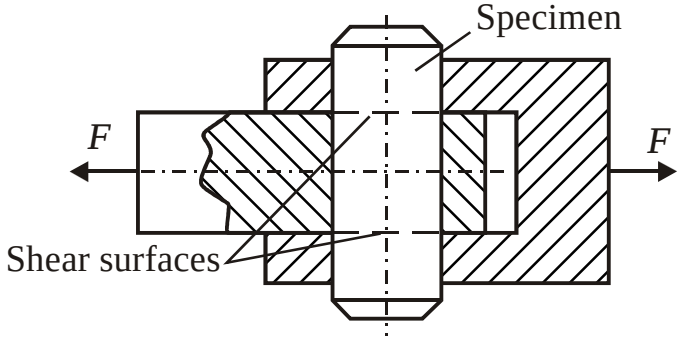
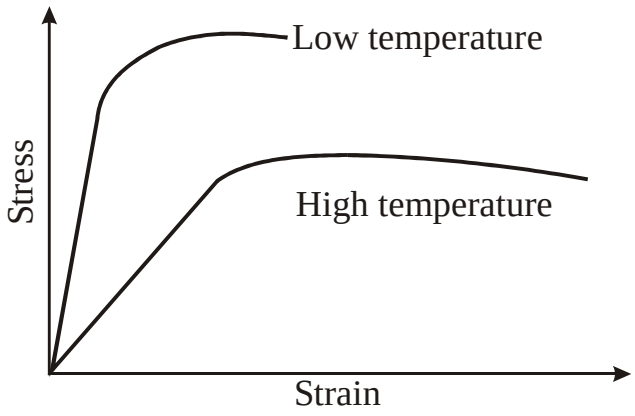


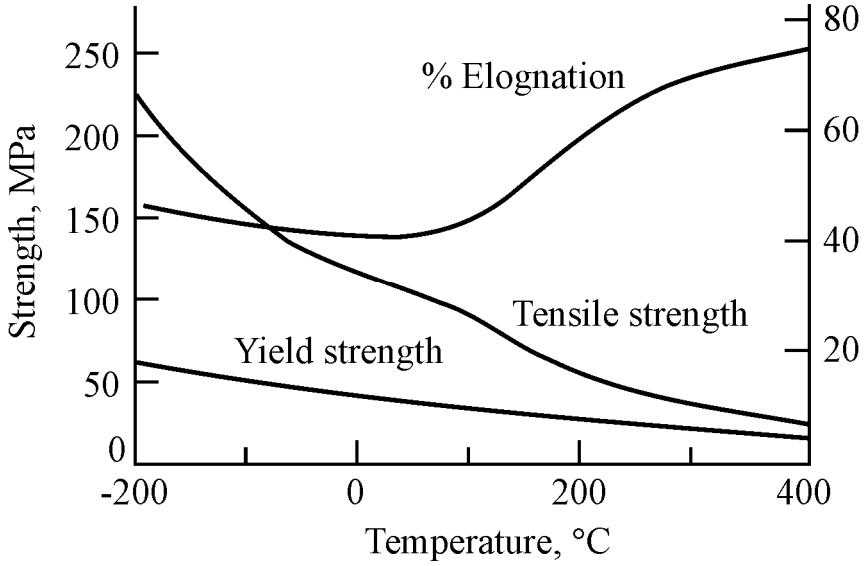
Figure 3.12 Shear test fixture for use in a tensile machine

3.1.6 Temperature Effects in Materials Testing

The tensile properties are significantly affected by temperature (Figure 3.13). The yield strength, tensile strength, and modulus of elasticity decrease at higher temperatures, whereas the ductility, as measured by the amount of strain at failure, commonly increases. A materials fabricator may wish to deform a material at a high temperature (known as *hot working*) to take advantage of the higher ductility and lower required forces.



a



b

Figure 3.13 The effect of temperature (a) on the stress–strain curve and (b) on the tensile properties of an aluminum alloy

3.1.7 Brittle Behavior

Ductile materials display an engineering stress-strain curve that goes through a maximum at the tensile strength. In more brittle materials, the maximum load or tensile strength occurs at the point of failure. In extremely brittle materials, such as ceramics, the yield strength, tensile strength, and breaking strength are all the same (Figure 3.14).

In many brittle materials, particularly ceramics and certain composite materials, the normal tensile test cannot easily be performed due to the presence of flaws at the surface. Often, placing the brittle material in the grips of the tensile testing ma-

chine will cause these flaws to promote cracking, invalidating the test. Preparation of tensile specimens of brittle materials may also be expensive. One approach used to minimize these problems is the ***bend test*** (Figure 3.15). By applying the load at three points and causing bending, a tensile force acts on the material opposite the middle point. Fracture begins at this location. The ***flexural strength*** or ***modulus of rupture*** (MOR), given by equation (3.10), is used to describe the strength of the material:

$$\text{Flexural strength} = \frac{3Fl}{2bh^2} \text{ MPa}, \tag{3.10}$$

where F is the applied load, l is the distance between the two outer points, b is the width of the specimen, and h is the height of the specimen.

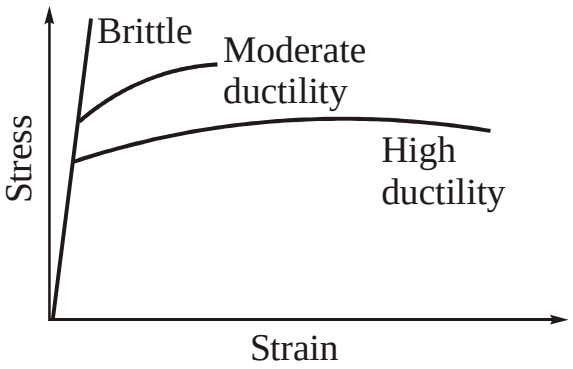


Figure 3.14 The stress-strain behavior for brittle materials compared with that of more ductile materials

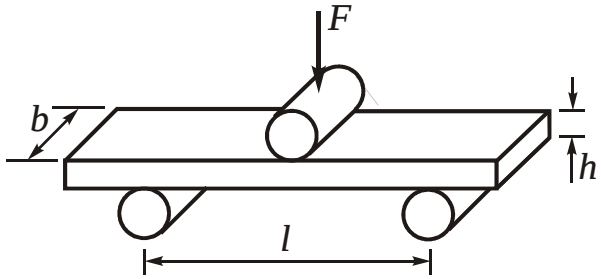


Figure 3.15 The modulus of rupture test often used for measuring the strength of brittle materials

Since cracks and flaws tend to remain closed in compression, brittle materials are often designed so that only compressive stresses are acting on the part. Often, we find that brittle materials fail at much higher compressive stresses than tensile stresses (Table 3.4), although ductile materials such as metals may have tensile and compressive strengths that are nearly equal.

Table 3.4 Comparison of the tensile, compressive, and flexural strengths of selected ceramic and composite materials

Material	Tensile strength, psi	Tensile strength, MPa	Compressive strength, psi	Compressive strength, MPa	Flexural strength, psi	Flexural strength, MPa
Polyester – 50% glass fibers	23,000	159	32,000	221	45,000	310
Polyester – 50% glass fabric	37,000	255	27,000	186	46,000	317
$A1_2O_3$	30,000	207	375,000	2586	50,000	345
SiC	25,000	172	100,000	689	37,000	255

Example 3.11

The flexural strength of a composite material reinforced with glass fibers is 45,000 psi. The specimen, which is 0.5 in. (0.013 m) wide, 0.375 in. (9.53×10^{-3} m) high, and 8 in. (0.203 m) long, is supported between two rods 5 in. (0.127 m) apart. What force is required to fracture the material?

Answer

In our case the dimensions are: b =0.5 in., h=0.375 in., and l =5 in. From equation (3.10)

$$45{,}000 = \frac{3Fl}{2bh^2} = \frac{(3)(F)(5)}{(2)(0.5)(0.375)^2} = 106.7F\,,$$

$$F = \frac{45{,}000}{106.7} = 422 \text{ lb} = 1877 \text{ N}.$$

3.2 Impact Test

3.2.1 Types of Impact Test

The tensile test is normally performed at a low strain rate, at which the specimen is very slowly loaded and elongated. When a material is subjected to a sudden, intense blow, in which the strain rate is extremely rapid, the material may behave in a much more brittle manner than is observed in the tensile test.

Impact strength is used to measure a material's ability to withstand shock loading. The classic definition of impact strength is the energy required to fracture a given volume of material, so called *impact energy* absorbed by specimen during failure. The units of this property are reported as foot-pounds (ft·lb) in the English system and joules/cubic meter (J/m^3) in the metric system (SI), where $1 \text{ ft} \cdot \text{lb} = 1.356 \text{ J}$.

The ability of a material to withstand an impact blow is often referred to as the *toughness* of the material. It is interesting, that ceramics and brittle metals such as gray cast iron have negligible toughness.

In metals and polymers the impact strength is most commonly measured by a pendulum-type impacting machine. In the test, a heavy pendulum which starts at an elevation h_0 swings through its arc, strikes and breaks the specimen, and reaches a lower final elevation h_f (Figure 3.16). By knowing the initial and final elevations of the pendulum, the *impact energy* as the difference in potential energy can be calculated.

The *Izod test* is often used for nonmetallic materials. The test specimen may be either notched or unnotched; V-notched specimens better measure the resistance of the material to crack propagation (Figure 3.17).

For most metals the specimen as shown in Figure 3.16 has a notch in it to prompt fracture in the desired spot. When the impact data are reported as Charpy V,

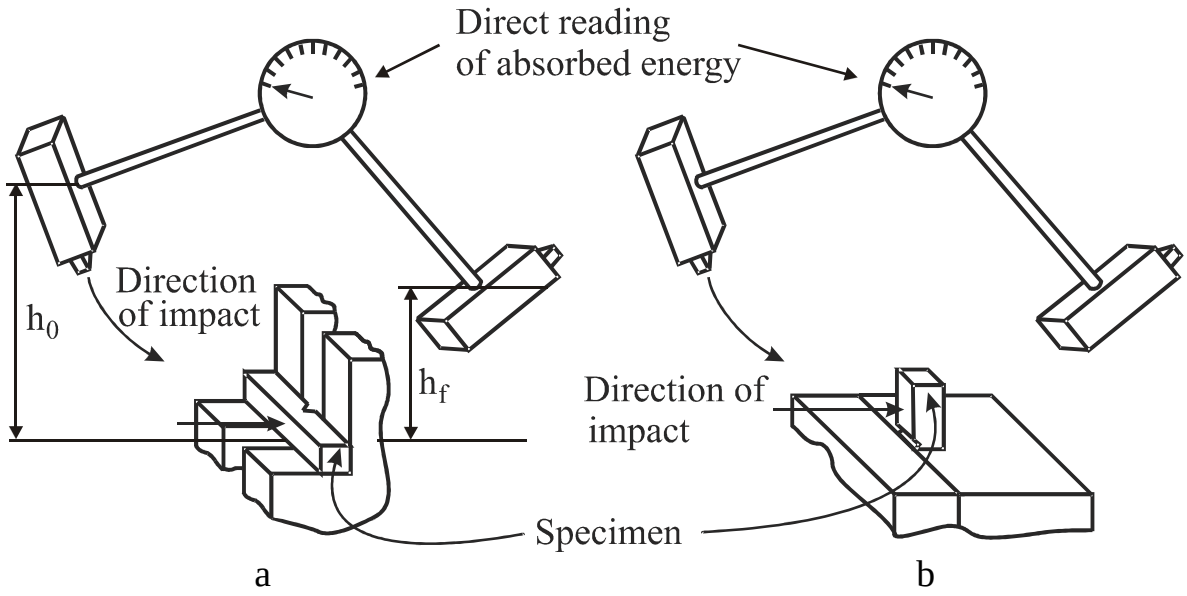


Figure 3.16 The principle of common impact test: Charpy (a), and Izod (b)

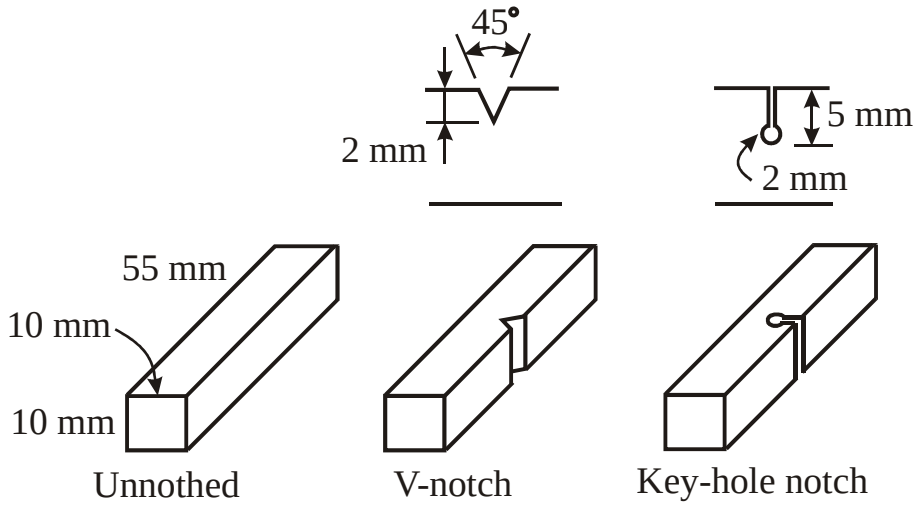


Figure 3.17 The dimensions of typical specimen in Charpy and Izod test

or notched Izod, it will mean that notched specimens were used. In data that do not indicate a notched specimen, chances are the material is really quite brittle. Notched impact data cannot be compared with unnotched.

The ***drop–weight*** type of test (Figure 3.18) is an important addition to the toughness testing field. Its big advantage is that it uses relatively large specimens (as large as several hundred square centimeters in cross section). The use of large specimens was prompted by research reports that indicated that the data obtained on the small specimens used in standard Charpy and Izod tests do not confirm service characteristics on heavy sections.

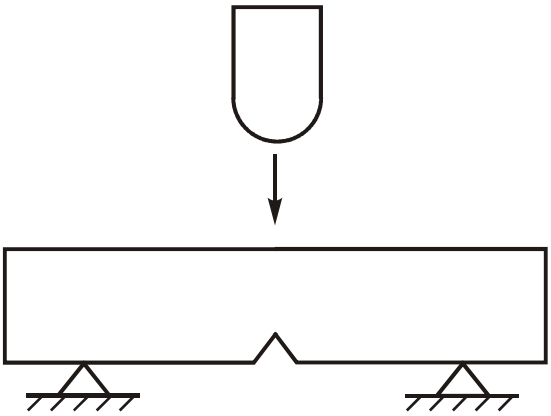


Figure 3.18 The principle of drop weight test

The *drop–weight* type of test (Figure 3.18) is an important addition to the toughness testing field. Its big advantage is that it uses relatively large specimens (as large as several hundred square centimeters in cross section). The use of large specimens was prompted by research reports that indicated that the data obtained on the small specimens used in standard Charpy and Izod tests do not confirm service characteristics on heavy sections. The standard notched and unnotched pendulum test specimens have a cross section only of the order of 0.2 in^2 (0.13×10^{-3} m^2). The drop-weight tests have the major disadvantage of being quite expensive, but produce the unique results for design of dynamically loaded structures.

3.2.2 Transition Temperature

Impact strength can be affected by temperature. At high temperatures, a large absorbed energy is required to cause the specimen to fail, whereas at low temperatures even a relatively ductile material may fail with little absorbed energy (Figure 3.19). If at low temperatures the material is brittle, the little deformation at the point of fracture is observed.

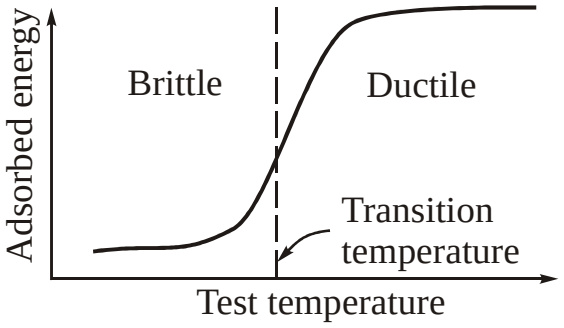


Figure 3.19 Typical results from a series of impact tests

The *transition temperature* is the temperature at which the material changes from ductile to brittle failure.

A material that may be subjected to an impact blow during service must have a transition temperature *below* the temperature of the material's surroundings.

For example, the transition temperature of a steel used for a carpenter's hammer should be below room temperature to prevent *chipping* of the steel.

If low temperatures are a possible service environment for a structure, it would be well to look into the *nil ductility temperature* (NDT). This parameter is a product of Charpy V tests; it is defined as the temperature at which the toughness of the material drops below some predetermined value (usually 15 ft·lb; 21 J). A typical impact strength versus temperature curve showing the NDT is illustrated in Figure 3.20. If the NDT of a steel is less than 32°F (0°C), it should not be used for impact-loaded parts that may operate at a lower temperature.

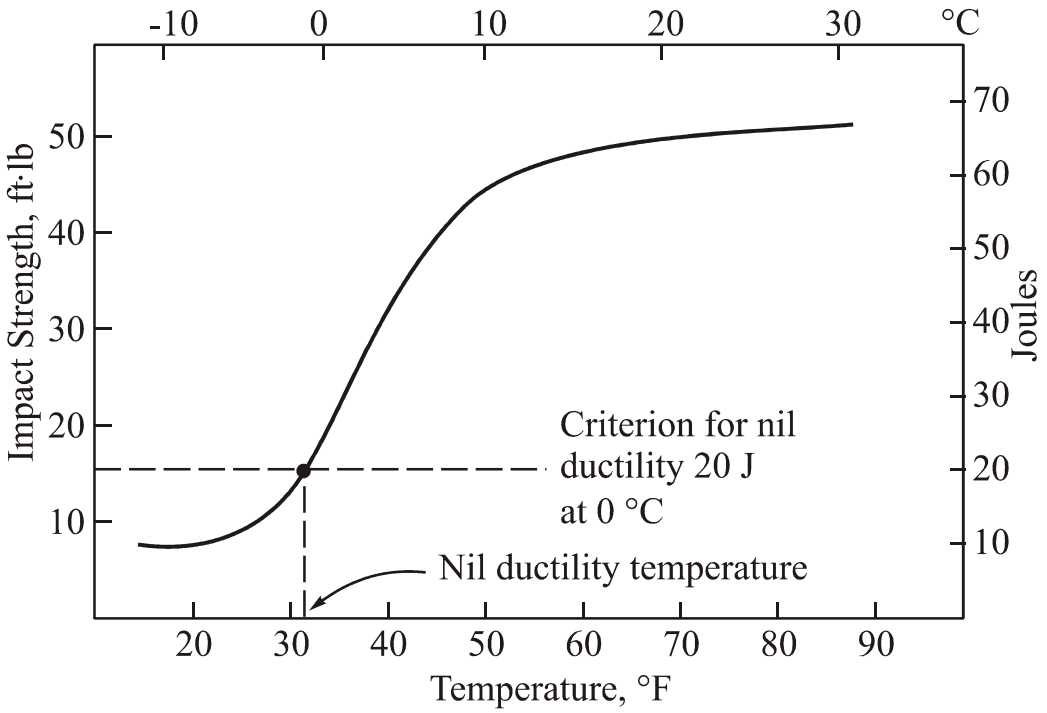


Figure 3.20 Use of impact test data to determine NDT

Not all materials have a distinct transition temperature (Figure 3.21). BCC metals have transition temperatures but most FCC metals do not. FCC metals have high absorbed energies, with the energy decreasing gradually and slowly as the temperature decreases.

3.2.3 Notch Sensitivity

Notches caused by poor machining, fabrication, or design cause stresses to be concentrated, reducing the toughness of the material. The *notch sensitivity* of a material can be evaluated by comparing the absorbed energies of notched versus unnotched specimens. The absorbed energies are much lower in notched specimens if the material is notch sensitive, as in ductile cast iron (Figure 3.22). However, some materials, such as gray cast iron, are not notch sensitive.

3.2.4 Relationship to Stress-Strain Diagram

The energy required to break a material also corresponds to the area contained within the true stress-true strain diagram. Materials that have both high strength and high ductility have a good toughness (Figure 3.23). Ceramics and many composites, on the other hand, have poor toughness because they display virtually no ductility.

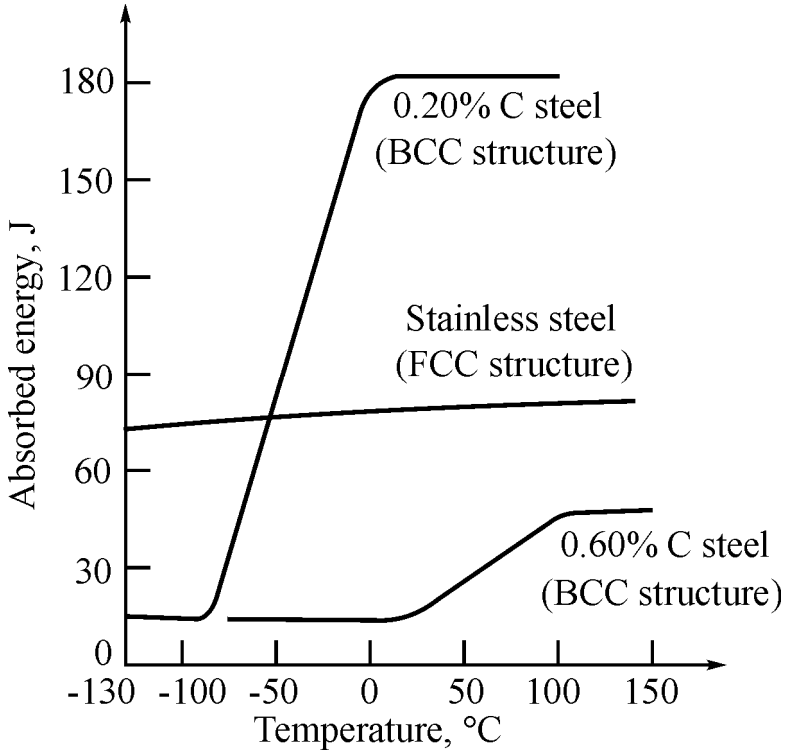


Figure 3.21 The Charpy V-notch properties for two plain-carbon steels (BCC structure) and an FCC stainless steel

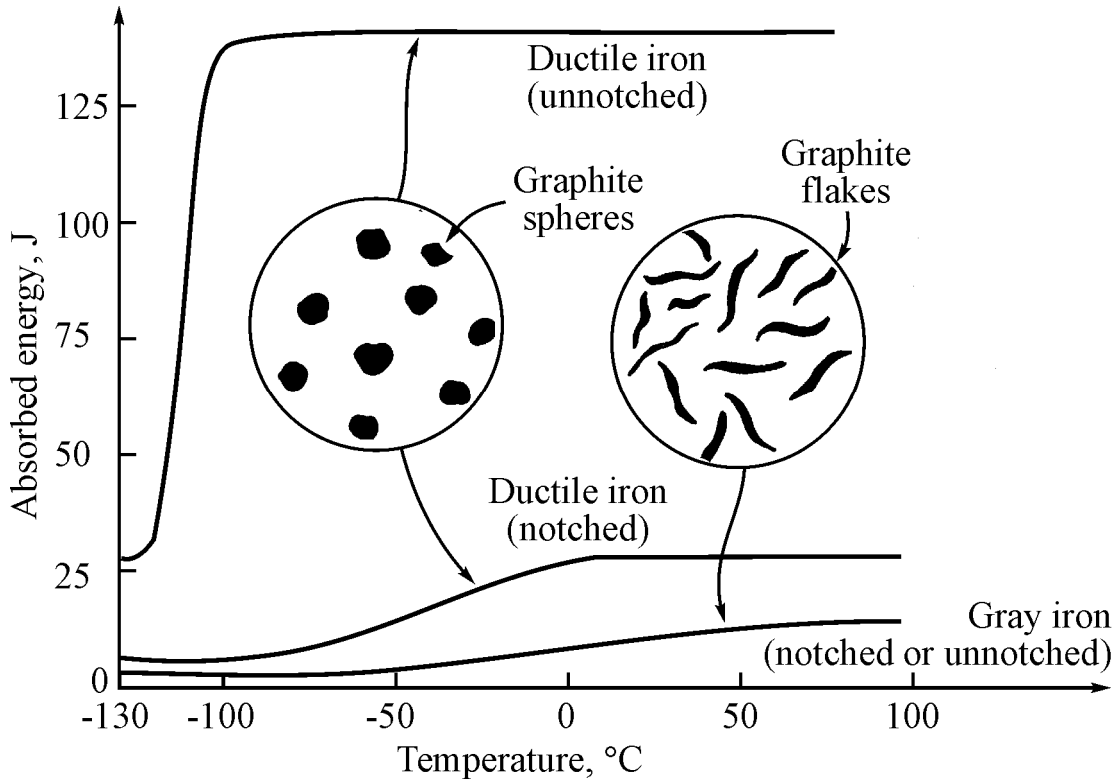


Figure 3.22 The effect of internal and external notches on impact properties. Gray iron structures contain sharp graphite flakes that act as notches and produce low energies. Ductile iron structures contain spherical graphite nodules that do not act as notches. An external notch has a significant effect only on ductile iron

3.2.5 Use of Impact Properties

The absorbed energy and transition temperature are very sensitive to the loading conditions. For example, a higher rate at which energy is applied to the specimen will reduce the absorbed energy and increase the transition temperature. The size of the specimen also affects the results – smaller energies might be required to break thicker materials. Finally, the configuration of the notch may affect the behavior – a surface crack permits lower absorbed energies than does a V-notch. Because we often cannot predict or control all of these conditions, the impact test is best used for comparison and selection of materials rather than as a design criterion.

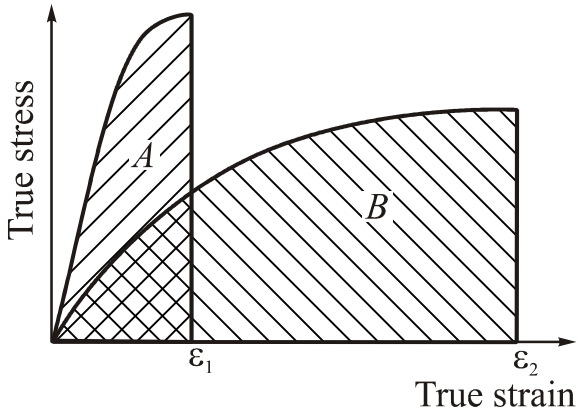


Figure 3.23 The area contained within the true stress-true strain curve is related the impact energy. Although material *B* has a lower yield strength, it absorbs a greater energy than material *A*

3.3 Fatigue Test

3.3.1 Nature of the Fatigue Test

In many applications, a component is subjected to the repeated application of loading which produce a stress below the yield strength of the material. This repeated stress may occur as a result of rotation, bending, or even vibration and random loading. Even though the stress is below the yield strength, the material may fail after a large number of applications of the stress. This mode of failure is known as *fatigue*.

Fatigue strength of material is determined by *endurance limit* and is obtained by repeated loading a specimen at given stress levels until it fails. Any form of loading can be used, and the stress level is usually calculated or measured by strain gauges. For example, a bending fatigue setup is illustrated in Figure 3.24. The specimen is loaded until, for example, the maximum stress in the sample is 40 ksi (275 MPa). At this stress level it may fail in 10 cycles. These data are recorded, and the stress level is reduced to maybe 30 ksi (206 MPa). A specimen may break after 1000 stress cycles at this low stress level. This procedure is repeated until a stress level is determined below which failure does not occur. A test duration of 10 million stress cycles is usually considered *infinite life* (Figure 3.25).

One of two common methods to measure the resistance to fatigue is the *rotating cantilever beam test* (Figure 3.26). One end of a machined, cylindrical specimen is mounted in a motor-driven *chuck*. A weight is suspended from the other end. The specimen initially has tensile force acting on the top surface, while the bottom surface

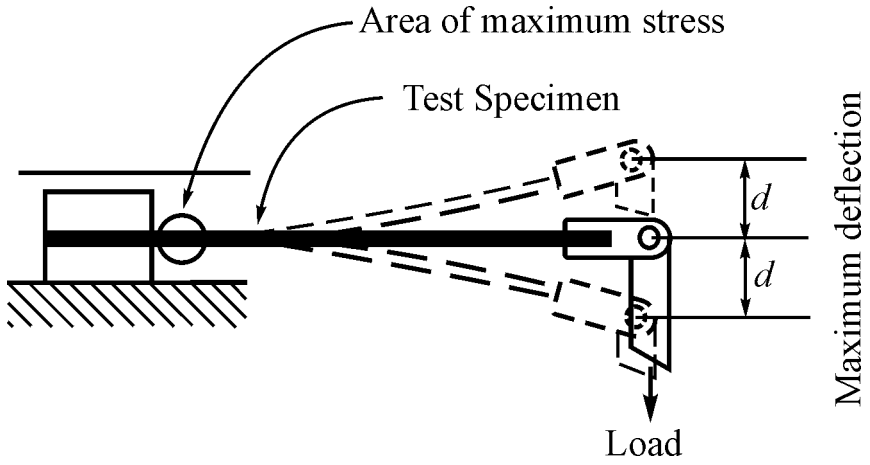


Figure 3.24 Typical test setup for bending fatigue

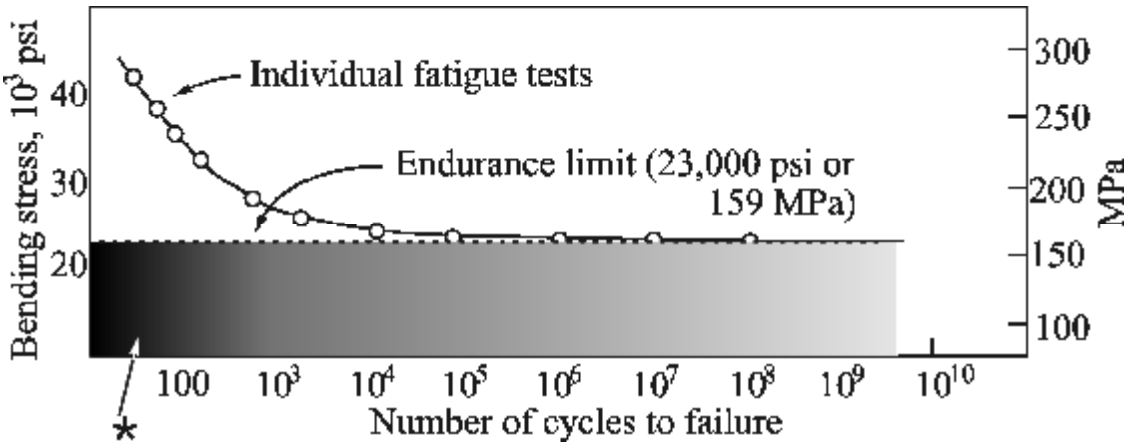


Figure 3.25 Use of an stress–number curve to establish fatigue strength: *– machine components made of this metal will not be subject to fatigue failure if the design stress is in this stress range

is compressed. After the specimen turns 90°, the locations that were originally in tension and compression have no stress acting on them. After a half revolution of 180°, the material that was originally in tension is now in compression. Thus, the stress at any point goes through a complete cycle from zero stress to maximum tensile stress to zero stress to maximum compressive stress. The maximum stress acting on the specimen is given by

$$s = 10.18\frac{l \cdot F}{d^3}, \tag{3.11}$$

where l is the length of the bar, F is the load, and d is the diameter of the specimen. Second common method is the *rotating two – supported beam test* (Figure 3.27).

In this case two movable bearings at the left and right parts of the specimen transfer the action of a tensile force in accordance with the scheme in Figure 3.28.

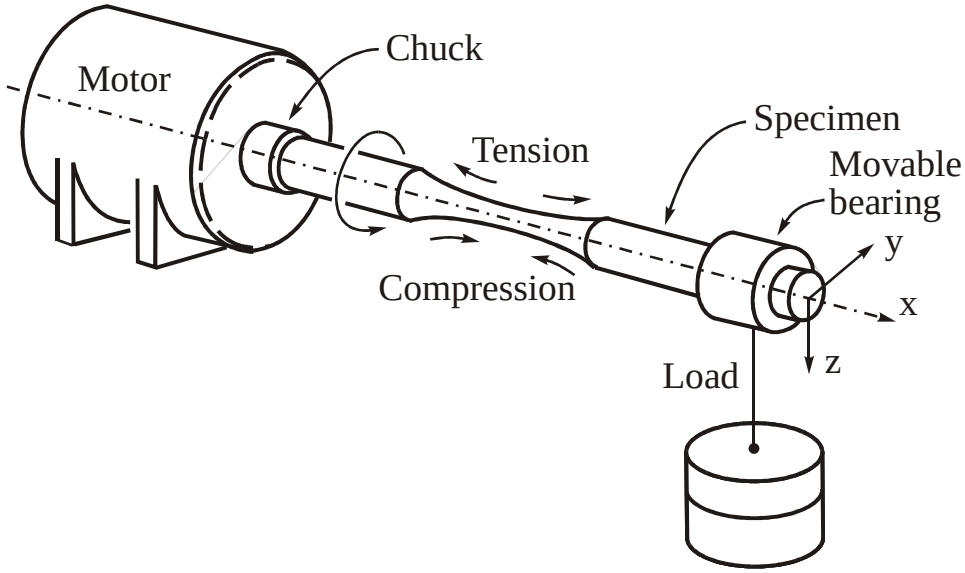


Figure 3.26 The rotating cantilever beam fatigue tester

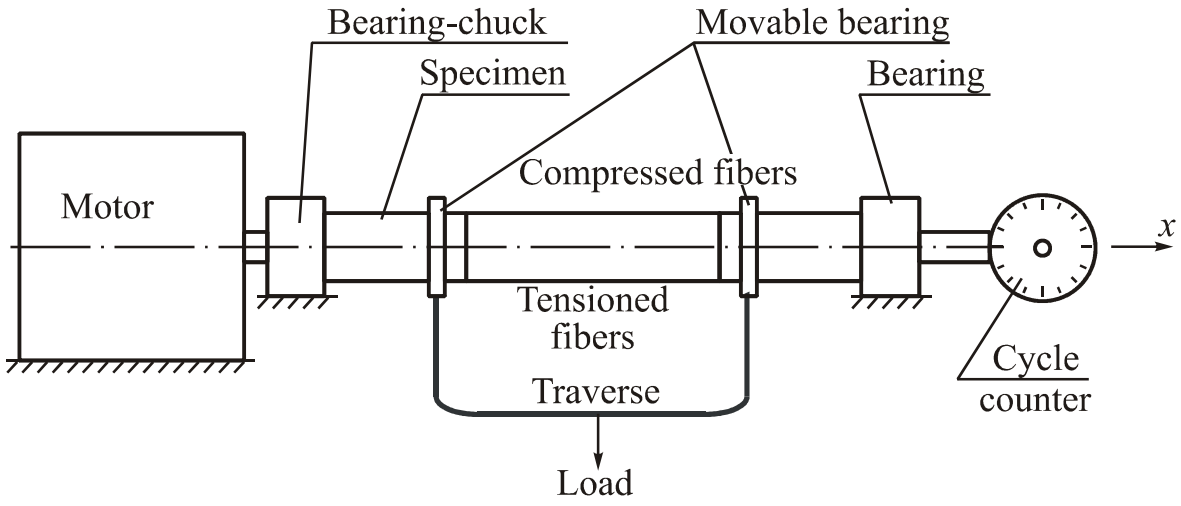


Figure 3.27 The rotating two supported beam tester

The maximum bending moment in an arbitrary cross-section of pure bending part of the specimen (CD) is given by

$$M_{B\max} = \frac{F}{2} \cdot a\,. \tag{3.12}$$

The corresponding maximum normal stress in an external points of the circular section are

$$s_{\max} = \frac{M_{B\max}}{W_{n.a.}} = \frac{32M_{B\max}}{pd^3} \approx \frac{5.1Fa}{d^3}\,. \tag{3.13}$$

During the test after a sufficient number of cycles, the specimen may fail. Generally, a series of specimens (up to 10) are tested at different applied stresses (the

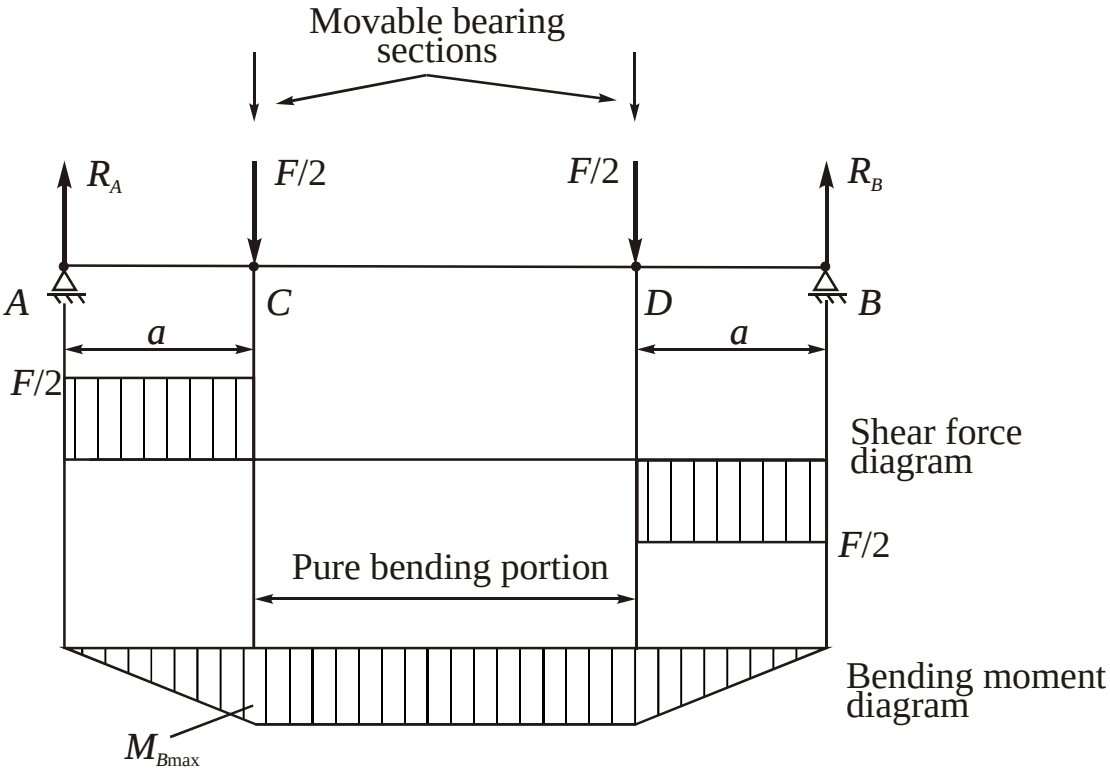


Figure 3.28 The mechanical scheme of the rotating two-supported beam test

first is loaded to $s_{\max_1} = 0{,}86 s_y$, $s_{\max_2} < s_{\max_1}$, $s_{\max_3} < s_{\max_2}$ etc.) and the stress is plotted versus of cycles to failure (see Figure 3.25, 3.29).

3.3.2 Results of the Fatigue Test

The fatigue test can tell us how long a part may survive or the maximum allowable loads that can be applied to prevent failure. The end result, the endurance limit of a material, is an extremely important design property.

3.3.2.1 Fatigue Life

The *fatigue life* is the term, which tells how long a part or component survives when a given stress s is repeatedly applied to the material. If we are designing a tool steel part that must undergo 100,000 cycles during its lifetime, in accordance with Figure 3.29 this part must be designed so that the maximum acting stress must be lower than 620 MPa.

3.3.2.2 Endurance Limit

The *endurance limit* is the stress below which failure by fatigue never occurs. It is our preferred design criterion. To prevent a tool steel part from failing, we must be sure that the applied stress is below 415 MPa (Figure 3.29). This property, rather than

allowable static stress, should be used in determining allowable operating stresses in

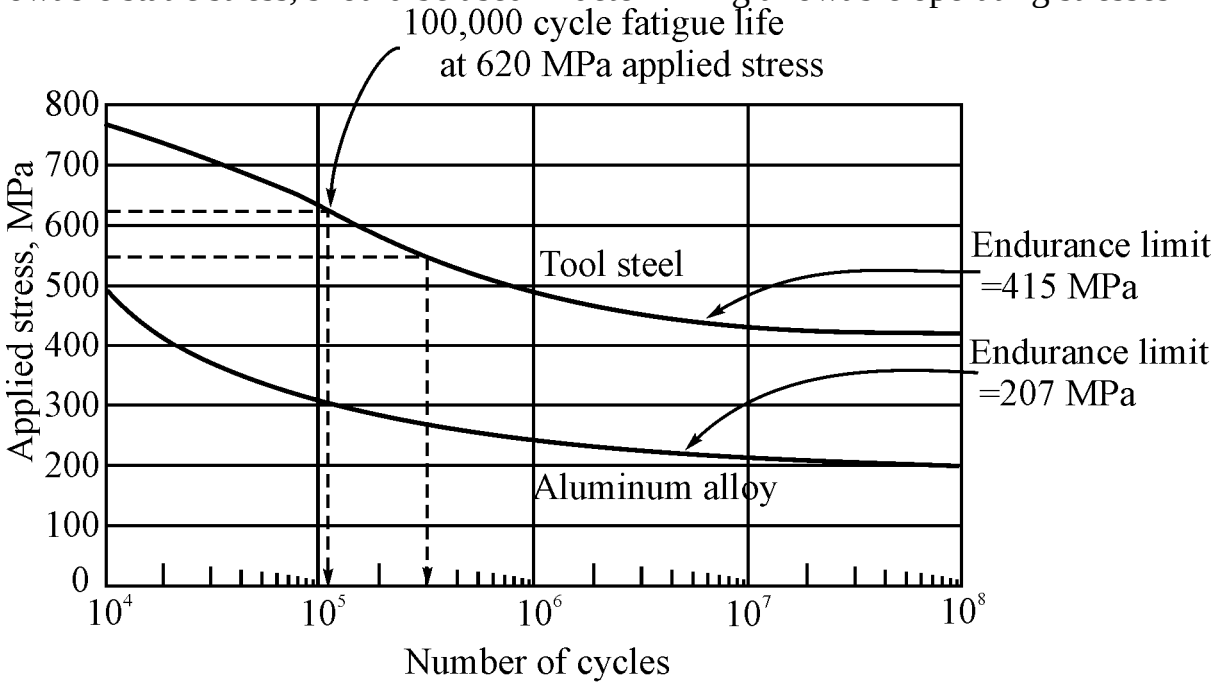


Figure 3.29 The stress-number of cycles to failure curve for a tool steel and an aluminum alloy

components that are subjected to cyclic loading in service. As an example, the American Institute of Steel Construction (AISI) recommends a design (allowable) stress for a 60 ksi tensile strength (A36) steel of 22 ksi (152 MPa) for static loading. In cyclic loading situations, the allowable stress is only about 13 ksi (89 MPa).

3.3.2.3 Fatigue Strength

Some materials, including many aluminum alloys, have no true endurance limit. For these materials, we may specify a minimum fatigue life; then ***the fatigue strength*** is the stress below which fatigue does not occur within this time period. In many aluminum alloys, the fatigue strength is based on 500 million cycles.

3.3.2.4 Notch Sensitivity in Fatigue

Fatigue cracks initiate at the surface of a loaded material, where the stresses are at a maximum. Any design or manufacturing defect at the surface concentrates stresses and encourages the formation of a fatigue crack. This susceptibility may be measured using a notched fatigue specimen (Figure 3.30). For this reason highly polished surfaces are prepared in order to minimize the likelihood of a fatigue failure.

3.3.2.5 Endurance Ratio

It was admitted that a cyclic loading significantly reduces the allowable stress

that a material can withstand. If handbook data are not available on the endurance limit of a material under consideration for use, a percentage of the tensile strength can be used. This percentage varies with different material systems, but for many

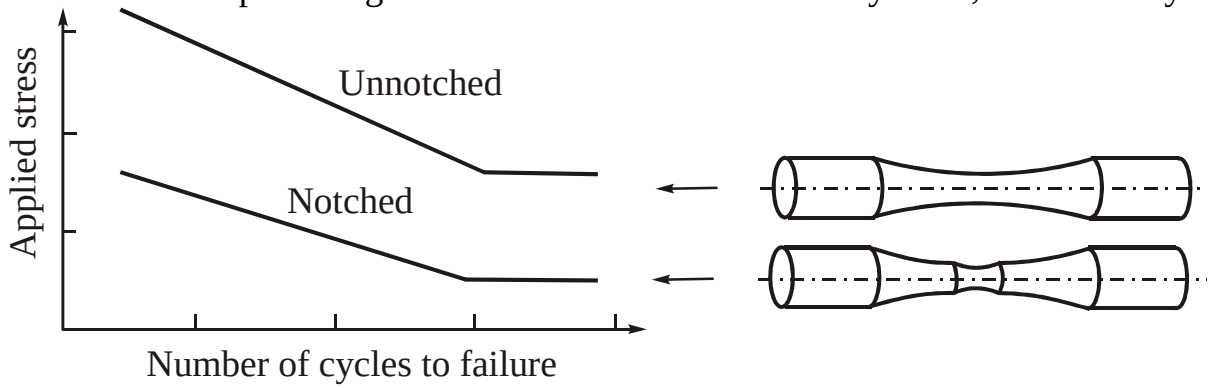


Figure 3.30 The effect of a notch on the fatigue properties of a metal

engineering metals (ferrous, or iron-base, alloys) the endurance limit can be approximated as 50% of the tensile strength of materials (in the absence of stress concentrations). This ratio of endurance limit to tensile strength is the *endurance ratio*:

$$\text{Endurance ratio} = \frac{\text{endurance limit}}{\text{tensile strength}} \approx 0.5. \tag{3.14}$$

If the tensile strength at the surface of the material increases, the resistance to fatigue also increases.

3.3.2.6 Temperature Effect in Fatigue

Temperature influences the fatigue resistance. As the temperature of the material increases, the strength decreases and consequently both fatigue life and endurance limit decrease.

Example 3.12

A 650-lb (2893 N) force is applied to a tool steel bar rotating at 3000 cycles/min. The bar is 1 in. (0.0254 m) in diameter and 12 in. (0.305 m) long. Estimate: (a) the time before the bar fails and (b) the diameter of the shaft that would prevent fatigue failure.

Answer

(a) $$s = \frac{10.18 \cdot l \cdot F}{d^3} = \frac{(10.18)(12)(650)}{(1)^3} = 79{,}400 \text{ psi} \cong 550 \text{ MPa}. \tag{3.15}$$

From Figure 3.29, the number of cycles to failure is 300,000. The time to failure is

$$t = \frac{300{,}000}{3000} = 100 \text{ min}. \tag{3.16}$$

(b) The endurance limit is 415 MPa.

$$d^3 = \frac{(10.18)(0.305)(2893)}{415 \cdot 10^6} = 21.64 \cdot 10^{-6}\ \text{m}^3, \qquad (3.17)$$
$$d = 0.028\ \text{m}.$$

3.4 Creep Test

3.4.1 Nature of Creep Test

If we apply a stress to a material at a high temperature, the material may stretch and eventually fail, even though the applied stress is less than the yield strength at that temperature. Long-term plastic deformation at high temperatures is known as *creep.*

This property is used to rate the resistance of a material to plastic deformation under sustained load. For metals, creep strength is often expressed as the stress necessary to produce 0.1% strain in 1000 hrs. In polymers, a percent deformation at a given stress is often used. Creep data must also show the testing temperature.

Typical creep testing is illustrated in Figure 3.31.

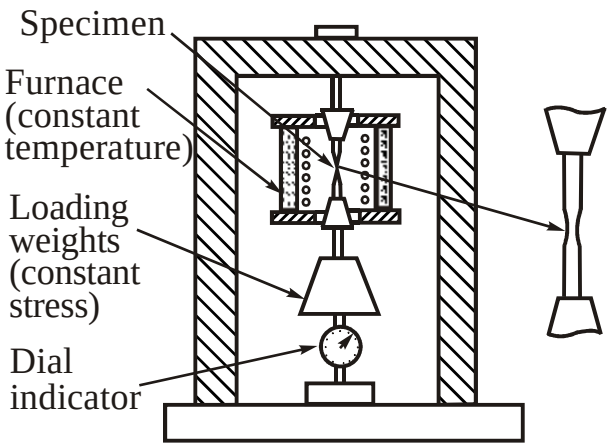


Figure 3.31 Creep tester. A specimen is placed in a furnace at an elevated temperature under a constant applied stress

To determine the creep characteristics of a material, a constant stress is applied to a cylindrical specimen placed in a furnace (Figure 3.31). As soon as the stress is applied, the specimen stretches elastically a small amount e_0 (Figure 3.32), depending on the applied stress and the modulus of elasticity of the material at the high temperature.

Table 3.5 gives the approximate temperatures at which several metals begin to creep. Creep is not too important with most ferrous metals unless the operating temperature is above 350…400°C.

Creep can be an important selection factor with low melting temperature metals and polymers. It is a principal cause of failure of fixtures and hangers in furnaces. In epoxy–bonded piping systems, the creep strength of the epoxy is often the weak link in the system. Polymeric bearings often develop excessive clearance owing to compressive creep. The solution to these types of problems is to use materials with good creep characteristics.

3.4.2 Dislocation Climb in Creep

As you know the high temperature permits dislocations in the metal to climb. In climb, atoms move either to or from the dislocation line by diffusion, causing the dislo-

cation to move in a direction that is perpendicular, not parallel, to the slip plane (Figure 3.33). The dislocation can now escape from lattice imperfections that block the slip process. The dislocation, after climbing away from the imperfection, continues to slip and causes additional deformation of the specimen even at low applied stresses.

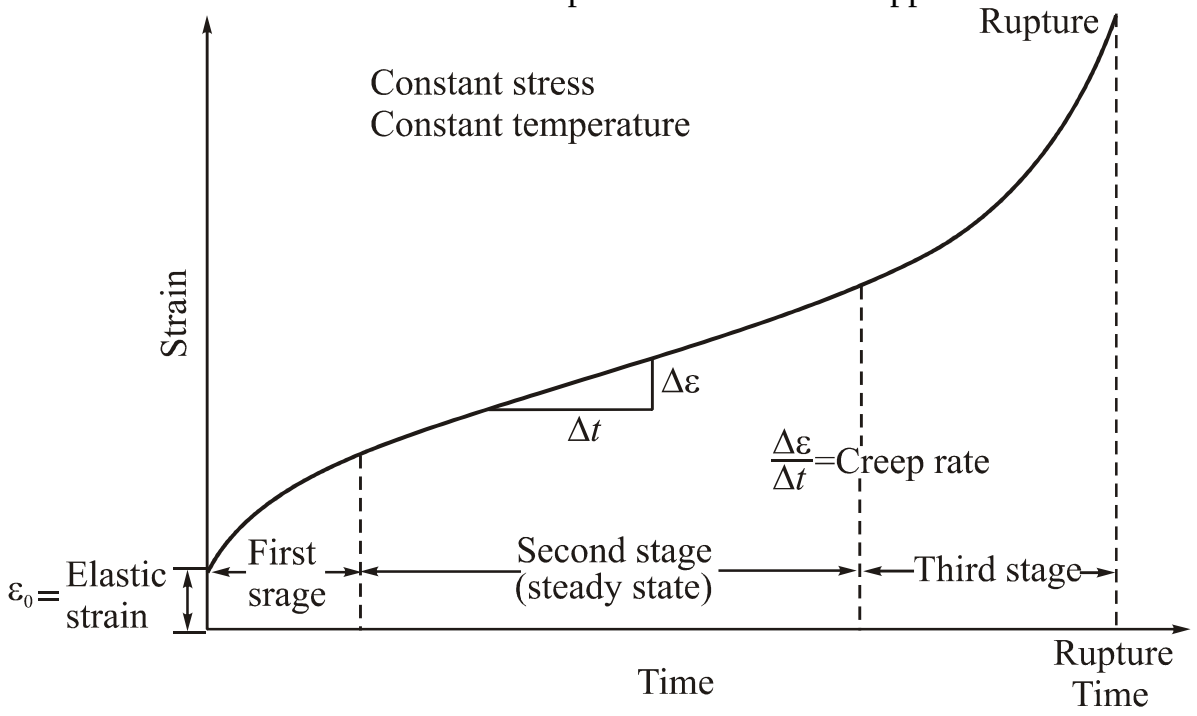


Figure 3.32 A typical creep curve showing the strain produced as a function of time for a constant stress and temperature

Table 3.5 Approximate temperatures at which creep becomes important for selected metals and alloys

Metal	Temperature, °C
Aluminum alloys	200
Titanium alloys	325
Low-alloy steels	375
High-temperature steels	550
Nickel and cobalt superalloys	650
Refractory metals (tungsten, molybdenum)	1000…1550

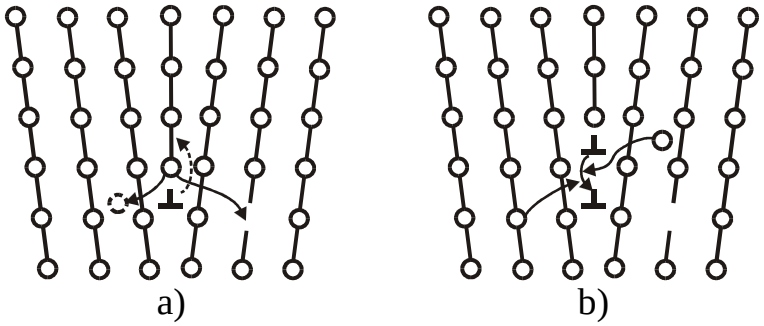


Figure 3.33 Dislocations can climb away from obstacles when atoms leave the dislocation line to create interstitials or to fill vacancies (a) or when atoms are attached to the dislocation line by creating vacancies or eliminating interstitials (b)

3.4.3 Creep Rate and Rupture Time

During the creep test, the strain or elongation is measured as a function of time and plotted to give the creep curve (Figure 3.32). In the first stage of creep, many dislocations climb away from obstacles, slip, and contribute to deformation of the metal. Eventually, the rate at which dislocations climb away from obstacles equals the rate at which dislocations are blocked by other imperfections. This leads to second-stage, or *steady-state*, *creep*. The slope of the steady-state portion of the creep curve is called the *creep rate*:

$$\text{Creep rate} = \frac{\Delta \text{ strain}}{\Delta \text{ time}}. \tag{3.18}$$

Eventually, during third-stage creep, necking begins, the stress increases, and the specimen deforms at an accelerated rate until failure occurs. The time required for failure to occur is the *rupture time*. Either a higher stress or a higher temperature reduces the rupture time and increases the creep rate (Figure 3.34).

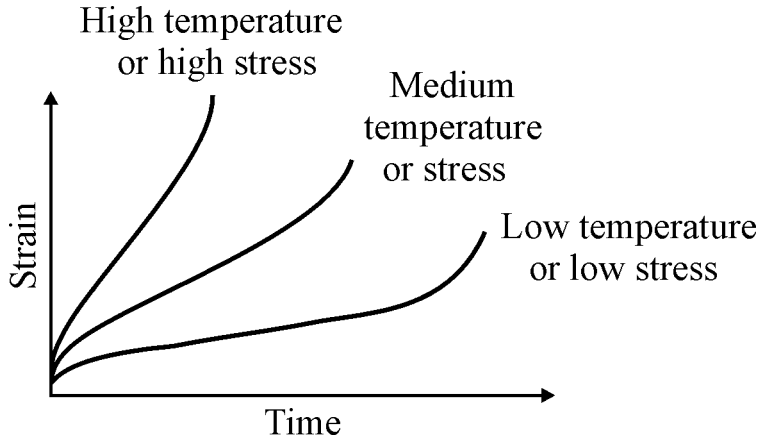


Figure 3.34 The effect of temperature or applied stress on the creep curve

Example 3.13

Use the results of a creep test in Table 3.6 and calculate the creep rate in (m./m.)/h.

Answer

The data in Table 3.6 are plotted in Figure 3.35. From the slope of the steady-state portion of the curve

$$\text{Creep rate} = \frac{\Delta e}{\Delta t} = \frac{0.021 - 0.009}{6000 - 1000} = \frac{0.012}{5000} = 2.4 \times 10^{-6} \text{ (m./m.)/h}. \qquad (3.19)$$

Table 3.6 Data from a creep test for Example 3.13

Time, h	0	250	1000	2250	3500	4750	6000	7100	7500	7750
Strain, m./m.	0.003	0.006	0.009	0.012	0.015	0.018	0.021	0.024	0.027	0.030

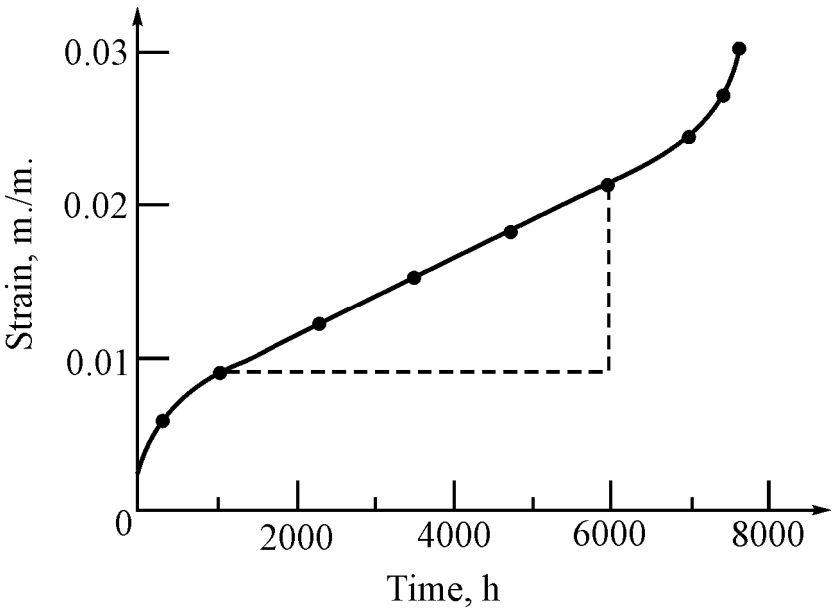


Figure 3.35 Graph of the data in Table 3.6 to produce a creep curve. The slope of the steady-state portion of the graph is the answer to Example 3.13

3.4.4 Use of Creep Data

Four ways are used to present the results from a series of creep tests are shown in Figure 3.36.

1. Stress-rupture curve

The *stress-rupture curve* shown in Figure 3.36 (a) permits us to estimate the expected lifetime of a component for a particular combination of stress and temperature. The property of *stress-rupture* complements creep data. It shows the stress at which a component will fail under sustained load at elevated temperature. Stress rupture tests a usually conducted with dead-weight loading of the specimen, and the

strain is not reported. A typical stress-rupture curve is shown in Figure 3.37.

Stress-rupture tests are not usually conducted on polymeric materials, but they are important for metals or ceramics intended for high-temperature service. Reviewing the data in Figure 3.37, it can be seen how stress-rupture data are used. If a part was to be used at 540°C, it would only last 1000 hours if the operating stress was 360 MPa. If the operating stress was lowered to 140 MPa, the expected service life would be in excess of 10,000 hours. At 820°C, a stress level of 140 MPa would result in failure after less than 1000 hours of service. Thus, stress-rupture data can be a useful tool in selecting materials.

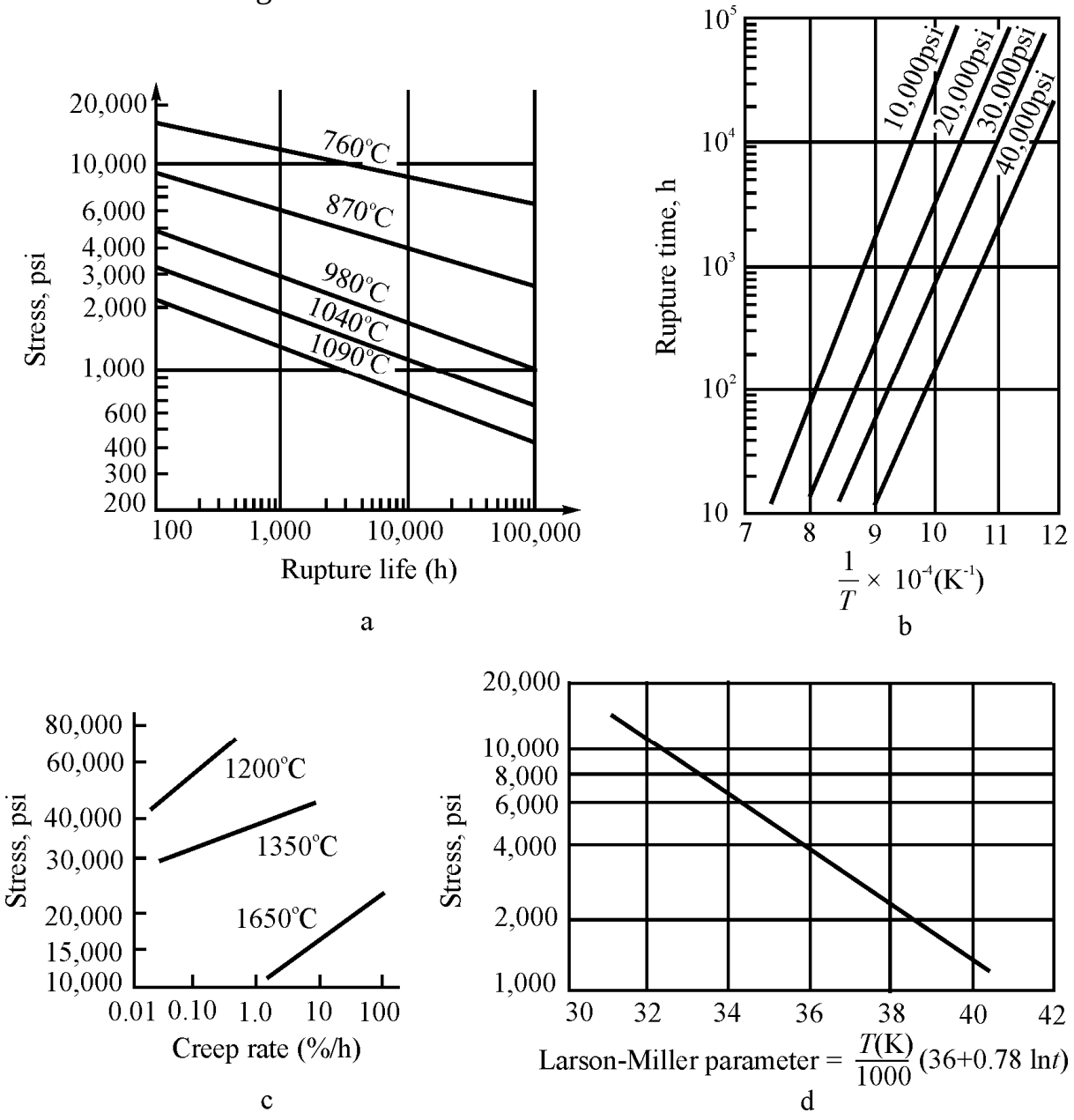


Figure 3.36 Results from a series of creep tests: (a) stress-rupture curves for an iron-chromium-nickel alloy; (b) rupture time versus reciprocal temperature for a nickel heat-resistant alloy; (c) minimum creep rate curves for a tantalum alloy; (d) Larson-Miller parameter for ductile cast iron

2. Rupture time versus temperature

Figure 3.36 (b) depicts the rupture time versus the reciprocal of temperature for a constant stress; this presentation of the data suggests an Arrhenius relationship for the rupture time and would permit an activation energy for the process to be calculated.

3. Stress versus creep rate

Using Figure 3.36 (c) an important selection factor – *creep rate* can be estimated

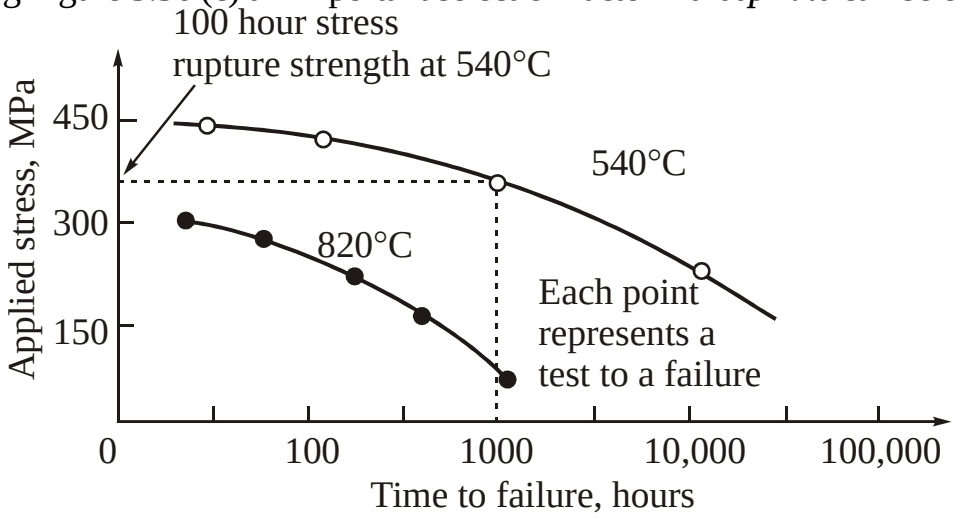


Figure 3.37 Typical stress-rupture data

for a particular combination of an applied stress and temperature.

4. Larson-Miller parameter

The *Larson-Miller parameter,* illustrated in Figure 3.36 (d) is used to consolidate the stress-temperature-rupture time relationship into a single curve.

Example 3.14

Using the Larson-Miller parameter for ductile cast iron, as shown in Figure 3.36 (d), determine the time required before the metal fails at an applied stress of 6000 psi (41,4 MPa) and temperatures of 400°C and 600°C.

Answer

The Larson-Miller parameter for 6000 psi is 34.3.

a) At 400 °C: $$34.3 = \frac{(400 + 273\text{K})}{1000}(36 + 0.78\ln t),$$

$$0.78\ln t = (34.4)\left(\frac{1000}{673}\right) - 36 = 14.97,$$

$$t = 2.2 \cdot 10^8 h = 25{,}000 \text{ years}. \qquad (3.20)$$

b) At 600 °C: $$34.3 = \frac{(600 + 273\text{K})}{1000}(36 + 0.78\ln t),$$

$$0.78\ln t = (34.4)\left(\frac{1000}{873}\right) - 36 = 3.29,$$
$$t = 67.9h = 2.8\,\text{days}. \qquad (3.21)$$

3.5 Hardness Test

3.5.1 Nature of the Hardness Test

Hardness is probably one of the most used selection factors. The hardness of materials is often equated with wear resistance and durability. In steels it serves as a measure of abrasion resistance and strength.

There are many ways of measuring hardness. In the early days of metallurgy, heat–treated steels were tested for hardness by filing an edge. If it did not file, it was hard. The hardness of ceramics and minerals was and still is measured by scratching the surface with different types of minerals. This is called the *Mohs hardness test.* Most present-day hardness tests consist of pushing a penetrator into the material and measuring the effects. Some of the most commonly used penetrators are shown in Figure 3.38. The loading mechanism varies with the various tests, as does the mechanism for measuring the effect of the indentation.

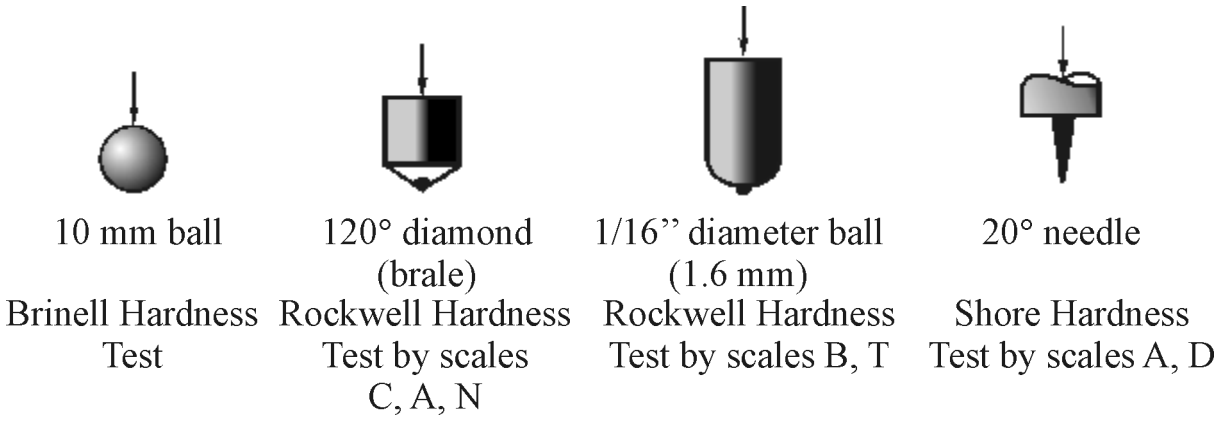


Figure 3.38 Typical penetrators used in hardness tests

The most commonly used are the *Rockwell hardness test* and the *Brinell hardness test.* In the Brinell hardness test a hard steel sphere, usually 10 mm in diameter, is forced into the surface of the material. The diameter of the impression left on the surface is measured using optical measuring device and the Brinell hardness number (HB) is calculated from the following equation:

$$\mathrm{HB} = \frac{F}{(p/2)D\left(D - \sqrt{D^2 - D_i^2}\right)}, \tag{3.22}$$

where F is the applied load in kilograms, D is the diameter of the indentor in millimeters, and D_i is the diameter of the impression in millimeters.

The Rockwell hardness test uses either a small diameter steel ball for soft materials or a diamond cone, or Brale, for harder materials. The depth of penetration of the indentor is automatically measured by the testing machine and converted to a Rockwell hardness number.

A more sophisticated tester is the *micro-hardness tester* (the Vickers and Knoop tests). This device has a precise diamond indentor that can be used to measure the hardness of microscopic particles or metal phases. The scale range is such that the hardness of polymers, metals, and ceramics can be measured.

The Vickers and Knoop test form such small indentations that a microscope is required to obtain the measurement (Figure 3.39).

A common hardness test for polymers and elastomers (plastics that behave like rubber) is the *Shore durometer test*. Hardness is measured by pushing a spring–loaded needle into the material (Figure 3.40).

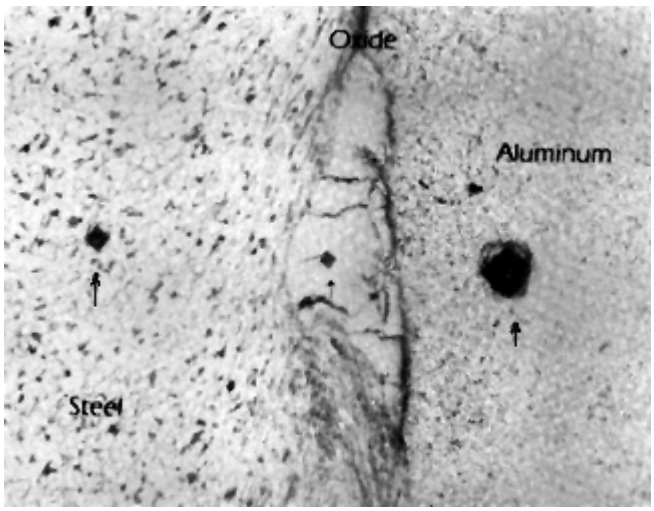


Figure 3.39 Microhardness impressions in an explosive bond joining aluminum to steel. The small size of the impression indicates that the inclusion trapped at the interface is harder than either aluminum or steel (x 200)

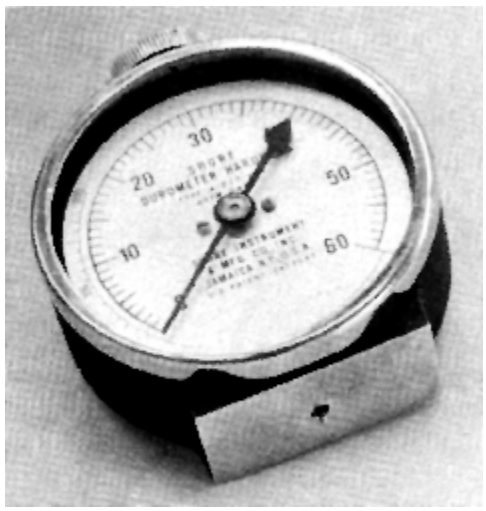


Figure 3.40 Shore durometer hardness tester. Needle on the bottom is the penetrator

3.5.2 Use of the Hardness Test for Material Selection

Hardness numbers are used primarily as a basis for comparison of materials, specifications for manufacturing and heat treatment, quality control, and correlation

with other properties and behavior of materials. For example, Brinell hardness is closely related to the tensile strength of steel by the relationship

$$\text{Tensile strength (psi)} = 500\,\text{HB}. \tag{3.23}$$

A Brinell hardness number can be obtained without destroying the component, yet provides a close approximation for the tensile strength.

Hardness correlates well with wear resistance. A material used to crush or grind either should be very hard to assure that the material is not eroded or abraded by the hard feed materials. Similarly, gear teeth in a transmission or drive system of a vehicle should be hard so that the teeth do not wear out. Typically we find that polymer materials are exceptionally soft, metals have an intermediate hardness, and ceramics are exceptionally hard.

Example 3.15

A Brinell hardness test is performed on steel using a 10 mm indentor with a load of 3000 kg. A 3.2-mm impression is measured on the surface of the steel. Calculate the *HB,* the tensile strength, and the endurance limit of the steel.

Answers

$$\text{HB} = \frac{3000}{\left(p/2\right)(10)\left(10 - \sqrt{10^2 - 3.2^2}\right)} = 363\,\text{kg/mm}^2. \tag{3.24}$$

$$\text{Tensile strength} = 500\,\text{HB} = (500)(363) = 181{,}600\ \text{psi} = 1252\ \text{MPa}.$$

$$\text{Endurance limit} = 0.5\ \text{tensile strengh} = (0.5)(181{,}600) = 90{,}800\ \text{psi} = 626\ \text{MPa}.$$

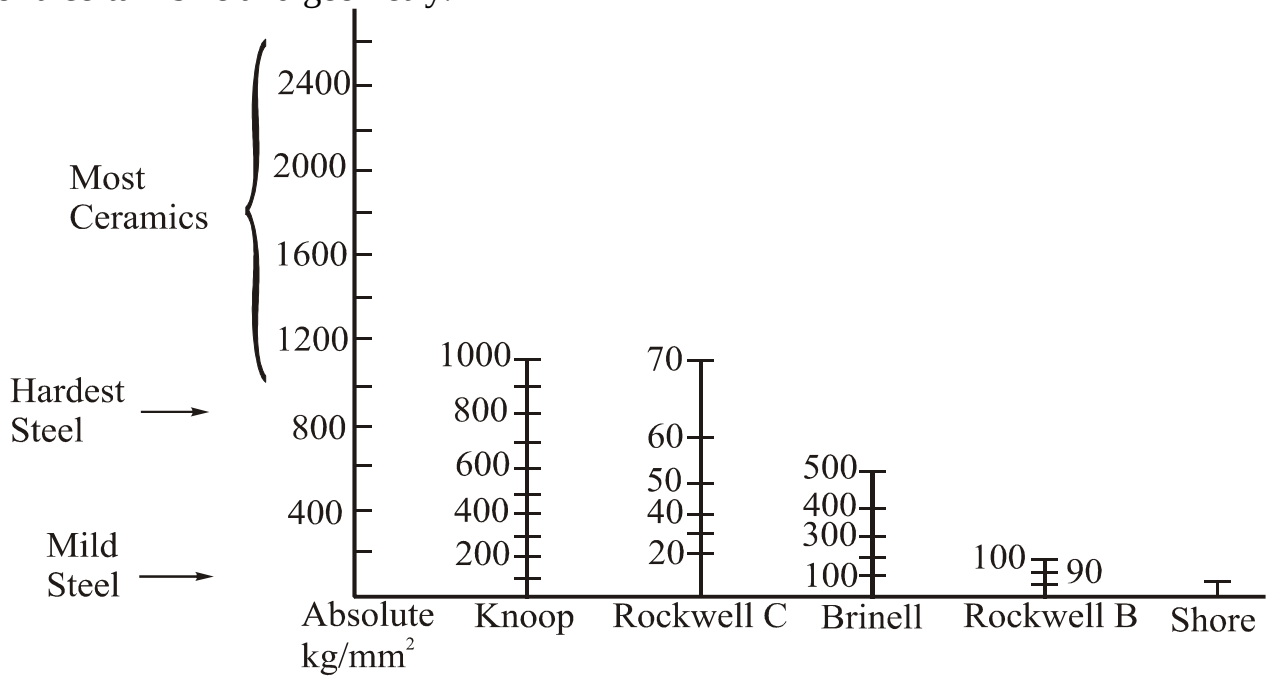
The hardness tests of most importance in material selection are those shown in Figure 3.41. They differ in penetrator, load, and applicability. Unfortunately, hardness numbers measured on one test cannot always be converted to a comparable hardness measured on another scale. An approximate conversion between some scales is shown in Figure 3.41. As a minimum, the designer should become familiar with the Rockwell B, C, and R tests, the Brinell test, and Shore durometer tests. It is the designer's responsibility to specify the desired hardness on engineering drawings where the material can be hardened by heat treatment or fabrication. Of primary concern are hardenable metals and elastomers. The Shore durometer hardness of elastomers can vary over a wide range.

There are various ways of specifying the hardness of metals; a system used by many industries is shown in Figure 3.42. The hardness of ceramics cannot usually be measured by any of the tests listed in Figure 3.41 except the Knoop or Vickers. The scale is shown to stop at 1000 HK, but it continues well above this value. Absolute hardness is measured by a microhardness machine, and the measurement is expressed as a pressure in kilograms/square millimeter (kg/mm^2). These hardness values are obtained by dividing the penetration load by the projected area of the indentation.

3.6 Fracture Characteristics

3.6.1 Introduction to Fracture Mechanics

Fracture mechanics is the discipline that studies the stress-strain state of materials containing cracks or other small flaws. All materials contain some flaws; we wish to know the maximum stress that the material can withstand if it contains flaws of a certain size and geometry.



Hardness Test	Indentor	Load	Application
Knoop or Vickers	Diamond	1 g to 2000 g	Microhardness of soft steels to ceramics
Brinell	Ball	500 & 3000 kg	Soft steels & metals to 40 HRC
Rockwell B	Ball	100 kg	Soft steels & nonferrous metals
Rockwell T	Ball	15, 30 & 45 kg	Thin soft metals
Rockwell N	Diamond	15, 30 & 45 kg	Hard thin sheet metals
Rockwell A	Diamond	50 kg	Cemented carbides
Rockwell R	Ball	10 kg	Polymers
Shore Durometer	Needle	Spring	Elastomers
Rockwell C	Diamond	150 kg	Hardened metals (thick)

Figure 3.41 Comparison of hardness tests

A typical *fracture mechanics test* may be performed by applying a tensile

stress to a specimen prepared with a flaw of known size and geometry (Figure 3.43).

If the specimen is thick enough, a "plain strain" condition is produced which gives the worst behavior of the material. The stress required to propagate a crack from the prepared flaw can be measured. The ***stress intensity factor K*** then can be calculated. In simple tests, the stress intensity factor is

$$K = fs\sqrt{ap}\,, \tag{3.25}$$

where f is a geometry factor for the specimen and flaw, s is the applied stress, and a

Specify hardness according to the code described in below.

This code is in agreement with the method of designation used by the following standards organizations:

1. American Society for Testing and Materials (ASTM)
2. American National Standards Institute (ANSI)
3. International Standards Organization (ISO)

XXX H X X

HARDNESS VALUE – Designate values in the appropriate scale range. Specify either limits, maximum or minimum as required

LATTER CODE FOR HARDNESS

LETTER DESIGNATION FOR HARDNESS MEASUREMENT METHOD

R=Rockwell
V=Vickers (DPH-Diamond Pyramid Hardness)
K=Knoop
B=Brinell

ROCKWELL HARDNESS SCALE DESIGNATIONS

(These designations are used only when the Rockwell test method has been specified)

B=Rockwell B scale
C=Rockwell C scale
15T=Rockwell Superficial 15T scale
15N=Rockwell Superficial 15N scale
etc.

Examples:

1) 50-60HRC means: a hardness value of 50 to 60 using the Rockwell C scale.

2) 85HR15T MAX means: a maximum hardness value of 85 using the Rockwell Superficial 15T scale.

3) 185-240 (1kgf) means: a hardness value of 185-240 using the Vickers hardness tester and a test load of 1 kilogram-force.

4) 500HK MIN (200gf) means: a minimum hardness value of 500 using the Knoop hardness tester and a test load of 200 grams-force.

Figure 3.42 Specification of hardness numbers for metals

is the flaw size as defined in Figure 3.43.

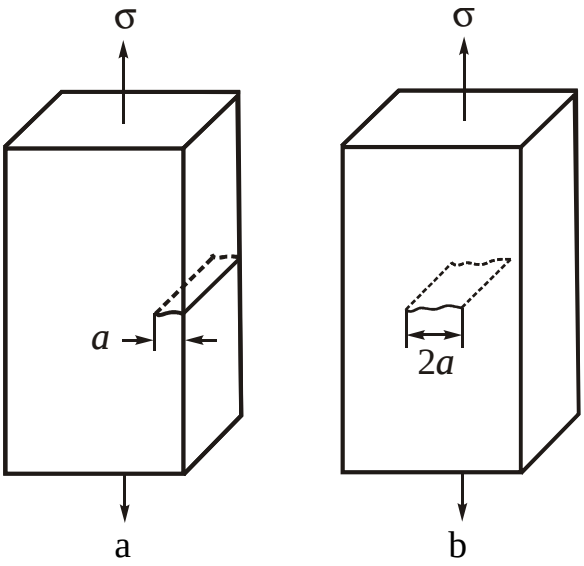


Figure 3.43 Two types of flaws in fracture toughness specimens: (a) - edge; (b) – internal

For thick plate, $f \approx 1$. If K is greater than or equal to a critical value K_{1c}, the flaw grows and the material fails. The *critical fracture toughness* K_{1c} is a property of the material (Table 3.7).

A similar approach can be used to determine the ease with which a flaw grows in torsion, impact, fatigue, or other loading conditions.

The ability of the material to resist the growth of a crack depends on a large variety of factors, including the following.

1. Larger flaws reduce the permitted stress. Special manufacturing techniques have been devised to improve fracture toughness. For example, liquid aluminum is passed through a ceramic filter to remove impurity particles, whereas the AOD process (argon-oxygen decarburization) has been developed to produce steels containing fewer oxide inclusions.

2. Increasing the strength of a given metal tends to reduce fracture toughness, as shown for the titanium alloy in Table 3.7. This is often associated with the lower ductility that the stronger alloys possess.

Table 3.7 The critical fracture toughness for selected materials

Material	Critical Fracture Toughness, psi·in$^{1/2}$	Critical Fracture Toughness, MPa·m$^{1/2}$	Yield Strength, psi	Yield Strength, MPa
Al-Cu alloy	22,000 33,000	24.2 36.3	66,000 47,000	455 324
Ti-6% Al-4% V	50,000 90,000	54.9 98.9	130,000 125,000	896 862
Ni-Cr steel	45,800 80,000	50.3 87.9	238,000 206,000	1641 1420
$A1_2O_3$	1,600	1.8	30,000	207
Si_3N_4	4,500	4.9	80,000	552
Transformation toughened ZrO_2	10,000	11.0	60,000	414
Si_3N_4-SiC composite	51,000	56.0	120,000	827

3. Thicker materials have a lower stress intensity factor *K* than thin materials (Figure 3.44 (a)). However, the fracture toughness is less predictable for thin sections, due to the increased section size sensitivity as the thickness of the specimen approaches the size of the flaws.

4. Increasing the temperature normally increases the fracture toughness of BCC and HCP metals. However, the fracture toughness of FCC metals is relatively unaffected by temperature (Figure 3.44 (b)).

5. The ability of a material to deform is critical. In ductile metals, the material near the tip of the flaw can deform, helping to absorb energy and blunt further crack growth. Brittle materials such as glass cannot deform; consequently, the crack propagates with little energy required. Each engineer must know some of the methods used to improve the fracture toughness of brittle materials such as ceramics, thermosetting polymers, and composites.

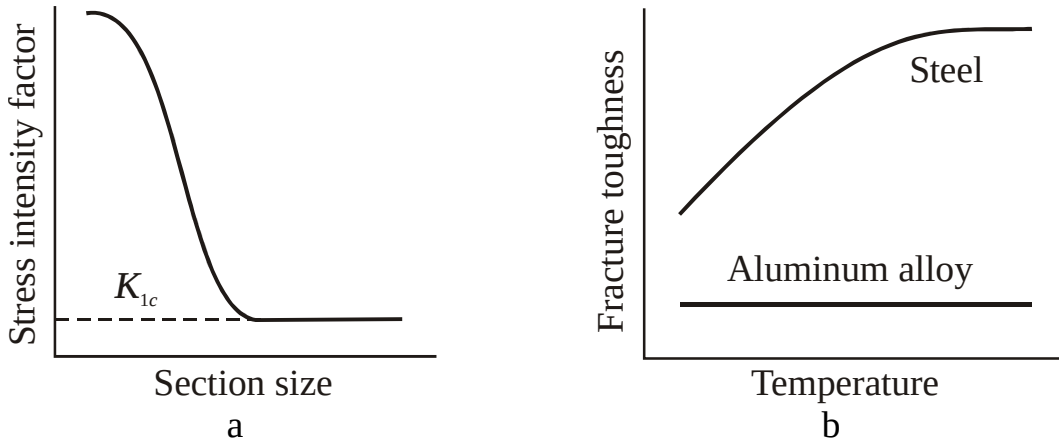


Figure 3.44 The effect of (a) section size, (b) temperature, and crystal structure on the stress intensity factor and fracture toughness of materials

3.6.2 Importance of Fracture Characteristics in Design

Our knowledge in fracture mechanics allows us to design and select materials while taking into account the inevitable presence of flaws. There are three variables to consider – the property of the material (K_{1c}), the stress s that the material must withstand, and the size of the flaw a.

We must be able to set an upper limit on the size of any flaw that is present by *nondestructive testing*. For example, *ultrasonic testing* or *X-ray radiography* may detect any flaw longer than 0.1 mm. This fixes the largest size a and gives us the worst condition that the material will face. If we know the magnitude of the applied stress, we can select a material that has a fracture toughness K_{1c} large enough to prevent the flaw from growing. Or, if the material has already been specified, we can calcu-

late the maximum permitted stress that can act on the material. Finally, if we know both the applied stress and the fracture toughness of the material, we can determine if our nondestructive testing capability is adequate.

Example 3.16

For a large plate, the geometry factor f is one. Suppose a steel-casting alloy has a critical fracture toughness of 80,000 psi·in$^{1/2}$ (87.9 MPa·m$^{1/2}$). The steel will be exposed to a stress of 45,000 psi (310 MPa) during service. Calculate the minimum size of a crack at the surface (edge crack) that will grow. Repeat the calculation for an internal crack.

Answer

$$K = fs\sqrt{ap}\ ,$$

$$80{,}000 = (1)(45{,}000)\sqrt{ap}\ ,$$

$$\text{or}\quad (87{,}9) = (1)(310)\sqrt{ap}\ .$$

$$\text{For a surface (edge) crack}: a = \frac{1}{p}\left(\frac{80{,}000}{45{,}000}\right)^2 = 1\,\text{in} = 25.4\,\text{mm}.$$

$$\text{For an internal crack}: 2a = 2\,\text{in} = 50.8\,\text{mm}.$$

3.7 Dimensional Properties

3.7.1 Main Definitions

Roughness is a relatively finely spaced surface irregularities, the height, width, and directions of which establish a definite surface pattern.

Waviness is a wavelike variation from a perfect surface; generally much wider in spacing and higher in amplitude than surface roughness.

Lay is the direction of a predominating surface pattern, usually after a machine operation.

Camber is a deviation from edge straightness; usually the maximum deviation of an edge from a straight line of given length.

Out of flat is the deviation of a surface from a flat plane, usually over a macroscopic area.

Surface finish is the microscopic and macroscopic characteristics that describe a surface.

3.7.2 Surface Finish

The surface characteristics of engineering materials often have a significant effect on serviceability and thus cannot be neglected in design. It is the designer's responsibility to specify the nature of the surface on machine components. About 20

mathematical parameters are applied to the characterization of a surface, but the most commonly used parameters are roughness, waviness, and lay (Figure 3.45). Lay is usually macroscopic and can be measured visually or with a simple loupe. Total surface profile, which is the net of the surface roughness and waviness, is usually measured by profilometer devices that electronically measure surface texture with a stylus not unlike a phonograph needle.

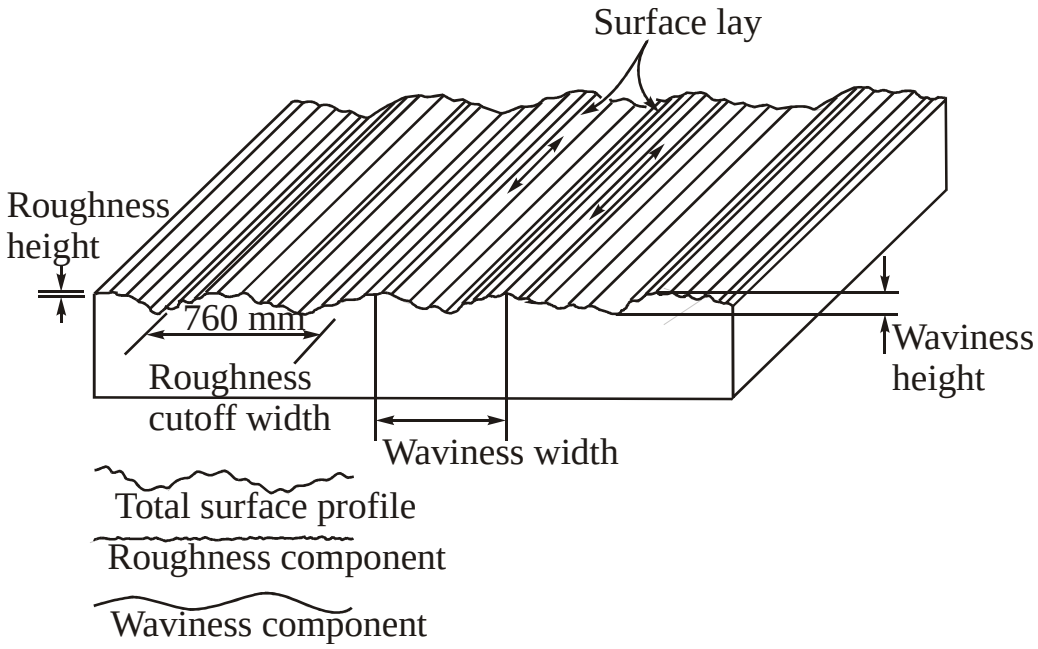


Figure. 3.45 Components of surface microtopography

The simplest profilometers yield only surface roughness data. The more sophisticated devices yield contour maps, single-line surface profiles, and roughness average data (Figure 3.46). Surface roughness is usually expressed as the arithmetic average (AA) of the peak-to-valley height of surface asperities in microinches (μin). The SI units are micrometers (μm). Since a profilometer stylus has a finite radius (usually 0.0001 in or 2.5 μm), it cannot reach the bottom of valleys of surface features; it cannot measure true depth. The AA roughness is approximately 25% of the true peak-to-valley height. Most profilometers average the surface roughness over a set increment of stylus travel. This is called the *cutoff width*. All the surface peaks in this distance are integrated to yield a single roughness reading.

The parameters of waviness are *waviness height* and *waviness width*. Surface lay has no quantitative units, but there are symbols to indicate a desired lay. The American National Standards Institute (ANSI) has devised a system for describing surface texture on engineering drawings (see Figure 3.47).

The surface finish importantly relate to selection and serviceability. There is an optimum range of surface roughness for parts intended for accurate fits, wear ap-

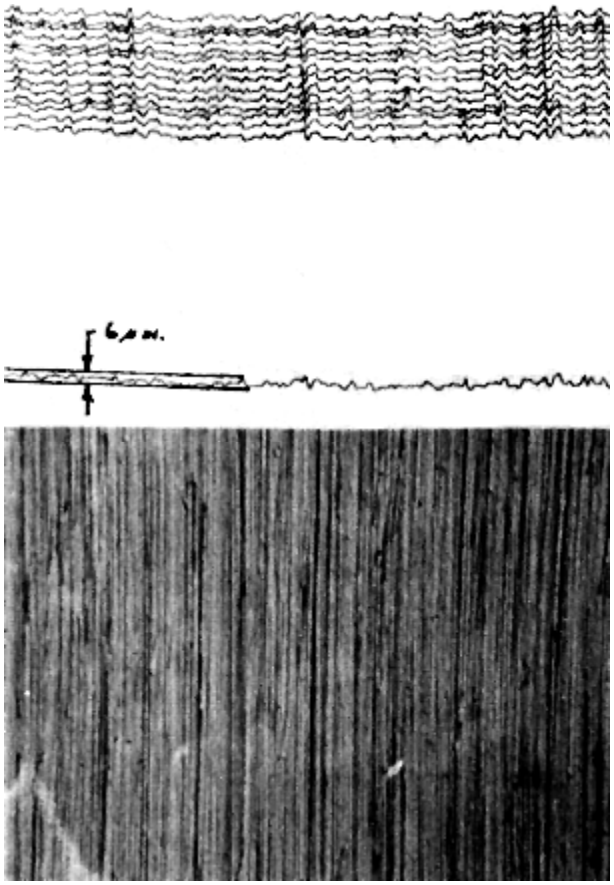


Figure 3.46 Profilometer map of a ground surface (top), single line trace (middle), photomicrograph at 200 × (bottom)

plications, release characteristics, and even nonfunctional surfaces. If a rotating shaft is too rough, it could abrade a soft bearing material. Coarse machine marks cause stress concentrations that can lead to fatigue failures. Surfaces with redundant finish characteristics unnecessarily increase fabrication costs.

Figure 3.48 presents some experience guidelines on finishes to call for on selected machine components. Figure 3.49 shows the surface finish ranges possible with various machining techniques. This illustration points out the inadequacy of using surface descriptors such as grind, turn, and drill. A ground surface can be as rough as 120 μin AA (3 μm) or as smooth as 4 μin AA (0.1 μm). Surface finish requirements should always be expressed by using quantitative limits on at least surface roughness. The preferred technique is the use of the ANSI system outlined in Figure 3.47.

3.7.3 Size and Shape Considerations in Material Selection

A primary material selection factor used by designers is material availability in the size and shape required for the part under design. A mechanical property study may show that type 317 stainless steel is the best material for a support column under design. If the job requires a 3.0 m long, 8 cm by 12 cm channel, and this shape is not available in small quantities from a warehouse, this material cannot be used. Similarly, if a material is required for an accurate machine baseplate, a primary selection factor may be the availability of a material with good flatness tolerances.

Camber, an edge bow in sheet or strip, is important in using sheet and strip materials. If a material is available in the desired thickness and overall size but comes in with excessive camber, it may not be usable for the intended application.

Stock tolerances are important if areas of a part are to be used in the as-received condition. Some material shapes are made with a tolerance of plus 1 % of the nominal thickness, minus nothing. If a part requires a minimum thickness of, for example, 1.25 mm, the thickness tolerances should be investigated on candidate ma-

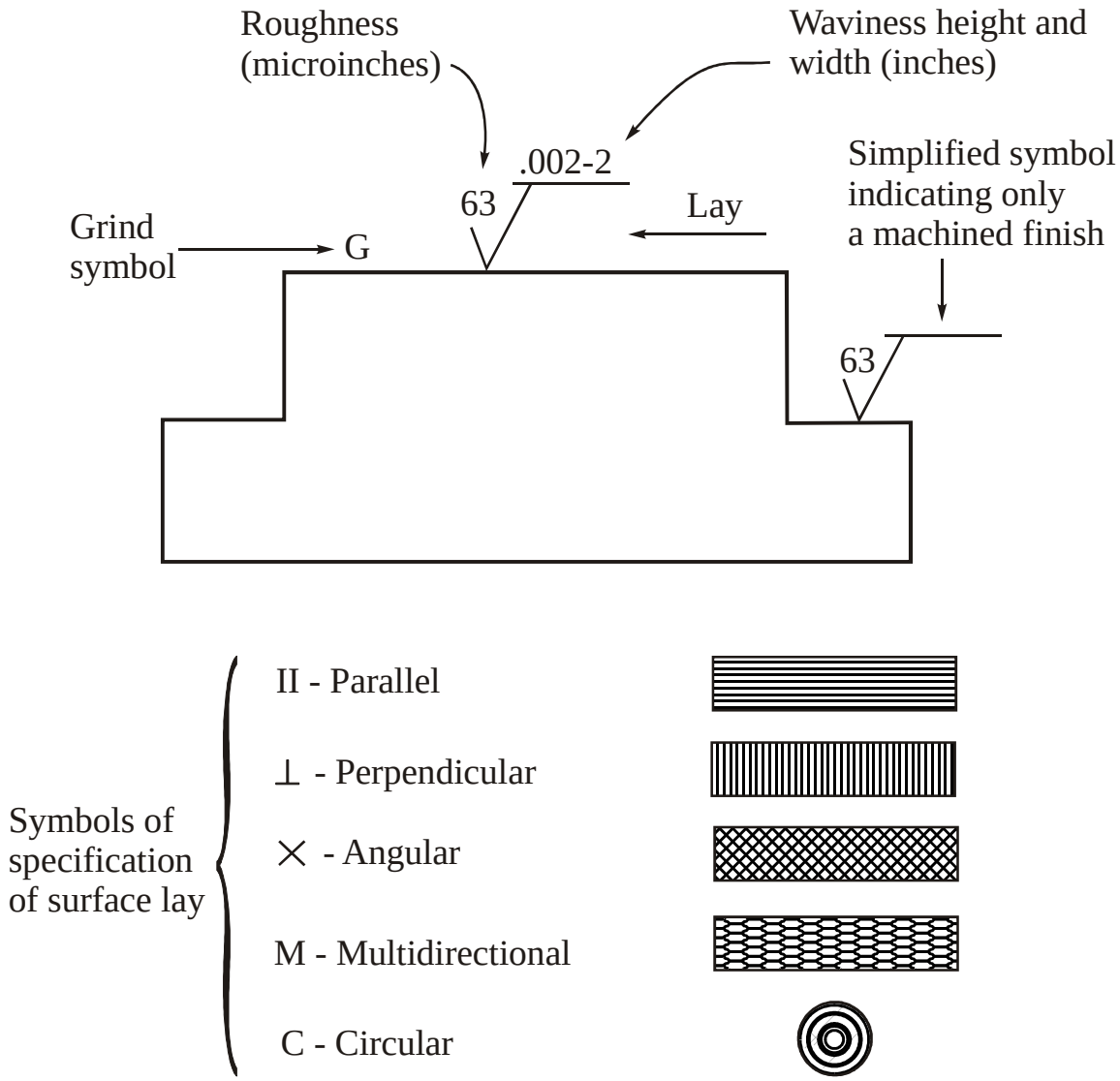


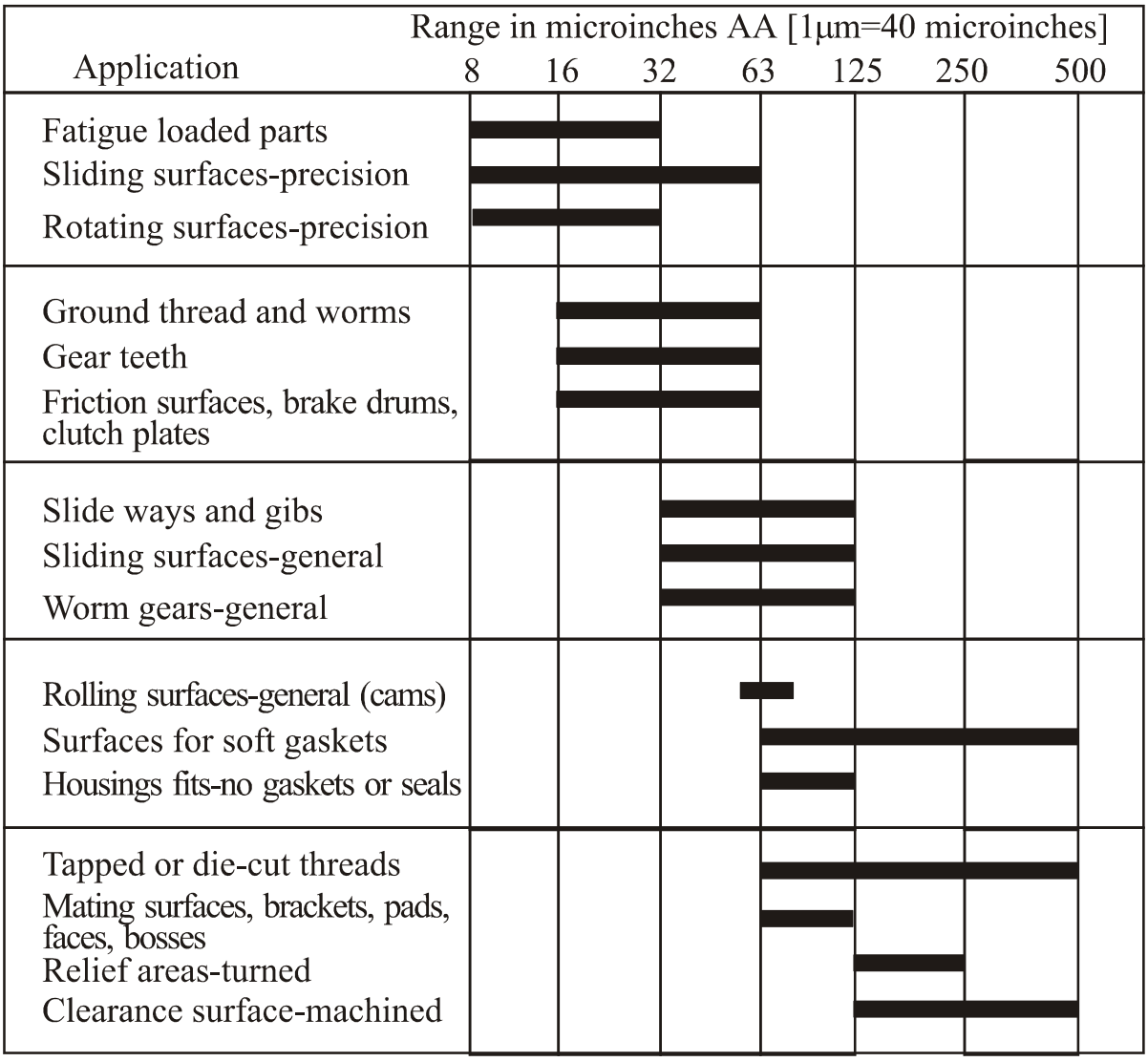
Figure 3.47 Specification of surface texture (American Standard Surface Texture ANSI B46.1-78)

terials for a part under design. If a material with a nominal thickness of 1.25 mm is ordered and it comes in with a thickness of 1.24 mm, it may be useless.

Occasionally, a particular material form will lead to dimensional problems. Hot-rolled steels have a loose "flaky" scale, and the surface finish is usually too poor to use without machining. If the designer did not consider this when the material was specified, it may make the purchased material unusable or it may significantly add to machining costs.

Castings may come from the foundry with gouges left from gate removal; sometimes flash or mold pickup are not removed. The designer can control these factors by drawing notation calling for sandblasted, flash-free castings free of surface defects.

Extruded shapes are usually bowed and twisted when they are made. If long lengths are required, the designer should use materials that are available as straight ened



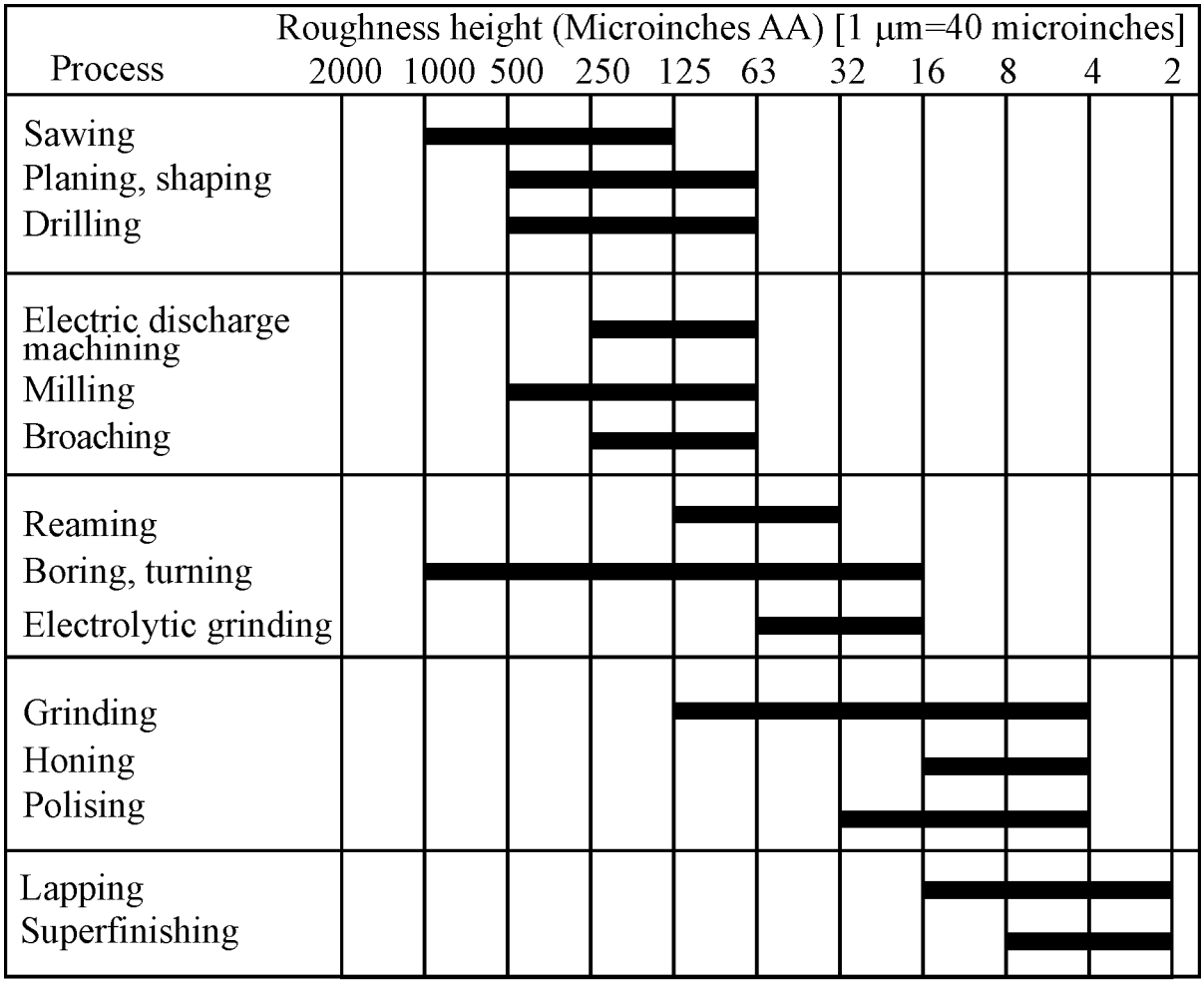
The ranges shown are ordinary considered desirable for the conditions listed.

Figure 3.48 Recommended surface roughness for machine parts

extrusions.

Mentioned above are some of the size and shape considerations that are part of the dimensional properties of materials. How should a designer deal with these factors? A checklist on dimensional property requirements should be mentally reviewed immediately after the part is designed. The checklist should contain the following factors:

1. Surface roughness requirements
2. Flatness requirements
3. Lay



The ranges shown above are typical of the processes listed.

Figure 3.49 Surface roughness produced by various machining techniques

4. Stock tolerances
5. Camber
6. Surface cleanliness
7. Edge tolerances
8. Bow tolerances
9. Surface reflectance
10. Should prefinished material be used?

The designer should establish which of these factors will affect part serviceability. If it is clear that some of these factors are important, then steps should be taken to specify dimensional requirements on engineering drawings and purchasing specifications.

Summary

The mechanical behavior of materials is described by their mechanical properties, which are the results of idealized, simple tests. These tests are designed to present different types of loading conditions. The tensile test describes the resistance of a material to a slowly applied load; the results define the yield strength, ductility, and stiffness of the material. The fatigue test permits us to understand how a material performs when a cyclical stress is applied, the impact test indicates the shock resistance of the material, and the creep test provides information on the load–carrying ability of the material at high temperatures. The hardness test, beside providing a measure of the wear and abrasion resistance of the material, can be correlated to a number of other mechanical properties. Fracture mechanics takes into account the presence of flaws in the material. Finally, dimensional properties are characterized by a number of indices, which permit us to choose recommended parameters for machine parts.

Our discussion of the properties of materials is far from being complete, but the properties described are the ones that refer to most applications of engineering materials in design. If the problem is selection of a material for a unique product design or a very specialized machine application, it may be necessary to consider a number of properties not mentioned here. As an example, there are probably 20 magnetic properties not discussed, as well as many electrical properties of polymers and ceramics. It must be noted that every property that can affect serviceability of a machine component should be given thorough consideration. One final question may arise with regard to material properties. Where do you find this property information? Engineering handbooks and industry–published data books usually present the most valid and unbiased data. Nevertheless extra care should be taken in observing the test conditions under which the data were obtained. It is possible to select a test that makes one material look favorable compared with others. The best method for ensuring validity of data is to use only data developed according to test procedures rigidly outlined by state standards, for example, the American Society for Testing Materials. Each vendor should show the ASTM procedure used with a symbol such as ASTM – ×××. Handbooks do not usually do this, but as mentioned previously they have no reason to enhance data to show one material to be better than another. The complete ASTM procedure for measuring a particular property can be readily obtained from the ASTM or in any engineering library.

Finally, the theme for proper use of material–property information in material selection is to analyze the data and make sure that the same test was used to measure the properties under comparison. This is especially true when considering use of different classes of materials (i.e., polymer versus metal versus ceramic).