ENGINEERING MATERIALS

Mechanical Engineering Department/ Year 4

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Properties of Materials

1. Introduction

When selecting a material for a product or application, it is important to ensure that its properties will be adequate for the anticipated operating conditions. The various requirements of each part or component must first be estimated or determined. These requirements typically include mechanical characteristics (strength, rigidity, resistance to fracture, the ability to withstand vibrations or impacts) and physical characteristics (weight, electrical properties, appearance) as well as features relating to the service environment (ability to operate under extremes of temperature or to resist corrosion). Candidate materials must possess the desired properties within their range of possibilities.

Much of a manufacturing education relates to an understanding of (1) the structure of materials, (2) the properties of materials, (3) the processing of materials, and (4) the performance of materials, and the interrelations between these four factors.

Most engineering materials do not have a single set of properties but rather offer a range or spectrum of possibilities. To help evaluate the properties of engineering materials, a variety of standard tests have been developed, and data from these tests have been tabulated and made readily available.

This chapter will begin to address the properties of engineering materials and begin to provide the whys behind various properties. Chapters 2 will introduce the types of

materials and their properties. Chapter 3 will discuss the subject of possibility of selecting the materials to produce desired products.

1.1   MECHANICAL AND PHYSICAL PROPERTIES

A common means of distinguishing one material from another is through their physical properties. These include such features as density (weight); melting point; optical properties (transparency, opaqueness, or color); the thermal properties of specific heat, coefficient of thermal expansion, and thermal conductivity; electrical conductivity; and magnetic properties. In some cases, physical properties are of prime importance when selecting a material, and several will be discussed in more detail near the end of this chapter. More often, however, material selection is dominated by the properties that describe how a material responds to applied loads or forces. These mechanical properties are usually determined by subjecting prepared specimens to standard test conditions. When using test results, however, it is important to remember that they apply only to the specific conditions that were employed. The actual service conditions of engineered products rarely duplicate the conditions of laboratory testing, so considerable caution should be exercised when applying test results.

1.1.1   MECHANICAL PROPERTIES (STATIC PROPERTIES)

When the forces that are applied to a material are constant, or nearly so, they are said to be static. Since static loadings are observed in many applications, it is important to characterize the behavior of materials under these conditions. For design engineers, the strength of a material may be of primary concern, along with the amount of elastic stretching or deflection that may be experienced while under load. Manufacturing engineers, looking to shape products, may be more concerned with the ability to mechanically deform the material without fracture. As a result, a number of standardized tests have been developed to evaluate the static properties of engineering materials. Test results can be used to determine if a given material or batch of material has the necessary properties to meet specified requirements. Other tests provide the materials characterization base used for material selection. In all cases, it is important to determine that the service conditions are indeed similar to those of testing. Even when

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the service conditions differ, the results of standard tests may be helpful in qualitatively rating and comparing various materials.

1.1.1.1   TENSILE TEST (Uniaxial)

The most common of the static tests is the uniaxial tensile test. The test begins with the preparation of a standard specimen with prescribed geometry, like the round and flat specimens described in Figure 1-1. The standard specimens ensure meaningful and reproducible results, and are designed to produce uniform uniaxial tension in the central portion of the specimen while ensuring reduced stresses in the enlarged ends or shoulders that are gripped.
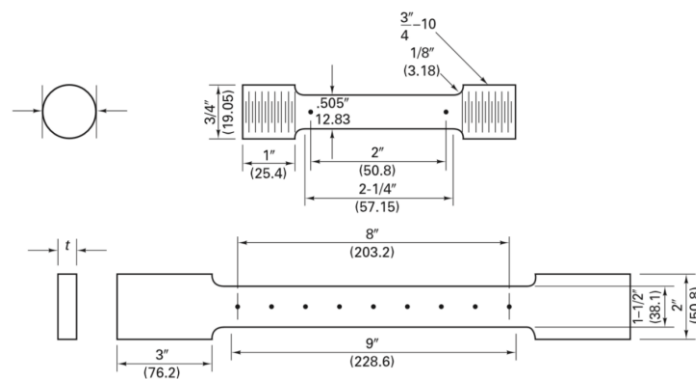

FIGURE 1-1 Two common types of standard tensile test specimens: (a) round; (b) flat. Dimensions are in inches, with millimeters in parentheses.
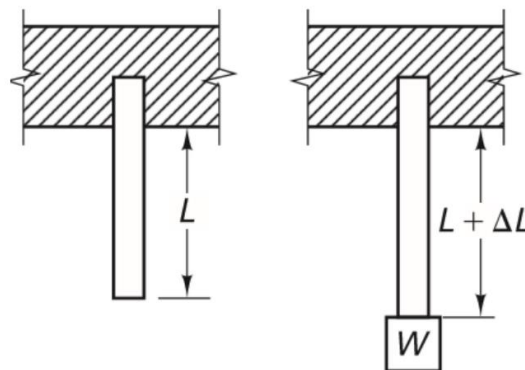

FIGURE 1-2 Tension loading and the resultant elongation.

The standard specimen is then loaded in tension in a testing machine. In Figure 1-2, the weight tends to stretch or lengthen the bar, so the strain is known as a tensile strain and the stress as a tensile stress. Other types of loadings produce other types of stresses and strains (Figure 1-3). Compressive forces tend to shorten the material and produce compressive stresses and strains. Shear stresses and strains result when two forces acting on a body are offset with respect to one another.
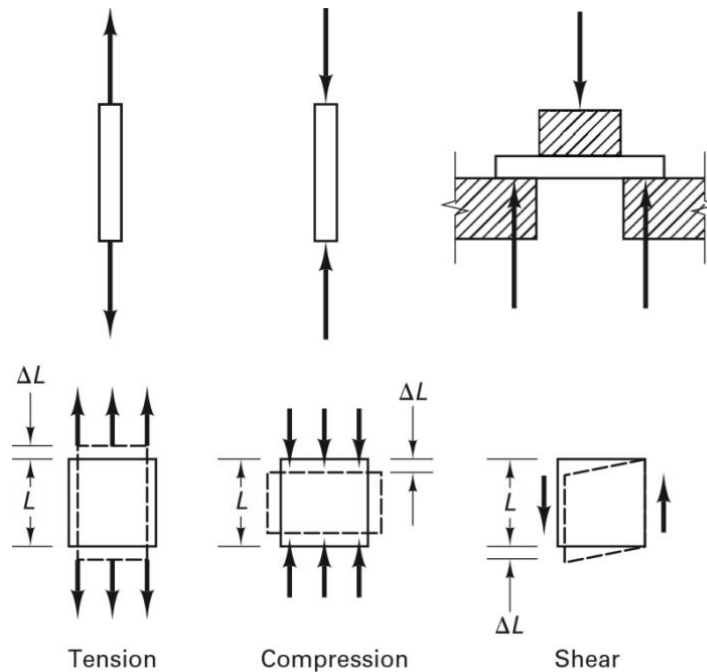

FIGURE 1-3 Examples of tension, compression, and shear loading, and their response.

> ➢ **Stress-strain**

  A plot of the coordinated load–elongation data produces a curve similar to that of Figure 1-4. Since the loads will differ for different sized specimens and the amount of elongation will vary with different gage lengths, it is important to remove these geometric or size effects if we are to produce data that are characteristic of a given material, not a particular specimen. If the load is divided by the original cross-sectional area, and the elongation is divided by the original gage length, the size effects are eliminated and the resulting plot becomes known as an engineering stress–engineering strain curve (see Figure 1-4).This is simply a load–elongation plot with the scales of

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both axes modified to remove the effects of specimen size. In Figure 1-4 it can be noted that the initial response is linear. Up to a certain point, the stress and strain are directly proportional to one another. The stress at which this proportionality ceases is known as the proportional limit. Below this value, the material obeys Hooke's law, which states that the strain is directly proportional to the stress. The proportionality constant, or ratio of stress to strain, is known as Young's modulus or the modulus of elasticity. This is an inherent property of a given material1 and is of considerable engineering importance. As a measure of stiffness, it indicates the ability of a material to resist deflection or stretching when loaded and is commonly designated by the symbol E. Up to a certain stress, if the load is removed, the specimen will return to its original length. The response is elastic or recoverable, like the stretching and relaxation of a rubber band. The uppermost stress for which this behavior is observed is known as the elastic limit.
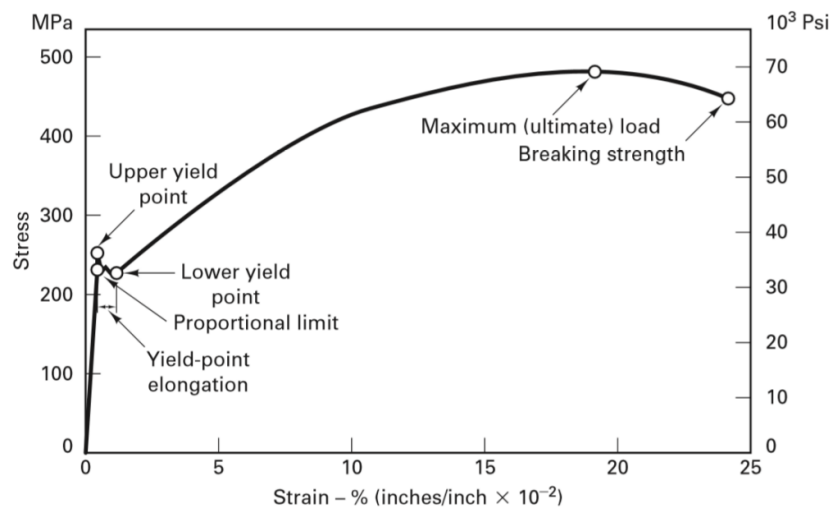

FIGURE 1-4 Engineering stress–strain diagram for a low-carbon steel.

The amount of energy that a material can absorb while in the elastic range is called the resilience. The area under a load–elongation curve is the product of a force and a distance, and is therefore a measure of the energy absorbed by the specimen. If the area is determined up to the elastic limit, the absorbed energy will be elastic (or potential) energy and is regained when the specimen is unloaded. If we perform the same calculation on an engineering stress–engineering strain diagram, the area beneath the elastic region corresponds to an energy per unit volume and is known as

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the modulus of resilience. Elongation beyond the elastic limit becomes unrecoverable and is known as plastic deformation. When the load is removed, only the elastic stretching will be recovered, and the specimen will retain a permanent change in shape. For most components, the onset of plastic flow represents failure, since the part dimensions will now be outside of allowable tolerances. In manufacturing processes where plastic deformation is used to produce a desired shape, the applied stresses must be sufficiently above the elastic limit to induce the required amount of plastic flow. Permanent deformation, therefore, may be either desirable or undesirable, and it is important to determine the conditions where elastic behavior transitions to plastic flow. Whenever the elastic limit is exceeded, increases in strain no longer require proportionate increases in stress. For some materials, a stress value may be reached where additional strain occurs without any further increase in stress. This stress is known as the yield point, or yield-point stress. For low-carbon steels, with curves like that in Figure 1-4, two distinct points are significant. The highest stress preceding extensive strain is known as the upper yield point, and the lower, relatively constant, "run-out" value is known as the lower yield point. The lower value is the one that usually appears in tabulated data. Most materials, however, do not have a well-defined yield point and exhibit stress–strain curves more like that shown in Figure 1-5. For these materials, the elastic to plastic deform a 1-inch length to a final length of 1.002 inches (a 0.2% strain). If the applied stresses are then kept below the 0.2% offset yield strength of the material, the user can be guaranteed that any resulting plastic deformation will be less than 0.2% of the original dimension. While 0.2% is a common offset for many mechanical products, applications that cannot tolerate that amount of deformation may specify offset values of 0.1% or even 0.02%.transition is not distinct, and detection of plastic deformation would be dependent upon machine sensitivity. To solve this dilemma, we elect to define a useful and easily determined property known as the offset yield strength. Offset yield strength does not describe the onset of plastic deformation but instead defines the stress required to produce a given, but tolerable, amount of permanent strain. By setting this strain, or "offset," to 0.2% (a common value), we can determine the stress required to plastically deform a 1-inch length to a final length of 1.002 inches (a 0.2% strain).

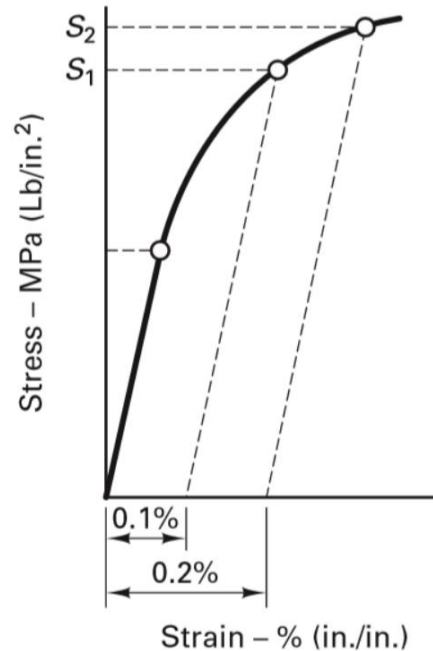

FIGURE 1.5 Stress–strain diagram for a material not having a well-defined yield point, showing the offset method for determining yield strength. Is the 0.1% offset yield strength; is the 0.2% offset yield strength.

 If the applied stresses are then kept below the 0.2% offset yield strength of the material, the user can be guaranteed that any resulting plastic deformation will be less than 0.2% of the original dimension. While 0.2% is a common offset for many mechanical products, applications that cannot tolerate that amount of deformation may specify offset values of 0.1% or even 0.02%. Offset yield strength is determined by drawing a line parallel to the elastic line, but displaced by the offset strain, and reporting the stress where the constructed line intersects the actual stress–strain curve. Figure 1-5 shows the determination of both 0.1% offset and 0.2% offset values, S_1 and S_2, respectively. The intersection values are reproducible and independent of equipment sensitivity. Offset yield values are meaningless unless they are reported in conjunction with the amount of offset strain used in their determination. The 0.2% value is most common and is generally assumed unless another number is specified. As shown in Figure 1.4, the load (or engineering stress) required to produce additional plastic deformation continues to increase. The load that a material or specimen can bear (load-

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bearing ability) can be computed by multiplying the material strength times its cross-sectional area. During tensile deformation, the specimen is getting longer. The cross-sectional area is decreasing, but the load-bearing ability of the specimen continues to increase! For this to occur, the material must be getting stronger.

During the plastic deformation portion of a tensile test, the weakest location of the specimen undergoes deformation and becomes stronger. Since it is no longer the weakest location, another location assumes that status and deforms. As a consequence, the specimen strengthens uniformly and maintains its original cylindrical or rectangular geometry. As plastic deformation progresses, however, the additional increments of strength decrease in magnitude, and a point is reached where the decrease in area cancels or dominates the increase in strength. When this occurs, the load-bearing ability peaks, and the force required to continue straining the specimen begins to decrease, as seen in Figure 1-4.The stress at which the load-bearing ability peaks is known as the ultimate strength, tensile strength, or ultimate tensile strength of the material. The weakest location in the test specimen at that time continues to be the weakest location by virtue of the decrease in area, and further deformation becomes localized. This localized reduction in cross-sectional area, known as necking, is shown in Figure 1-6. If the straining is continued, necking becomes intensified and the tensile specimen will ultimately fracture. The stress at which fracture occurs is known as the breaking strength or fracture strength. For ductile materials, necking precedes fracture, and the breaking strength is less than the ultimate tensile strength. For a brittle material, fracture usually terminates the stress–strain curve before necking, and possibly before the onset of plastic flow.

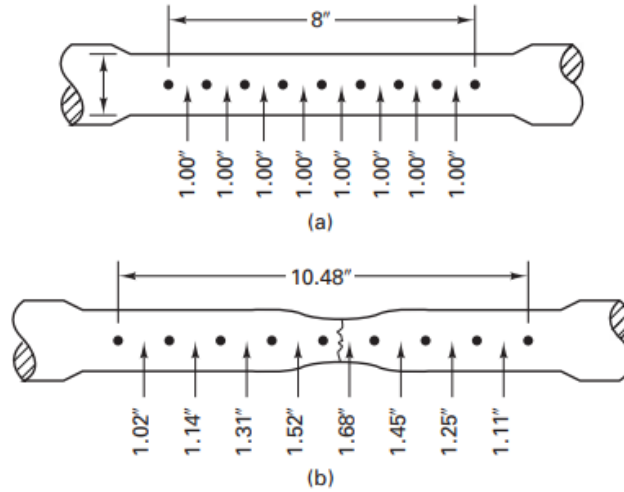Figure 1-7 shows Stress-strain graphs for a number of materials.

FIGURE 1-6 Final elongation in various segments of a tensile test specimen: (a) original geometry; (b) shape after fracture.
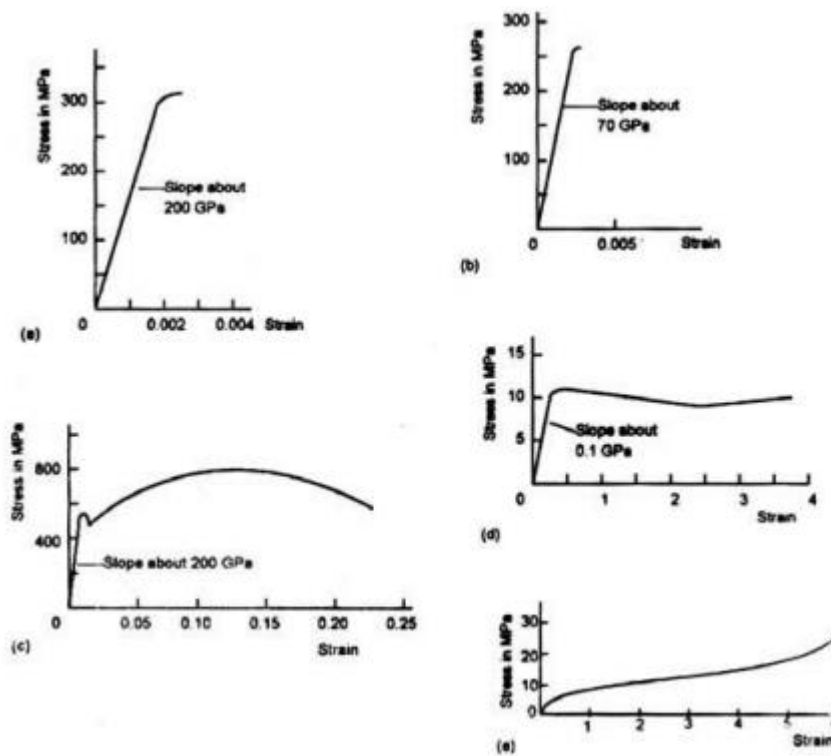

Figure 1-7: The stress-strain graphs for a number of materials :a) cast iron, (b) glass, (c) mild steel, (d)polyethylene, (e) rubber

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➢ **Ductility and Brittleness**

One of the simplest ways to evaluate ductility is to determine the percent elongation of a tensile test specimen at the time of fracture. A reasonably ductile material, such as mild steel, will have a percentage elongation of about 20%. A brittle material such as a cast iron less than 1%. Thermoplastics tend to have percentage elongations of the order of 50 to 500%, thermosets of the order of 0.1 to 1%.

Another measure of ductility is the *percent reduction* in area that occurs in the necked region of the specimen. This can be computed as

$$R.A = \frac{A_o - A_f}{A_o} * 100\%$$

Where A_o is the original cross-sectional area and A_f is the smallest area in the necked region. Percent reduction in area, therefore, can range from 0% (for a brittle glass specimen that breaks with no change in area) to 100% (for extremely plastic soft bubble gum that pinches down to a point before fracture).

➢ **Toughness:** The ability of a material to withstand shocks without damage. This is more of a bulk material property. For example, Lead is tough but not hard.

➢ **Strain Hardening**

➢ **Stiffness**: The ability to withstand bulk deformation. How difficult is it to bend or form? Glass is stiff when at room temperature and so difficult to form. It is also relatively hard but not tough. However, above a certain temperature, it is not stiff and not hard so it can be formed.

➢ **True Stress – True Strain Curve**

True stress, can be computed by taking simultaneous readings of the load and the minimum specimen diameter.

➢ **Damping Capacity**

1.1.1.2 COMPRESSION TESTS

When a material is subjected to compressive loadings, the relationships between stress and strain are similar to those for a tension test. Up to a certain value of stress, the material behaves elastically. Beyond this value, plastic flow occurs. In general, however, a compression test is more difficult to conduct than a standard tensile test. Test specimens must have larger cross-sectional areas to resist bending or buckling. As deformation proceeds, the material strengthens by strain hardening and the cross section of the specimen increases, combining to produce a substantial increase in required load. Friction between the testing machine surfaces and the ends of the test specimen will alter the results if not properly considered. The type of service for which the material is intended, however, should be the primary factor in determining whether the testing should be performed in tension or compression.

1.1.1.3 HARDNESS TESTING

Hardness: ability of a material surface to withstand locals deformation. An engineering example of this is case hardened steel which has a harder surface than interior. The wear resistance and strength of a material can also be evaluated by assessing its "hardness." Hardness is actually a hard-to-define property of engineering materials. The most common of the hardness tests are based on resistance to permanent deformation in the form of penetration or indentation.

A- Brinell Hardness Test

The Brinell hardness test was one of the earliest accepted methods of measuring hardness. A tungsten carbide or hardened steel ball 10 mm in diameter is pressed into the flat surface of a material by a standard load of 500 or 3000 kg, and the load is maintained for 10 to 15 seconds to permit the full amount of plastic deformation to occur. The load and ball are then removed, and the diameter of the resulting spherical indentation (usually in the range of 2 to 5 mm) is measured using a special grid or

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traveling microscope. The Brinell hardness number (BHN) is equal to the load divided by the surface area of the spherical indentation when the units are expressed as kilograms per square millimeter. Figure 1-8 shows a typical Brinell tester, along with a schematic of the testing procedure. Portable testers are available for use on pieces that are too large to be brought to a bench top machine.
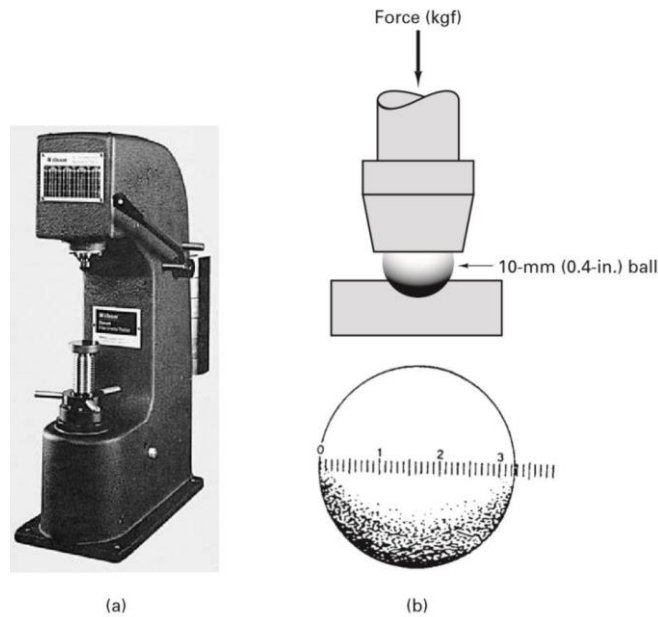

FIGURE 1-8 (a) Brinell hardness tester; (b) Brinell test sequence showing loading and measurement of the indentation under magnification with a scale calibrated in millimeters.

The Brinell test measures hardness over a relatively large area and is somewhat indifferent to small-scale variations in the material structure. It is relatively simple and easy to conduct, and is used extensively on irons and steels. On the negative side, however, the Brinell test has the following limitations:

 1. It cannot be used on very hard or very soft materials.

 2. The results may not be valid for thin specimens. It is best if the thickness of material is at least 10 times the depth of the indentation. Some standards specify the minimum hardnesses for which the tests on thin specimens will be considered valid.

 3. The test is not valid for case-hardened surfaces.

4. The test must be conducted far enough from the edge of the material so that no edge bulging occurs.

5. The substantial indentation may be objectionable on finished parts.

6. The edge or rim of the indentation may not be clearly defined or may be difficult to see.

B- The Rockwell Test.

The widely used Rockwell hardness test is similar to the Brinell test, with the hardness value again being determined through an indentation produced under a static load. Figure 1-9 shows the key features of the Rockwell test. Rockwell tests should not be conducted on thin materials (typically less than 1.5 mm or 1/16 in.), on rough surfaces, or on materials that are not homogeneous, such as gray cast iron. Because of the small size of the indentation, variations in roughness, composition, or structure can greatly influence test results.

C- Vickers Hardness Test.

The Vickers hardness test is also similar to the Brinell test but uses a 136° square-based diamond pyramid as the indenter and loads between 1 and 120 kg, Figure 1-10 shows the indenter for the Vickers test. Like the Brinell value, the Vickers hardness number is also defined as load divided by the surface area of the indentation expressed in units of kilograms per square millimeter. The advantages of the Vickers approach include increased accuracy in determining the diagonal of a square impression as opposed to the diameter of a circle and the assurance that even light loads will produce some plastic deformation. The use of diamond as the indenter material enables the test to evaluate any material and effectively places the hardness of all materials on a single scale. Like the other indentation or penetration methods, the Vickers test has a number of attractive features: (1) it is simple to conduct, (2) little time is involved, (3) little

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surface preparation is required, (4) the marks are quite small and are easily hidden or removed, (5) the test can be done on location, (6) it is relatively inexpensive, and (7) it provides results that can be used to evaluate material strength or assess product quality.
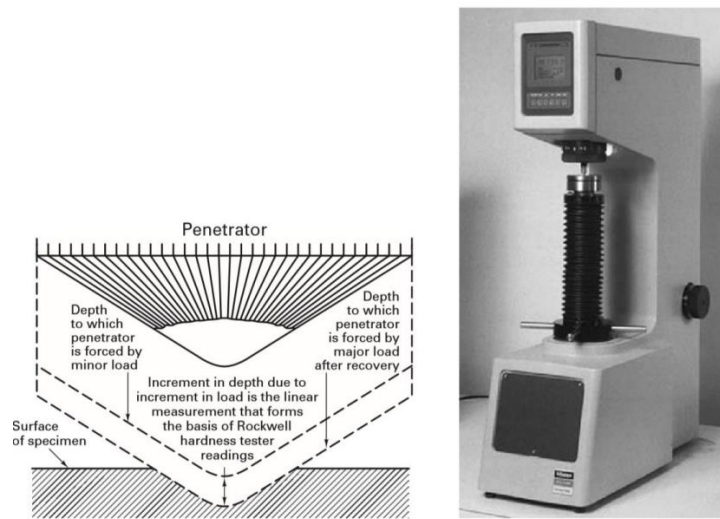

FIGURE 1-9 (a) Operating principle of the Rockwell hardness tester; (b) typical Rockwell hardness tester with digital readout
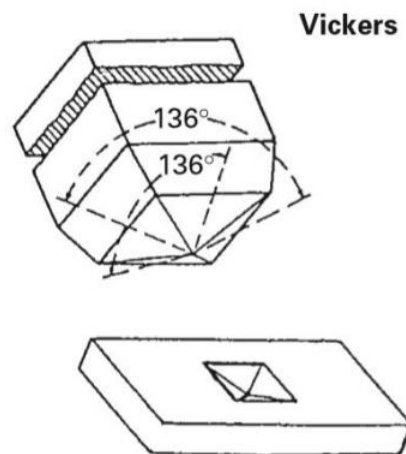

FIGURE 1-10 Comparison of the diamond-tipped indenter used in the Vickers hardness tests.

1.1.2 MECHANICAL PROPERTIES (DYNAMIC PROPERTIES)

In many engineering applications, products or components are subjected to various types of dynamic loading. These may include (1) sudden impacts or loads that vary rapidly in magnitude, (2) repeated cycles of loading and unloading, or (3) frequent changes in the mode of loading, such as from tension to compression. To handle these conditions, we must be able to characterize the mechanical properties of engineering materials under dynamic loadings. Most dynamic tests subject standard specimens to a well-controlled set of test conditions. The conditions of actual application, however, rarely duplicate the controlled conditions of a standardized test. While identical tests on different materials can indeed provide a comparison of material behavior, the assumption that similar results can be expected for similar conditions may not always be true. Since dynamic conditions can vary greatly, the quantitative results of standardized tests should be used with extreme caution, and one should always be aware of the test limitations.

1.1.2.1 IMPACT TEST

Several tests have been developed to evaluate the toughness or fracture resistance of a material when it is subjected to a rapidly applied load, or impact. Of the tests that have become common, two basic types have emerged: (1) bending impacts, which include the standard Charpy and Izod tests, and (2) tension impacts. The bending impact tests utilize specimens that are supported as beams. In the **Charpy test**, shown schematically in Figure 1-11, the standard specimen is a square bar containing a V-, keyhole-, or U-shaped notch. The test specimen is positioned horizontally, supported on the ends, and an impact is applied to the center, behind the notch, to complete a three-point bending. The **Izod test** specimen, while somewhat similar in size and appearance, is supported vertically as a cantilever beam and is impacted on the unsupported end, striking from the side of the notch (Figure 1-12). Impact testers, like the one shown in Figure 1-13, supply a predetermined impact energy in the form of a swinging pendulum. After breaking or deforming the specimen, the pendulum continues its upward swing with an energy equal to its original minus that absorbed by the impacted specimen. The

loss of energy is measured by the angle that the pendulum attains during its upward swing.

The test specimens for bending impacts must be prepared with geometric precision to ensure consistent and reproducible results. Notch profile is extremely critical, for the test measures the energy required to both initiate and propagate a fracture. The effect of notch profile is shown dramatically in Figure 1-14. Here two specimens have been made from the same piece of steel with the same reduced cross-sectional area. The one with the keyhole notch fractures and absorbs only 43 ft-lb of energy, whereas the unnotched specimen resists fracture and absorbs 65 ft-lb during the impact.
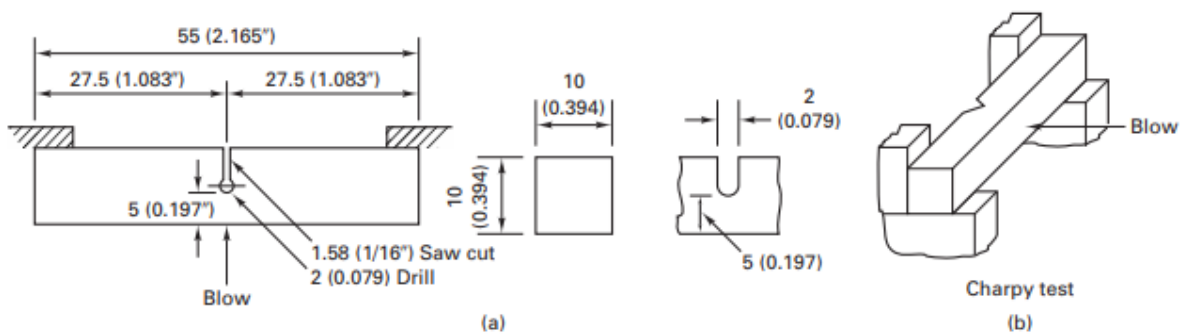
FIGURE 1-11 (a) Standard Charpy impact specimens. Illustrated are keyhole and U notches; dimensions are in millimeters with inches in parentheses. (b) Standard V-notch specimen showing the three-point bending type of impact loading.
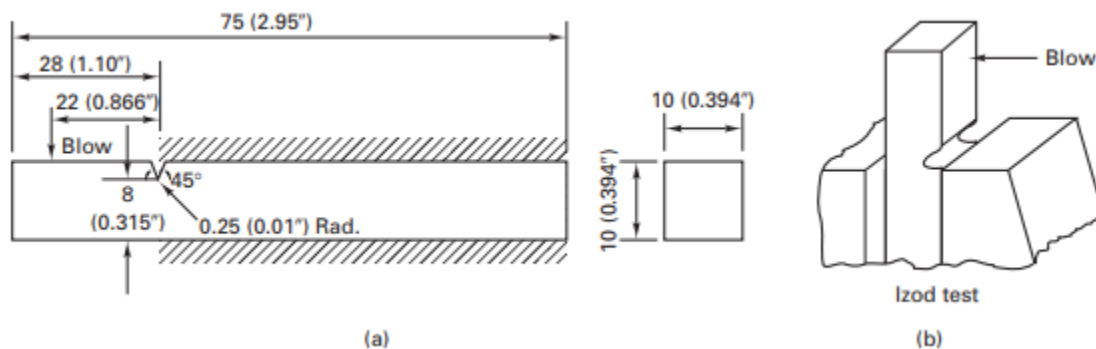
FIGURE 1-12 (a) Izod impact specimen; (b) cantilever mode of loading in the Izod test.

FIGURE 1-13 Impact testing machine

FIGURE 1-14 Notched and unnotched impact specimens before and after testing. Both specimens had the same cross-sectional area, but the notched specimen fractures while the other doesn't

Caution should also be placed on the use of impact data for design purposes. The test results apply only to standard specimens containing a standard notch. Moreover, the tests evaluate material behavior under very specific conditions. Changes in the form of the notch, minor variations in the overall specimen geometry, or faster or slower rates of loading (speed of the pendulum) can all produce significant changes in the results. Under conditions of sharp notches, wide specimens, and rapid loading, many ductile materials lose their energy-absorbing capability and fail in a brittle manner. [For

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example, the standard impact test should not be used to evaluate materials for bullet-proof armor, since the velocities of loading are extremely different.]

The tensile impact test, illustrated schematically in Figure 1-15, eliminates the use of a notched specimen and thereby avoids many of the objections inherent in the Charpy and Izod tests. Turned specimens are subjected to uniaxial impact loadings applied through drop weights, modified pendulums, or variable-speed flywheels.
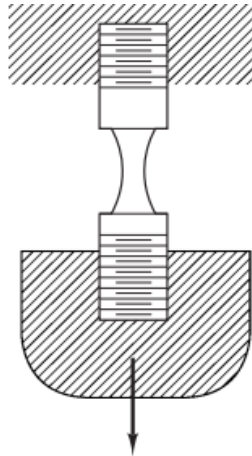
FIGURE 1-15 Tensile impact test.

1.1.2.2 FATIGUE AND THE ENDURANCE LIMIT

Materials can also fail by fracture if they are subjected to repeated applications of stress, even though the peak stresses have magnitudes less than the ultimate tensile strength and usually less than the yield strength. This phenomenon, known as fatigue, can result from either the cyclic repetition of a particular loading cycle or entirely random variations in stress. Almost 90% of all metallic fractures are in some degree attributed to fatigue.

For experimental simplicity, a periodic, sinusoidal loading is often utilized, and conditions of equal-magnitude tension–compression reversals provide further simplification. These conditions can be achieved by placing a cylindrical specimen in a rotating drive and hanging a weight so as to produce elastic bending along the axis, as

shown in Figure 1-16. As a result of the elastic bending, material at the bottom of the specimen is stretched, or loaded in tension, while material on the top surface is compressed. As the specimen turns, the surface of the specimen experiences a sinusoidal application of tension and compression with each rotation. By conducting multiple tests, subjecting identical specimens to different levels of maximum loading, and recording the number of cycles necessary to achieve fracture, curves such as that in Figure 1-17 can be produced. These curves are known as *stress versus number of cycles, or S–N, curves.* If the material being evaluated in Figure 1-17 were subjected to a standard tensile test, it would require a stress in excess of 480 MPa to induce failure. Under cyclic loading with a peak stress of only 380 MPa, the specimen will fail after about 100,000 cycles.
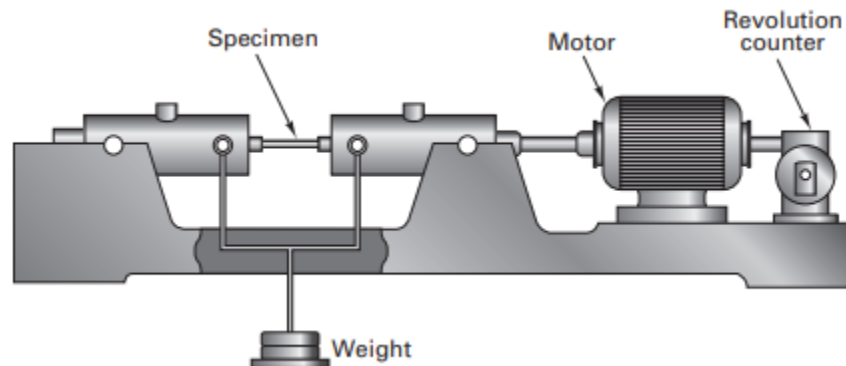
FIGURE 1-16 Schematic diagram of a Moore rotating beam fatigue machine.

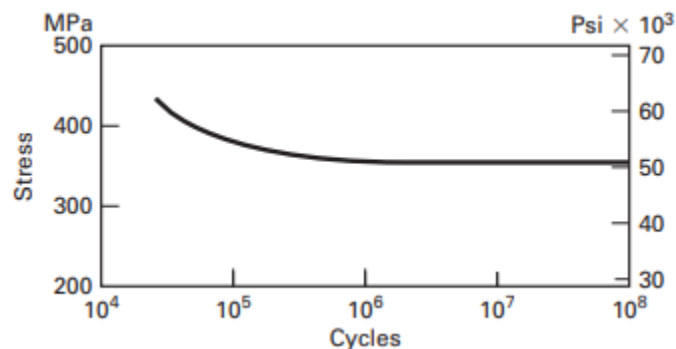FIGURE 1-17 Typical SN curve for steel showing an endurance limit. Specific numbers will vary with the type of steel and treatment.

If the peak stress were further reduced to 350 MPa, the fatigue lifetime would be extended by an order of magnitude to approximately 1,000,000 cycles. With a further reduction to any value below 340 MPa, the specimen would not fail by fatigue, regardless of the number of stress application cycles.

The stress below which the material will not fail regardless of the number of load cycles is known as the endurance limit or endurance strength, and may be an important criterion in many designs. Above this value, any point on the curve is the fatigue strength, the maximum stress that can be sustained for a specified number of loading cycles.

A different number of loading cycles is generally required to determine the endurance limit for different materials. For steels, 10 million cycles are usually sufficient. For several of the nonferrous metals, 500 million cycles may be required. The fatigue resistance of an actual product is sensitive to a number of additional factors. One of the most important of these is the presence of stress raisers (or stress concentrators), such as sharp corners, small surface cracks, machining marks, or surface gouges. Data for the S–N curves are obtained from polished-surface, "flaw-free" specimens, and the reported lifetime is the cumulative number of cycles required to initiate a fatigue crack and then grow or propagate it to failure. If a part already contains a surface crack or flaw, the number of cycles required for crack initiation can be reduced significantly.

Operating temperature can also affect the fatigue performance of a material. Figure 1-18 shows S–N curves for Inconel 625 (a high-temperature Ni–Cr–Fe alloy) determined over a range of temperatures. As temperature is increased, the fatigue strength drops significantly. Since most test data are generated at room temperature, caution should be exercised when the product application involves elevated service temperatures.

Fatigue lifetime can also be affected by changes in the environment like corrosion, the nature of the environmental (vacuum or humidity) and the frequency of the loading cycles.
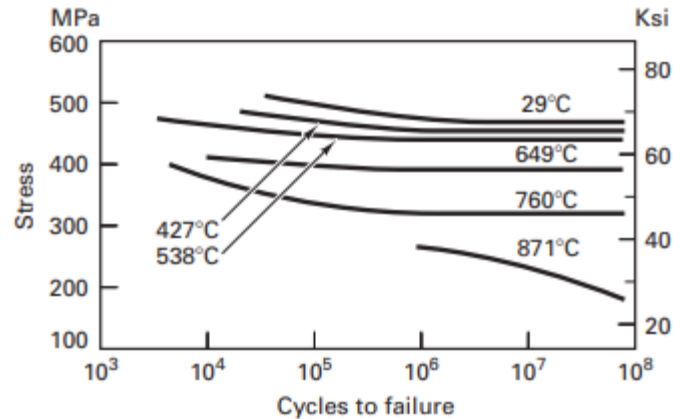
FIGURE 1-18 Fatigue strength of Inconel alloy 625 at various temperatures.

Since reliable fatigue data may take a considerable time to generate, we may prefer to estimate fatigue behavior from properties that can be determined more quickly. Table 1-1 shows the approximate ratio of the endurance limit to the ultimate tensile strength for several engineering metals. For many steels the endurance limit can be approximated by 0.5 times the ultimate tensile strength as determined by a standard tensile test. For the nonferrous metals, however, the ratio is significantly lower.

TABLE 1-1 Ratio of Endurance Limit to Tensile Strength for Various Materials

Material	Ratio
Aluminum	0.38
Beryllium copper (heat-treated)	0.29
Copper, hard	0.33
Magnesium	0.38
Steel	
AISI 1035	0.46
Screw stock	0.44
AISI 4140 normalized	0.54
Wrought iron	0.63

FATIGUE FAILURES Components that fail as a result of repeated or cyclic loadings are commonly called fatigue failures. These fractures form a major part of a larger group known as progressive fractures. Consider the fracture surface shown in Figure 1-19.

The two arrows identify the points of fracture initiation, which often correspond to discontinuities in the form of <mark>surface cracks, sharp corners, machining marks, or even "metallurgical notches," such as an abrupt change in metal structure</mark>. With each repeated application of load, the stress at the tip of the crack exceeds the strength of the material, and the crack grows a very small amount. Crack growth continues with each successive application of load until the remaining cross section is no longer sufficient to withstand the peak stresses. Sudden overload fracture then occurs through the remainder of the material. The overall fracture surface tends to exhibit two distinct regions: <mark>a smooth</mark>, relatively flat region where the crack was propagating by cyclic fatigue, and <mark>a rough region</mark>, corresponding to the ductile overload tearing.
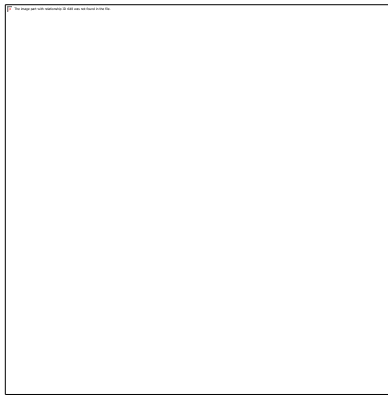
FIGURE 1-19 Progressive fracture of an axle within a ball-bearing ring, starting at two points (arrows).

The smooth areas of the fracture often contain a series of parallel ridges radiating outward from the origin of the crack. These ridges may not be visible under normal examination, however. They may be extremely fine; they may have been obliterated by a rubbing action during the compressive stage of repeated loading; or they may be very few in number if the failure occurred after only a few cycles of loading ("low-cycle fatigue").

1.2 TEMPERATURE EFFECTS (BOTH HIGH AND LOW)

The test data used in design and engineering decisions should always be obtained under conditions that simulate those of actual service. A number of engineered structures, such as aircraft, space vehicles, gas turbines, and nuclear power plants, are required to operate under temperatures as low as (-130°C) or as high as (1250°C). To cover these extremes, the designer must consider both the short- and long-range effects of temperature on the mechanical and physical properties of the material being considered. From a manufacturing viewpoint, the effects of temperature are equally important. Numerous manufacturing processes involve heat, and the elevated temperature and processing may alter the material properties in both favorable and unfavorable ways. A material can often be processed successfully, or economically, only because heating or cooling can be used to change its properties. Elevated temperatures can be quite useful in modifying the strength and ductility of a material. Figure 1-20 summarizes the results of tensile tests conducted over a wide range of temperatures using a medium-carbon steel. As expected, an increase in temperature will typically induce a decrease in strength and hardness and an increase in elongation. For manufacturing operations such as metal-forming, heating to elevated temperature may be extremely attractive because the material is now both weaker and more ductile.
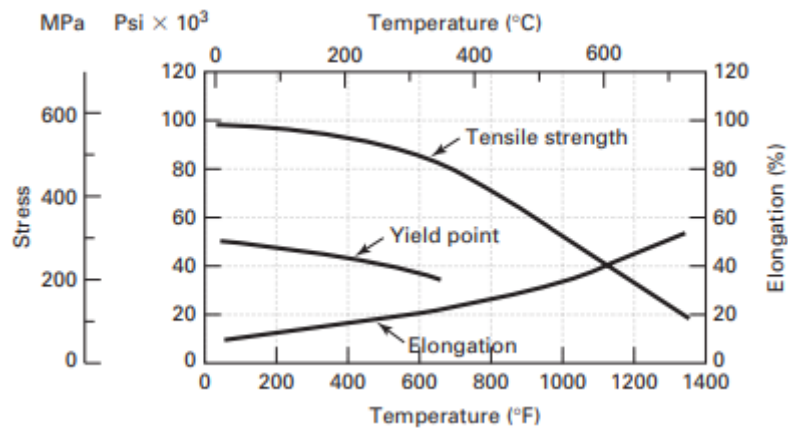
FIGURE 1-20 The effects of temperature on the tensile properties of a medium-carbon steel.

The effect of temperature on impact properties became the subject of intense study in the 1940s when the increased use of welded-steel construction led to catastrophic

failures of ships and other structures while operating in cold environments. Figure 1-21 shows the effect of decreasing temperature on the impact properties of two low-carbon steels. Although similar in form, the two curves are significantly different. The steel indicated by the solid line becomes brittle (requires very little energy to fracture) at temperatures below (- 4°C) while the other steel retains good fracture resistance down to (-26°C). The temperature at which the response goes from high energy absorption to low energy absorption is known as the ==ductile-to-brittle transition temperature==. While all steels tend to exhibit this transition, the temperature at which it occurs varies with carbon content and alloy. Special caution should be taken, therefore, when selecting steels for low-temperature applications.
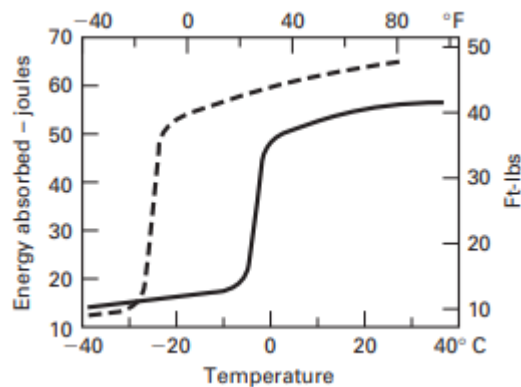
FIGURE 1-21 The effect of temperature on the impact properties of two low-carbon steels.

1.2.1 CREEP

Long-term exposure to elevated temperatures can also lead to failure by a phenomenon known as creep. If a tensile-type specimen is subjected to a constant load at elevated temperature, it will elongate continuously until rupture occurs, even though the applied stress is below the yield strength of the material at the temperature of testing. While the ==rate of elongation is often quite small==, creep can be an important consideration when ==designing equipment such as steam or gas turbines, power plant boilers==, and other devices that operate ==under loads or pressures for long periods of time at high temperature.==

If a test specimen is subjected to conditions of <mark>fixed load and fixed elevated temperature</mark>, an elongation-versus-time plot can be generated, similar to the one shown in Figure 1-22. The curve contains three distinct stages: a short-lived initial stage, a rather long second stage where the elongation rate is somewhat linear, and a short-lived third stage leading to fracture. Two significant pieces of engineering data are obtained from this curve: <mark>the rate of elongation in the second stage, or *creep rate*</mark>, and <mark>the *total elapsed time to rupture*</mark>. These results are unique to the material being tested and the specific conditions of the test. Tests conducted at higher temperatures or with higher applied loads would exhibit higher creep rates and shorter rupture times.
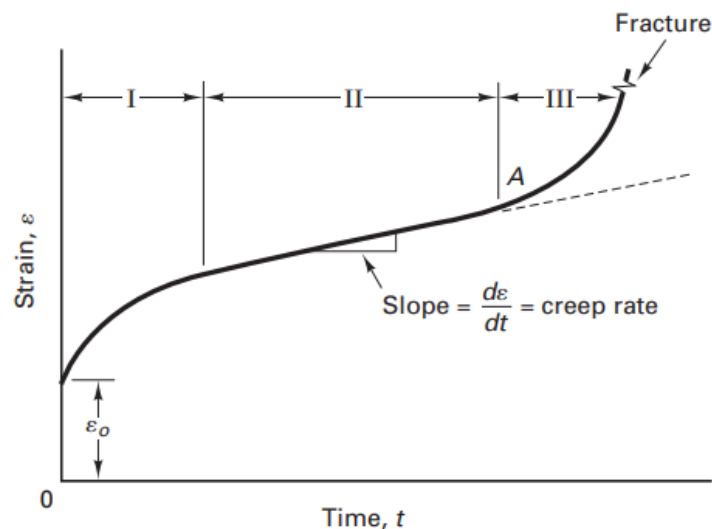
FIGURE 1-22 Creep curve for a single specimen at a fixed temperature, showing the three stages of creep and reported creep rate. Note the nonzero strain at time zero due to the initial application of the load.

1.3 PHYSICAL PROPERTIES

For certain applications, the physical properties of an engineering material may be even more important than the mechanical ones. These include the thermal, electrical, magnetic, and optical characteristics. We have already seen several ways in which the mechanical properties of materials change with variations in temperature. In addition to

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these effects, there are some truly thermal properties that should be considered. The ***heat capacity*** or ***specific heat*** of a material is the amount of energy that must be added to or removed from a given mass of material to produce a 1° change in temperature. This property is extremely important in processes such as casting, where heat must be extracted rapidly to promote solidification, or heat treatment, where large quantities of material are heated and cooled. ***Thermal conductivity*** measures the rate at which heat can be transported through a material. While this may be tabulated separately in reference texts, it is helpful to remember that for metals, thermal conductivity is directly proportional to electrical conductivity. Metals such as copper, gold, and aluminum that possess good electrical conductivity are also good transporters of thermal energy. ***Thermal expansion*** is another important thermal property. Most materials expand upon heating and contract upon cooling, but the amount of expansion or contraction will vary with the material. For components that are machined at room temperature but put in service at elevated temperatures, or castings that solidify at elevated temperatures and then cool, the manufactured dimensions must be adjusted to compensate for the subsequent changes.

Electrical conductivity and ***electrical resistivity*** may also be important design considerations. These properties will vary not only with the material but also with the temperature and the way the material has been processed. From the standpoint of ***magnetic response***, materials are often classified as diamagnetic, paramagnetic, ferromagnetic, antiferromagnetic, and ferrimagnetic. These terms refer to the way in which the material responds to an applied magnetic field. Material properties, such as saturation strength, remanence, and magnetic hardness or softness, describe the strength, duration, and nature of this response. Still other physical properties that may assume importance include weight or density, melting and boiling points, and the various optical properties, such as the ability to transmit, absorb, or reflect light or other electromagnetic radiation.

2. ENGINEERING MATERIALS

2.1   Introduction to Engineering Materials

Engineering materials are available with a wide range of useful properties and characteristics. Some of these are inherent to the particular material, but many others can be varied by controlling the manner of production and the details of processing. The final properties of engineering materials are clearly affected by their past processing history. In this chapter we will introduce the major types of engineering materials, summarized in Figure 2-1.

The basic factors for classifications of materials in material science and engineering are: (i) The chemical composition of the material.

(ii) The mode of the occurrence of the material in the nature.

(iii) The refining and the manufacturing process to which the material is subjected prior it acquires the required properties.

(iv) The atomic and crystalline structure of material.

(v) The industrial and technical use of the material.

2.1 METALLIC AND NONMETALLIC MATERIALS

While engineering materials are often grouped as metals, ceramics, polymers, and composites, a simpler distinction might be to separate them into ***metallic*** and ***nonmetallic***. The common ***metallic*** materials include iron, copper, aluminum, magnesium, nickel, titanium, lead, tin, and zinc as well as the alloys of these metals, such as steel, brass, and bronze. They possess the metallic properties of luster, high thermal conductivity, and high electrical conductivity; they are relatively ductile; and some have good magnetic properties. Some common ***nonmetals*** are wood, brick, concrete, glass, rubber, and plastics. Their properties vary widely, but they generally

tend to be weaker, less ductile, and less dense than the metals, and to have poor electrical and thermal conductivities.

Although metals have traditionally been the more important of the two groups, the nonmetallic materials have become increasingly important in modern manufacturing. Advanced ceramics, composite materials, and engineered plastics have emerged in a number of applications. In many cases, metals and nonmetals are viewed as competing materials, with selection being based on how well each is capable of providing the required properties. Where both perform adequately, total cost often becomes the deciding factor, where total cost includes both the cost of the material and the cost of fabricating the desired component. Factors such as product lifetime, environmental impact, energy requirements, and recyclability are also considered.
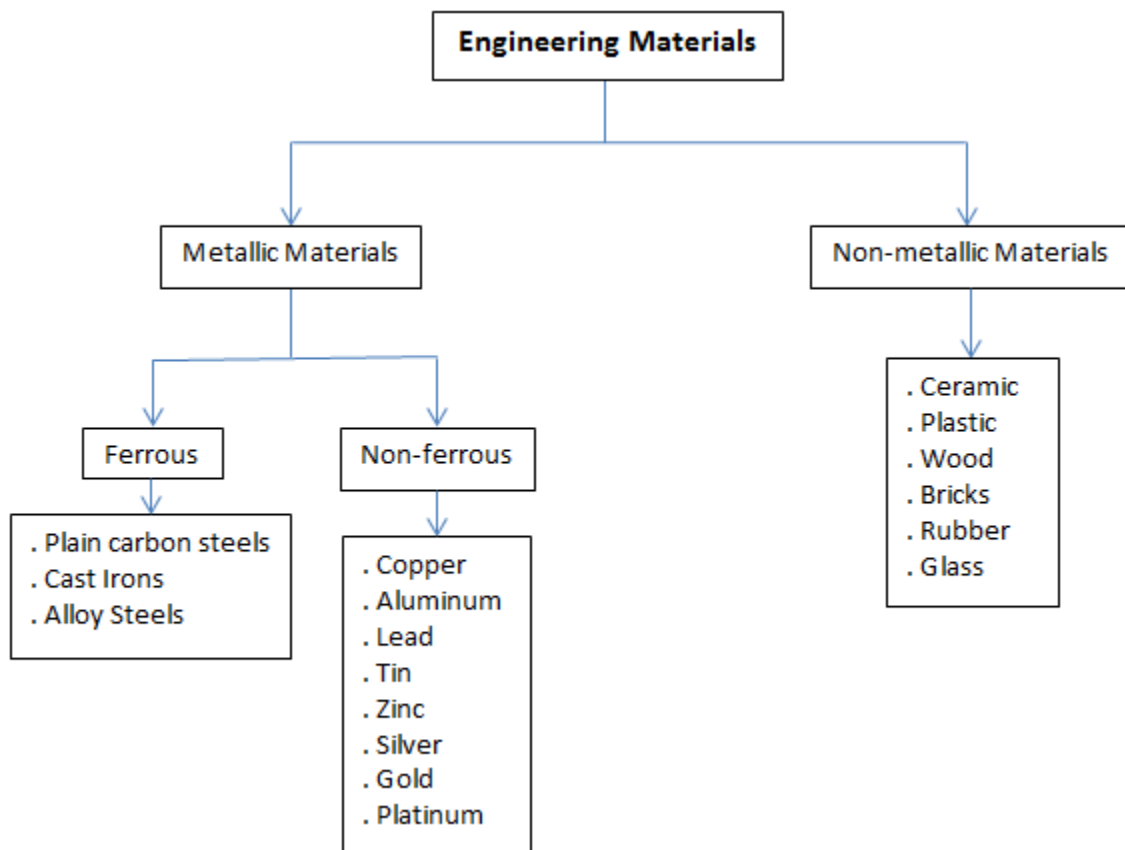
FIGURE 2-1 Classification of common engineering materials.

2.2 FERROUS METALS

In this section we will introduce the major ferrous (iron-based) metals and alloys. We see them everywhere in our lives in the cars we drive, the homes in which we live, the cans we open, and the appliances that enhance our standard of living. According to the American Iron and Steel Institute, over 50% of the steels made today did not exist 10 years ago and over 70% of the steel used in automotive production meets this criteria. The newer steels are stronger than ever, easier to shape, and more corrosion resistant. All steel is recyclable, and this recycling does not involve any loss in material quality. Because steel is magnetic, it is easily separated and recovered from demolished buildings, junked automobiles, and discarded appliances. Figure 2-2 summarized ferrous metal alloys based on iron.

```
                          Ferrous Metal Alloys
         ┌──────────────────────┼──────────────────────┐
    Cast Irons            Plain-Carbon Steels        Alloy Steels
         │                       │                       │
    Gray Irons              High-Carbon            Low-Alloy Steels
         │                       │                       │
  Malleable Iron           Medium-Carbon             HSLA Steels
         │                       │                       │
   Ductile Iron             Low-Carbon           Microalloyed Steels
         │                                               │
Compacted Graphite Iron                         Advanced High-Strength
         │                                              Steels
Austempered Ductile Iron                                │
         │                                       Maraging Steels
    White Iron                                          │
                                                 Stainless Steels
                                                        │
                                                   Tool Steels
```

FIGURE 2-2 Classification of common ferrous metals and alloys.

Iron has been the most important of the engineering metals; it is the fourth most plentiful element in the earth's crust. However, the iron is rarely found in the metallic state. Instead, it occurs in a variety of mineral compounds, known as ores, the most

attractive of which are iron oxides coupled with companion impurities. To produce metallic iron, the ores are processed in a manner that breaks the iron–oxygen bonds (chemical reducing reactions). Ore, limestone, coke (carbon), and air are continuously introduced into specifically designed furnaces and molten metal is periodically withdrawn. The resulting pig iron tends to have roughly the following composition:

Carbon 3.0–4.5%

Manganese 0.15–2.5%

Phosphorus 0.1–2.0%

Silicon 1.0–3.0%

Sulfur 0.05–0.1%

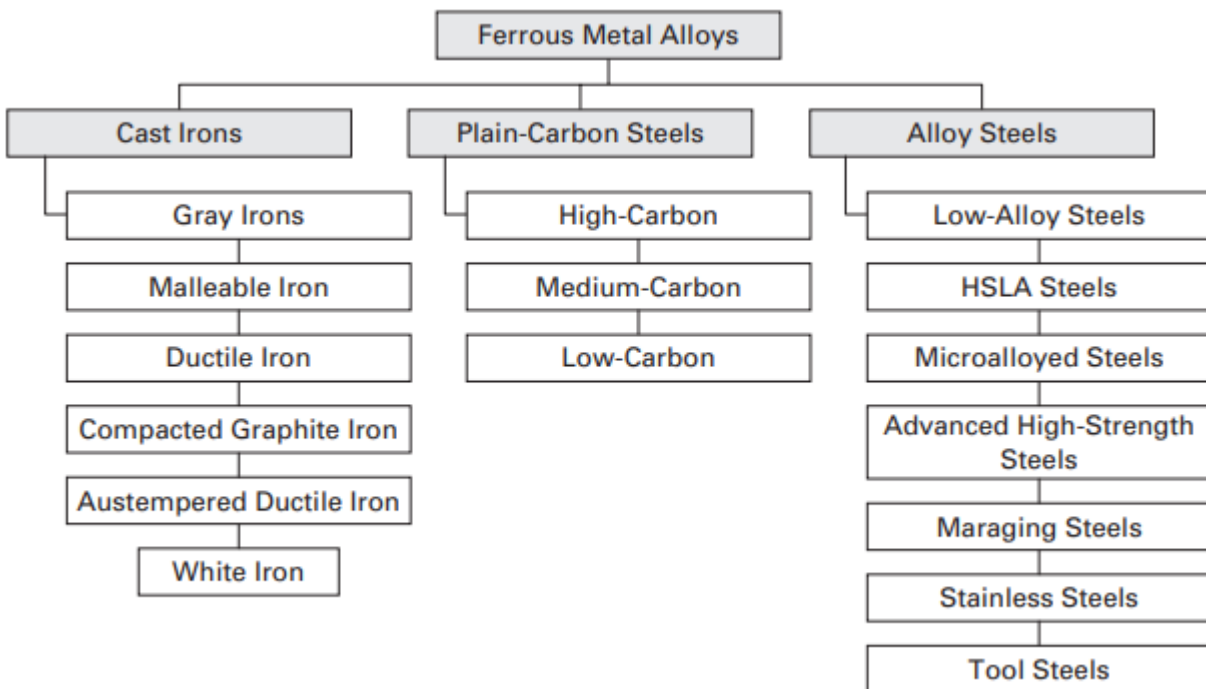A small portion of this iron is cast directly into final shape and is classified as cast iron. Most pig iron, however, is further processed into steel.

Steel is an extremely useful engineering material. It offers strength, rigidity, and durability. From a manufacturing perspective, its formability, joinability, and paintability, as well as repairability, are all attractive. The automotive and construction industries are major consumers of steel; the material is also used extensively in containers, appliances, and machinery as well as the infrastructure of such industries as oil and gas.

The manufacture of steel is essentially an oxidation process that decreases the amount of carbon, silicon, manganese, phosphorus, and sulfur in a molten mixture of pig iron and/or steel scrap.

2.2.1 CAST IRONS

Iron–carbon alloys with more than 2.11% carbon experience the eutectic reaction during cooling and are known as cast irons. The term cast iron applies to an entire family of metals with a wide variety of properties. Being relatively inexpensive, with good fluidity and rather low liquidus temperatures, they are readily cast and occupy an important

place in engineering applications. Most commercial cast irons also contain a significant amount of silicon. A typical cast iron contains 2.0 to 4.0% carbon, 0.5 to 3.0% silicon, less than 1.0% manganese, and less than 0.2% sulfur.

Various types of cast iron can be produced, depending on the chemical composition, cooling rate, and the type and amount of inoculants that are used.

A. Gray cast iron, the least expensive and most common variety, is characterized by those features that promote the formation of graphite. Typical compositions range from 2.5 to 4.0% carbon, 1.0 to 3.0% silicon, and 0.4 to 1.0% manganese. The microstructure consists of three-dimensional graphite flakes (which form during the eutectic reaction) dispersed in a matrix of ferrite, pearlite, or other iron-based structure that forms from the cooling of austenite.

B. Malleable cast iron, has significantly greater ductility than that of gray cast iron because the more favorable graphite shape removes the internal notches. The rapid cooling required to produce the starting white iron structure restricts the size and thickness of malleable iron products such that most weigh less than 5 kg. Various types of malleable iron can be produced, depending on the type of heat treatment that is employed known as ferritic malleable cast iron, pearlitic malleable cast iron.

C. Ductile or nodular cast iron, produces when the magnesium (in the form of an MgFeSi or MgNi alloy) is added just prior to solidification, the graphite will form as smooth-surface spheres. Subsequent control of cooling can produce a variety of matrix structures, with ferrite or pearlite being the most common. By controlling the matrix structure, properties can be produced that span a wide range from 2 to 18% elongation, (275 to 620 MPa) yield strength, and (415 to 825 MPa) tensile strength. The combination of good ductility, high strength, toughness, wear resistance, machinability, low-melting-point castability, and up to a 10% weight reduction compared to steel makes ductile iron an attractive engineering material.

D. Austempered ductile iron (ADI), ductile iron that has undergone a special austempering heat treatment to modify and enhance its properties, has emerged

as a significant engineering material. It combines the ability to cast intricate shapes with strength, fatigue, and wear-resistance properties that are similar to those of heat-treated steel. Compared to conventional as-cast ductile iron, it offers nearly double the strength at the same level of ductility. Compared to steel, it also offers an 8 to 10% reduction in density (so strength to-weight ratio is excellent) and enhanced damping capability, both due to the graphite nodules, but generally poorer machinability and with about a 20% lower elastic modulus.

E. <u>Compacted graphite cast iron (CGI)</u> is also attracting considerable attention. Produced by a method similar to that used to make ductile iron (an Mg–Ce–Ti addition is made), compacted graphite iron is characterized by a graphite structure that is intermediate to the flake graphite of gray iron and the nodular graphite of ductile iron, and it tends to possess some of the desirable properties and characteristics of each.

F. <u>White cast iron</u> has all of its excess carbon in the form of iron carbide and receives its name from the white surface that appears when the material is fractured. Features promoting its formation are those that favor cementite over graphite: a low carbon equivalent (1.8 to 3.6% carbon, 0.5 to 1.9% silicon, and 0.25 to 0.8% manganese) and rapid cooling. Because the large amount of iron carbide dominates the microstructure, white cast iron is very hard and brittle, and finds applications where high abrasion resistance is the dominant requirement.

2.2.2 PLAIN-CARBON STEEL

While theoretically an alloy of only iron and carbon, commercial steel actually contains manganese, phosphorus, sulfur, and silicon in significant and detectable amounts. When these four additional elements are present in their normal percentages and no minimum amount is specified for any other constituent, the product is referred to as plain-carbon steel. Strength is primarily a function of carbon content, increasing with increasing carbon. Unfortunately, the ductility, toughness, and weldability of plain-carbon steels decrease as the carbon content is increased, and hardenability is quite low.

Plain-carbon steels are generally classed into three subgroups based on their carbon content.

A- <u>Low-carbon steels</u> have less than 0.20% carbon and possess good formability (can be strengthened by cold work) and weldability. Their structures are usually ferrite and pearlite, and the material is generally used as it comes from the hot-forming or cold-forming processes, or in the as-welded condition.

B- <u>Medium-carbon steels</u> have between 0.20 and 0.50% carbon, and they can be quenched to form martensite or bainite if the section size is small and a severe water or brine quench is used. The best balance of properties is obtained at these carbon levels, where the high toughness and ductility of the low-carbon material is in good compromise with the strength and hardness that come with higher carbon contents. These steels are extremely popular and find numerous mechanical applications.

C- <u>High-carbon steels</u> have more than 0.50% carbon. Toughness and formability are quite low, but hardness and wear resistance are high. Severe quenches can form martensite, but hardenability is still poor. Quench cracking is often a problem when the material is pushed to its limit.

Figure 2-3 depicts the characteristic properties of low-, medium-, and high-carbon steels using a balance of properties that shows the offsetting characteristics of "strength and hardness" and "ductility and toughness."
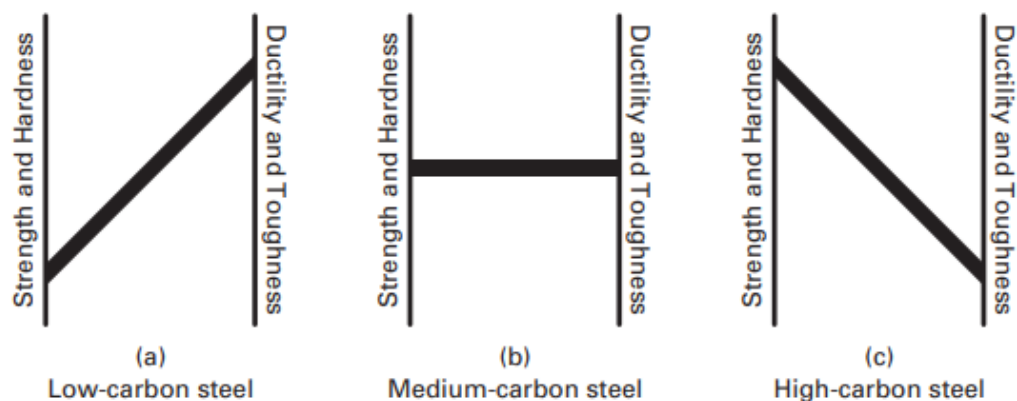

FIGURE 2-3 A comparison of low-carbon, medium-carbon, and high-carbon steels in terms of their relative balance of properties.

The plain-carbon steels are generally the lowest-cost steel material and should be given first consideration for many applications. Their limitations, however, may become restrictive. When improved performance is required, these steels can often be upgraded by the addition of one or more alloying elements.

2.2.3 ALLOY STEELS

The differentiation between plain-carbon and alloy steel is often somewhat arbitrary. Both contain carbon, manganese, and usually silicon. Copper and boron are possible additions to both classes. Steels containing more than 1.65% manganese, 0.60% silicon, or 0.60% copper are usually designated as alloy steels. Also, steel is considered to be an alloy steel if a definite or minimum amount of other alloying element is specified. The most common alloy elements are chromium, nickel, molybdenum, vanadium, tungsten, cobalt, boron, and copper, as well as manganese, silicon, phosphorus, and sulfur in amounts greater than are normally present.

Alloy steels are generally classified according to the percentage of alloy addition

A- Low-alloy steel when the steel contains less than 8% of total alloy addition. Steels with more than 8% alloying elements are high-alloy steels.

B- High-strength low-alloy (HSLA) materials provide increased strength-to-weight compared to conventional carbon steels for only a modest increase in cost. They are available in a variety of forms, including sheet, strip, plate, structural shapes, and bars. The dominant property requirements generally are high yield strength, good weldability, and acceptable corrosion resistance. Ductility and hardenability may be somewhat limited, however. The increase in strength, and the resistance to martensite formation in a weld zone, is obtained by controlling the amounts of carbon, manganese, and silicon, with the addition of small amounts of niobium, vanadium, titanium, or other alloys. About 0.2% copper can be added to improve corrosion resistance. Because of their higher yield strength, weight savings of 20 to 30% can often be achieved with no sacrifice to strength or safety. Rolled and welded HSLA steels are being used in automobiles, trains, bridges, and

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buildings. Because of their low alloy content and high-volume application, their cost is often little more than that of the ordinary plain-carbon steels.

C- Microalloyed steels occupy a position between carbon steels and the alloy grades, and they are being used increasingly as substitutes for heat-treated steels in the manufacture of small- to medium-sized discrete parts. These low- and medium-carbon steels contain small amounts (0.05 to 0.15%) of alloying elements, such as niobium, vanadium, titanium, molybdenum, zirconium, boron. The primary effect of the alloy addition is to provide grain refinement and/or precipitation strengthening. Yield strengths between (500 and 750 MPa) can be obtained without heat treatment. Weldability can be retained or even improved if the carbon content is simultaneously decreased. Microalloyed steels can often provide attractive cost savings. Energy savings can be substantial, straightening or stress relieving after heat treatment is no longer necessary, and quench cracking is not a problem. Due to the increase in material strength, the size and weight of finished products can often be reduced. As a result, the cost of a finished forging could be reduced by 5 to 25%.

D- Advanced High-Strength Steels (AHSS) are combined a large amounts of low-carbon and HSLA steels. The AHSS steels have high strength (provides improved fatigue and crash performance, along with the possibility of weight reduction) with enhanced ductility. While previous high-strength grades, such as HSLA, suffered from reduced formability, the AHSS materials enable the stamping or hydroforming of more complex parts.

E- Maraging Steels When superhigh strength is required from steel, the maraging grades become a very attractive option. These alloys contain between 15 and 25% nickel, plus significant amounts of cobalt, molybdenum, and titanium, all added to a very low-carbon steel. They can be hot worked at elevated temperatures, machined, or cold worked in the air-cooled condition, and then aged to yield strengths in excess of (1725 MPa), with good residual elongation. Maraging alloys are very useful in applications where ultra-high strength and good toughness are important.

F- Stainless Steels: Low-carbon steel with the addition of 4 to 6% chromium acquires good resistance to many of the corrosive media encountered in the chemical industry. This behavior is attributed to the formation of a strongly adherent iron chromium oxide on the surface. If more improved corrosion resistance and outstanding appearance are required, materials should be specified that use a superior oxide that forms when the amount of chromium in solution (excluding chromium carbides and other forms where the chromium is no longer available to react with oxygen) exceeds 12%.When damaged, this tough, adherent, corrosion-resistant oxide (which is only 1–2 nanometers thick) actually heals itself, provided oxygen is present, even in very small amounts. Materials that form this superior protective oxide are known as the true stainless steels.

Several classification schemes have been devised to categorize the Stainless steels such as:

➢ Ferritic stainless steels (due to Chromium, since it is a ferrite stabilizer) exhibit a ductile-to-brittle transition as the temperature is reduced. The ferritic alloys are the cheapest type of stainless steel, however, and, as such, they should be given first consideration when a stainless alloy is required.

➢ Martensitic stainless steels exhibit good corrosion resistance and tend to be used when strength and hardness are the dominant requirements. The martensitic stainless steels cost about one and half times as much as the ferritic alloys, with part of the increase being due to the additional heat treatment.

➢ Austenitic stainless steels (due to Nickel; since is an austenite stabilizer, with sufficient amounts of both chromium and nickel and low carbon) these alloys may cost two to three times as much as the ferritic variety. They are offer the best combination of corrosion resistance and toughness of the stainless varieties and may be polished to a mirror finish.

➢ Precipitation-hardening variety alloys are basically martensitic or austenitic types modified by the addition of alloying elements such as aluminum that permit the precipitation of hard intermetallic compounds at the temperatures used to temper

martensite. With the addition of age hardening, these materials are capable of attaining high-strength properties such as (1790-MPa) yield strength, (1825-MPa) tensile strength, and a 2% elongation.

➢ Duplex stainless steels contain between 18 and 25% chromium, 4 to 7% nickel, and up to 4% molybdenum; they can be water quenched from a hot-working temperature to produce a microstructure that is approximately half ferrite and half austenite. This mixed structure offers a higher yield strength and greater resistance to stress corrosion cracking and pitting corrosion than either the full-austenitic or full-ferritic grades.

G- Tool steels are high-carbon, high-strength, ferrous alloys that have been modified by alloy additions to provide a desired balance of strength, toughness, and wear resistance when properly heat treated.

The primary role of an alloy addition is usually to increase hardenability, but other effects are also possible, such as modified toughness or machinability. The most common hardenability-enhancing elements (in order of decreasing effectiveness) are manganese, molybdenum, chromium, silicon, and nickel. Boron is an extremely powerful hardenability agent. Only a few thousandths of a percent are sufficient to produce a significant effect in low-carbon steels Table 2-1 summarizes the primary effects of the common alloying elements in steel. A working knowledge of this information may be useful in selecting an alloy steel to meet a given set of requirements. Alloying elements are often used in combination, however, resulting in the immense variety of alloy steels that are commercially available. To provide some degree of simplification, a classification system has been developed and has achieved general acceptance in a variety of industries.

TABLE 2-1 Principal Effects of Major Alloying Elements in Steel

Element	Percentage	Primary Function
Aluminum	0.95–1.30	Alloying element in nitriding steels
Bismuth	—	Improves machinability
Boron	0.001–0.003	Powerful hardenability agent
Chromium	0.5–2	Increase of hardenability
	4–18	Corrosion resistance
Copper	0.1–0.4	Corrosion resistance
Lead	—	Improved machinability
Manganese	0.25–0.40	Combines with sulfur to prevent brittleness
	>1	Increases hardenability by lowering transformation points and causing transformations to be sluggish
Molybdenum	0.2–5	Stable carbides; inhibits grain growth
Nickel	2–5	Toughener
	12–20	Corrosion resistance
Silicon	0.2–0.7	Increases strength
	2	Spring steels
	Higher percentages	Improves magnetic properties
Sulfur	0.08–0.15	Free-machining properties
Titanium	—	Fixes carbon in inert particles Reduces martensitic hardness in chromium steels
Tungsten	—	Hardness at high temperatures
Vanadium	0.15	Stable carbides; increases strength while retaining ductility, Promotes fine grain structure

2.3 NONFERROUS METALS AND ALLOYS

Nonferrous metals and alloys have assumed increasingly important roles in modern technology. Because of their number and the fact that their properties vary widely, they provide an almost limitless range of properties for the design engineer. While they tend to be more costly than iron or steel, these metals often possess certain properties or combinations of properties that are not available in the ferrous metals, such as:

1. Resistance to corrosion

2. Ease of fabrication

3. High electrical and thermal conductivity

4. Light weight

5. Strength at elevated temperatures

6. Color

Nearly all the nonferrous alloys possess at least two of the qualities listed above, and some possess nearly all. For many applications, specific combinations of these properties are highly desirable. Figure 2-4 classifies some of the nonferrous metals by advantageous engineering properties, and Table 2-2 shows the increasing role of the nonferrous metals in a typical family vehicle.

As a whole, the strength of the nonferrous alloys is generally inferior to that of steel. Also, the modulus of elasticity is usually lower, ease of fabrication is often attractive. Those alloys with low melting points are easy to cast in sand molds, permanent molds, or dies. Many alloys have high ductility coupled with low yield points, the ideal combination for cold working. Good machinability is also characteristic of many nonferrous alloys.

TABLE 2-2 The Material Content of a Typical Family Vehicle (in pounds)

Material	1978	1990	2002
Steel	2103	1682.5	1757
Stainless steel	26	34	56.5
Cast iron	512	454	328
Plastics	180	229	255
Aluminum	112.5	158.5	279.5
Copper	37	48.5	50
Zinc	31	18.5	8.5
Magnesium	1	3	9.5
Powder metal	15.5	24	40.5
Other materials	551.5	488.5	573
Total	3569.5	3140.5	3357.5
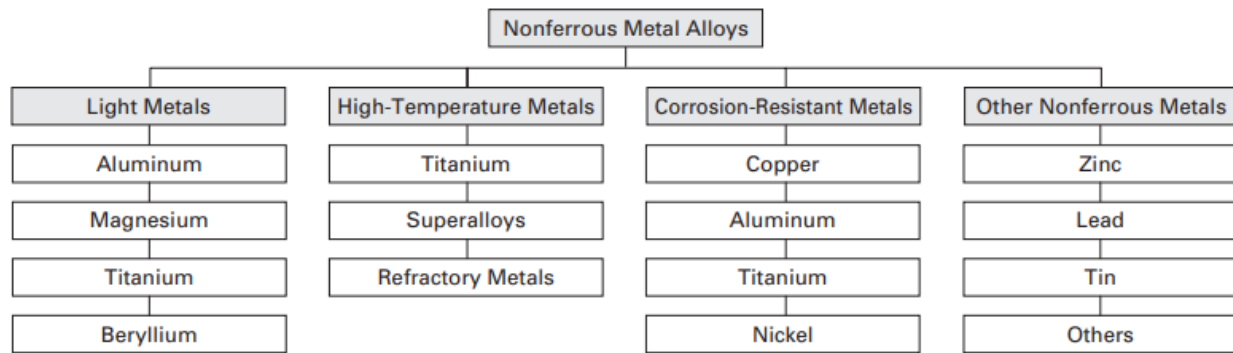
FIGURE 2-4 Some common nonferrous metals and alloys, classified by attractive engineering property.

2.3.1   COPPER AND COPPER ALLOYS

Copper has been an important engineering metal for over 6000 years. As a pure metal, it has been the backbone of the electrical industry. It is also the base metal of a number of alloys, generically known as brasses and bronzes. Compared to other engineering materials, copper and copper alloys offer three important properties: (1) high electrical and thermal conductivity, (2) useful strength with high ductility, and (3) corrosion resistance to a wide range of media. Because of its excellent conductivity, about one-third of all copper produced is used in some form of electrical application. Other large areas of use include plumbing, heating, and air conditioning.

Pure copper in its annealed state has a tensile strength of only about (200 MPa), with an elongation of nearly 60%. Through cold working, the tensile strength can be more than doubled to over (450 MPa), with a decrease in elongation to about 5%. Because of its relatively low strength and high ductility, copper is a very desirable metal for applications where extensive forming is required. Since the recrystallization temperature for copper is less than (260°C), the hardening effects of cold working can also be easily removed. Copper and copper alloys lend themselves nicely to the whole spectrum of fabrication processes, including casting, machining, joining, and surface finishing by either plating or polishing.

Copper is heavier than iron. While strength can be quite high, the strength-to-weight ratio for copper alloys is usually less than that for the weaker aluminum and magnesium materials. In addition, problems can occur when copper is used at elevated temperature. Copper alloys tend to soften when heated above 220°C, and if copper is stressed for a long period of time at high temperature, intercrystalline failure can occur at about half of its normal room-temperature strength. While offering good resistance to adhesive wear, copper and copper alloys have poor abrasive wear characteristics. Strength and conductivity also tend to increase with a drop in temperature. Additional features include offering a wide spectrum of colors, including yellow, red, brown, and silver.

The most common copper and copper Alloys are

- a- Commercially pure copper (electrolytic tough-pitch (ETP) copper)
- b- Copper-based alloys
- c- Copper–zinc alloys (brass)
- d- Copper–tin alloys (tin bronzes)
- e- Copper–nickel alloys

2.3.2 ALUMINUM AND ALUMINUM ALLOYS

Although aluminum has only been a commercial metal for about 120 years, it now ranks second to steel in both worldwide quantity, and it is clearly the most important of the nonferrous metals. It has achieved importance in virtually all segments of the economy, with principal uses in transportation, containers and packaging, building construction, electrical applications, and mechanical equipment.

A number of unique and attractive properties account for the engineering significance of aluminum. These include its workability, light weight, corrosion resistance, good electrical and thermal conductivity, optical reflectivity, and a nearly limitless array of available finishes. Aluminum can be recycled repeatedly with no loss in quality, and recycling saves 95% of the energy required to produce aluminum from ore.

From an engineering viewpoint aluminum is relatively low modulus of elasticity, which is also about one-third that of steel. Under identical loadings, an aluminum component will deflect three times as much as a steel component of the same design. Since the

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modulus of elasticity cannot be significantly altered by alloying or heat treatment, it is usually necessary to provide stiffness and buckling resistance through design features such as ribs or corrugations. These can be incorporated with relative ease, however, because aluminum adapts easily to the full spectrum of fabrication processes.

Aluminum alloys can be divided into two major groups based on the method of fabrication. Wrought alloys are those that are shaped as solids and are therefore designed to have attractive forming characteristics, such as low yield strength, high ductility, good fracture resistance, and good strain hardening. Casting alloys achieve their shape as they solidify in molds or dies. Attractive features for the casting alloys include low melting point, high fluidity, and attractive as-solidified structures and properties.

The most common aluminum and aluminum alloys are:

   a- Aluminum–lithium alloys
   b- Aluminum foam (mixing ceramic particles with molten aluminum)

2.3.3   MAGNESIUM AND MAGNESIUM ALLOYS

Magnesium is the lightest of the commercially important metals. Like aluminum, magnesium is relatively weak in the pure state and for engineering purposes is almost always used as an alloy. Even in alloy form, however, the metal is characterized by poor wear, creep, and fatigue properties. It has the highest thermal expansion of all engineering metals. Strength drops rapidly when the temperature exceeds so magnesium should not be considered for elevated-temperature service. Its modulus of elasticity is even less than that of aluminum.

On the more positive side, magnesium alloys have a relatively high strength-to-weight ratio, with some commercial alloys attaining strengths as high as (380 MPa). High energy absorption means good damping of noise and vibration, as well as impact and dent resistance.

2.3.4 ZINC-BASED ALLOYS

Zinc is used as the base metal for a variety of die-casting alloys. For this purpose, zinc offers low cost, a low melting point (only 380°C), and the attractive property of not adversely affecting steel dies when in contact with molten metal. Unfortunately, pure zinc is almost as heavy as steel and is also rather weak and brittle. Therefore, when alloys are designed for die casting, the alloy elements are usually selected for their ability to increase strength and toughness in the as-cast condition while retaining the low melting point.

2.3.5 TITANIUM AND TITANIUM ALLOYS

Titanium is a strong, lightweight, corrosion-resistant metal that has been of commercial importance since about 1950. Because its properties are generally between those of steel and aluminum, its importance has been increasing rapidly. The yield strength of commercially pure titanium is about (210 MPa), but this can be raised to (1300 MPa) or higher through alloying and heat treatment, a strength comparable to that of many heat-treated alloy steels. Good mechanical properties are retained up to temperatures of so the metal is often considered to be a high-temperature engineering material. On the negative side, titanium and its alloys suffer from high cost, fabrication difficulties, a high energy content (they require about 10 times as much energy to produce as steel), and a high reactivity at elevated temperatures (above 535°C).

2.3.6 NICKEL-BASED ALLOYS

Nickel-based alloys are most noted for their outstanding strength and corrosion resistance, particularly at high temperatures, and are available in a wide range of wrought and cast grades. Wrought alloys are generally known by trade-names, such as Monel, Hastelloy, Inconel, Incoloy, and others. General characteristics include good formability and, good creep resistance.

Nickel-based alloys have also been used for electrical resistors and heating elements. These materials are primarily nickel–chromium alloys and are known by the trade name Nichrome. They have excellent resistance to oxidation while retaining useful strength at red heats.

2.3.7 SUPERALLOYS and REFRACTORY METALS

Titanium and titanium alloys have already been cited as being useful in providing strength at elevated temperatures, but the maximum temperature for these materials is approximately 535ºC (1000ºF). Jet engine, gas-turbine, rocket, and nuclear applications often require materials that possess high strength, creep resistance, oxidation and corrosion resistance, and fatigue resistance at temperatures up to and in excess of 1100ºC (2000ºF). One class of materials offering these properties is the superalloys, first developed in the 1940s. These alloys are based on nickel, iron and nickel, or cobalt and have the ability to retain most of their strength even after long exposures to extremely high temperatures. Strength comes from solid-solution strengthening, precipitation hardening, and dispersed alloy carbides or oxides. The nickel-based alloys tend to have higher strengths at room temperature, with yield strengths up to (1200 MPa) and ultimate tensile strengths as high as (1450 MPa). Unfortunately, the density of all superalloy metals is significantly greater than that of iron, so their use is often at the expense of additional weight. Most of the superalloys are difficult to form or machine, so methods such as electrodischarge, electrochemical, or ultrasonic machining are often used, or the products are made to final shape as investment castings. Powder metallurgy techniques are also used extensively. Because of their ingredients, all of the alloys are quite expensive, and this limits their use to small or critical parts where the cost is not the determining factor.

Going to higher temperatures, we look to the refractory metals, which include niobium, molybdenum, tantalum, rhenium, and tungsten. All have melting points near or in excess of 2500°C (14500°F). They retain a significant fraction of their strength at elevated temperature and can be used at temperatures as high as 1650°C (3000°F) provided that protective ceramic coatings effectively isolate them from gases in their operating environment. Coating technology is quite challenging, however, since the ceramic coatings must (1) have a high melting point, (2) not react with the metal they are protecting, (3) provide a diffusion barrier to oxygen and other gases, and (4) have thermal-expansion characteristics that match the underlying metal. While the refractory metals could be used at higher temperatures, the uppermost temperature is currently

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being set by limitations and restrictions imposed by the coating. Other materials and technologies that offer promise for high-temperature service include intermetallic compounds, engineered ceramics, and advanced coating systems. The intermetallic compounds provide properties that are between those of metals and ceramics, and they are excellent candidates for high-temperature applications. They are hard, stiff, creep resistant, and oxidation resistant, with good high-temperature strength that often increases with temperature. Figure 2-5 compares the upper limit for useful mechanical properties for a variety of engineering metals.

°F

3000 Refractory metals

2200 Superalloys

1000 Titanium

650 Alloy steels
500 Carbon steels

350 Aluminum
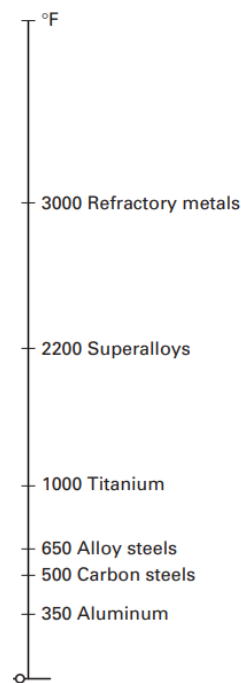
FIGURE 2-5 Temperature scale indicating the upper limit to useful mechanical properties for various engineering metals.

2.3.8 LEAD AND TIN, AND THEIR ALLOYS

The dominant properties of lead and lead alloys are high density coupled with strength and stiffness values that are among the lowest of the engineering metals. The principal uses of lead as a pure metal include storage batteries, cable cladding, and radiation absorbing or sound- and vibration-damping shields. Lead-acid batteries are clearly the dominant product. . Other applications utilize the properties of good corrosion resistance, low melting point, and the ease of casting or forming. As a pure metal, tin is

used primarily as a corrosion-resistant coating on steel. In the form of alloys, lead and tin are almost always used together. Bearing material and solder are the two most important uses. One of the oldest and best bearing materials is an alloy of 84% tin, 8% copper, and 8% antimony, known as genuine or tin Babbitt. Because of the high cost of tin, however, lead Babbitt composed of 85% lead, 5% tin, 10% antimony, and 0.5% copper, is a more widely used bearing material.

Soft solders are basically lead–tin alloys with a chemical composition near the eutectic value of 61.9% tin. While the eutectic alloy has the lowest melting temperature, the high cost of tin has forced many users to specify solders with a lower-than-optimum tin content. A variety of compositions are available, each with its own characteristic melting range.

2.3.9   GRAPHITE

While technically not a metal, graphite is an engineering material with considerable potential. It offers properties of both a metal and nonmetal, including good thermal and electrical conductivity, inertness, the ability to withstand high temperature, and lubricity. In addition, it possesses the unique property of increasing in strength as the temperature is elevated. Polycrystalline graphite can have mechanical strengths up to (70 MPa) at room temperature, which double when the temperature reaches (2500ºC).

2.4 AISI–SAE CLASSIFICATION SYSTEM

The most common classification scheme for alloy steels is the AISI–SAE identification system. This system, which classifies alloys by chemistry, was started by the Society of Automotive Engineers (SAE) to provide some standardization for the steels used in the automotive industry.

2.4.1   CARBON STEELS

Both plain-carbon and low-alloy steels are identified by a four-digit number, where the first number indicates the major alloying elements and the second number designates a subgrouping within the major alloy system. These first two digits can be interpreted by

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looking them up on a list, such as the one presented in Table 2-3. The last two digits of the number indicate the approximate amount of carbon, expressed as "points," where one point is equal to 0.01%. Thus, a 1080 steel would be a plain-carbon steel with 0.80% carbon. Similarly, a 4340 steel would be a Mo–Cr–Ni alloy with 0.40% carbon. Because of the double-digit groupings, these steels are identified as a "ten eighty" and a "forty-three forty." Letters may also be incorporated into the designation. The letter B between the second and third digits indicates that the base metal has been supplemented by the addition of boron. Similarly, an L in this position indicates a lead addition for enhanced machinability. A letter prefix may also be employed to designate the process used to produce the steel, such as E for electric furnace. When hardenability is a major requirement, one might consider the H grades of AISI steels, designated by an H suffix attached to the standard designation. The chemistry specifications are somewhat less stringent, but the steel must now meet a hardenability standard. Other designation organizations, such as the American Society for Testing and Materials (ASTM) and the U.S. government ("Military" specifications and federal), have specification systems based more on specific applications. Acceptance into a given classification is generally determined by physical or mechanical properties rather than the chemistry of the metal. ASTM designations are often used when specifying structural steels.

TABLE 2-3 AISI–SAE Standard Steel Designations and Associated Chemistries

AISI Number	Type	Alloying Elements (%)					
		Mn	Ni	Cr	Mo	V	Other
1XXX	Carbon steels						
10XX	Plain carbon						
11XX	Free cutting (S)						
12XX	Free cutting (S) and (P)						
15XX	High manganese						
13XX	High manganese	1.6–1.9					

2XXX	Nickel steels		3.5–5.0				
3XXX	Nockel–chromium		1.0–3.5	0.5–1.75			
4XXX	Molybdenum						
40XX	Mo				0.15–0.30		
41XX	Mo, Cr			0.40–0.10	0.08–0.35		
43XX	Mo, Cr, Ni		1.65–2.00	0.40–0.90	0.20–0.30		
44XX	Mo				0.35–0.60		
46XX	Mo, Ni (low)		0.70–2.00		0.15–0.30		
47XX	Mo, Cr, Ni		0.90–1.20	0.35–0.55	0.15–0.40		
48XX	Mo, Ni (high)		3.25–3.75		0.20–0.30		
5XXX	Chromium						
50XX				0.20–0.60			
51XX				0.70–1.15			
6XXX	Chromum–vanadium						
61XX				0.50–1.10		0.10–0.15	
8XXX	Ni, Cr, Mo						
81XX			0.20–0.40	0.30–0.55	0.08–0.15		
86XX			0.40–0.70	0.40–0.60	0.15–0.25		
87XX			0.40–0.70	0.40–0.60	0.20–0.30		
88XX			0.40–0.70	0.40–0.60	0.30–0.40		
9XXX	Other						
92XX	High silicon						1.20–2.20Si
93XX	Ni, Cr, Mo		3.00–3.50	1.00–1.40	0.08–0.15		
94XX	Ni, Cr, Mo		0.30–0.60	0.30–0.50	0.08–0.15		

2.4.2 Stainless Steels

Several classification schemes have been devised to categorize the Stainless Steels and alloys. The (AISI) groups the metals by chemistry and assigns a three-digit number that identifies the basic family and the particular alloy within that family. In this text, however, we will group these alloys into microstructural families, since it is the basic

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structure that controls the engineering properties of the metal. Table 2-4 presents the AISI designation scheme for stainless steels and correlates it with the microstructural families.

TABLE 2-4 (A) AISI Designation Scheme for Stainless Steels

Series	Alloys	Structure
200	Chromium, nickel, manganese, or nitrogen	Austenitic
300	Chromium and nickel	Austenitic
400	Chromium and possibly carbon	Ferritic or martensitic
500	Low chromium (<12%) and possibly carbon	Martensitic

TABLE 2-4 (B)

Structure	AISI type
Martensitic (hardenable by heat treatment)	410
	420
	440C
Ferritic (more corrosion resistant than martensitic, but not hardenable by heat treatment)	405
	430
	446
Austenitic (best corrosion resistance, but hardenable only by cold working)	201
	202
	301
	302
	302B
	304L
	310
	316
	321

2.4.3   TOOL STEELS

Several classification systems have been developed, some using chemistry as a basis and others employing hardening method or major mechanical property. The AISI system uses a letter designation to identify basic features such as quenching method, primary application, special alloy or characteristic, or specific industry involved. Table 2-5 lists seven basic families of tool steels, the corresponding AISI letter grades, and the associated feature or characteristic. Individual alloys within the letter grades are then listed numerically to produce a letter–number identification system.

TABLE 2-5 Basic Types of Tool Steel and Corresponding AISI Grades

Type	AISI Grade	Significant Characteristic
Water-Hardening	W	
Cold-work	O	Oil-hardening
	A	Air-hardening medium alloy
	D	High-carbon–high-chromium
Shock-resisting	S	
High-speed	T	Tungsten alloy
	M	Molybdenum alloy
Hot-work	H	H1–H19: chromium alloy
		H20–H39: tungsten alloy
		H40–H59: molybdenum alloy
Plastic-mold	P	
Special-purpose	L	Low alloy
	F	Carbon–tungsten

Water-hardening tool steels (**W** grade) are essentially high-carbon plain-carbon steels. They are the least expensive variety and are used for a wide range of parts that are usually quite small and not subject to severe usage or elevated temperature. The alloy additions and higher hardenability of the oil- or air-hardening grades (**O** and **A** designations, respectively) enable hardening by less severe quenches. Tighter

dimensional tolerances can be maintained during heat treatment, and the cracking tendency is reduced. The high-chromium tool steels, designated by the letter **D**, contain between 10 and 18% chromium, and are also air-hardening and offer outstanding deep-hardening wear resistance. Shock-resisting tool steels (**S** designation) offer the high toughness needed for impact applications. Low carbon content (approximately 0.5% carbon) is usually specified to assure the necessary toughness, with carbide-forming alloys providing the necessary abrasion resistance, hardenability, and hot-work characteristics. One popular member of the tungsten high-speed tool steels (**T** designation) offer a balanced combination of shock resistance and abrasion resistance and are used for a wide variety of cutting applications. The molybdenum high-speed steels (**M** designation) were developed to reduce the amount of tungsten and chromium required to produce the high-speed properties. Hot-work tool steels (**H** designation) were developed to provide strength and hardness during prolonged exposure to elevated temperature.

2.4.4   CAST IRON

A designation system for cast irons has been developed by the ASTM. Table 2-6 shows the malleable and ductile irons grades.

Table 2-6 the malleable and ductile irons grades

Cast Iron	Class or Grade
Malleable Iron	M3210
	M4504
	M5003
	M5503
	M7002
	M8501
Ductile Iron	60-40-18
	65-45-12
	80-50-06
	100-70-03
	120-90-02

2.4.5   ALUMINUM AND ALUMINUM ALLOYS

A- WROUGHT ALUMINUM ALLOYS

 The wrought aluminum alloys are generally identified using the standard four-digit designation system for aluminums. The first digit indicates the major alloy element or elements, as shown in Table 2-7. The second digit is usually zero. Nonzero numbers are used to indicate some form of modification or improvements to the original alloy. The last two digits simply indicate the particular alloy within the family. For example, 2024 simply means alloy number 24 within the 2xxx, or aluminum–copper, system. For the 1xxx series, the last three digits are used to denote the purity of the aluminum.

TABLE 2-7 AISI Designation Scheme for wrought aluminum alloys

Major Alloying Element	AISI
Aluminum, 99.00% and greater	1XXX
Copper	2XXX
Manganese	3XXX
Silicon	4XXX
Magnesium	5XXX
Magnesium and silicon	6XXX
Zinc	7XXX
Other element	8XXX

B- ALUMINUM CASTING ALLOYS

Aluminum alloys are cast in considerable quantity by a variety of processes. Table 2-8 lists some of the commercial aluminum casting alloys and uses the three-digit designation system of the Aluminum Association to designate alloy chemistry. The first digit indicates the alloy group as shown in Table 2-8. The second and third digits identify the particular alloy or aluminum purity, and the last digit, separated by a decimal point, indicates the product form (e.g., casting or ingot).

TABLE 2-8 AISI Designation Scheme for casting aluminum alloys

Major Alloying Element	AISI
Aluminum, 99.00% and greater	1XX.X
Copper	2XX.X
Silicon with Cu and/or Mg	3XX.X
Silicon	4XX.X
Magnesium	5XX.X
Zinc	7XX.X
Tin	8XX.X
Other elements	9XX.X

2.4.6 MAGNESIUM ALLOYS AND THEIR FABRICATION

A designation system for magnesium alloys has been developed by the ASTM, identifying both chemical composition and temper, and is presented in specification B93.Two prefix letters designate the two largest alloying metals in order of decreasing amount, using the following format:

A aluminum   F iron   M manganese   R chromium   B bismuth

H thorium   N nickel   S silicon   C copper   K zirconium   P lead

T tin   D cadmium   L beryllium   Q silver   Z zinc   E rare earth

Aluminum is the most common alloying element and, along with zinc, zirconium, and thorium, promotes precipitation hardening. Manganese improves corrosion resistance, and tin improves castability. The two letters are then followed by two or three numbers and a possible suffix letter. The numbers correspond to the rounded-off whole-number percentages of the two main alloy elements and are arranged in the same order as the letters. Thus the AZ91 alloy would contain approximately 9% aluminum and 1% zinc. A suffix letter is used to denote variations of the same base alloy, such as AZ91A. The temper-designation suffix is quite similar to that used with the aluminum alloys.

2.5 NONMETALLIC MATERIALS

Because of their wide range of attractive properties, the nonmetallic materials have always played a significant role in manufacturing. Wood has been a key engineering material down through the centuries, and artisans have learned to select and use the various types and grades to manufacture a broad spectrum of quality products. Stone and rock continue to be key construction materials, and clay products can be traced to antiquity. Even leather has been a construction material and was used for fenders in early automobiles. More recently, however, the family of nonmetallic materials has expanded from the natural materials just described and now includes an extensive list of plastics (polymers), elastomers, ceramics, and composites. Most of these are manufactured materials, so a wide variety of properties and characteristics can be obtained. New variations are being created on a continuous basis, and their uses and applications are expanding rapidly. Many observers now refer to a materials revolution as these new materials compete with and complement steel, aluminum, and the other more traditional engineering metals. New products have emerged, utilizing the new properties, and existing products are continually being reevaluated for the possibility of material substitution. As the design requirements of products continue to push the limits of traditional materials, the role of the manufactured nonmetallic materials will no doubt continue to expand.

2.5.1 POLYMERS

A polymer (the name means "many parts") is long chain molecule made up many repeating units, called monomers. Polymers can be natural (organic) or synthetic. The properties of polymers are linked directly to their structure, which is dictated mostly by intermolecular bonds.

Polymers are everywhere: in plastics (bottles, toys, packaging), cosmetics, shampoos and other hair care products, contact lenses, nature (crab shells, amber), food (proteins, starches, gelatin, gum, gluten), fabric, balls, sneakers, and even in your DNA!.

Compared with metals:

♣ Polymers have lower density, lower stiffness and tend to creep.

 ♣ High thermal expansion and corrosion resistance.

♣ Low electrical and thermal conductivities.

♣ The prime weakness is that polymers do not withstand high temperatures.

2.5.2 PLASTICS

It is difficult to provide a precise definition of the term plastics. From a technical viewpoint, the term is applied to engineered materials characterized by large molecules that are built up by the joining of smaller molecules. On a more practical level, these materials are natural or synthetic resins, or their compounds, that can be molded, extruded, cast, or used as thin films or coatings. They offer low density, low tooling costs, good resistance to corrosion and chemicals, cost reduction, and design versatility. From a chemical viewpoint, most are organic substances containing hydrogen, oxygen, carbon, and nitrogen.

Plastics are used to save lives in applications such as artificial organs, shatter-proof glass, and bullet-proof vests. They reduce the weight of cars, provide thermal insulation to our homes, and encapsulate our medicines. They form the base material in products as diverse as shower curtains, contact lenses, and clothing, and compose some of the primary components in televisions, computers, cell phones, and furniture. Even the Statue of Liberty has a plastic coating to protect it from corrosion.

2.5.2.1 MOLECULAR STRUCTURE OF PLASTICS

 To understand the properties of plastics, it is important to first understand their molecular structure. For simplicity, let's begin with the paraffin-type hydrocarbons, in which carbon and hydrogen combine in the relationship (CnH2n+2).Theoretically, the atoms can link together indefinitely to form very large molecules, extending the series depicted in Figure 2-6. The bonds between the various atoms are all pairs of shared electrons (covalent bonds). Bonding within the molecule, therefore, is quite strong, but the attractive forces between adjacent molecules are much weaker. Because there is no

provision for additional atoms to be added to the chain, these molecules are said to be saturated. Carbon and hydrogen can also form molecules where the carbon atoms are held together by double or triple covalent bonds. Ethylene and acetylene are common examples (Figure 2-7). Because these molecules do not have the maximum number of hydrogen atoms, they are said to be unsaturated and are important in the polymerization process, where small molecules link to form large ones with the same constituent atoms. In all of the described molecules, four electron pairs surround each carbon atom and one electron pair is shared with each hydrogen atom. Other atoms or structures can be substituted for carbon and hydrogen. Chlorine, fluorine, or even a benzene ring can take the place of hydrogen. Oxygen, silicon, sulfur, or nitrogen can take the place of carbon. Because of these substitutions, a wide range of organic compounds can be created.
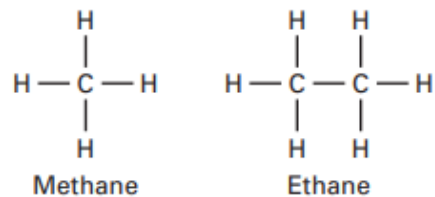
FIGURE 2-6 The linking of carbon and hydrogen to form methane and ethane molecules. Each dash represents a shared electron pair or covalent bond

FIGURE 2-7 Double and triple covalent bonds exist between the carbon atoms in unsaturated ethylene and acetylene molecules.

2.5.2.2 FORMING MOLECULES BY POLYMERIZATION

The polymerization process, or linking of molecules, occurs by either an addition or condensation mechanism. Figure 2-8 illustrates polymerization by addition, where a number of basic units (monomers) link together to form a large molecule (polymer) in

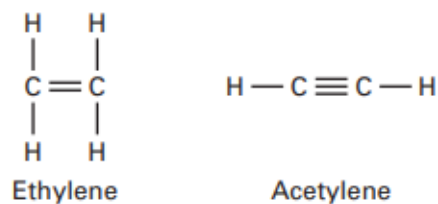which there is a repeated unit (mer). Activators or catalysts, such as benzoyl peroxide, initiate and terminate the chain. Thus, the amount of activator relative to the amount of monomer determines the average molecular weight (or average length) of the polymer chain. The average number of mers in the polymer, known as the degree of polymerization, ranges from 75 to 750 for most commercial plastics. Chain length controls many of the properties of a plastic. Increasing the chain length tends to increase toughness, creep resistance, melting temperature, melt viscosity, and difficulty in processing.
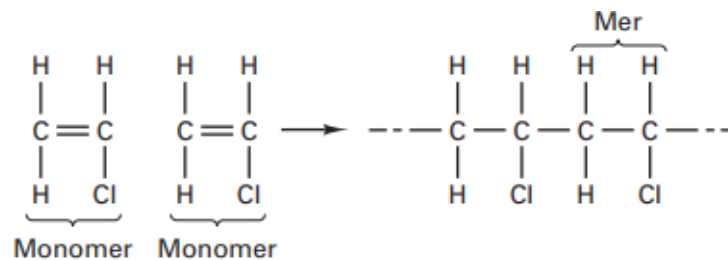
FIGURE 2-8 Addition polymerisation—the linking of monomers; in this case, identical ethylene molecules.

Copolymers are a special category of polymer where two different types of mers are combined into the same addition chain. The formation of copolymers (Figure 2-9), analogous to alloys in metals, greatly expands the possibilities of creating new types of plastics with improved physical and mechanical properties. Terpolymers further extend the possibilities by combining three different monomers.

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FIGURE 2-9 Addition polymerization with two kinds of mers—here, the copolymerization of butadiene and styrene.

2.5.2.3 PROPERTIES AND APPLICATIONS

Because there are so many varieties of plastics and new ones are being developed almost continuously, it is helpful to have knowledge of both the general prope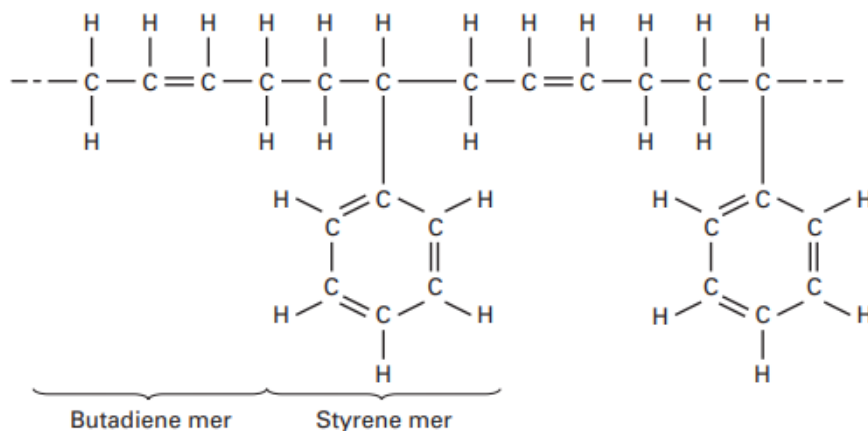rties of plastics and the unique or specific properties of the various families. General properties of plastics include:

1. *Light weight.* Most plastics have specific gravities between 1.1 and 1.6, compared with about 1.75 for magnesium (the lightest engineering metal).

2. *Corrosion resistance.* Many plastics perform well in hostile, corrosive, or chemical environments. Some are notably resistant to acid corrosion.

3. *Electrical resistance.* Plastics are widely used as insulating materials.

4. *Low thermal conductivity.* Plastics are relatively good thermal insulators.

5. *Variety of optical properties.* Many plastics have an almost unlimited color range, and the color goes throughout, not just on the surface. Both transparent and opaque materials are available.

6. *Formability or ease of fabrication.* Objects can frequently be produced from plastics in a single operation. Raw material can be converted to final shape through such processes as casting, extrusion, and molding. Relatively low temperatures are required for the forming of plastics.

7. *Surface finish.* The same processes that produce the shape also produce excellent surface finish. Additional surface finishing may not be required.

8. *Comparatively low cost.* The low cost of plastics generally applies to both the material itself and the manufacturing process. Plastics frequently offer reduced tool costs and high rates of production.

9. *Low energy content.*

2.5.2.4 THERMOSETTING AND THERMOPLASTIC MATERIALS

The terms thermosetting and thermoplastic refer to the material's response to elevated temperature. Addition polymers (or linear condensation polymers) can be viewed as long chains of bonded carbon atoms with attached pendants of hydrogen, fluorine, chlorine, or benzene rings. All of the bonds within the molecules are strong covalent bonds. For these materials, the intermolecular forces strongly influence the mechanical and physical properties. In general, the linear polymers tend to be flexible and tough. Because the intermolecular bonds are weakened by elevated temperature, plastics of this type soften with increasing temperature and the individual molecules can slide over each other in a molding process. When the material is cooled, it becomes harder and stronger. The softening and hardening of these thermoplastic or heat-softening materials can be repeated as often as desired, and no chemical change is involved.

Because thermoplastic materials contain molecules of different lengths, they do not have a definite melting temperature but, instead, soften over a range of temperatures. Above the temperature required for melting, the material can be poured and cast, or formed by injection molding. When cooled to a temperature where it is fully solid, the material can retain its amorphous structure, but with companion properties that are somewhat rubbery. The application of a force produces both elastic and plastic deformation. Large amounts of permanent deformation are available and make this range attractive for molding and extrusion. At still lower temperatures, the bonds become stronger and the polymer is stiffer and somewhat leathery. Many commercial polymers, such as polyethylene, have useful strength in this condition.

Many thermoplastics can partially crystallize* when cooled below the melting temperature. When polymers "crystallize," the chains closely align over appreciable distances, with a companion increase in density. In addition, the polymer becomes stiffer, harder, less ductile, and more resistant to solvents and heat. The ability of a polymer to crystallize depends on the complexity of its molecules, the degree of polymerization (length of the chains), the cooling rate, and the amount of deformation during cooling.

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*It should be noted that the term crystallize, when applied to polymers, has a different meaning than when applied to metals and ceramics. Metals and ceramics are crystalline materials, meaning that the atoms occupy sites in a regular, periodic array, known as a lattice. In polymers, it is not the atoms that become aligned, but the molecules. Since van der Waals bonding has a bond strength that is inversely related to the separation distance, the parallel alignment of the crystallized state is a lower-energy configuration and is promoted by slow cooling and equilibrium-type processing conditions.

The four most common thermoplastic polymers are: polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyvinyl chloride (PVC).

In contrast to the thermoplastic polymers, thermosetting plastics usually have a highly cross-linked or three-dimensional framework structure in which all atoms are connected by strong, covalent bonds. These materials are generally produced by condensation polymerization where elevated temperature promotes an irreversible reaction, hence the term thermosetting. Once set, subsequent heating will not produce the softening observed with the thermoplastics. Instead, thermosetting materials maintain their mechanical properties up to the temperature at which they char or burn. Since deformation requires the breaking of primary bonds, the thermosetting polymers are significantly stronger and more rigid than the thermoplastics. They can resist higher temperatures and have greater dimensional stability, but they also have lower ductility and poorer impact properties. As a helpful analogy, thermoplastic polymers are a lot like candle wax. They can be softened or melted by heat, and then cooled to assume a solid shape. Thermosets are more like egg whites or bread dough. Heating changes their structure and properties in an irreversible fashion. Although classification of a polymer as thermosetting or thermoplastic provides insight as to properties and performance, it also has a strong effect on fabrication. For example, thermoplastics can be easily molded. After the hot, soft material has been formed to the desired shape, however, the mold must be cooled so that the plastic will harden and be able to retain its shape upon removal. The repetitive heating and cooling cycles affect mold life, and the time required for the thermal cycles influences productivity. When a part is produced from thermosetting materials, the mold can remain at a constant temperature throughout the

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entire process, but the setting or curing of the resins now determines the time in the mold. Since the material hardens as a result of the reaction and has strength and rigidity even when hot, product removal can be performed without cooling the mold.

2.5.2.5 COMMON TYPES OR FAMILIES OF PLASTICS

A- THERMOPLASTICS

- *Polyethylenes (BE)*: the most common polymer; inexpensive, tough, good chemical resistance to acids, bases, and salts; high electrical resistance; low strength; easy to shape and join; reasonably clear in thin-film form; subject to weathering via ultraviolet light; flammable; used for grocery bags, milk jugs and other food containers, tubes, pipes, sheeting, and electrical wire insulation. Variations include: low-density polyethylene (LDPE—floats in water), high-density polyethylene (HDPE), ultra-high-molecular-weight polyethylene (UHMW).
- *Polypropylene (PP)*: inexpensive; stronger, stiffer, and better heat resistance than polyethylene; transparent; reasonable toughness; used for beverage containers, luggage, pipes, and ropes.
- *Polystyrenes (PS)*: high dimensional stability and stiffness with low water absorption; best all-around dielectric; clear, hard, and brittle at room temperature; often used for rigid packaging; can be foamed to produce expanded polystyrene (trade name of Styrofoam); burns readily; softens at about 95ºC.
- *Polyvinyl chloride (PVC)*: general-purpose thermoplastic; good resistance to ultraviolet light (good for outside applications); easily molded or extruded; always used with fillers, plasticizers, and pigments; uses include gas and water pipes as well as window frames.

B- THERMOSETS
- *Epoxies*: good strength, toughness, elasticity, chemical resistance, moisture resistance, and dimensional stability; easily compounded to cure at room temperature; used as adhesives, bonding agents, coatings, and in fiber laminates.

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- *Melamines*: excellent resistance to heat, water, and many chemicals; full range of translucent and opaque colors; excellent electric arc resistance; tableware (but stained by coffee); used extensively in treating paper and cloth to impart water-repellent properties.

- *Polyesters (can be thermoplastic or thermoset)*: strong and good resistance to environmental influences; uses include boat and car bodies, pipes, vents and ducts, textiles, adhesives, coatings, and laminates.

- *Silicones*: heat and weather resistant; low moisture absorption; chemically inert; high dielectric properties; excellent sealants.

2.5.3 CERAMICS

The first materials used by humans were natural materials such as wood and stone. The discovery that certain clays could be mixed, shaped, and hardened by firing led to what was probably the first man-made material. Traditional ceramic products, such as bricks and pottery, have continued to be key materials throughout history. More recently, ceramic materials have assumed important roles in a number of engineering applications. Most of these utilize their outstanding physical properties, including the ability to withstand high temperatures, provide a wide variety of electrical and magnetic properties, and resist wear. In general, ceramics are hard, brittle, high-melting-point materials with low electrical and thermal conductivity, low thermal expansion, good chemical and thermal stability, good creep resistance, high elastic modulus, and high compressive strengths that are retained at elevated temperature.

Glass and glass products now account for about half of the ceramic materials market. Advanced ceramic materials (including the structural ceramics, electrical and magnetic ceramics, and fiber-optic material) compose another 20%. Whiteware and porcelain enameled products (such as household appliances) account for about 10% each.

Ceramic materials are compounds of metallic and nonmetallic elements (often in the form of oxides, carbides, and nitrides) and exist in a wide variety of compositions and forms. Most have crystalline structures, but unlike metals, the bonding electrons are generally captive in strong ionic or covalent bonds. Because of the strength of the primary bonds, most ceramics have high melting temperatures, high rigidity, and high compressive strength.

The crystal structures of ceramic materials can be quite different from those observed in metals. In many ceramics, atoms of significantly different size must be accommodated within the same structure, and the interstitial sites, therefore, become extremely important. As with metals, the same chemistry material can often exist in more than one structural arrangement (polymorphism). Silica (SiO_2), for example, can exist in three forms quartz, tridymite, and crystobalite depending on the conditions of temperature and pressure. Ceramic materials can also exist in the form of chains, similar to the linear molecules in plastics. A non-crystalline structure is also possible in solid ceramics. This amorphous condition is referred to as the glassy state, and the materials are known as glasses.

Elevated temperatures can be used to decrease the viscosity of glass, allowing the atoms to move as groups and the material to be shaped and formed. When the temperature is dropped, the material again becomes hard and rigid. The crystalline ceramics do not soften, but they can creep at elevated temperature by means of grain boundary sliding. Therefore, when ceramic materials are produced for elevated-temperature service, large grain size is generally desired.

2.5.3.1 CLAY AND WHITEWARE PRODUCTS

Many ceramic products are still based on clay, to which various amounts of quartz and feldspar and other materials are added. Selected proportions are mixed with water, shaped, dried, and fired to produce the structural clay products of brick, roof and structural tiles, drainage pipe, and sewer pipe, as well as the whiteware products of

sanitary ware (toilets, sinks, and bathtubs), dinnerware, china, decorative floor and wall tile, pottery, and other artware.

2.5.3.2 REFRACTORY MATERIALS

Refractory materials are ceramics that have been designed to provide acceptable mechanical or chemical properties at high operating temperatures. They may take the form of bricks and shaped products, bulk materials (often used as coatings), and insulating ceramic fibers. Most are based on stable oxide compounds, where the coarse oxide particles are bonded by finer refractory material. Various carbides, nitrides, and borides can also be used in refractory applications. Refractory ceramics fall into three distinct classes: acidic, basic, and neutral. Common acidic refractories are based on silica (SiO_2) and alumina (Al_2O_3) and can be compounded to provide high-temperature resistance along with high hardness and good mechanical properties. Magnesium oxide (MgO) is the core material for most basic refractories. These are generally more expensive than the acidic materials but are often required in metal-processing applications to provide compatibility with the metal. Neutral refractories, containing chromite (Cr_2O_3), are often used to separate the acidic and basic materials since they tend to attack one another. The combination is often attractive when a basic refractory is necessary on the surface for chemical reasons, and the cheaper acidic material is used beneath to provide strength and insulation.

2.5.3.3 ABRASIVES

Because of their high hardness, ceramic materials, such as silicon carbide and aluminum oxide (alumina), are often used for abrasive applications, such as grinding. Materials such as manufactured diamond and cubic boron nitride have such phenomenal properties that they are often termed super-abrasives.

2.5.3.4 CERAMICS FOR ELECTRICAL AND MAGNETIC APPLICATIONS

Ceramic materials also offer a variety of useful electrical and magnetic properties. Some ceramics, such as silicon carbide, are used as resistors and heating elements for electric furnaces. Others have semiconducting properties and are used for thermistors and rectifiers. Dielectric, piezoelectric, and ferroelectric behavior can also be utilized in many applications. Barium titanate, for example, is used in capacitors and transducers. High-density clay-based ceramics and aluminum oxide make excellent high-voltage insulators. The magnetic ferrites have been used in a number of magnetic applications. Considerable attention has also been directed toward the "high-temperature" ceramic superconductors.

2.5.3.5 GLASSES

When some molten ceramics are cooled at a rate that exceeds a critical value, the material solidifies into a hard, rigid, non-crystalline (i.e., amorphous) solid, known as a glass. Most commercial glasses are based on silica (SiO_2), lime ($CaCO_3$), and sodium carbonate ($NaCO_3$), with additives to alter the structure or reduce the melting point. Various chemistries can be used to optimize optical properties, thermal stability, and resistance to thermal shock.

Glass is soft and moldable when hot, making shaping rather straightforward. When cool and solid, glass is strong in compression but brittle and weak in tension. In addition, most glasses exhibit excellent resistance to weathering and attack by most chemicals. Traditional applications include automotive and window glass, bottles and other containers, light bulbs, mirrors, lenses, and fiberglass insulation. There is also a wide variety of specialty applications, including glass fiber for fiber-optic communications, glass fiber to reinforce composites, cookware, TV tubes and monitors, and a variety of medical and biological products. Glass and other ceramic fibers have been used for filtration, where they provide a chemical inertness and the possibility to withstand elevated temperature.

2.5.3.6 CERMETS

Cermets are combinations of metals and ceramics (usually oxides, carbides, nitrides, or carbonitrides) united into a single product by the procedures of powder metallurgy. This usually involves pressing mixed powders at pressures ranging from (70 to 280 MPa) followed by sintering in a controlled-atmosphere furnace at about (1650ºC). Cermets combine the high hardness and refractory characteristics of ceramics with the toughness and thermal shock resistance of metals. They are used as jet engine nozzles, and aircraft brakes, as well as in other applications requiring hardness, strength, and toughness at elevated temperature. Cemented tungsten carbide (tungsten carbide particles cemented in a cobalt binder) has been used in dies and cutting tools for quite some time. The more advanced cermets now enable higher cutting speeds than those achievable with high-speed tool steel, tungsten carbide, or the coated carbides.

2.5.3.7 CEMENTS

Various ceramic materials can harden by chemical reaction, enabling their use as a binder that does not require firing or sintering. Sodium silicate hardens in the presence of carbon dioxide and is used to produce sand cores in metal casting. Plaster of paris and portland cement both harden by hydration reactions.

2.5.3.8 CERAMIC COATINGS

Wide spectrums of enamels, glazes, and other ceramic coatings have been developed to decorate, seal, and protect substrate materials. Porcelain enamel can be applied to carbon steel in the perforated tubs of washing machines, where the material must withstand the scratching of zippers, buttons, and snaps along with the full spectrum of laundry products. Chemical reaction vessels are often glass lined.

2.5.4   COMPOSITE MATERIALS

A composite material is a non-uniform solid consisting of two or more different materials that are mechanically or metallurgically bonded together. Each of the various components retains its identity in the composite and maintains its characteristic structure and properties. There are recognizable interfaces between the materials. The composite material, however, generally possesses characteristic properties (or combinations of properties), such as stiffness, strength, weight, high-temperature performance, corrosion resistance, hardness, and conductivity, which are not possible with the individual components by themselves. Analysis of these properties shows that they depend on (1) the properties of the individual components; (2) the relative amounts of the components; (3) the size, shape, and distribution of the discontinuous components; (4) the orientation of the various components; and (5) the degree of bonding between the components. The materials involved can be organics, metals, or ceramics. Hence a wide range of freedom exists, and composite materials can often be designed to meet a desired set of engineering properties and characteristics.

There are many types of composite materials and several methods of classifying them. One method is based on geometry and consists of three distinct families: laminar or layered composites, particulate composites, and fiber-reinforced composites.

2.5.4.1 LAMINAR OR LAYERED COMPOSITES

 Laminar composites have distinct layers of material bonded together in some manner and include thin coatings, thicker protective surfaces, claddings, bimetallics, laminates, sandwiches, and others. They are used to impart properties such as reduced cost, enhanced corrosion resistance or wear resistance, electrical insulation or conductivity, unique expansion characteristics, lighter weight, improved strength, or altered appearance.

Plywood is probably the most common engineering material in this category and is an example of a laminate material. Layers of wood veneer are adhesively bonded with their grain orientations at various angles to one another. Strength and fracture resistance are

improved, properties are somewhat uniform within the plane of the sheet, swelling and shrinkage tendencies are minimized, and large pieces are available at reasonable cost.

Laminated plastics are made from layers of reinforcing material that have been impregnated with thermosetting resins, bonded together, and cured under heat and pressure. They can be produced as sheets, or rolled tightly to form a rod. Common applications include a variety of decorative items, such as Formica countertops, imitation hardwood flooring, and furniture.

Bimetallic strip is a laminate of two metals with significantly different coefficients of thermal expansion. As Figure 2-10 illustrates, changes in temperature now produce flexing or curvature in the product. The unique property of shape varying with temperature is often employed in thermostat and other heat-sensing applications.
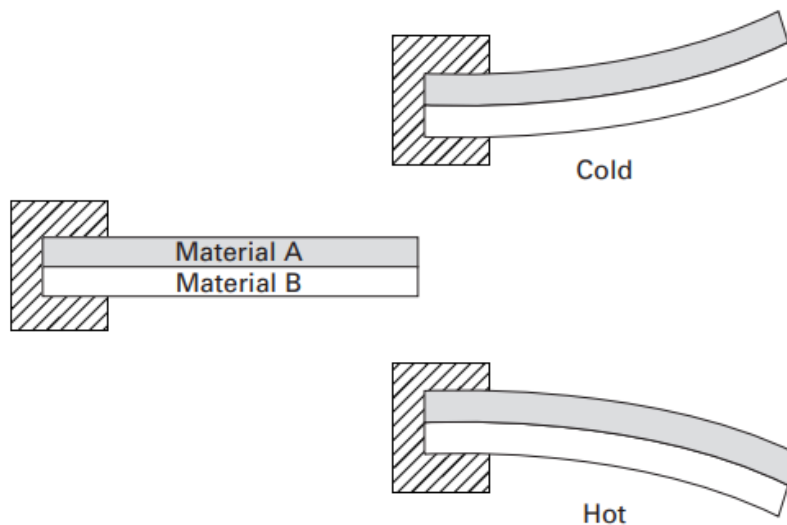
FIGURE 2-10 Schematic of a bimetallic strip where material A has the greater coefficient of thermal expansion. Note the response to cold and hot temperatures.

Sandwich material is a laminar structure composed of a thick, low-density core placed between thin, high-density surfaces. Corrugated cardboard is an example of a sandwich structure. Other engineering sandwiches incorporate cores of polymer foam or honeycomb structure to produce a lightweight, high-strength, high-rigidity composite.

It should be noted that the properties of laminar composites are always anisotropic that is, they are not the same in all directions. Because of the variation in structure, properties will always be different in the direction perpendicular to the layers.

2.5.4.2 PARTICULATE COMPOSITES

Particulate composites consist of discrete particles of one material surrounded by a matrix of another material. *Concrete* is a classic example, consisting of sand and gravel particles surrounded by hydrated cement. *Asphalt* consists of similar aggregate in a matrix of bitumen, a thermoplastic polymer. In both of these examples, the particles are rather coarse. Other particulate composites involve extremely fine particles and include many of the multicomponent powder metallurgy products, specifically those where the dispersed particles do not diffuse into the matrix material.

Dispersion-strengthened materials are particulate composites where a small amount of hard, brittle, small-sized particles (typically, oxides or carbides) are dispersed throughout a softer, more ductile metal matrix. Since the dispersed material is not soluble in the matrix, it does not redissolve, overage, or overtemper when the material is heated. Pronounced strengthening can be induced, which decreases only gradually as temperature is increased. Creep resistance, therefore, is improved significantly.

 Other types of particulate composites, known as *true particulate composites*, contain large amounts of coarse particles. They are usually designed to produce some desired combination of properties rather than increased strength. Cemented carbides, for example, consist of hard ceramic particles, such as tungsten carbide, tantalum carbide, or titanium carbide, embedded in a metal matrix, which is usually cobalt. Although the hard, stiff carbide could withstand the high temperatures and pressure of cutting, it is extremely brittle. Toughness is imparted by combining the carbide particles with cobalt powder, pressing the material into the desired shape, heating to melt the cobalt, and then re-solidifying the compacted material. Varying levels of toughness can be imparted by varying the amount of cobalt in the composite.

Because of their unique geometry, the properties of particulate composites are usually isotropic, that is, uniform in all directions. This may be particularly important in engineering applications.

2.5.4.3 FIBER-REINFORCED COMPOSITES

The most popular type of composite material is the fiber-reinforced composite geometry, where continuous or discontinuous thin fibers of one material are embedded in a matrix of another. The objective is usually to enhance strength, stiffness, fatigue resistance, or strength-to-weight ratio by incorporating strong, stiff, but possibly brittle, fibers in a softer, more ductile matrix.

Wood and bamboo are two naturally occurring fiber composites, consisting of cellulose fibers in a lignin matrix. Bricks of straw and mud may well have been the first human-made material of this variety, dating back to near 800 B.C. Automobile tires now use fibers of nylon, rayon, aramid (Kevlar), or steel in various numbers and orientations to reinforce the rubber and provide added strength and durability. Steel-reinforced concrete is actually a double composite, consisting of a particulate matrix reinforced with steel fibers.

Glass-fiber-reinforced resins, the first of the modern fibrous composites, were developed shortly after World War II in an attempt to produce lightweight materials with high strength and high stiffness. Glass fibers are still the most widely used reinforcement, primarily because of their lower cost and adequate properties for many applications. Current uses of glass fiber-reinforced plastics include sporting goods, boat hulls, and bathtubs.

The properties of fiber-reinforced composites depend strongly on several characteristics: (1) the properties of the fiber material; (2) the volume fraction of fibers; (3) the aspect ratio of the fibers, that is, the length-to-diameter ratio; (4) the orientation of the fibers; (5) the degree of bonding between the fiber and the matrix; and (6) the properties of the matrix. While more fibers tend to provide greater strength and stiffness, the volume fraction of fibers generally cannot exceed 80% to allow for a continuous

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matrix. Long, thin fibers (higher aspect ratio) provide greater strength, and a strong bond is usually desired between the fiber and matrix.

The matrix materials should be strong, tough, and ductile so that they can transmit the loads to the fibers and prevent cracks from propagating through the composite. In addition, the matrix material is often responsible for providing the electrical properties, chemical behavior, and elevated-temperature stability.

2.5.4.4 AREAS OF APPLICATION

Many composite materials are stronger than steel, lighter than aluminum, and stiffer than titanium. They can also possess low thermal conductivity, good heat resistance, good fatigue life, low corrosion rates, and adequate wear resistance. For these reasons they have become well established in several areas.

Aerospace applications frequently require light weight, high strength, stiffness, and fatigue resistance. As a result, composites may well account for a considerable fraction of the weight of a current airplane design.

Sports are highly competitive, and fractions of a second or tenths of a millimeter often decide victories. As a result, both professionals and amateurs are willing to invest in athletic equipment that will improve performance. The materials of choice have evolved from naturally occurring wood, twine, gut, and rubber to a wide variety of high-technology metals, polymers, ceramics, and composites. Golf club shafts, baseball bats, fishing rods, archery bows, tennis rackets, bicycle frames, skis, and snowboards are now available in a wide variety of fibrous composites.

Other applications include such diverse products as boat hulls, bathroom shower and tub structures, chairs, architectural panels, agricultural tanks and containers, pipes and vessels for the chemical industry, and external housings for a variety of consumer and industrial products.

3. SELECTION of MATERIALS

3.1   INTRODUCTION

A number of questions need to be answered before a decision can be made as to the specification required of a material and hence a decision as to the optimum material for a particular task. The questions can be grouped under four general headings:

 1. What properties are required?

 2. What are the processing requirements and their implications for the choice of material?

 3. What is the availability of materials?

 4. What is the cost?

 The following indicate the type of questions that are likely to-be considered in trying arriving at answers to the above general questions:

3.1.1 Properties:

 1. What mechanical properties are required?

This means consideration of such properties as strength, stiffness, hardness, ductility, toughness, fatigue resistance, wear properties, etc. Coupled with this question is another one: Will the properties be required at low temperatures, about room temperature or high temperatures?

 2. What chemical properties are required?

This means considering the environment to which the material will be exposed and the possibility of corrosion.

 3. What thermal properties are required?

This means consideration of such properties as specific heat capacity, linear coefficient of expansion and thermal conductivity.

4. What electrical properties are required?

For example, does the material need to be a good conductor of electricity or perhaps an insulator?

5. What magnetic properties are required?

Does the material need to have soft or hard magnetic properties or perhaps be essentially non-magnetic?

6. What dimensional conditions are required?

For example, does the material need to be capable of a good surface finish, have dimensional stability, be flat, have a particular size, etc.

3.1.2 Processing Parameters:

1. Are there any special processing requirements which will limit the choice of material?

For example, does the material have to be cast or perhaps extruded?

2. Are there any material treatment requirements?

For example, does the material have to be annealed or perhaps solution hardened?

3. Are there any special tooling requirements?

For example, does the hardness required of a material mean special cutting tools are required?

3.1.3 Availability:

1. Is the material readily available?

Is it, for example, already in store, or perhaps quickly obtainable from normal suppliers?

2. Are there any ordering problems for that material?

Is the material only available from special suppliers? Is there a minimum order quantity

3. What form is the material usually supplied in?

For example, is the material usually supplied in bars or perhaps sheet? This can affect the processes that can be used.

3.1.4 Cost:

1. What is the cost of the raw material?

Could a cheaper material be used?

2. What quantity is required?

What quantity of product is to be produced per week, per month, per year? What stocking policy should be adopted for the material?

3. What are the cost implications of the process requirements?

Does the process require high initial expenditure? Are the running costs high or low? Will expensive skilled labor be required?

4. What are the cost penalties for over specification?

If the material is, for example stronger than is required, will this significantly increase the cost? If the product is manufactured to higher quality than is required, what will be the cost implications?

3.2 SELECTION FOR PROPERTIES

3.2.1 Selection for Static Strength

Static strength can be defined as: the ability to resist a short-term steady load at moderate temperatures without breaking or crushing or suffering excessive deformations.

Types of Stress

Uniaxial Stress

Measure of Static Strength:

Yield Strength ——>for ductile

Tensile Strength ——>for brittle

Biaxial or Tri-axial Stress

Measure of Material Failure:

Max. Principal stress——>for brittle

Max. Shear Stress——>for ductile
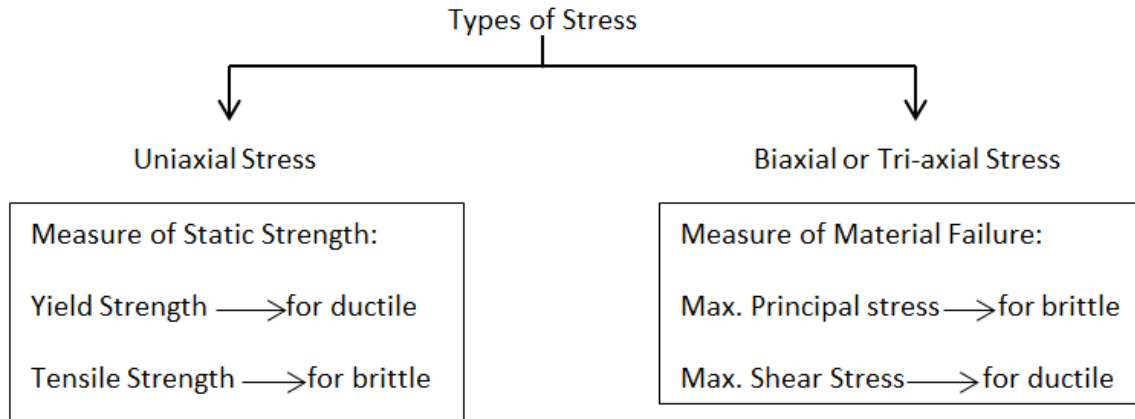
Biaxial or tri-axial stresses, e.g. a shell subject to internal pressure

- The maximum principal stress theory predicts failure as occurring when the maximum principal stress reaches the tensile strength value, or the elastic limit stress value.
- The maximum shear stress theory considers failure to occur when the maximum shear stress reaches the value of the maximum shear stress that occurs for the material at the elastic limit.

It should be recognized that a requirement for strength in a component requires not only a consideration of the static strength of the material but also the design.

For bending: an I-beam is more efficient than a rectangular cross-section beam because the material in the beam is concentrated at the top and bottom surfaces where the stresses are high. Experiment shows that this shape is good in sustaining vertical bending loads, and I-beams of this type are employed in building construction. Selection of different shapes or the same shape but with different height-to-width ratios will change the material performance as a structural element.

Table 3-1 gives a general comparison of tensile strength of a range of materials.

Strength (Mpa)	Material
60-100	Polymers
80-300	Magnesium alloy
160-400	Zinc alloys

100-600	Aluminum alloys
250-1300	Carbon and low alloy steels
250-1500	Nickel alloys
500-1800	High alloy steels
100-1800	Composite materials
1000 to > 10000	Ceramics

3.2.2   Selection for Stiffness

Stiffness: the ability of a material to resist deflection when loaded. If we consider a cantilever of length L subject to a point load F at its free end (Figure 3-1), then the deflection y at the free end is given by:

$$Y = \frac{F * L^3}{3 * E * I}$$
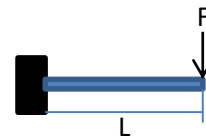
Where: E : tensile modulus I : second moment of area of the beam cross-section with respect to the neutral axis.

Because Y proportion $\frac{1}{E}$ for a given shape and length cantilever, and E proportion stiffness.

The deflection of beam is a function of both E and I. Thus a beam can be made stiffer by increasing its I. The I is increased by placing as much as possible of the material as far as possible from the axis of bending. Thus an I-section is a particularly efficient way of achieving stiffness. Similarly a tube is more efficient than a solid rod. Table 3-2 shows the materials according to tensile modulus E.

Tensile modulus E	Material
0.2-10	Polymers
43-96	Zinc alloys
70-80	Aluminum alloys
200-210	Steels
80-1000	Ceramics

3.2.3   Selection for Fatigue Resistance

The failure of a component when subject to fluctuating loads is as a result of cracks which tend to start at some discontinuity in the material and grow until failure occurs. The main factors affecting fatigue properties are: Stress concentrations caused by component design, Corrosion, Surface finish/treatment, Temperature, The microstructure of the alloy and its heat treatment.

3.2.4   Selection for Toughness

Toughness: can be defined as the resistance offered by a material to fracture (crack propagation).

A measure of toughness is given by two main measurements:

1- The resistance of a material to impact loading which is measured in the Charpy or I-zod tests by the amount of energy needed to fracture a test piece, the higher the energy the more ductile a material is.
2- The resistance of a material to the propagation of an existing crack in a fracture toughness test.

Within a given type of metal alloy there is an inverse relationship between yield stress and toughness, the higher the yield stress the lower the toughness. The toughness of plastics is improved by incorporating rubber or another tougher polymer, copolymerization, or incorporating tough fibers.

3.2.5   Selection for Creep and Temperature Resistance

Creep: can be defined as the deformation of a material with the passage of time when the material is subject to constant stress. Creep increases as the temperature increases.

For most metals creep is essentially a high-temperature effect. This is not the case with plastics. Here creep can be significant at room temperatures. Generally thermosets have higher temperature resistance than thermoplastics; however, the addition of suitable fillers and fibers can improve the temperature properties of thermoplastics.

Table 3- 3 shows the temperature limitation and materials.

Temperature limit (˚C)	Materials
Room Temp. -150 ˚C	Only lead has limits
150 ˚C -400 ˚C	Plain Carbon steels are widely used in this range
400 ˚C -600 ˚C	Titanium alloys, low alloy steels are widely used
600 ˚C -1000 ˚C	Austenitic Stainless steel, Ni-Cr-Fe alloys, Cobalt base alloy
Above 1000 ˚C	Refractory metals, Ceramic

3.2.6   Selection for corrosion resistance

Corrosion can often be much reduced by the selection of appropriate materials. Corrosion resistance can be increased by:

1- Painting (providing a protective coating of the surface)
2- The addition of Chromium to steel.

- Carbon steels and low-alloy steels are not particularly corrosion resistant, rust being the evidence of such corrosion. In an industrial atmosphere, in fresh and sea water, plain carbon steels and low-alloy steel have poor resistance. Painting, by providing a protective coating of the surface, can reduce such corrosion.
- Stainless steels have an excellent resistance in an industrial atmosphere and fresh water but can suffer some corrosion in sea water.
- The corrosion resistance of grey cast iron is good in an industrial atmosphere but not so good in fresh or sea water, though still better than that of plain carbon steels.

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- Aluminum when exposed to air develops an oxide layer on its surface which then protects the substrate from further attack. In air, aluminum and its alloys have good corrosion resistance. When immersed in fresh or sea water, most aluminum alloys offer good corrosion resistance, though there are some exceptions which must be clad in order to have good corrosion resistance.

- Copper in air forms a protective green layer which protects it from further attack and thus gives good corrosion resistance. Copper has also good corrosion resistance in fresh and sea water, hence the widespread use of copper piping for water distribution systems and central heating systems. Copper alloys likewise have good corrosion resistance in industrial atmospheres, fresh and sea water, e.g. brass with more than 15% zinc.

- Nickel and its alloys have excellent resistance to corrosion in industrial air, fresh and sea water,

- Titanium and its alloys have excellent resistance, probably the best resistance of all metals, in industrial air, fresh and sea water and is thus widely used where corrosion could be a problem.

- Plastics do not corrode in the same way as metals and thus, in general, have excellent corrosion resistance. For example, the increasing use of plastic pipes for the transmission of water and other chemicals.

- Polymers can deteriorate as a result of exposure to ultraviolet radiation, e.g. that in the rays from the sun, heat and mechanical stress. To reduce such effects, specific additives are used as fillers in the formulation of a plastic.

- Most ceramic materials show excellent corrosion resistance.

- Glasses are exceedingly stable and resistant to attack, hence the widespread use of glass containers. Enamels, made of silicate and borosilicate glasses, are widely used as coatings to protect steels and cast irons from corrosive attack.

Table 3-4 shows corrosion resistance in various environments.

Environments	Corrosion Resistance	Material
Salt water	High resistance	Ceramic, stainless steel, Ni alloys
	Medium resistance	Aluminum alloys
	Low resistance	Carbon steel, low-alloy steel
Strong acids	High resistance	Silicon carbide, Ti alloys, Ni alloys
	Medium resistance	Magnesium oxide, AL alloys
	Low resistance	Carbon steel

3.2.7 Selection for wear resistance

Wear: is the progressive loss of material from surfaces as a result of contact with other surfaces. It can occur as a result of sliding or rolling contact between surfaces or from the movement of fluids containing particles over surfaces. Because wear is a surface effect, surface treatments and coatings play an important role in improving wear resistance. Lubrication can be considered to be a way of keeping surfaces apart and so reducing wear. Surface treatment such as carburizing and nitriding improve wear resistance.

- Mild steels have poor wear resistance. However, increasing the carbon content increase the wear resistance.
- Grey cast iron has good wear resistance.
- Cobalt-base alloys offer good wear resistance.

3.2.8 Selection for thermal properties

Thermal properties that are generally of interest in the selection of materials include how much a material will expand for a particular change in temperature; how much the temperature of a piece of material will change when there is a heat input into it, and how good a conductor of heat it is.

- In general, **metals** have high thermal conductivities while **polymers** and **ceramics** have low conductivities. The specific heat capacity of a material is the energy required to raise the temperature of 1 kg of that material by 1°C.

- In general, **metals** have low specific heats while **polymers** having higher values.

- **Materials** expand when heated and the problems of differential expansion between different materials in a component can often be an important concern.

- In general, **ceramics** have low coefficients of expansion, **metals** higher values and **polymers** even higher.

3.2.9   Selection for electrical properties

The conductivity is highest when the material is of the highest purity and in the fully annealed conduction.

- In general, **metals** are good electrical conductors with low resistivity. The metals in common use in engineering which have the highest electrical conductivities are **silver**, **copper** and **aluminum**. In each the conductivity is highest annealed condition when the material is of the highest purity and in the fully. Often, however, a compromise has to be reached in that the high purity, fully annealed, metals do not have sufficient strength to enable them to be.

- **Polymers** and **ceramics** have, in general, very low electrical conductivities and are classified as being electrical insulators.

3.2.10 Selection for magnetic properties

Soft magnetic materials:

- Easy to magnetize and demagnetize.

- Used for making temporary magnets.

- Soft magnetic materials should not possess any void and its structure should be homogeneous so that the materials are not affected by impurities.

- A typical soft magnetic material used for a transformer core is an iron-3% silicon alloy

Hard magnetic materials:

- Materials which retain their magnetism and are difficult to demagnetize.
- These materials retain their magnetism even after the removal of the applied magnetic field. So, these materials are used for making permanent magnets.
- Impurities increase the strength of hard magnetic materials.
- The main materials used for permanent magnets are the iron-cobalt-nickel-aluminum alloys, ferrites and rare earth alloys.

Case Study:

Situation	Key property	Materials
Pipes used in the distribution of hot water	Corrosion resistance	Copper
A component where strength is required at temp. in the region of 700˚C	Creep resistance	Austenitic stainless steel
A component which is required to be stiff	Modulus of elasticity	Steel
A component where strength is required in a marine environment	Corrosion resistance	stainless steel
A container to hold acids	Corrosion resistance	Glass
A component to be used with direct stresses of about (1000Mpa)	Tensile strength	Alloy steel
A transformer core	Soft magnetic	Iron-silicon alloy

3.3 SELECTION OF PROCESSES

It is a cutting process, like planning, shaping, boring and turning.

The following factors are relevant in determining the optimum process or processes:

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1. Operations should be designed so that the minimum amount of material is removed. This reduces material costs, energy costs involved in the machining and costs due to tool wear.

2. The time spent on the operation should be kept to a minimum to keep labor costs low.

3. The skills required affect the labor costs.

4. The properties of the material being machined should be considered; in particular the hardness:

i.) In general, the harder a material the longer it will take to cut. The hardness also, however, affects the choice of tool material that can be used, ii.) In the case of very hard materials, grinding is a process that can be used because the tool material and the abrasive particles can be very hard. iii.) Where a considerable amount of machining occurs, the use of free machining grades of materials (machinable materials) should be considered as a means of minimizing cutting times.

In general, machining process is:

- A relatively expensive process when compared with many other methods of forming materials.
- The machining process is, however, a very flexible process which allows the generation of a wide variety of forms.
- A significant part of the total machining cost of a product is due to setting-up times when there is a change from one machining step to another.
- By reducing the number of machining steps and hence the number of setting-up times a significant saving becomes possible. Thus, the careful sequencing of machining operations and the choice of machine to be used is important.

3.4 AVAILABLE FORMS OF MATERIALS

A major factor affecting the choice of material is the form and size it can be supplied in. If the design indicates, for example, an I-girder with specified dimensions in particular steel and that is not a size in which the material is normally supplied, then there may well have to be a change in the material used since the cost of obtaining the non-standard size of the material may rule it out. The 'as supplied' form and size can determine whether further processing is required and, if so, to what extent. The surface conditions of the supplied material may also be important, particularly if the material is to be used without further processing. Thus, for example, hot rolled steel could have a loose flaky scale on its surface and thus have to be machined.

➢ A particular manufacturer might supply **steel** as: rounds, squares, flats, circular hollow sections, square hollow sections, rectangular hollow sections, rolled steel joists, sheets, plates, etc. with a variety of sizes and surface finishes.

➢ **Polymeric** materials are generally supplied as granules ready for, processing. However, the composition of the granules, for what is the same polymeric material, can vary depending in what other materials, e.g. fibers, have been added.

3.5 COST OF MATERIALS

Costs can be considered in relation to:

• The basic costs of the raw materials: In comparing the basic costs of materials, the comparison is often on the basis of the cost per unit weight or cost per unit volume.

The costs of materials change with time, and to eliminate the need to specify any particular unit of currency, relative costs are used for the purpose of materials selection when we only require determining the optimum material.

• The costs of manufacturing products: The costs of manufacturing will depend on the processes used. Some processes require a large capital outlay and then can be used to

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produce large numbers of the product at a relatively low cost per item. Other processes may have little in the way of setting-up costs but a large cost per unit product.

• The life and maintenance costs of the finished product: The cost of maintaining a material during its life can often be a significant factor in the selection of materials. A feature common to many metals is the need for a surface coating to protect them from corrosion by the atmosphere.