11

Bearing Materials

11.1 FUNDAMENTAL PRINCIPLES OF TRIBOLOGY

During the twentieth century, there has been an increasing interest in the friction and wear characteristics of materials. The science of friction and wear of materials has been named *Tribology* (the science of rubbing). A lot of research has been conducted that resulted in significant progress in the understanding of the fundamental principles of friction and wear of various materials. Several journals are dedicated to the publication of original research in this subject, and many reference books have been published where the research findings are presented. The most important objective of the research in tribology is to reduce friction and wear as well as other failure modes in bearings. On the other hand, there are many important applications where it is desirable to maximize friction, such as in brakes and in the friction between tires and road.

The following is a short review of the fundamental principles of tribology that are important to practicing engineers. More detailed coverage of the research work in tribology has been published in several books that are dedicated to this subject. Included in the tribology literature are books by Bowden and Tabor (1956), Rabinowicz (1965), Bowden and Tabor (1986), Blau (1995), and Ludema (1996).

It is well known that sliding surfaces of machine elements have a certain degree of surface roughness. Even highly polished surfaces are not completely smooth, and this roughness can be observed under the microscope or measured by a profilometer. The surface roughness is often compared to a mountainous terrain, where the hills are referred to as *surface asperities*. The root mean square (RMS) of the surface roughness is often used to identify the surface finish, and it can be measured by a profilometer. The RMS roughness value of the best-polished commercial surfaces is about 0.01–250 μm (micrometers). Sliding surfaces are separated by the asperities; therefore, the actual contact area between two surfaces exists only at a few points, where contacts at the tip of the asperities take place. Each contact area is microscopic, and its size is of the order of 10–50 μm. Actual total contact area, A_r, that supports the load is very small relative to the apparent area (by several orders of magnitude).

A very small contact area at the tip of the surface asperities supports the external normal load, F, resulting in very high compression stresses at the contact. The high compression stresses cause elastic as well as plastic deformation that forms the actual contact area, A_r. Experiments indicated that the actual contact area, A_r, is proportional to the load, F, and the actual contact area is not significantly affected by the apparent size of the surface. Moreover, the actual contact area, A_r, is nearly independent of the roughness value of the two surfaces. Under load, the contact area increases by elastic and plastic deformation. The deformation continues until the contact area and compression strength p_h (of the softer material) can support the external load, F. The ultimate compression stress that the softer material can support, p_h, depends on the material hardness, and the equation for the normal load is

$$F = p_h A_r \tag{11-1}$$

The compression strength, p_h, is also referred to as the *penetration hardness*, because the penetration of the hard asperity into the soft one is identical to a hardness test, such as the Vickers test. For elastic materials, p_h is about three times the value of the compression yield stress (Rabinovitz, 1965).

11.1.1 Adhesion Friction

The recent explanation of the friction force is based on the theory of adhesion. Adhesion force is due to intermolecular forces between two rubbing materials. Under high contact pressure, the contact areas adhere together in the form of microscopic junctions. The magnitude of a microscopic junction is about 10–50 μm; in turn, the friction is a continual process of formation and shearing of the microscopic junctions. The tangential friction force, F_f, is the sum of forces required for continual shearing of all the junction points. This process is repeated continually as long as an external tangential force, F_f, is provided to break the adhesion contacts to allow for a relative sliding. The equation for the friction force is

$$F_f = \tau_{av} A_r \tag{11-2}$$

Here, τ_{av} is the average shear stress required for shearing the adhesion joints of the actual adhesion contacts of the total area A_r. Equation (11-2) indicates that, in fact, the friction force, F_f, is proportional to the actual total contact area, A_r, and is not affected by the apparent contact area. This explains the Coulomb friction laws, which state that the friction force F_t is proportional to the normal force F_n. The adhesion force is proportional to the actual area A_r, which, in turn, is proportional to the normal force, F, due to the elasticity of the material at the contact. When the normal force is removed, the elastic deformation recovers and there is no longer any friction force.

In many cases, the strength of the adhesion joint is higher than that of the softer material. In such cases, the shear takes place in the softer material, near the junction, because the fracture takes place at the plane of least resistance. In this way, there is a material transfer from one surface to another. The average shear strength, τ_{av}, is in fact the lower value of two: the junction strength and the shear strength of the softer material.

The adhesion and shearing of each junction occurs during a very short time because of its microscopic size. The friction energy is converted into heat, which is dissipated in the two rubbing materials. In turn, the temperature rises, particularly at the tip of the asperities. This results in a certain softening of the material at the contact, and the actual contact areas of adhesion increase, as does the junction strength.

11.1.2 Compatible Metals

A combination of two metals is *compatible* for bearing applications if it results in a low dry friction coefficient and there is a low wear rate. Compatible metals are often referred to as *score resistant*, in the sense that the bearing resists fast scoring, in the form of deep scratches of the surface, which results in bearing failure.

In general, two materials are compatible if they form two separate phases after being melted and mixed together; namely, the two metals have very low solid solubility. In such cases, the adhesion force is a relatively weak bond between the two surfaces of the sliding metals, resulting in low τ_{av}. In turn, there is relatively low friction force between compatible materials. On the other hand, when the two metals have high solubility with each other (can form an alloy), the metals are not compatible, and a high friction coefficient is expected in most cases (Ernst and Merchant, 1940). For example, identical metals are completely soluble; therefore, they are not compatible for bearing applications, such as steel on steel and copper on copper. Aluminum and mild steel are soluble and have a high friction coefficient. On the other hand, white metal (babbitt), which is an alloy of tin, antimony, lead, and copper, is compatible against steel. Steel journal and white metal bearings have low dry friction and demonstrate outstanding score resistance.

Roach, et al. (1956) tested a wide range of metals in order to compare their score resistance (compatibility) against steel. Table 11-1 summarizes the results by classifying the metals into compatibility classes of good, fair, poor, and very poor. Good compatibility means that the metal has good score resistance against steel.

In this table, the atomic number is listed before the element, and the melting point in degrees Celsius is listed after the element. Cadmium has been found to be an intermediate between "good" and "fair" and copper an intermediate between "fair" and "poor." The melting point does not appear to affect the compatibility with steel. Zinc, for example, has a melting point between those of lead and antimony, but has poorer compatibility in comparison to the two.

It should be noted that many metals that are classified as having a good compatibility with steel are the components of white metals (babbitts) that are widely used as bearing material. Roach et al. (1956) suggested an explanation that the shear strength at the junctions determines the score resistance. Metals that are mutually soluble tend to have strong junctions that result in a poor compatibility (poor score resistance).

However, there are exceptions to this rule. For example, magnesium, barium, and calcium are not soluble in steel but do not have a good score resistance against steel. Low friction and score resistance depends on several other factors. Hard metals do not penetrate into each other and do not have a high friction coefficient. Humidity also plays an important role, because the moisture layer acts as a lubricant.

Under light loads, friction results only in a low temperature of the rubbing surfaces. In such cases, the temperature may not be sufficiently high for the metals to diffuse into each other. In turn, there would not be a significant score of the surfaces, although the metals may be mutually soluble. In addition, it has been suggested that these types of bonds between the atoms, in the boundary of the two metals, play an important role in compatibility. Certain atomic bonds are more brittle, and the junctions break easily, resulting in a low friction coefficient.

11.1.3 Coulomb Friction Laws

According to Coulomb (1880), the tangential friction force, F_f, is not dependent on the sliding velocity or on the apparent contact area. However, the friction

TABLE 11-1 Elements Compatible with Steel, from Roach et al. (1956)

Good			Fair			Poor			Very Poor		
Atomic number	Element	Melting Temp. °C	Atomic number	Element	Melting Temp. °C	Atomic number	Element	Melting Temp. °C	Atomic number	Element	Melting Temp. °C
32	Germanium	958	6	Carbon		12	Magnesium	651	4	Beryllium	1280
47	Silver	960	34	Selenium	220	13	Aluminum	660	14	Silicon	1420
49	Indium	155	52	Tellurium	452	30	Zinc	419	20	Calcium	810
50	Tin	232	29	Copper	1083	56	Barium	830	22	Titanium	1800
51	Antimony	630				74	Tungsten	3370	24	Chromium	1615
81	Thallium	303							26	Iron	1535
82	Lead	327							27	Cobalt	1480
83	Bismuth	271							28	Nickel	1455
									40	Zirconium	1900
									41	Niobium (Columbium)	1950
									42	Molybdenum	2620
									45	Rhodium	1985
									46	Palladium	1553
									58	Cerium	640
									73	Tantalum	2850
									77	Iridium	2350
									78	Platinum	1773
									79	Gold	1063
									90	Thorium	1865
									92	Uranium	1130
		48 Cadmium 321			29 Copper 1083						

force, F_f, is proportional to the normal load, F. For this reason, the friction coefficient, f, is considered to be constant and it is defined as

$$f = \frac{F_f}{F} \tag{11-3}$$

Equation (11-3) is applicable in most practical problems. However, it is already commonly recognized that the friction laws of Coulomb are only an approximation. In fact, the friction coefficient is also a function of the sliding velocity, the temperature, and the magnitude of the normal load, F.

Substituting Eqs. (11-1) and (11-2) into Eq. (11-3) yields the following expression for the friction coefficient:

$$f = \frac{F_f}{F} = \frac{\tau_{\mathrm{av}}}{p_h} \tag{11-4}$$

Equation (11-4) is an indication of the requirements for a low friction coefficient of bearing materials. A desirable combination is of relative high hardness, p_h, and low average shear strength, τ_{av}. High hardness reduces the contact area, while a low shear strength results in easy breaking of the junctions (at the adhesion area or at the softer material). A combination of hard materials and low shear strength usually results in a low friction coefficient.

An example is white metal, which is a multiphase alloy with a low friction coefficient against steel. The hard phase of the white metal has sufficient hardness, or an adequate value of p_h. At the same time, a soft phase forms a thin overlay on the surface. The soft layer on the surface has mild adhesion with steel and can shear easily (low τ_{av}). This combination of a low ratio τ_{av}/p_h results in a low friction coefficient of white metal against steel, which is desirable in bearings. The explanation is similar for the low friction coefficient of cast iron against steel. Cast iron has a thin layer of graphite on the surface of very low τ_{av}. An additional example is porous bronze filled with PTFE, where a thin layer of soft PTFE, which has low τ_{av}, is formed on the surface.

Any reduction of the adhesive energy decreases the friction force. Friction in a vacuum is higher than in air. The reduction of friction in air is due to the adsorption of moisture as well as other molecules from the air on the surfaces. In the absence of lubricant, in most practical cases the friction coefficient varies between 0.2 and 1. However, friction coefficients as low as 0.05 can be achieved by the adsorption of boundary lubricants on metal surfaces in practical applications. All solid lubricants, as well as liquid lubricants, play an important role in forming a thin layer of low τ_{av}, and in turn, the friction coefficient is reduced.

In addition to adhesion friction, there are other types of friction. However, in most cases, adhesion accounts for a significant portion of the friction force. In most practical cases, adhesion is over 90% of the total friction. Additional types of the friction are plowing friction, abrasive friction, and viscous shear friction.

11.2 WEAR MECHANISMS

Unless the sliding surfaces are completely separated by a lubrication film, a certain amount of wear is always present. If the sliding materials are compatible, wear can be mild under appropriate conditions, such as lubrication and moderate stress. However, undesirably severe wear can develop if these conditions are not maintained, such as in the case of overloading the bearing or oil starvation. In addition to the selection of compatible materials and lubrication, the severity of the wear increases with the surface temperature. The bearing temperature increases with the sliding speed, V, because the heat, q, that is generated per unit of time is equal to the mechanical power needed to overcome friction. The power losses are described according to the equation

$$q = f\,FV \tag{11-5}$$

In the absence of liquid lubricant, heat is removed only by conduction through the two rubbing materials. The heat is ultimately removed by convection from the materials to the air. Poor heat conductivity of the bearing material results in elevated surface temperatures. At high surface temperatures, the friction coefficient increases with a further rise of temperature. This chain of events often causes scoring wear and can ultimately cause, under severe conditions, seizure failure of the bearing. The risk of seizure is particularly high where the bearing runs without lubrication. In order to prevent severe wear, compatible materials should always be selected. In addition, the PV value should be limited as well as the magnitudes of P and V separately.

11.2.1 Adhesive Wear

Adhesive wear is associated with adhesion friction, where strong microscopic junctions are formed at the tip of the asperities of the sliding surfaces. This wear can be severe in the absence of lubricant. The junctions must break due to relative sliding. The break of a junction can take place not exactly at the original interface, but near it. In this way, small particles of material are transferred from one surface to another. Some of these particles can become loose, in the form of wear debris. Severe wear can be expected during the sliding of two incompatible materials without lubrication, because the materials have strong adhesion.

For two rubbing metals, high adhesion wear is associated with high solid solubility with each other (such as steel on steel). Adhesion junctions are formed by the high contact pressure at the tip of the surface asperities. However, much stronger junctions are generated when the temperature at the junction points is relatively high. Such strong junctions often cause scoring damage. The source of elevated surface temperature can be the process, such as in engines or turbines, as well as friction energy that generates high-temperature hot spots on the rubbing surfaces. When surface temperature exceeds a certain critical value, wear rate will accelerate. This wear is referred to in the literature as *scuffing* or *scoring*, which can be identified by material removed in the form of lines along the sliding direction. Overheating can also lead to catastrophic bearing failure in the form of seizure.

11.2.2 Abrasion Wear

This type of wear occurs in the presence of hard particles, such as sand dust or metal wear debris between the rubbing surfaces. Also, for rough surfaces, plowing of one surface by the hard asperities of the other results in abrasive wear. In properly designed bearings, with adequate lubrication, it is estimated that 85% of wear is due to abrasion. It is possible to reduce abrasion wear by proper selection of bearing materials. Soft bearing materials, in which the abrasive particles become embedded, protect the shaft as well as the bearing from abrasion.

11.2.3 Fatigue Wear

The damage to the bearing surface often results from fatigue. This wear is in the form of pitting, which can be identified by many shallow pits, where material has been removed from the surface. This type of wear often occurs in line-contact or point-contact friction, such as in rolling-element bearings and gears. The maximum shear stress is below the surface. This often results in fatigue cracks and eventually causes peeling of the surface material.

In rolling-element bearings, gears, and railway wheels, the wear mechanism is different from that in journal bearings, because there is a line or point contact and there are alternating high compression stresses at the contact. In contrast, the surfaces in journal bearings are conformal, and the compression stresses are more evenly distributed over a relatively larger area. Therefore, the maximum compression stress is not as high as in rolling contacts, and adhesive wear is the dominant wear mechanism. In line and point contact, the surfaces are not conformal, and fatigue plays an important role in the wear mechanisms, causing pitting, i.e., shallow pits on the surface. Fatigue failure can start as surface cracks, which extend into the material, and eventually small particles become loose.

11.2.4 Corrosion Wear

Corrosion wear is due to chemical attack on the surface, such as in the presence of acids or water in the lubricant. In particular, a combination of corrosion and fatigue can often cause an early failure of the bearing.

11.3 SELECTION OF BEARING MATERIALS

A large number of publications describe the wear and friction characteristics of various bearing materials.* However, when it comes to the practical design and selection of materials, numerous questions arise concerning the application of this knowledge in practical situations. We must keep in mind that the bearing material is only one aspect of an integrated bearing design, and even the best and most expensive materials would not guarantee successful operation if the other design principles are ignored.

Although hydrodynamic bearings are designed to operate with a full oil film, direct contact of the material surfaces occurs during starting and stopping. Some bearings are designed to operate with boundary or mixed lubrication where there is a direct contact between the asperities of the two surfaces. Proper material combination is required to minimize friction, wear, and scoring damage in all bearing types, including those operating with hydrodynamic or hydrostatic fluid films. In a hydrostatic bearing, the fluid pressure is supplied by an external pump, and a full fluid film is maintained during starting and stopping. The hydrostatic fluid film is much thicker in comparison to the hydrodynamic one. However, previous experience in machinery indicates that the bearing material is important even in hydrostatic bearings. Experience indicates that there are always unexpected vibrations and disturbances as well as other deviations from normal operating conditions. Therefore, the sliding materials are most likely to have a direct contact, even if the bearing is designed to operate as a full hydrodynamic or hydrostatic bearing. For example, in a certain design of a machine tool, the engineers assumed that the hydrostatic bearing maintains full film lubrication at all times, and selected a steel-on-steel combination. However, the machines were recalled after a short operating period due to severe bearing damage.

There is a wide range of bearing materials to select from—metals, plastics, and composite materials—and there is no one ideal bearing material for all cases. The selection depends on the application, which includes type of bearing, speed, load, type of lubrication, and operating conditions, such as temperature and maximum contact pressure.

In general, a bearing metal should have balanced mechanical properties. On the one hand, the metal matrix should be soft, with sufficient plasticity to conform to machining and alignment errors as well as to allow any abrasive particles in the lubricant to be embedded in the bearing metal. On the other hand, the metal should have sufficient hardness and compression strength, even at high operating temperature, to avoid any creep and squeezing flow of the metal under load, as well as having adequate resistance to fatigue and impact. The selection is a

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*Examples are Kennedy et al. (1998), Kingsbury (1997), Blau (1992), Booser (1992), Kaufman (1980), and Peterson and Winer (1980).

tradeoff between these contradictory requirements. For the manufacture of the bearing, easy melting and casting properties are required. In addition, the bearing metal must adhere to the steel shell and should not separate from the shell by metal fatigue.

The following is a discussion of the most important performance characteristics that are usually considered in the selection of bearing materials.

11.3.1 Score and Seizure Resistance

Compatibility between two materials refers to their ability to prevent scoring damage and seizure under conditions of friction without adequate lubrication. Compatible materials demonstrate relatively low friction coefficient under dry and boundary lubrication conditions. In metals, junctions at the tip of the surface asperities are formed due to high contact pressure. When these junctions are torn apart by tangential friction force, the surfaces are scored. The high friction energy raises the surface temperature, and in turn stronger junctions are formed, which can result in bearing failure by seizure. Similar metals are not compatible because they tend to have relatively high friction coefficients, e.g., steel on steel. A more compatible combination would be steel on bronze or steel on white metal. Most plastic bearings are compatible with steel shafts.

11.3.2 Embeddability

This is an important characteristic of soft bearing materials, where small hard particles become embedded in the bearing material and thus prevent abrasion damage. Dust, such as silica, and metal particles (wear products) are always present in the oil. These small, hard particles can cause severe damage, in the form of abrasion, particularly when the oil film is very thin, at low speeds under high loads. The abrasion damage is more severe whenever there is overheating of the bearing. When the hard particles are embedded in the soft bearing metal, abrasion damage is minimized.

11.3.3 Corrosion Resistance

Certain bearing metals are subject to corrosion by lubricating oils containing acids or by oils that become acidic through oxidation. Oil oxidation takes place when the oil is exposed to high temperatures for extended periods, such as in engines. Oxidation inhibitors are commonly added to oils to prevent the formation of corrosive organic acids. Corrosion fatigue can develop in the bearing metal in the presence of significant corrosion. Corrosion-resistant materials should be applied in all applications where corrosives may be present in the lubricant or the environment. Improved alloys have been developed that are more corrosion resistant.

11.3.4 Fatigue Resistance

In bearings subjected to oscillating loads, such as in engines, conditions for fatigue failure exist. Bearing failure starts, in most cases, in the form of small cracks on the surface of the bearing, which extend down into the material and tend to separate the bearing material from the housing. When sufficiently large cracks are present in the bearing surface, the oil film deteriorates, and failure by overheating can be initiated. It is impossible to specify the load that results in fatigue, because many operating parameters affect the fatigue process, such as frequency of oscillating load, metal temperature, design of the bearing housing, and the amount of journal flexure. However, materials with high fatigue resistance are usually desirable.

11.3.5 Conformability

This is the ability to deform and to compensate for inaccuracy of the bearing dimensions and its assembly relative to the journal. We have to keep in mind that there are always manufacturing tolerances, and metal deformation can correct for some of these inaccuracies. An example is the ability of a material to conform to misalignment between the bearing and journal. The conformability can be in the form of plastic or elastic deformation of the bearing and its support. The characteristic of having large plastic deformation is also referred to as *deformability.* This property indicates the ability of the material to yield without causing failure. For example, white metal, which is relatively soft, can plastically deform to correct for manufacturing errors.

11.3.6 Friction Coefficient

The friction coefficient is a function of many parameters, such as lubrication, temperature, and speed. Proper selection of the rubbing materials is important, particularly in dry and boundary lubrication. A low coefficient of friction is usually desirable in most applications. In most cases, a combination of hard and soft materials results in a low friction coefficient. A low coefficient of friction is usually related to the compatibility (score-resistance) characteristic, where partial welding of the surface asperities occurring at hot spots on the rubbing surfaces can increase friction.

11.3.7 Porosity

This property indicates the ability of the material to contain fluid or solid lubricants. An example of a porous metal is sintered bronze, which can be impregnated with oil or white metal. Such porous bearings offer a significant advantage, of reduction in maintenance cost in applications of boundary lubrication, where only a small amount of lubricant is required.

11.3.8 Thermal Conductivity

For most applications, a relatively high thermal conductivity improves the performance of the bearing. The friction energy is dissipated in the bearing as heat, and rapid heat transfer reduces the operating temperature at the sliding contact.

11.3.9 Thermal Expansion

The thermal expansion coefficient is an important property in bearing design. It is desirable that the thermal expansion of the bearing be greater than the journal, to reduce the risk of thermal seizure. However, if the expansion coefficient is excessively large in comparison to that of the steel shaft, a very large clearance would result, such as in plastic bearings. Unique designs with elastic flexibility are available to overcome the problem of overexpansion.

11.3.10 Compressive Strength

A high compressive strength is required for most applications. The bearing should be capable of carrying the load at the operating temperature. This characteristic is in conflict with that of conformability and embeddability. Usually for high compressive strength, high-hardness bearing material is required. However, for conformability and embeddability, relatively low hardness values are desired.

11.3.11 Cost

The bearing material should be cost effective for any particular application. To reduce the bearing cost, material should be selected that can be manufactured in a relatively low-cost process. For metals, easy casting and machining properties are desirable to reduce the manufacturing cost. For metal bearings, a bronze bushing is considered a simple low-cost solution, while silver is the most expensive. Plastic bearings are widely used, primarily for their low cost as well as their low-cost manufacturing process. Most plastic bearings are made in mass production by injection molding.

11.3.12 Manufacturing

Consideration should be given to the manufacturing process. Bearing metals must have a relatively low melting point and have good casting properties. Also, they should exhibit good bonding properties, to prevent separation from the backing material during operation.

11.3.13 Classification of Bearing Materials

Bearing materials can be metallic or nonmetallic. Included in the metallic category are several types of white metals (tin and lead-based alloys), bronzes, aluminum alloys, and porous metals. Certain thin metallic coatings are widely used, such as white metals, silver, and indium. The nonmetallic bearing materials include plastics, rubber, carbon-graphite, ceramics, cemented carbides, metal oxides, glass, and composites, such as glass-fiber- and carbon-fiber-reinforced PTFE (Teflon).

11.4 METAL BEARINGS

11.4.1 White Metal: Tin- and Lead-Based Alloys (Babbitts)

Isaac Babbitt invented and in 1839 obtained a U.S. patent on the use of a soft white alloy for a bearing. This was a tin-based alloy with small amounts of added copper, antimony, and lead. These alloys are often referred to as *babbitts*. The term *white metal* is used today for tin- as well as lead-based alloys. A white metal layer is cast as a bearing surface for steel, aluminum, bronze, or cast iron sleeves. White metal can undergo significant plastic deformation, resulting in excellent embeddability and conformability characteristics. Hard crystals are dispersed in the soft matrix and increase the hardness of the alloy, but they do not have a significant adverse effect on the frictional properties because the soft matrix spreads out on the surface during sliding to form a thin lubricating film. This results in a low friction coefficient, since the shearing stress of the soft matrix is relatively low. The limit to the use of white metals is their relatively low melting temperature. Also, there are limits to the magnitude of steady compression pressure—7 $\mathrm{N/mm^2}$ (7 Mpa)—and much lower limits whenever there is fatigue under oscillating loads. Using very thin layers of white metal can extend the limit. Of course, the maximum loads must be reduced at elevated temperature, such as in engines, where the temperature is above 100°C, where white metal loses nearly 50% of its compression strength. Specifications and tables of properties of white metals are included in ASTM B23 (1990).

White metal has considerable advantages as a bearing material, and it is recommended as the first choice for most applications. In order to benefit from these advantages, the design should focus on limiting the peak pressure and maximum operating temperature. Soft sleeve materials can tolerate some mis-alignment, and dust particles in the oil can be embedded in the soft material, thus preventing excessive abrasion and wear. However, white metal has a relatively low melting point and can creep if the maximum pressure is above its compressive strength. Thin white metal linings offer better resistance to creep and fatigue; see Fig. 11-1.

At the beginning of the twentieth century, white metal linings were much thicker (5 mm and more) in comparison to current applications. The requirement to reduce the size of machines resulted in smaller bearings that have to support higher compressive loads. Also, faster machines require bearings with greater fatigue strength. These requirements were met by reducing the thickness of the white metal lining to 800 μm, and in heavy-duty applications to as low as 50–120 μm. Fatigue strength is increased by decreasing the thickness of the white metal lining. The reduction of thickness is a tradeoff between fatigue resistance and the properties of embeddabilty and conformability of the thicker white metal lining. For certain applications, thick layers of white metal are still applied successfully.

In automotive engines, a very thin lining, of thickness below 800 μm, is commonly applied. Tin-based white metal has been used exclusively in the past, but now has been replaced in many cases by the lower-cost lead-based white metal. The yield point of the lead-based white metal is lower, but when the white metal layer is very thin on a backing lining of good heat-conductor metals, such as aluminum or copper-lead, the lead-based white metal bearings give satisfactory performance.

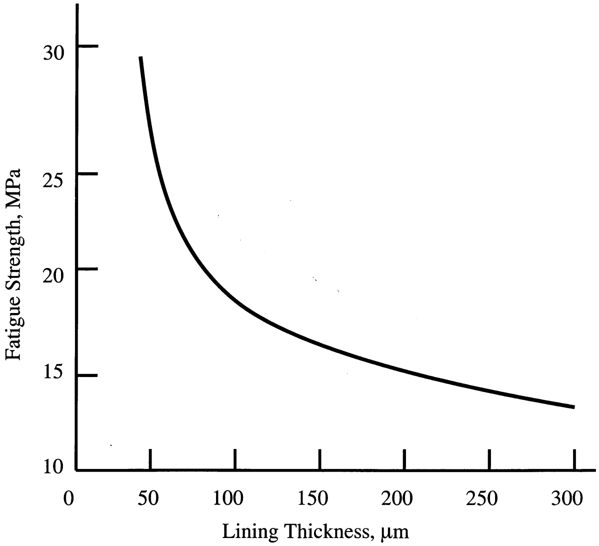

FIG. 11-1 Fatigue resistance as a function of white metal thickness.

One advantage of the white metal is good adhesion to the shell material, such as steel or bronze. Also, it has better seizure resistance in comparison to harder materials, in the case of oil starvation or during starting and stopping. A thick wall lining has the advantage that the sleeve can be replaced (in most cases by centrifugal casting). For large bearings, there is an additional advantage in applying a thick layer, since the white metal can be scraped and fitted to the journal during assembly of the machine. Therefore, a thick white metal layer is still common in large bearings. White metal has been considered the best bearing material, and the quality of other bearing materials can be determined by comparison to it.

11.4.2 Tin-Based Versus Lead-Based White Metals

The advantages of tin-based white metals in comparison to their lead-based counterparts include higher thermal conductivity, higher compression strength, higher fatigue and impact strength, and higher corrosion resistance. On the other hand, lead-based white metals exhibit a lower friction coefficient, better bonding to the shells, and better properties for casting. However, the increase in use of lead-based white metal is attributed mostly to its lower cost.

11.4.3 Copper–Lead Alloys

These alloys contain from 28% to 40% Pb. They are used primarily in the automotive and aircraft industries. They are also used in general engineering applications. They have a higher load capacity and higher fatigue resistance in comparison to white metal. Also, they can operate at higher temperatures. But they have a relatively lower antiseizure characteristic. These alloys are usually cast or sintered to a steel backing strip. The higher-lead-content alloy is used on steel or cast iron–backed bearings. These are commonly used for medium-duty automotive bearings. In order to maintain the soft copper matrix, the tin content in these alloys is restricted to a low level. The higher lead content improves the corrosion and antiseizure properties. However, in most applications, the corrosion and antiseizure properties are improved by a thin lead-tin or lead-indium overlay.

In engine bearings, bare copper-lead bearings are no longer common. Corrosive acids that are formed in the crankcase lubricant attack the lead material. Many of the copper-lead alloys, with lead contents near 25%, are plated with additional overlays. This forms the three-layer bearing—a steel backing covered by a layer of copper-lead alloy and a thin overlay of lead-tin or lead-indium. Such three-layer metal bearings are widely applied in automotive and diesel engines. Sintered and impregnated porous alloys are included in this group, such as SAE 482, 484, and 485.

11.4.4 Bronze

All bronzes can be applied as bearing materials, but the properties of bronzes for bearings are usually improved by adding a considerable amount of lead. Lead improves the bearing performance by forming a foundation for the hard crystals. But lead involves manufacturing difficulties, since it is not easily kept in solution and its alloys require controlled casting.

Bronzes with about 30% lead are referred to as *plastic bronze*. This significant lead content enhances the material's friction properties. However, the strength and hardness are reduced. These bronzes have higher strength than the white metals and are used for heavy mill bearings. A small amount of nickel in bearing bronze helps in keeping the lead in solution. Also, the resistance to compression and shock is improved. Iron content of up to 1% improves the resistance to shock and hardens the bronze. However, at the same time it reduces the grain size and tends to segregate the lead.

11.4.5 Cast Iron

In most applications, the relatively high hardness of cast iron makes it unsuitable as a bearing material. But in certain applications it is useful, particularly for its improved seizure resistance, caused by the graphite film layer formed on its surface. The most important advantages of cast iron are a low friction coefficient, high seizure resistance, high mechanical strength, the formation of a good bond with the shell, and, finally, low cost.

11.4.6 Aluminum Alloys

Aluminum alloys have two important advantages. The major advantage is their high thermal conductivity (236 W/m°C). They readily transfer heat from the bearing, resulting in a lower operating temperature of the bearing surface. The second advantage is their high compressive strength [34 Mpa (5000 psi)]. The aluminum alloys are widely used as a backing material with an overlay of white metal.

Examples of widely used aluminum alloys in automotive engines are an alloy with 4% silicon and 4% cadmium, and alloys containing tin, nickel, copper, and silicon. Also, aluminum-tin alloys are used, containing 20% to 30% tin, for heavily loaded high-speed bearings. These bearings are designed, preferably with steel backings, to conserve tin, which is relatively expensive, as well as to add strength. Addition of 1% copper raises the hardness and improves the physical qualities. The limit for the copper component is usually 3%. The copper is alloyed with the aluminum. However, the tin exists in the form of a continuous crystalline network in the aluminum alloy. These alloys must have a matrix of aluminum through which various elements are dispersed and not dissolved.

11.4.7 Silver

Silver is used only in unique applications in which the use of silver is required. Its high cost prohibits extensive application of this material. One example of an important application is the connecting rod bearings in aircraft engines. The major advantages of silver are its high thermal conductivity and excellent fatigue resistance. However, other mechanical properties of silver are not as good. Therefore, a very thin overlay of lead or lead-indium alloy (thickness of 25–100 μm) is usually applied to improve compatibility and embeddability.

11.4.8 Porous Metal Bearings

Porous metal bearings, such as porous sintered bronze, contain fluid or solid lubricants. The porous material is impregnated with oil or a solid lubricant, such as white metal. A very thin layer of oil or solid lubricant migrates through the openings to the bearing surface. These bearings are selected for applications where boundary lubrication is adequate with only a small amount of lubricant. Porous bearings impregnated with lubricant offer a significant advantage of reduction of maintenance cost.

11.5 NONMETAL BEARING MATERIALS

Nonmetallic materials are widely used for bearings because they offer diversified characteristics that can be applied in a wide range of applications. Generally, they have lower heat conductivity, in comparison to metals; therefore, they are implemented in applications that have a low PV (load–speed product) value. Nonmetallic bearings are selected where self-lubrication and low cost are required (plastic materials) and where high temperature stability must be maintained as well as chemical resistance (e.g., carbon graphite). Nonmetallic bearing materials include the following groups:

Plastics: PTFE (Teflon), nylon, phenolics, fiber-reinforced plastics, etc.
Ceramics
Carbon Graphite
Rubber
Other diverse materials, such as wood and glass

11.5.1 Plastic Bearing Materials

Lightly loaded bearings are fabricated mostly from plastic materials. Plastics are increasingly used as bearing materials, not only for the appropriate physical characteristics, but also for their relatively low cost in comparison to metal bearings. Many polymers, such as nylon, can be formed to their final shape by injection molding, where large quantities are manufactured in mass production, resulting in low unit manufacturing cost. Plastic bearings can be used with or without liquid lubrication. If possible, liquid lubrication should be applied, because it reduces friction and wear and plays an important role in cooling the bearing. Whenever liquid lubrication is not applied, solid lubricants can be blended into the base plastics to reduce friction, often referred to as improving the *lubricity* of plastics.

Polymer is synthetically made of a monomer that is a basic unit of chemical composition, such as ethylene or tetrafluorethlene. The monomer molecules always have atoms of carbon in combination with other atoms. For example, ethylene is composed of carbon and hydrogen, and in tetrafluorethlene, the hydrogen is replaced by fluorine. The polymers are made by polymerization; that is, each monomer reacts with many other similar monomers to form a very long-chain molecule of repeating monomer units (see Fig. 11-2). The polymers become stronger as the molecular weight increases. For example, low-molecu-

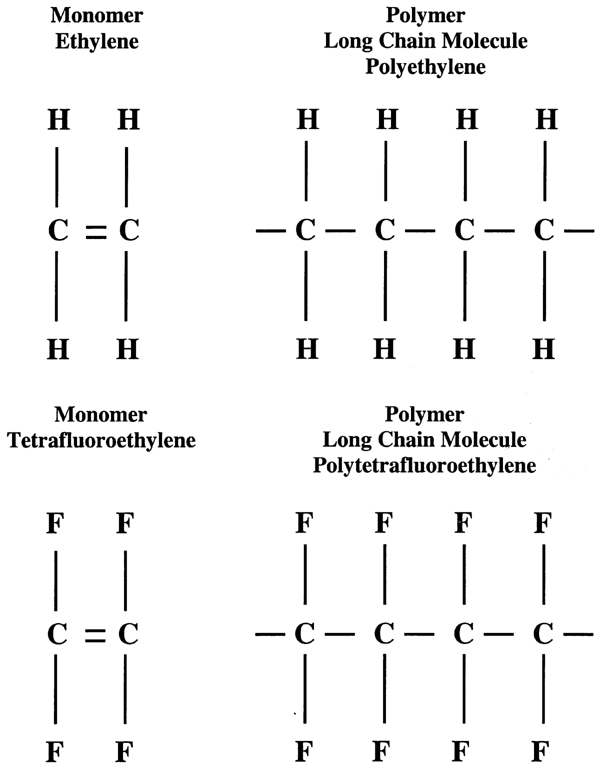

FIG. 11-2 Examples of monomers and their multiunit polymers.

lar-weight polyethylene, which has at least 100 units of CH_2, is a relatively soft material. Increasing the number of units makes the material stronger and tougher. The longest chain is ultrahigh-molecular-weight polyethylene (UHMWPE). It has up to half a million units of CH_2, and it is the toughest polyethylene. This material has an important application as a bearing material in artificial replacement joints, such as hip joints.

Over the last few decades, there has been an increasing requirement for low-cost bearings for various mass-produced machinery and appliances. This resulted in a dramatic rise in the development and application of new plastic materials for bearings. It was realized that plastics are lighter and less expensive than metals, have good surface toughness, can be manufactured by mass production processes such as injection molding, and are available in a greater variety than metallic sleeve bearings. In automotive applications, plastic bearings have steadily replaced bronze bushings for most lightly loaded bearings. The recent rise in the use of plastic bearings can also be attributed to the large volume of research and development that resulted in a better understanding of the properties of various polymers and to the development of improved manufacturing technology for new engineering plastics. An additional reason for the popularity of plastic bearings is the development of the technology of composite materials. Fiber-reinforced plastics improve the bearing strength, and additives of solid lubricants improve wear resistance. Also, significant progress has been made in testing and documenting the properties of various plastics and composites.

Widely used engineering plastics for bearings include phenolics, acetals, polyamides, polyesters, and ultrahigh-molecular-weight polyethylene. For many applications, composites of plastics with various materials have been developed that combine low friction with low wear rates and creep rates and good thermal conductivity. Reinforced plastics offer a wide selection of wear-resistant bearing materials at reasonable cost. Various plastics can be mixed together in the polymer melt phase. Also, they can be combined in layers, interwoven, or impregnated into other porous materials, including porous metals. Bearing materials can be mixed with reinforcement additives, such as glass or carbon fibers combined with additives of solid lubricants. There are so many combinations that it is difficult to document the properties of all of them.

11.5.1.1 Thermoplastics vs. Thermosets

Polymers are classified into two major groups: thermoplastics and thermosets.

11.5.1.1.1 Thermoplastics

The intermolecular forces of thermoplastics, such as nylon and polyethylene, become weaker at elevated temperature, resulting in gradual softening and melting (similar to the melting of wax). Exposure to high temperature degrades the polymer properties because the long molecular chains fracture. Therefore, thermoplastics are usually processed by extrusion or injection molding, where high pressure is used to compress the high-viscosity melt into the mold in order to minimize the process temperature. In this way, very high temperature is not required to lower the melt viscosity.

11.5.1.1.2 Thermosets

Unlike the thermoplastics, the thermosets are set (or cured) by heat. The final stage of polymerization is completed in the mold by a cross-linking reaction between the molecular chains. The thermosets solidify under pressure and heat and will not melt by reheating, so they cannot be remolded. An example of thermosets is the various types of phenolics, which are used for bearings. In the first stage, the phenolics are partially polymerized by reacting phenol with formaldehyde under heat and pressure. This reaction is stopped before the polymer completely cures, and the resin can be processed by molding it to its final shape. In the mold, under pressure and heat, the reaction ends, and the polymer solidifies into its final shape. Although the term *thermoset* means "set by heat", the thermosets include polymers such as epoxy and polyester, which do not require heat and which cure via addition of a curing agent. These thermosets are liquid and can be cast. Two ingredients are mixed together and cast into a mold, where the molecular chains cross-link and solidify. In most cases, heat is supplied to the molds to expedite the curing process, but it can be cured without heating.

11.5.1.2 Solid Lubricant Additives

Whenever liquid lubrication is not applied, solid lubricants can reduce friction and wear. Solid lubricants are applied only once during installation, but better results can be achieved by blending solid lubricants in the plastic material. Bearings made of thermoplastics can be blended with a variety of solid lubricants, resulting in a significant reduction of the friction and improved wear resistance. Solid lubricant additives include graphite powder and molybdenum disulfide, MoS_2, which are widely used in nylon bearings. Additional solid lubricant additives are PTFE and silicone, separately or in combination, which are blended in most plastics to improve the friction and wear characteristics. The amount of the various additives may vary for each plastic material; however, the following are recommended quantities, as a fraction of the base plastic:

PTFE	15–20%
Silicone	1–5%
Graphite	8–10%
MoS_2	2–5%

These solid lubricants are widely added to nylon and acetal, which are good bearing materials. In certain cases, solid lubricants are blended with base plastics having poor tribological properties but desirable other properties. An example is polycarbonate, which has poor wear resistance but can be manufactured within precise tolerances and has relatively high strength. Bearings and gears are made of polycarbonate blended with dry lubricants.

11.5.1.3 Advantages of Plastic Bearings

Low cost: Plastic materials are less expensive than metals and can be manufactured by mass production processes, such as injection molding. When mass-produced, plastic hearings have a far lower unit manufacturing cost in comparison to metals. In addition, plastics can be easily machined. These advantages are important in mass-produced machines, such as home appliances, where more expensive bearings would not be cost effective. In addition to initial cost, the low maintenance expenses of plastic bearings is a major advantage when operating without liquid lubricant.

Lubricity (*self-lubrication*): Plastic bearings can operate well with very little or no liquid lubricant, particularly when solid lubricants are blended with the base plastics. This characteristic is beneficial in applications where it is necessary for a bearing to operate without liquid lubrication, such as in the pharmaceutical and food industries, where the lubricant could be a factor in contamination. In vacuum or cryogenic applications it is also necessary to operate without oil lubrication.

Plastic bearings have relatively high compatibility with steel shafts, because they do not weld to steel. This property results in a lower friction coefficient and eliminates the risk of bearing seizure. The friction coefficient of plastic bearings in dry and boundary lubrication is lower than that of metal bearings. Their friction coefficients range from 0.15 to 0.35, and coefficients of friction as low as 0.05 have been obtained for certain plastics.

Conformability: This is the ability to deform in order to compensate for inaccuracy of the bearing dimensions. Plastics are less rigid in comparison to metals, and therefore they have superior conformability. Plastic materials have a relatively low elastic modulus and have the ability to deform to compensate for inaccuracy of the bearing-journal assembly. Tolerances are less critical for plastics than for metals because they conform readily to mating parts.

Vibration absorption: Plastic bearings are significantly better at damping vibrations. This is an important characteristic, since undesirable vibrations are always generated in rotating machinery. Also, most plastics can absorb relatively high-impact loads without permanent deformation. In many applications, plastic bearings are essential for quiet operation.

Embeddability: Contaminating particles, such as dust, tend to be embedded into the plastic material rather than scoring, which occurs in metal bearings. Also, plastics are far less likely to attract dust when running dry, compared with oil- or grease-lubricated bearings.

Low density: Plastics have low density in comparison to metals. Lightweight materials reduce the weight of the machine. This is an important advantage in automotives and particularly in aviation.

Corrosion resistance: An important property of plastics is their ability to operate in adverse chemical environments, such as acids, without appreciable corrosion. In certain applications, sterility is an additional important characteristic associated with the chemical stability of plastics.

Low wear rate: Plastics, particularly reinforced plastics, have relatively lower wear rates than metals in many applications. The exceptional wear resistance of plastic bearings is due to their compatibility with steel shafts and embeddability.

Design flexibility: Bearing parts can be molded into a wide variety of shapes and can be colored, painted, or hot-stamped where appearance is important, such as in toys and baby strollers.

Electrical insulation: Plastics have lower electrical conductivity in comparison to metals. In certain applications, such as electric motors, sparks of electrical discharge can damage the bearing surfaces, and an electrical insulator, such as a plastic bearing, will prevent this problem.

Wide temperature range: Plastics can operate without lubricants, at low and high temperatures that prohibit the use of oils or greases. Some plastics have coefficients of friction that are significantly lower at very low temperatures than at room temperature. Advanced engineering plastic compounds have been developed with PV ratings as high as 1230 Pa-m/s (43,000 psi-fpm), and they can resist operating temperatures as high as 260°C. But these compounds are not as low cost as most other plastics.

11.5.1.4 Disadvantages of Plastic Bearings

A major disadvantage is low thermal conductivity, which can result in high temperatures at the bearing surface. Most low-cost plastic materials cannot operate at high temperatures because they have low melting temperatures or because they deteriorate when exposed continuously to elevated temperatures. The combination of low thermal conductivity (in comparison to metals) and low melting temperatures restricts plastic bearings to light-load applications and low-speed (low *PV* rating in comparison to metals). The adverse effect of low thermal conductivity can be reduced by using a thin plastic layer inside a metal sleeve, but this is of higher cost. The following are additional disadvantages of plastic materials in bearing applications.

Plastics have a relatively high thermal coefficient of expansion. The difference in the thermal coefficient of expansion can be 5–10 times greater for plastics than for metals. Innovative bearing designs are required to overcome this problem. Several design techniques are available, such as an expansion slot in sleeve bearings. The effect of thermal expansion can be minimized by using a thin plastic layer inside a metal sleeve so that expansion will be limited in overall size. If thermal expansion must be completely restrained, structural materials can be added, such as glass fibers.

Another general disadvantage of plastics is creep under heavy loads, due to their relatively low yield point. Although plastics are compatible with steel shafts, they are not recommended to support nonferrous shafts, such as aluminum, due to the adhesion between the two surfaces.

11.5.1.5 PTFE (Teflon)

PTFE (Teflon) is a thermoplastic polymer material whose unique characteristics make it ideal for bearing applications (Tables 11-2 and 11-3). The chemical composition of PTFE is polytetrafluoroethylene. The molecular structure is similar to that of ethylene, but with all the hydrogen atoms replaced by fluorine (see Fig. 11-2). The characteristics of this structure include high chemical inertness due to the strong carbon-fluorine bonding and stability at low and high temperatures. It has very low surface energy and friction coefficient. At high loads and low sliding velocity, the friction coefficient against steel is as low as 0.04.

PTFE is relatively soft and has low resistance to wear and creep. However, these properties can be improved by adding fibers or particulate of harder materials. Wear resistance can be improved 1000 times by these additives.

TABLE 11-2 Bearing Design Properties of PTFE

	Max pressure		Max velocity		*PV*		Max Temp.	
Material	MPa	Psi	m/s	ft/min	psi-ft/min	Pa-m/s	°C	°F
PTFE	3.4	500	0.51	100	1000	35,000	260	500
Reinforced PTFE	17.2	2500	5.1	1000	10,000	350,000	260	500

TABLE 11-3 Physical and Mechanical Properties of PTFE

Properties	
Coefficient of thermal expansion ($10^{-5} \times$ in./in.-°F)	5.5–8.4
Specific volume (in.^{3}/lb)	13
Water absorption % (24 h, 1/8 in. thick)	<0.01
Tensile strength (psi)	3350
Elongation (%)	300
Thermal conductivity (BTU-in./h-ft^2-°F)	1.7
Hardness (Shore D)	50–65
Flexural modulus (10^5 psi)	0.5–0.9
Impact strength (Izod, ft-lb./in.)	3
Thermal conductivity (BTU/h-ft-°F)	0.14

PTFE has high melt viscosity. Manufacturing processes of injection molding or extrusion without lubricity additives cannot be used for PTFE, because the melt viscosity is too high for such processes. The common manufacturing process is sintering from powder (similar to powder metallurgy). Also, it can be extruded by adding lubricant to reduce the melt viscosity (lubricated extrusion).

PTFE has exceptionally low friction against all materials. However, it is relatively soft, and under load it would creep even at room temperature, and it has low wear resistance. In practice, the problem of low wear resistance, which is unacceptable for a bearing material, is solved by adding materials such as glass fiber, carbon, bronze, and metallic oxides. This reinforcement can reduce the wear rate by three orders of magnitude, while the friction coefficient is only slightly increased. Although reinforced PTFE is more expensive, it has superior properties as a bearing material relative to other plastics. PTFE has a volume expansion of about 1% at a temperature transition crossing above 65°F. This unusual property should be considered whenever precision of parts of close tolerances is required.

The friction coefficient of PTFE decreases with increasing load and sliding speed. In addition, it is not significantly affected by temperature. PTFE is also used successfully as a solid lubricant, similar to graphite powder and molybdenum disulfide (MoS_2). PTFE solid lubricants are compounded with binders and are used for bonded coatings on wear surfaces, which are effective in reducing friction and wear. PTFE is used in journal and sliding bearings as well as in components of rolling-element bearings (bearing cage). In addition, it is used in many other applications, such as gaskets, seals, packing and piston rings. It has the lowest dry coefficient of friction against any sliding material. Dry coefficients of friction of PTFE against steel have been measured in the range from 0.05 to

0.1. It has a wide operating temperature range, and can be applied at higher temperatures relative to other plastics and white metal. In addition, PTFE can be added to other materials in order to decrease friction. A thin layer, referred to as a third body layer, is formed on the surface and acts as a solid lubricant. Another important advantage of PTFE is its ability to resist corrosion, including that by strong acids.

The advantages of PTFE as a bearing material can be summarized as follows.

1. It has the lowest dry friction in comparison to any other solid material.
2. It has self-lubricating property and acts as a thin layer of a third body to lower the friction when added to other materials.
3. It retains strength at high temperature relative to white metals and other plastics.
4. There is no cold-welding, which causes seizure in metal contacts.
5. It is chemically inert and therefore resists corrosion.
6. It can elongate elastically up to 400% and then return to its original dimensions; thus PTFE bearings are useful in applications that require better resistance to impact loading.

However, PTFE also has several disadvantages in bearings. The two major disadvantages are its high cost and its relatively low load capacity. In addition, it has a tendency to creep under load. In order to overcome the last problem, PTFE resin is usually applied in modified forms, such as reinforced by glass fibers or graphite fibers. Unmodified PTFE has a PV rating of only 35,000 Pa-N/m^2 (1000 psi-fpm), whereas PTFE filled with glass or graphite fibers has a PV rating of more than 10,000 psi-fpm. It means that the PV as well as the maximum sliding speed of PTFE filled with glass or graphite fibers is ten times that of PTFE without reinforcement. Additional disadvantages are its low stiffness as well as its relatively high coefficient of thermal expansion.

The most important disadvantages of PTFE as bearing material can be summarized as follows.

1. It is relatively expensive because it is difficult to manufacture. In particular, it is difficult to control its molecular weight and the degree of cross-linking, which determines its rigidity.
2. It exhibits low load capacity (low resistance to deformation) and has very high rates of creep and fatigue wear relative to other plastics.
3. It has very high thermal expansion.

PTFE has many applications in machinery for sliding contacts. It finds application in journal and sliding bearings, as well as in rolling-element bearing cages. Also, it is used for gaskets, seals, and piston rings. It is modified and added to porous metals, such as in sintered bronze. It is often reinforced by various materials, such as fiberglass, metal powders, ceramics, and graphite fibers. Other fillers, such as polyester, cotton, and glass, are also used. The fillers do not eliminate the low-friction characteristic due to the formation of a third body, which demonstrates very low friction against other solid materials. These combinations improve the properties and enable the manufacture of bearings and sliding parts with improved friction properties. Examples include automotive joints, aircraft accessories, textile machines, and business machines. Its chemical inertness is an important advantage in chemical and food-processing machinery.

Reinforced PTFE has strong bonds to steel and other rigid backing material. Reinforced PTFE liners are used in high-load, low-speed bearings to eliminate oil lubrication. Woven fabrics impregnated with PTFE are used in automotive thrust washers, ball-and-socket joints, aircraft controls and accessories, bridge bearings, and electrical switches. Woven PTFE fabrics are easily applied to bearing surfaces, they resist creep and are used for relatively higher loads.

11.5.1.6 Nylon

Nylons (polyamides) are widely used thermoplastic engineering polymers. Nylon is a crystalline material that has a variety of compositions and that can be formed by various processes, including injection molding, extrusion, and sintering. The most widely used composition is nylon 6/6, which is used primarily for injection molding and extrusion (Tables 11-4 and 11-5). Nylons are used in the form of reinforced compounds, such as glass-fiber composites, to improve strength and toughness as well as other properties.

Generally, the nylons have relatively high toughness and wear resistance as well as chemical resistance, and excellent fatigue resistance. Their low friction coefficient makes them a very good choice as bearing materials. However, they absorb water and expand. This property causes them to have low dimensional stability in comparison to other engineering plastics. Moisture adversely affects their strength and rigidity while improving their impact resistance. Nylon has the widest use of all engineering plastics in bearings. Nylon bearings are used mostly in household appliances, such as mixers and blenders, and for other lightly loaded applications. Nylon resins are used extensively in the automobile industry because they are resistant to fuels and heat and can be used under the hood of

TABLE 11-4 Design Properties of Nylon

	Max pressure		Max velocity		*PV*		Max Temp.	
Material	MPa	Psi	m/s	ft/min	psi-ft/min	Pa-m/s	°C	°F
Nylon	6.9	1000	5.1	1000	3000	105,000	93	200

TABLE 11-5 Physical and Mechanical Properties of Nylon

Characteristic	Nylon 6/6	Nylon 6
Coefficient of thermal expansion (10^{-5} × in./in.-°F)	4	4.5
Specific volume (in.^{3}/lb)	24.2	24.5
Water absorption % (24 h, 1/8 in. thick)	1.2	1.6
Tensile strength (psi)	12,000	11,800
Elongation (%)	60	200
Tensile modulus (10^5 psi)	4.2	3.8
Hardness (Rockwell *R*)	120	119
Flexural modulus (10^5 psi)	4.1	3.9
Impact strength (Izod, ft-lb./in.)	1.0	0.8
Thermal conductivity (BTU/h-ft^2-°F)	0.14	0.14

motor vehicles. Examples are cooling fans, speedometer gears, and a variety of wiring connectors. They are implemented widely for wear applications, such as plastic gears, cams, and liners, for wear protection. A major advantage is that nylon can operate without lubrication. Where the bearings must run dry, such as in the food industry, nylon is widely used. In farm equipment, greases or oils can cause dust to stick to the bearing, and nylon brushings are applied without lubricants. Also, they can be used with a wide variety of lubricants.

Nylon is commonly used in bearing materials as an injection-molded sleeve or sintered as a layer inside a metal sleeve. The molded form is stronger than the sintered one. But the sintered form can operate at higher loads and speeds (relatively higher *PV* value). A commonly used engineering material for molding and extrusion is nylon 6/6, which has a *PV* rating of 3000 psi-fpm. Characteristics of nylon include an operaring temperature of 200°F, low coefficients of friction, no requirement for lubrication, good abrasion resistance, low wear rate, and good embeddability, although it is harder than PTFE, which has lower coefficient of friction when operating against steel. Like most plastics, nylon has low thermal conductivity, and failure is usually the result of overheating. Fiber fillers, such as graphite, can improve wear resistance and strength. Glass can reduce the amount of cold flow, a major problem, which occurs in all nylons, and PTFE fibers can improve frictional properties.

In many bearing applications, molded nylon is mixed with powder fillers such as graphite and molybdenum disulfide (MoS_2). These fillers increase load capacity, stiffness, and wear resistance of the bearing as well as its durability at elevated temperatures. Reinforced nylon can withstand a maximum operating temperature of 300°F (in comparison, the operating temperature of unreinforced nylon is only 200°F).

Nylon is not adversely affected by petroleum oils and greases, food acids, milk, or other types of lubricants. The process fluid can act as the lubricant as well as the coolant. This design frequently avoids the necessity for fluid sealing and prevents contamination. Like most plastics, nylon has good antiseizure properties and softens or chars, rather than seizing.

Like most plastics, nylon has a low thermal conductivity (0.24 W/m °C), which is only about 0.5% of the conductivity of low carbon steel (54 W/m °C). The heat generated in the bearing by friction is not transferred rapidly through the nylon sleeve, resulting in high operating temperatures of the bearing surface. Therefore, these bearings usually fail under conditions of high PV value. In hydrodynamic bearings, the heat transfer can be enhanced by a large flow rate of oil for cooling.

The main disadvantage of the nylon bearing is creep, although the creep is not as large as in other, less rigid thermoplastics, such as PTFE. Creep is the plastic deformation of materials under steady loads at high temperatures for long periods of time. To minimize this problem, nylon bearings are supported in metal sleeves or filled with graphite. The added graphite improves wear resistance and strength. A second important disadvantage is nylon's tendency to absorb water.

11.5.1.7 Phenolics

Phenolic plastics are the most widely used thermosetting materials. They are used primarily in reinforced form, usually containing organic or inorganic fibers. Compression molding, injection molding, and extrusion can process phenolics. They are low-cost plastics and have good water and chemical resistance as well as heat resistance (Tables 11-6 and 11-7). As bearing materials, phenolics exhibit very good resistance to seizure.

Phenolics have excellent resistance to water, acids, and alkali solutions. Phenolic bearings can be lubricated by a variety of fluids, including process fluids, due to their chemical resistance. However, these bearings have a disadvantage in their thermal conductivity. The thermal conductivity of phenolics is low (0.35 W/m °C). The heat generated in the bearing by friction cannot be easily transferred through the phenolic sleeve, resulting in slow heat transfer and a high temperature of the rubbing surfaces. Phenolic bearings usually fail under conditions of high PV value. This problem can he solved by proper designs. Large, heavily loaded bearings must have a large feed of lubricating oil for cooling.

TABLE 11-6 Bearing Design Properties of Phenolics

Max pressure		Max velocity		*PV*		Max Temp.	
MPa	Psi	m/s	ft/min	psi-ft/min	Pa-m/s	°C	°F
41.4	6000	12.7	2500	15,000	525,000	93	200

TABLE 11-7 Physical and Mechanical Properties of Phenolics

Characteristic	General purpose	Special purpose
Coefficient of thermal expansion ($10^{-5} \times$ in./in.-°F)	3.95	
Specific gravity (in.^{3}/lb)	1.35–1.46	1.37–1.75
Water absorption % (24 h, 1/8 in. thick)	0.6–0.7	0.20–0.40
Tensile strength (psi)	6500–7000	7000–9000
Elongation (%)	×60	×200
Tensile modulus (10^5 psi)	11–13	10
Hardness (Rockwell *E*)	70–95	76
Flexural modulus (10^5 psi)	11–14	10–19
Impact strength (Izod, ft-lb./in.)	0.30–0.35	0.50
Thermal conductivity (BTU/h-ft-°F	0.2	0.25

An additional disadvantage of phenolic bearings is that they tend to swell or expand. The reason is that phenolics contain fillers, which can absorb liquids. Large bearings require large radial clearances due to swelling and warping. To correct this problem, designers must allow greater clearances or add elastic support to the bearings, such as springs. The springs allow for clearance during operation and additional space for absorption.

In bearings, this material is usually found in the form of laminated phenolics. Mixing filler sheets of fabric with phenolic resin produces the bearing. Finally, the bearing goes through a curing process of high temperature and pressure. Laminated phenolics work well with steel or bronze bearings, with oil, water, or other liquid as a lubricant. They also have good conformability, by having a low modulus of elasticity ($3.45-66.9 \times 10^3$ MPa). These plastics also have a high degree of embeddability. This property is advantageous in ship stern tube bearings, which are lubricated by water containing sand and other sediments.

Phenolics are used as composite materials that consist of cotton fabric, asbestos, or other fillers bonded with phenolic resin. Phenolics have relatively high strength and shock resistance. They have a *PV* rating of 525,000 Pa-m/s (15,000 psi-fpm), and the limiting maximum temperature is 93°C (200°F). Phenolic bearings have been replacing metal bearings in many applications, such as propeller shaft bearings in ships, electrical switch gears, and water turbine bearings. Laminated phenolics can serve as a bearing material in small instruments.

11.5.1.8 Polyamide (Polyphenelen Sulfide)

Polyamide is used whenever the bearing operates at higher temperature. Polyamide performs well under relatively high temperatures, up to 500°F for continuous operation and up to 900°F for intermittent operation. However, exposure to 500°F reduces its tensile strength from 9600 to 7500 psi, but continuous exposure (up to 4000 hours) would not cause further deterioration (Table 11-8). It has very low thermal expansion for plastic, about twice the expansion rate of aluminum. When operating dry, it has a relatively low coefficient of friction.

Polyamide is expensive relative to other engineering plastics; and, similar to nylon, it has a tendency to absorb water. Dry bearings, bushings, thrust washers, piston rings, gears, and ball bearing cages are often manufactured using polyamide, most of them designed for high-temperature operation.

This group of engineering plastics has varying properties. They have excellent resistance to chemical attack and to burning. Polyamide is noted for its high surface toughness and its long service life. A disadvantage of this group is that they tend to absorb moisture. Polyamides are usually used with fillers. The use of fillers creates useful materials for bearings with *PV* factors of 20,000–30,000 psi-fpm. Polyamide with 15% graphite filler by weight is widely used. The filler improves the characteristics, raises the limiting temperature of 550°F, and increases its *PV* rating 10-folds to 300,000 psi-fpm. The reinforced polyamide is also more resistant to wear and creep in comparison to unfilled polyamide. Polyamides are often filled with glass fibers to improve their compressive strength and resistance to creep.

TABLE 11-8 Bearing Design Properties of Polyamide

Characteristic	General purpose	Bearing grade
Coefficient of thermal expansion ($10^{-5} \times$ in./in.-°F)	2	1.3–1.5
Specific gravity	1.40	1.45
Water absorption % (24 h, 1/8 in. thick)	0.28	0.20
Tensile strength (psi) @ 300°F	15,200	9,600
Elongation (%) @ 300°F	17	7
Tensile modulus (10^5 psi)		
Hardness (Rockwell *R*)		
Flexural modulus (10^5 psi) @ 300°F	5.2	7.3
Impact strength (Izod, ft-lb./in.)	2.5	1.1

11.5.1.9 Acetal

Acetal is a rigid plastic that is used as a bearing material due to its low cost, particularly for light-duty (low-load) applications. Acetal has a low density that is important in certain applications, such as aviation. It is tough over a wide range of temperatures; however, it has a maximum useful temperature of only 185°F.

TABLE 11-9 Bearing Design Properties of Acetal

	Max pressure		Max velocity		*PV*		Max Temp.	
Material	MPa	Psi	m/s	ft/min	psi-ft/min	Pa-m/s	°C	°F
Acetal	6.9	1000	5.1	1000	3000	105,000	82	180

Although strong acids and bases can attack it, acetal is inert to many chemicals, particularly organic solvents (Tables 11-9 and 11-10).

Acetal has higher compressive strength in comparison to unfilled polyamides. It has a *PV* rating of 3000 psi-fpm, similar to that of nylon 6/6. Acetal on steel does not demonstrate stick-slip friction, which is important for quiet bearing operation. This property is associated with the friction coefficient of acetal on steel, which increases with the sliding speed. However, its major disadvantages are that it has a higher wear rate and is not as abrasion resistant, e.g., in comparison to polyamides.

Acetal demonstrates stability in a wet environment, due to its low moisture absorption as well as its resistance to wet abrasion. Acetal is commonly used in a wide variety of automotive, appliance, and various other industrial applications. When acetal is filled with internal lubricants, it yields lower friction than nonlubricated acetal; however, this significantly raises its cost and lowers its compressive strength. Applications include ball bearing cages and a number of aviation applications that take advantage of its very low density.

TABLE 11-10 Physical and Mechanical Properties of Acetal

Characteristic	Copolymer	Homopolymer
Coefficient of thermal expansion ($10^{-5} \times$ in./in.-°C)	8.5	10
Specific volume (in.^{3}/lb)	19.7	19.5
Water absorption % (24 h, 1/8 in. thick)	0.22	0.25
Tensile strength (psi) @ 73°F	8000	10,000
Elongation (%)	60	40
Thermal conductivity (BTU-in./h-ft^2-°F)	1.6	2.6
Tensile modulus (10^5 PSI)	4.1	5.2
Hardness (Rockwell *M*)	80	94
Flexural modulus (10^5 psi) @ 73°F	3.75	4.1
Impact strength (Izod, ft-lb./in.) (notched)	1.3	1.4
Thermal conductivity (BTU/h-ft-°F)	0.46	0.74

11.5.1.10 High-Density Polyethylene (UHMWPE)

Ultra high-molecular-weight polyethylene (UHMWPE) (Table 11-11) has good abrasion resistance as well as a smooth, low-friction surface. The friction coefficient of UHMWPE on steel increases with the sliding speed. This characteristic is important, because it does not result in stick-slip friction and produces quiet bearing operation. It is often used in place of acetal, nylon, or PTFE materials. One important application of UHMWPE is in artificial joint implants. For example, in hip joint replacement, the socket (bearing) is made of UHMWPE, while the matching femur head replacement is fabricated from cobalt-chromium steel. More information on artificial joint implants is in Chap. 20.

TABLE 11-11 Physical and Mechanical Properties of UHMWPE

Characteristic	Low-density	UHMWPE
Specific volume (in.^{3}/lb)	30.4–29.9	29.4
Water absorption % (24 h, 1/8 in. thick)	<0.01	<0.02
Tensile strength (psi)	600–2300	4000–6000
Elongation (%)	90–800	200–500
Tensile modulus (10^5 psi)	0.14–0.38	0.2–1.1
Hardness (Rockwell *R*)	10	55
Flexural modulus (10^5 psi)	0.08–0.60	1.0–1.7
Impact strength (Izod, ft-lb./in.)	No break	No break
Thermal conductivity (BTU/h-ft-°F)	0.67	0.92

11.5.1.11 Polycarbonate

Polycarbonate plastics are used as a bearing material in applications where the bearing is subjected to high-impact loads. Polycarbonates have exceptionally high impact strength over a wide temperature range. They are high-molecular-weight, low-crystalline thermoplastic polymers unaffected by greases, oils, and acids (Tables 11-12 and 11-13).

Polycarbonates have been tested for balls in plastic ball bearings for use in army tank machine gun turrets, where its toughness is a prime consideration.

11.5.2 Ceramic Materials

There is an increasing interest in bearing materials that can operate at elevated temperatures, much higher than the temperature limit of metal bearings. Ceramic materials are already used in many applications in machinery, and there is continuous work to develop new ceramic materials. The most important qualities

TABLE 11-12 Bearing Design Properties of Polycarbonate

	Max pressure		Max velocity		*PV*		Max Temp.	
Material	MPa	Psi	m/s	ft/min	psi-ft/min	Pa-m/s	°C	°F
Polycarbonate (Lexan)	6.9	1000	5.1	1000	3000	105,000	104	220

of ceramics are their high strength and hardness, which are maintained at high temperature.

During the last two decades, there was significant progress in the development of advanced engineering ceramics. New manufacturing processes, such as sintered hot-pressing and hot isostatically pressing (HIP), have improved the characteristics of engineering ceramics. Silicon nitride manufactured by a hot isostatically pressed sintering process has a much better resistance to wear and fatigue in comparison to silicon nitride from previous manufacturing processes. It has been demonstrated that rolling elements made of silicon nitride have considerable benefits, and they are already applied in many critical applications. More detailed discussion of the merits of silicon nitride for rolling bearings is included in Chapter 13. The following is a discussion of research and development in ceramics for potential future applications in sliding bearings.

The general characteristics of engineering ceramics established them as potential candidates for materials in bearing design. They are much lighter than steel, and at the same time they have twice the hardness of steel. Their operating temperature limit is several times higher than that of steel. In addition, they require minimal lubrication. They are chemically inert and electrically nonconductive. In addition, ceramics are nonmagnetic and have lower thermal conduc-

TABLE 11-13 Physical and Mechanical Properties of Polycarbonate

Characteristic	General purpose	20% glass reinforced
Specific volume (in.^{3}/lb)	23	20.5
Water absorption % (24 h,1/8 in. thick)	0.15	0.16
Tensile strength (psi)	9000–10,500	16,000
Elongation (%)	110–125	4–6
Tensile modulus (10^5 psi)	3.4	8.6
Hardness (Rockwell *M*)	62–70	91
Flexural modulus (10^5 psi)	3.0–3.4	8.0
Impact strength (Izod, ft-lb./in.)	12–16	2
Thermal conductivity (BTU/h-ft-°F)	0.11	0.12

tivity in comparison to metals. In rolling-contact applications, rolling elements made of silicone nitride exhibit much better fatigue resistance in comparison to steel.

However, ceramics have also several disadvantages. Ceramic bearings are much more expensive to manufacture than their steel counterparts. The manufacturing cost of ceramic parts is two to five times the cost of similar steel parts. Ceramic parts are very hard, and expensive diamond-coated tools are required for machining and cutting ceramic parts. Ceramic materials are brittle and do not have plastic deformation; therefore, ceramic parts cannot be shaped by plastic deformation like metals. In addition, ceramics are not wear-resistant materials, because they are very sensitive to the traction force during rubbing (although silicone nitride has demonstrated wear resistance in rolling contact).

Ceramics have additional disadvantages. A major characteristic is their brittleness and low tensile stress. They exhibit no plastic behavior; therefore, stress concentration will cause failure. Ceramics deform elastically up to their fracture point. Their high modulus of elasticity results in fracture at relatively small strains. When used in conjunction with steel shafts and housings, they create fitting problems due to their low linear thermal expansion in comparison to steel. In very high- and very low-temperature environments, these problems are exacerbated.

11.5.2.1 Hot Isostatic Pressing (HIP)

Ceramic parts are manufactured from powder by hot-press shaping or by the improved manufacturing technique of hot isostatic pressing (HIP). This last technique offers many advantages of improved mechanical characteristics of the parts. The early manufacturing process of ceramics was by hot-pressing. The parts did not have a uniform structure, and many surface defects remained, to be removed later by various expensive processes. The parts were not accurate and required finishing machining by diamond-coated cutting tools. Moreover, the finished parts did not have the characteristics required for use in rolling-element bearings.

The recently introduced hot isostsatic pressing (HIP) process offered many advantages over the previous hot-pressing process. The HIP process uses very high pressure of inert gas at elevated temperatures to eliminate defects of internal voids. High-pressure argon, nitrogen, helium, or air is applied to all grain surfaces under uniform temperature. Temperatures up to 2000°C (3630°F) and pressures up to 207 MPa (30,000 psi) are used. The temperature and pressure are accurately controlled. This process bonds similar and dissimilar materials, to form parts very close to the final shape from metals, ceramic, and graphite powders. The term *isostatlc* means that the static pressure of the hot gas is equal in all directions throughout the part.

This process is already widely used for shaping parts from ceramic powders as well as other mixtures of metals and nonmetal powders. This process minimizes surface defects and internal voids in the parts. The most important feature of this process is that it results in strong bonds between the powder boundaries of similar or dissimilar materials. In turn, it improves significantly the characteristics of the parts for many engineering applications.

In addition, the HIP process reduces the cost of manufacturing, because it forms net or near-net shapes (close to the required dimensions of the part). The cost is reduced because the parts are near final and very little machining is required.

11.5.2.2 Engineering Ceramics

Ceramics have been used in bearings for many years in low-load applications where lubrication is limited or not possible. An example is the small sphere of alumina used in accurate instruments or mechanical watches. These bearings are commonly referred to as "watch jewels." However, these are not engineering ceramics. There is a need for bearings for high-temperature applications at high speed and load, such as aircraft engines. For this purpose, a lot of research and development has been conducted in engineering ceramics.

Engineering ceramics are dissimilar to regular ceramics, such as porcelain or clay bricks, because of their much higher strength and toughness at high operating temperatures. Engineering ceramics are compounds of metallic and nonmetallic elements, such as Si_3N_4, SiC, and Al_2O_3, that are sintered at high pressure and temperature by HIP process in order to form a strong bond between the particles. In conventional ceramics (porcelain), the particles are linked by weak bonds (mechanical linkage of particles). On the other hand, sintered engineering ceramics that are made by a hot-pressed or hot-isostatically-pressed process have particles that are bonded together by a stronger bond. The physical explanation for the improved properties of engineering ceramics is that they have strong bonds at the grain boundaries. The energy of equilibrium of these bonds is similar to that of metal grains.

During the last two decades, there were a lot of expectations that ceramics materials would be used in engines, including piston and sleeve materials. This would allow operation of the engines at higher temperatures, resulting in improved efficiency. We have to keep in mind that according to the basic principles of thermodynamics (Carnot cycle), efficiency increases with engine temperature. These expectations did not materialize at this time, because ceramic surfaces require liquid lubricants (in a similar way to metals). However, liquid lubricants that can operate at elevated temperatures in conjunction with ceramics are still not available. Research was conducted in an attempt to operate ceramic bearings at high temperatures with various types of solid powders as lubricants.

However, this work did not reach the stage of successful implementation in bearings.

The ceramic materials proved to have inferior tribological properties, such as relatively high sliding wear in comparison to compatible metal bearing materials. A large volume of research was conducted, and is still taking place, in an attempt to improve the tribological properties of engineering ceramics by various coatings or surface treatment. During the sliding of ceramics against steel, adhesive wear has been identified as the major wear mechanism. Let us recall that adhesive wear is affected by the lowest shear strength of the sliding bodies and by the compatibility of the two materials. Although some improvements have been reported, ceramic bearing materials are still not widely used for replacement of metals in plain bearings.

The main engineering ceramics in use, or in the development stage, are silicon nitride, silicon carbide, zirconia, alumina oxide, and ruby sapphire. Silicon carbide and silicon nitride are already used in various applications as high-temperature and high-strength engineering ceramics. The purpose of the following discussion is to provide the bearing designer a summary of the unique characteristics of engineering ceramics that can make them useful candidates as bearing materials. Bearings made of ceramics are of significant interest for the following reasons.

1. *High-temperature performance*: Ceramics retain high strength at elevated temperature and have a relatively high yield-point stress at temperatures above 1000°C (1832°F). This is a major advantage for potential high-temperature bearing materials. However, the available lubricants do not resist a similarly high temperature, and it is necessary to operate the bearing without lubricant. Air is considered a potential fluid film that can operate at elevated temperatures and can be used for hydrostatic or hydrodynamic lubrication. In some unique applications, such as high-speed small turbines, ceramic air bearings are already in use. In the future, it is expected that ceramics will be increasingly used for high-temperature applications, such as in aircraft engines.
2. *Low density*: An additional advantage of ceramic materials is that their density is relatively low. The density of ceramics is about a third that of steel. For example, low density reduces the centrifugal forces of rotating rolling elements. It reduces the contact stresses between the rolling elements and the outer race. This fact allows the operating of rolling bearings at higher speed.
3. *Low coefficient of expansion*: In general, a low coefficient of expansion is desirable, in particular in rolling-element bearings. Thermal stresses, due to thermal expansion, cause seizure in sleeve bearings as well as in rolling-element bearings. However, other parts in the

machine are usually made of steel, and there is a compatibility problem due to the difference in thermal expansion. A major problem is the difficulty of mounting ceramic bearings on metallic shafts and inside metallic housings, because of the large differences in thermal expansion coefficient between metals and ceramics.

4. *Corrosion resistance*: Ceramics are chemically inert and have good corrosion resistance. Ceramics can be used in a corrosive environment, such as strong acids, where steel alloys fail due to fast corrosion.

Although ceramics are not ideal tribological materials, they are considered by many to be the future technology. Ceramics enable operation at temperature ranges not previously accessible. They allow grease lubrication or unlubricated applications where steel requires more expensive and complex oil lubrication equipment.

In general, ceramics are expected in the future to replace metals in order to reduce weight and allow higher temperatures to increase engine efficiency and speed of operation. By using ceramics in gas turbines, the operating temperature will increase from the metal limited range of 1800–2100°F to 2500°F. This would result in considerable fuel savings. The characteristics of ceramic bearings, when fully used, not only would reduce fuel consumption, but also will reduce maintenance cost and increase power density (engine weight), which is particularly important in aircraft. The ability of ceramic rolling elements to operate with very little or no lubrication offers great potential for improving aircraft safety.

11.5.2.3 Ceramics for Plain Bearings

In ceramics, adhesive wear has been identified as the most significant mechanism of sliding wear against bearing steel. As was discussed in Sec. 11.2.1, adhesive wear is influenced by two factors—the shear strength of the sliding pair and the compatibility of the two materials.

Attempts were made to modify ceramic material surfaces to minimize the adhesive wear so that they would be competitive with metal plain bearings. For example, experiments have been conducted to improve the wear resistance of silicon nitride by adding whiskers of silicon carbide in various amounts (Ueki, 1993). The results showed that silicon carbide improves fracture toughness, which is correlated with reduced wear.

It is already known that water is a good lubricant for ceramic sliding friction. Tests of the effect of water on ceramic slideways were conducted*. For all ceramics it was found that the coefficient of friction decreases with increasing humidity. Zirconia demonstrated the highest friction coefficient and wear rates, relative to other ceramics. Zirconia's wear rate increased dramatically with increasing sliding velocity when submersed in water, while the wear rates of

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*Fischer and Tomizawa, 1985; Tomizawa and Fischer, 1987; and Ogawa and Aoyama, 1991.

alumina oxide, silicon carbide, and silicon nitride decreased with increasing sliding velocities. The minimum friction coefficient of silicon carbide and silicon nitride is as low as 0.01 in the presence of water.

Experiments were conducted in oil-lubricated ceramic journal bearings. The experiments showed lower friction coefficient for silicon nitride journals (in comparison to steel journals) for bearings made of tin-coated Al-Si alloy, forged steel, and cast aluminium matrix composite with silicon carbide reinforcement (cast MMC). All bearings were lubricated with SAE 10W-30 oil (Wang et al., 1994).

11.5.2.3.1 Silicon Carbide and Silicon Nitride

As discussed earlier, these are the best-performing high-temperature, high-strength ceramics. They have high-temperature-oxidation resistance and the highest strength in structures. Silicon nitride has higher strength than silicon carbide up to 2600°F, but above this temperature silicon carbide is stronger. Silicon carbide and silicon nitride are inert to most chemicals, and for most applications they exhibit similar corrosion resistance. An important design consideration is that they have the lowest thermal expansion coefficient in comparison to other ceramics. In addition, they have the lowest density. They also have the highest compressive strengths. Silicon nitride is the only ceramic material used as a roller bearing material (see Chap. 13).

Ceramic journal bearings are widely used in very corrosive environments where metals cannot be used. For example, sealed pumps driven by magnetic induction are used for pumping corrosive chemicals. Most sealed pumps operate with ceramic sleeve bearings of silicon carbide. The ceramic sleeves are used because of their corrosion resistance and for their nonmagnetic properties.

However, the use of a silicon carbide sleeve in a sliding bearing was not successful in all cases. These bearings operate with the process fluid as lubricant. These fluids, such as gas and water often have low viscosity. These bearings perform well as hydrodynamic bearings with a full fluid film only at the high rated speeds. During starting and stopping there is direct contact of the journal with the ceramic sleeve. The silicon carbide sleeve is brittle and suffers severe wear from a direct contact; it does not have long life in pumps that operate with frequent start-ups. In such cases, all-ceramic rolling bearings made of silicon nitride proved to be a better selection. The silicone nitride rolling bearings are not so sensitive to frequent start-ups and show good corrosion resistance to chemicals.

11.5.2.3.2 Alumina Oxide

Alumina oxide has a high maximum useful temperature and good compressive strength. It was the first ceramic to be investigated as an advanced bearing material. Currently, it is being researched and developed as a candidate for plain bearings. It is also currently used in certain plain bearings. It was reported that in the presence of lubricant it has a low coefficient of friction similar to PTFE. However, for the sliding of dry ceramics, the coefficient of friction is higher than that of compatible metals (Ogawa and Aoyama, 1991).

11.5.2.3.3 Zirconia

Zirconia has the highest friction coefficient and wear rates relative to other ceramics. Zirconia's wear rate increased dramatically with increasing sliding velocity. Zirconia has the lowest operating temperature and the lowest modulus of elasticity and a very high hardness.

Researchers have been trying to modify the Zirconia manufacturing process in order to increase its compressive strength and temperature range by reducing its grain size. Zirconia was considered a good candidate for roller-element bearings because it has relatively low modulus of elasticity. Low-modulus elasticity allows ceramics to flake like metals when failing as rolling elements. Silicon nitride is the only other ceramic that flakes. The others fail catastrophically.

11.5.2.3.4 Ruby Sapphire

Ruby sapphire has the highest hardness and maximum useful temperature. It is being investigated for use in plain and rolling bearings. It is the engineering ceramic with the least reported data.

11.5.3 Other Nonmetallic Bearing Materials

11.5.3.1 Cemented Carbide

This generally consists of tungsten carbide (97%) and Co (3.0%). It can withstand extreme loading and high speeds. It must have good alignment and good lubrication. This material is used in high-speed precision grinders.

11.5.3.2 Rubber

Rubber bearings are used mostly on propeller shafts and rudders of ships, in hydraulic turbines, and in other industrial equipment that processes water or slurries. The compliance of the rubber helps to isolate vibration, provide quiet operation, and compensate for misalignment (see Chapt. 9).

11.5.3.3 Wood

Wood bearings have been replaced by plastic and rubber bearings. The main advantage of wood bearings are their clean operation, low cost, and self-lubrication properties. Common wood materials are rock maple and oak.

11.5.3.4 Carbon Graphite

Carbon graphite has good self-lubricating properties. Carbon graphite bearings are stable over a wide range of temperatures and are resilient to chemical attack. In some cases, metal or metal alloys are added to the carbon graphite composition to improve such properties as compressive strength and density. Carbon graphite has poor embeddability; therefore, filtered and clean lubricants should be used. Usually, carbon graphite does not require lubrication. In most cases, it is used in textile and food-handling machinery.

11.5.3.5 Molybdenum Disulfide (MoS_2)

Molybdenum disulfide is similar to graphite in appearance, and it has very low friction coefficient. In many applications it is mixed with a binder, such as a thermosetting plastic, in order to ensure retention of the lubricant on the surface. It has a satisfactory wear life.

11.5.3.6 Polymer–Metal Combination

Other types of bearings in the plastic family are the polymer–metal combination. These are very well known and considered quite valuable as far as bearing materials are concerned. One variety is made of a porous bronze film layer coated with a Teflon-lead mixture, plus an all-steel backing. This configuration results in favorable conductive heat transfer as well as low-friction properties. Industry reports application of temperatures up to 530°F, which indicate this bearing is desirable. This bearing material is used in bushings, thrust washers, and flat strips for handling rotating, oscillating, sliding, radial, and thrust loads. Acetal copolymer is being applied in small gears that need structural strength, while still providing low friction and wear.

Problems

11-1 List the plastic bearing materials according to the following:

   a. Increasing *PV* value
   b. Increasing allowed temperature

11-2 White metal (babbitt) is currently used as very thin layer. Give an example of two applications where it would be beneficial to have a thicker white metal.

11-3 What materials are used in car engine bearings? Explain the reasons for the current selection.

11-4 Select a bearing material for a low-cost mass-produced food mixer. Explain your selection.

11-5 Summarize the characteristics of nylon 6 that are significant for the selection of a bearing material. Give three examples of machines where bearings of nylon 6 can be used and three examples where this material would not be appropriate.