9

Surface Damage

9.1 Introduction

Previous chapters have dealt with damage occurring within the body of a part (yielding, fracture, excessive deflection, buckling). In addition, various kinds of damage can occur to the *surface* of a part, which render it unfit for use. To begin the list, the surface may corrode, either in a normal atmosphere or in other, usually more corrosive, environments such as salt water. Surface corrosion may combine with static or fatigue stresses to produce a *more* destructive action than would be expected by considering the actions of corrosion and stress separately. High relative velocities between solid parts and liquid particles can cause *cavitation* of the liquid, which may be destructive to the surface of the part. When two solid members are pressed together, *contact stresses* are produced, and these require special consideration. When the members are in *sliding* contact, several types of deterioration coming under the general heading of *wear* can occur. The severity of wear can be reduced by using a *lubricant* (as an oil, grease, or solid film) between the rubbing surfaces.

Experience indicates that more machine parts "fail" through surface deterioration than by breakage. In an automobile, for example, consider the range of surface damage represented by corroded exhaust systems, rusted body panels, and worn piston rings, suspension joints, and other rubbing parts (not to mention upholstery and floor covering).

The economic cost of surface damage underscores its importance. The National Bureau of Standards reported to Congress that the estimated total annual costs of corrosion and wear in the United States were $70 billion and $20 billion, respectively, in 1978 dollars [1].

9.2 Corrosion: Fundamentals

Corrosion is the degradation of a material (normally a metal) by chemical or electrochemical reaction with its environment. Most corrosion results from electrochemical, or *galvanic*, action. This is a complex phenomenon, giving rise to the specialized discipline of *corrosion engineering*.

Figure 9.1 shows an *electrode* of chemically pure iron in a homogeneous *electrolyte* (ion carrier, such as fresh water, salt water, moist atmosphere, mud, etc.). Positively charged Fe^{2+} ions go into solution, leaving an excess of electrons (i.e., a negative charge) on the iron electrode. When an equilibrium *electrode potential* is reached, no further electrochemical action takes place.
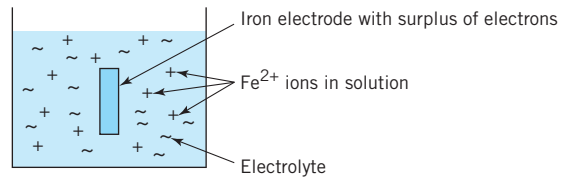
In Figure 9.2, the iron electrode is incompletely plated, leaving exposed iron, as shown. If the plating is tin, for example, the plating tends to lose positively charged ions, with a corresponding negative charge remaining in the tin coating. At the same time, the exposed iron surface tends to lose positive iron ions, leaving a negative charge in the body of the iron. Table 9.1 shows that iron (no. 17 in the table) is more active than tin (no. 14) in the galvanic series. This means that iron has the greater tendency to ionize and develops the greater negative charge (electrode potential) in the body of the metal. Hence, an electrical current will flow within the metals, with electrons going from the iron (which becomes the *anode*) to the tin coating (now the *cathode*). A flow of ions through the electrolyte completes the circuit. This process involves a continuous discharge of iron ions; hence the iron *corrodes*. The current is in the direction to *prevent* a discharge of tin ions; thus the tin cathode does *not* corrode. This phenomenon is commonly observed in rusted "tin" cans, where breaks in the tin coating cause the exposed steel to corrode. The iron ions discharged into the electrolyte commonly combine with hydroxyl and oxygen ions and precipitate out as ferric hydroxide and ferric oxide, or *rust*.

Although the relative order of metals in the galvanic series is generally similar for most commonly encountered electrolytes, exceptions do occur. An interesting case in point is this same "tin" can. The various acids, alkalies, and organic substances in canned foods provide electrolytes in which the inner steel surface of the can is *cathodic* with respect to tin and is therefore protected. Furthermore, tin salts, which may be present in extremely low concentration owing to corrosion of the tin, are nontoxic. Hence, tin plate is considered ideal for handling beverages and foods.

Suppose, in Figure 9.2, that the plating is not tin but *zinc* (no. 19). Reference to Table 9.1 indicates that in ordinary environments the zinc will go into solution (corrode), and the direction of current through the electrolyte will oppose the discharge of positively charged iron ions. Thus, the iron becomes the *cathode* and does not corrode. Zinc coating represents the common practice of *galvanizing* ferrous materials to protect them against corrosion.

Most corrosion phenomena involve two metal electrodes in contact, as iron and zinc, or iron and tin, in Figure 9.2. Closely related electrochemical phenomena can be illustrated with Figure 9.3, where the two electrodes (*A* and *B*) are not in direct contact. Suppose these electrodes are zinc (no. 19) and carbon
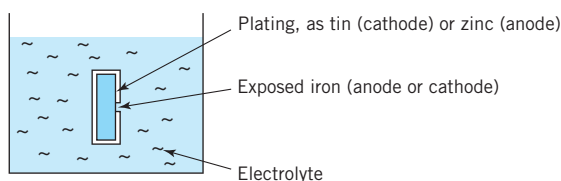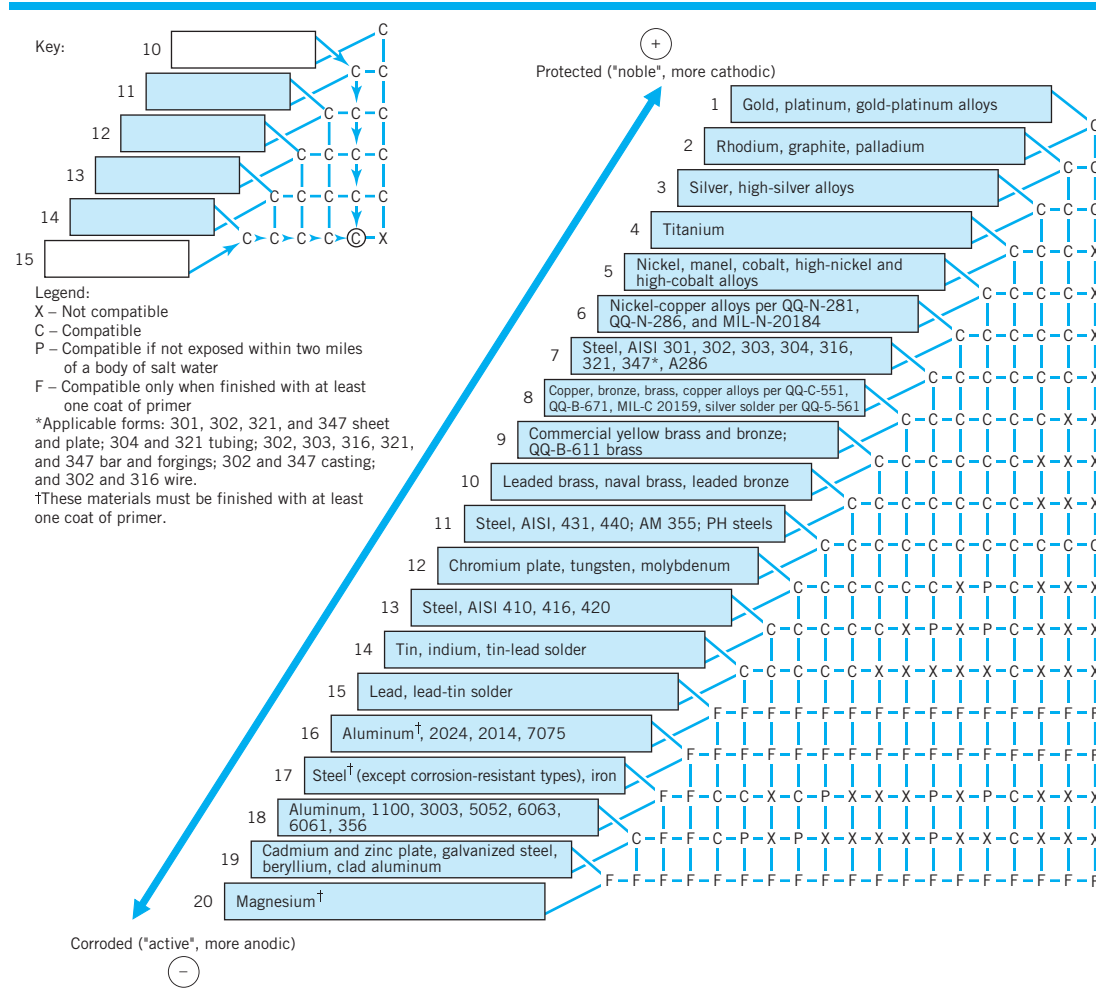
TABLE 9.1   Galvanic Series: Corrosion Compatibility Chart

Key:

10, 11, 12, 13, 14, 15

Legend:
X – Not compatible
C – Compatible
P – Compatible if not exposed within two miles of a body of salt water
F – Compatible only when finished with at least one coat of primer
*Applicable forms: 301, 302, 321, and 347 sheet and plate; 304 and 321 tubing; 302, 303, 316, 321, and 347 bar and forgings; 302 and 347 casting; and 302 and 316 wire.
†These materials must be finished with at least one coat of primer.

Protected ("noble", more cathodic) +

1 Gold, platinum, gold-platinum alloys
2 Rhodium, graphite, palladium
3 Silver, high-silver alloys
4 Titanium
5 Nickel, manel, cobalt, high-nickel and high-cobalt alloys
6 Nickel-copper alloys per QQ-N-281, QQ-N-286, and MIL-N-20184
7 Steel, AISI 301, 302, 303, 304, 316, 321, 347*, A286
8 Copper, bronze, brass, copper alloys per QQ-C-551, QQ-B-671, MIL-C 20159, silver solder per QQ-5-561
9 Commercial yellow brass and bronze; QQ-B-611 brass
10 Leaded brass, naval brass, leaded bronze
11 Steel, AISI, 431, 440; AM 355; PH steels
12 Chromium plate, tungsten, molybdenum
13 Steel, AISI 410, 416, 420
14 Tin, indium, tin-lead solder
15 Lead, lead-tin solder
16 Aluminum†, 2024, 2014, 7075
17 Steel† (except corrosion-resistant types), iron
18 Aluminum, 1100, 3003, 5052, 6063, 6061, 356
19 Cadmium and zinc plate, galvanized steel, beryllium, clad aluminum
20 Magnesium†

Corroded ("active", more anodic) −

Source: From C. F. Littlefield and E. C. Groshart, "Galvanic Corrosion," *Machine Design*, 35: 243 (May 9, 1963).

(graphite) (no. 2). Reference to Table 9.1 indicates that the greater concentration of electrons would be on the zinc. (Zinc has the greater tendency to lose positive ions, thereby leaving it with a negative charge with respect to the carbon). If terminals *A* and *B* are connected by a wire, electrons will flow through the wire. This is what happens in an ordinary carbon–zinc dry cell.
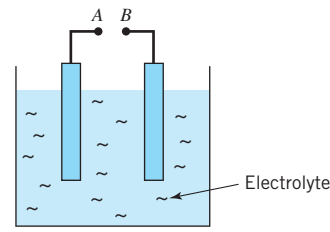
Again, referring to Figure 9.3, suppose electrode *A* is iron (no. 17) and *B* is copper (no. 8), and that the two terminals are connected by a battery that *forces* a flow of positive charges from the copper, through the electrolyte, and to the

FIGURE 9.3
Two electrodes, with terminals for external connection to a conductor or battery.

(*a*) Water tank

(*b*) Underground pipe

Zinc strips between steel spring leaves

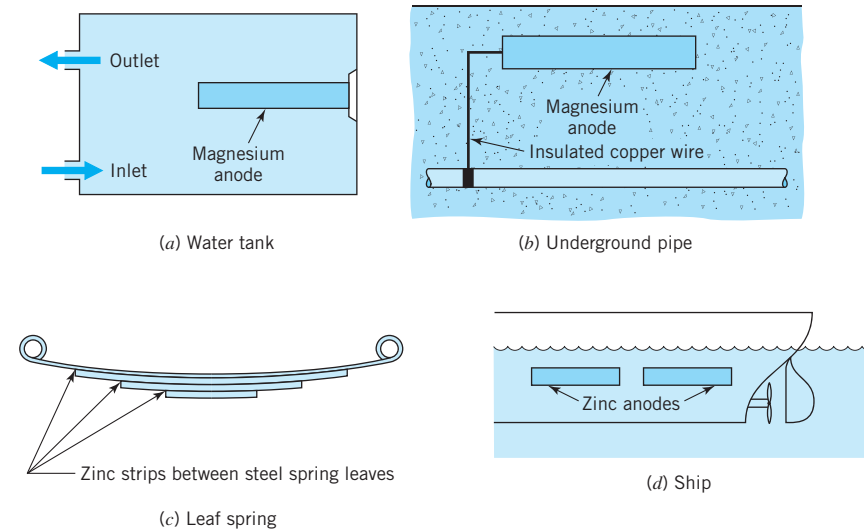(*c*) Leaf spring

Zinc anodes

(*d*) Ship

FIGURE 9.4
Cathodic protection of steel using sacrificial anodes.

iron. This is accomplished by copper ions (positive) going into solution, corroding the copper away, and then migrating to the iron electrode where they are deposited. This process is *electroplating*.

　　Figures 9.4 and 9.5 illustrate practical applications of the principles just given in suppressing corrosion. In Figure 9.4, the natural flow of galvanic current is such that the equipment to be protected is the *cathode*, and the zinc and magnesium plates are *sacrificial anodes*. (When these become depleted, they can be easily replaced.) In Figure 9.5, an external direct voltage source forces a flow of electrons to the equipment to be protected, making it the cathode.

9.3　Corrosion: Electrode and Electrolyte Heterogeneity

In the previous section it was assumed that the electrodes and the electrolyte were homogeneous. Many actual corrosion situations deviate substantially from this "ideal" condition, and these deviations markedly affect the nature and extent of the resulting corrosion. For example, aluminum and titanium exposed to ordinary
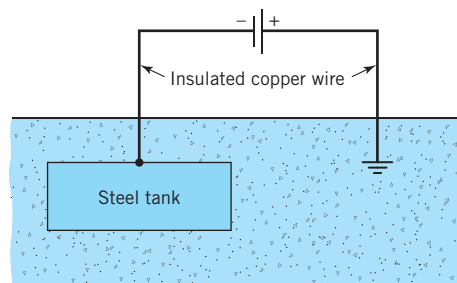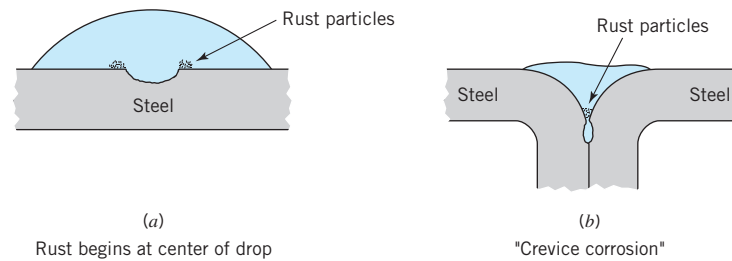

FIGURE 9.5
Cathodic protection of underground tank using small direct-current impressed voltage.

(a)
Rust begins at center of drop

(b)
"Crevice corrosion"

FIGURE 9.6
Corrosion caused by oxygen starvation of the electrolyte at the center of a
droplet or stagnant puddle.

atmosphere form protective oxide films (Al_2O_3, and TiO_2) on their surfaces that
electrically insulate the body of the material. The corrosion current density is there-
fore almost nil. This explains why aluminum can be used for boats, despite its posi-
tion in the galvanic series (no. 18 in Table 9.1). Iron, chromium, nickel, titanium, and
many of their important alloys exhibit the phenomenon of *passivation*, which means
that insulating oxide films are maintained *in certain environments*. When the metal
is in the *active* condition (without the oxide film), corrosion current densities are fre-
quently 10^4 to 10^6 times those for the *passive* state.

Another important form of electrode heterogeneity is the microstructure of the
metal. For example, when pearlite is etched with a mild acid, the microstructure
can be seen because the ferrite and carbide constituents become anodes and cath-
odes in a multitude of minute galvanic cells. Whichever is the anode corrodes, thus
enabling it to be visually distinguished. (Ferrite and carbide have very close elec-
trode potentials, and their relative position in the galvanic series depends on the
electrolyte used.)

Another important cause of local galvanic action (and corrosion) is hetero-
geneity of the electrolyte. A common (and enormously costly!) example is the
variation in composition of the salt–mud–water deposit under car bodies in the
northern United States, which sets up vigorous localized galvanic action. Another
example is the corrosion of buried pipe that passes through strata of soil of vary-
ing salt content.

Figure 9.6 illustrates two instances in which a drop of electrolyte (usually water)
creates electrolyte heterogeneity by sealing off atmospheric oxygen from the center
of the drop, compared to the oxygen-rich electrolyte near the edge. Corrosion occurs
at the oxygen-starved interior. Figure 9.6*b* illustrates what is commonly called
crevice corrosion. A related observation that the reader may have made is that
smooth surfaces tend to corrode less rapidly than rough surfaces.

9.4 Design for Corrosion Control

First, consider *material selection*. Materials toward the inactive, or "noble," end of
the galvanic series for the electrolyte involved develop lower electrical potentials
tending to send their ions into solution, and thus corrode more slowly. This is not the
whole story, though, because, as noted previously, the *rate* with which metal ions go
into solution can be dramatically reduced by oxide films. Thus, aluminum corrodes

extremely slowly in seawater, despite its position in the galvanic series. The same thing is true of stainless steels when, in most environments, these films change the metal's action from "active" to "passive."

Differences in *microstructure* caused by *heat treating* and welding can influence the intensity of galvanic action within the multitude of surface galvanic cells. Certain low-alloy steels (called "weathering" steels) have been developed that effectively resist atmospheric corrosion by forming protective rust films. These steels are used primarily for architectural construction. After initial weathering, they have a uniform reddish-brown (rust) color, and galvanic action nearly stops. Because weathering steels need not be painted, their use often results in a substantial cost saving over the life of the structure.

Chemical treatment of metal surfaces may produce surface films that offer some degree of insulation of the base metal from the environment. Common examples are *phosphate coatings* on steel ("Parkerizing" or "Bonderizing") and *oxide coatings* on steel (brown, black, or blue in color). The effectiveness of these films is usually minimal, unless they are combined with rubbing with oils or waxes (as with gun barrels). Phosphate coatings on steel help provide good adherence of paint and decrease the tendency for corrosion to undercut the paint film at scratches or other discontinuities. *Anodizing* of aluminum alloys produces a stable aluminum oxide film that has excellent corrosion resistance and that can be dyed in a variety of colors. (Common experience indicates that the protective oxide film on unanodized aluminum rubs off to produce a black stain.)

Metal surfaces can be sealed from possible contact with an electrolyte by *nonporous coatings*, such as porcelain enamel applied to bathroom fixtures or rubber coatings vulcanized to steel plates.

Ordinary *paints* provide a good barrier for the diffusion of water and oxygen to a metal surface but are permeable to some extent. Because of this, and because paint films can become scratched and otherwise damaged, it is important to use an effective *primer*. The pigments in the prime coat applied to bare metal should be effective corrosion inhibitors. Any water reaching the metal surface then dissolves a small amount of primer pigment, making the water less corrosive. (The action of inhibitors is discussed later in this section.)

Where appearance and weight considerations are not stringent, it is sometimes more economical to make a part *with larger dimensions* (heavier than necessary) to allow for anticipated future corrosion than it is to provide effective corrosion protection. In addition, the impact of corrosion damage can often be reduced by designing equipment so that parts vulnerable to corrosion can be *easily replaced*.

The preceding discussion assumed that only a single metal was involved. When corrosion of two or more metals connected by an electrode is to be minimized, *the metals should be as close together as possible in the galvanic series*. For example, cadmium is very close to aluminum in most environments; hence, cadmium-plated screws can be used in direct contact with aluminum parts. But if a copper washer is introduced, the aluminum normally corrodes rapidly. In fact, aluminum has been found to corrode rapidly in rainwater that had previously contacted copper flashings or gutters. Other common examples of galvanic corrosion include the corroding of aluminum car door sills in contact with a steel body structure when exposed to road salt in northern areas, or salt air near the coasts; steel pipe connected to aluminum plumbing; steel screws in brass marine hardware; and lead–tin solder on copper wire.

Table 9.1 shows the compatibility with respect to galvanic corrosion of commonly used metals and alloys when placed together in most atmospheric environments. Anodized aluminum is compatible with all other metals. The chart assumes that the two metals have comparable exposed areas. If one metal has only a small fraction of the exposed surface of a second metal with which it is normally compatible, it may suffer galvanic attack. In addition, when there are large temperature differences, thermoelectric action may be a significant factor.

When it is necessary to use dissimilar metals together, the corroding galvanic circuit can often be broken by using an *electrical insulator*, as shown in Figure 9.7*a*.

Sometimes galvanic cells are deliberately designed into a component or system by providing a *sacrificial anode* to protect a metal cathode. This was illustrated by the zinc coating (galvanizing) of steel in connection with Figure 9.2, and other examples in Figure 9.4. In the United States alone, thousands of tons of magnesium are used annually as sacrificial electrodes.

Figure 9.5 showed an alternative method of cathodically protecting underground tanks or pipe. The cost of the *external electrical energy* consumed is an obvious factor limiting the application of this method.

An important factor in the design of metal parts to resist corrosion is the *area effect*. To minimize corrosion of the anode, its exposed surface area should be large in comparison to the cathode surface area. This results in a *low current density* at the anode, hence a low corrosion rate. The area effect is clearly illustrated by the examples depicted in Figure 9.2. Where the plating was zinc (as in galvanized steel), the large zinc surface results in low current density and a low rate of corrosion. Where the plating was tin, the small area of exposed ferrous material results in rapid corrosion, as observed in discarded and rusted "tin" cans.

Design for corrosion control also requires careful attention to factors relating to the *electrolyte*. The electrolyte may be a liquid in which metal electrodes are totally immersed or its function may be provided by exposure to spray or mist, by alternate wetting and drying, as by rain, by contact with moist earth, or merely from humidity in the atmosphere. It is important to eliminate or minimize crevices where corrosion can occur, as shown in Figure 9.6*b*. Parts should be designed so that moisture can drain completely, without leaving residual liquid to encourage corrosion, as shown in Figure 9.6*a*. This means that smooth butt-welded joints tend to corrode more slowly than bolted or riveted lap joints. Surfaces that are smooth tend to corrode less than rough surfaces, for they have less tendency to retain liquid electrolyte. Unavoidable crevices should be sealed, ideally with vulcanized rubber or the equivalent.

Surfaces subject to retaining deposits of mud and salt (such as auto underbody surfaces) should be designed to facilitate *cleaning*, for heterogeneous mixtures of soil and salt in contact with a metal can cause destructive galvanic action.

Electrolytes tend to cause the least galvanic action when they are stagnant. Agitation and temperature gradients tend to remove ion concentration near the electrode
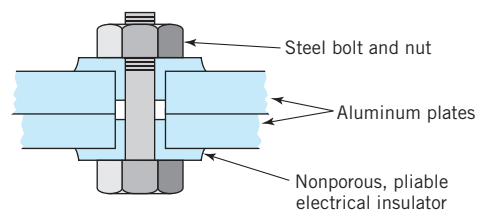

Steel bolt and nut

Aluminum plates

Nonporous, pliable electrical insulator

FIGURE 9.7*a*
Insulator breaking the galvanic circuit between a steel bolt and aluminum plates.

surfaces, thus increasing galvanic currents. Hence, temperature gradients and fluid velocities should be minimized.

Atmospheric corrosion tends to be greatest at high temperatures and high humidity. For example, corrosion rates of structural steel in tropical climates are reportedly at least twice that encountered in temperate climates.

In recirculating cooling systems, *inhibitors* (chemicals added to the liquid coolant in small concentration) are used to make the liquid a less effective electrolyte. These inhibitors act to encourage *passivation* (recall Section 9.3) of the metals subject to corrosion and otherwise impede the movement of ions in the region of the electrodes. The inhibitor must be appropriate to the liquid and the metals involved.

For further study, Refs. 13 and 4 in particular are suggested. References 2, 3, 8, and 14 also contain helpful information about corrosion.

Figure 9.8*a* illustrates comparative rankings of the resistance of various materials to corrosive attack by six environments. The comparative rankings range from A (excellent) to D (bad). The chart should be used with caution and only for broad guidance. Appendix C-19 gives the classes and abbreviations for Figure 9.8*a*.

SAMPLE PROBLEM 9.1 Compare Corrosion of Riveted Metal Plates

Metal plates having a total exposed area of 1 m^2 are fastened together with rivets having a total exposed area of 100 cm^2. The environment involves moisture and possibly some salt. Consider two cases: (1) steel plates with copper rivets, and (2) copper plates with steel rivets. (a) For each case, which metal will corrode? (b) How do the rates of corrosion compare for the two cases? (c) If twice as many rivets are used, what influence would this have on the total rate of corrosion?

SOLUTION

Known: Metal plates having a known total exposed area are fastened together with rivets having a known total exposed area. The environment involves moisture and possibly some salt. Consider two cases: (1) steel plates with copper rivets and (2) copper plates with steel rivets.

Find:
  a. For each case, determine which metal will corrode.
  b. Compare the rates of corrosion for the two cases.
  c. Determine the influence of using twice as many rivets on the total rate of corrosion.
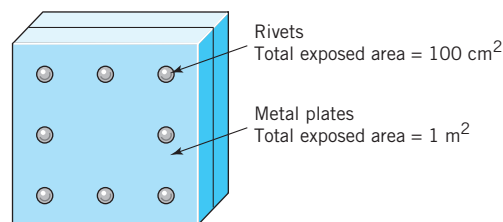
Schematic and Given Data:

Rivets
Total exposed area = 100 cm^2

Metal plates
Total exposed area = 1 m^2

FIGURE 9.7*b*

Metal plates fastened together with rivets.

Assumption: The steel is an ordinary non–corrosion-resistant steel.

Analysis:

a. Assuming an ordinary non–corrosion-resistant steel, the steel would be the more active (anodic) and would corrode in both cases (1) and (2).

b. Because the current density is 100 times greater at the rivet surface than at the plate surface due to area effect, the corrosion rate is highest if the rivets are steel.

c. Doubling the number of steel rivets would minimally affect the corrosion rate of an individual rivet because the current at each rivet would remain about the same. Doubling the number of copper rivets would about double the corrosion rate of the steel plates, again because the current density at each rivet would remain about the same, thereby doubling the current density of the plates.

Comment:

[An] important factor in galvanic corrosion is the area effect, or the ratio of the cathodic to anodic areas. An unfavorable area ratio consists of a large cathode and a small anode. For a given current flow, the current density is greater for a small electrode than for a larger one. The greater the current density at an anodic area the greater the corrosion rate. Corrosion of the anodic area may be 100 or 1000 times greater than if the anode and the cathodic area were equal in size.

See Mars G. Fontana, *Corrosion Engineering*, 3rd ed., McGraw-Hill, New York, 1986.

9.5 Corrosion Plus Static Stress

When static *tensile* stresses exist in a metal surface subjected to certain corrosive environments, the combined action can cause brittle cracking and fracture that would not be predicted on the basis of considering these two factors separately. Such cracks are called *stress–corrosion* cracks and have been known to engineers since at least 1895, when it was noted that surface cracks developed on iron tires of wagon wheels after periods of exposure to a humid atmosphere. These tires were subjected to residual tensile stresses because they had been forced onto the wheels with an interference fit.

Although the vulnerability of engineering metals to stress–corrosion cracking varies greatly, nearly all are susceptible to some degree and in some environments. Stress–corrosion cracking is a complex phenomenon not yet fully understood. Environments causing severe galvanic corrosion of a metal are not necessarily the same as those associated with serious stress–corrosion cracking of that metal. The relative resistance of materials to ordinary galvanic corrosion in a specific environment is not usually the same as the relative resistance of these materials to stress–corrosion cracking. For example, stress–corrosion cracking has been observed in certain stainless steels that are completely corrosion-resistant when unstressed.

The stress associated with stress–corrosion cracking is *always* tensile and is the sum of the residual and operating stresses existing at the *local site* where cracks initiate
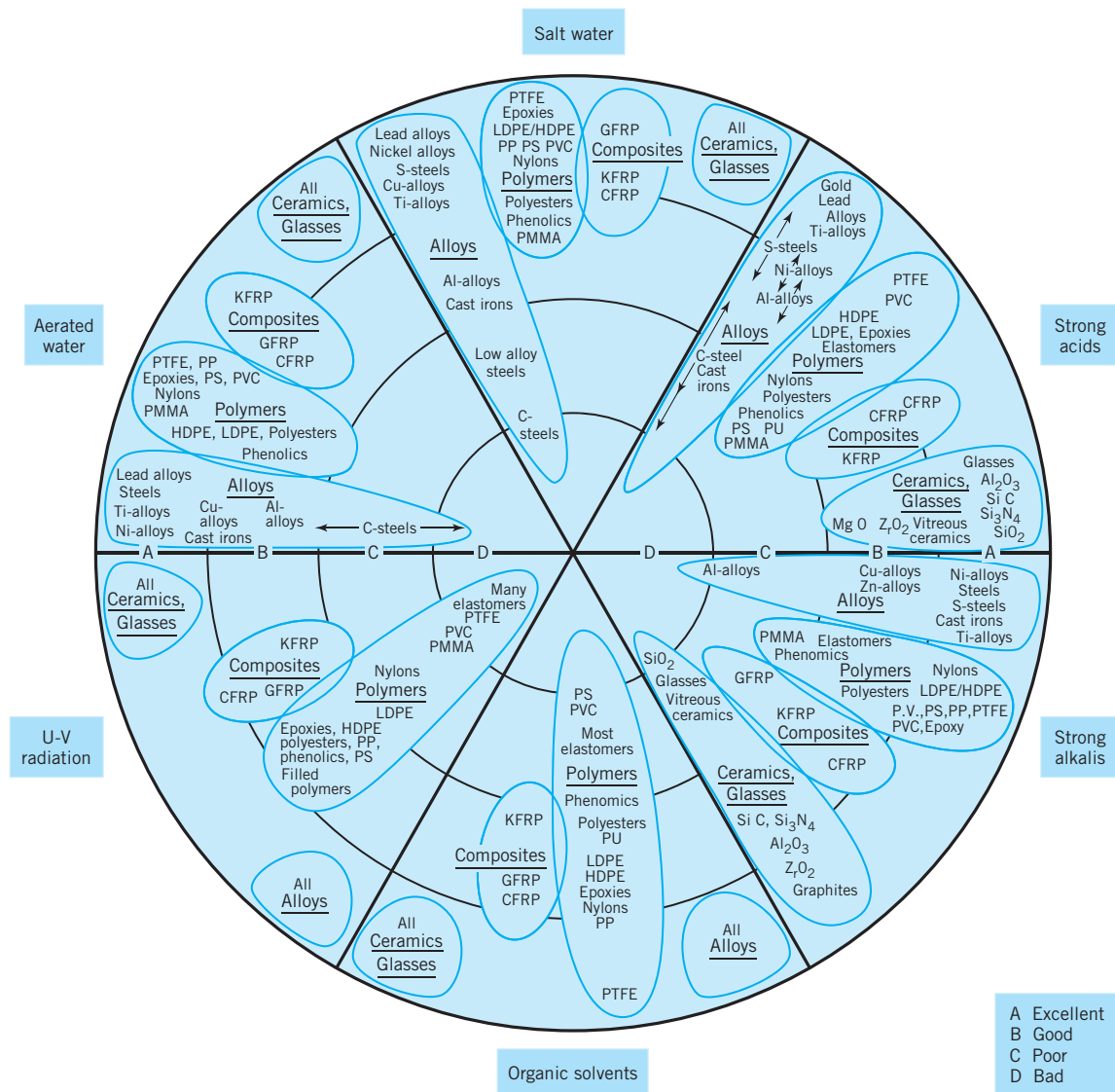
FIGURE 9.8*a*
Comparative ranking of the ability of materials to resist corrosive attack from various environments.
(From M. F. Ashby, *Materials Selection in Mechanical Design*, Pergamon Press, 1992.)

and propagate. (Residual stresses are caused by the processing and assembly of parts, as opposed to operating stresses caused by the applied loads; see Sections 4.14 and 4.15.) This total stress necessary for stress–corrosion cracking is most often of the order of 50 to 75 percent of the tensile yield strength. Residual stresses alone can easily be this high.

Stress–corrosion cracks may occur after a period of time varying from a few minutes to several years, depending on the corrosive environment and the surface tensile stress. Attempts to determine stress levels below which stress–corrosion cracks would never occur (analogous to the "endurance limit" for fatigue loading of
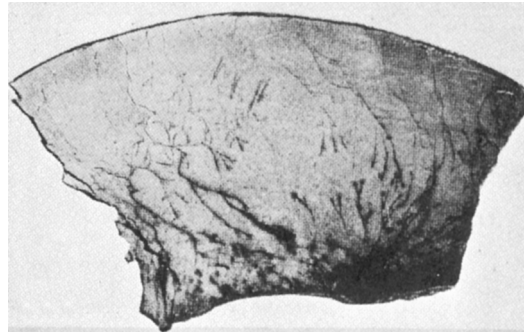
FIGURE 9.8*b*
Stress–corrosion cracking of a
stainless steel conveyor blade
[5a].

ferrous materials) have not yet been successful. However, engineers are gaining a better understanding of stress–corrosion cracking failures through studies applying fracture mechanics (see Sections 6.3 and 6.4).

When stress–corrosion cracking occurs, there are usually multiple cracks originating at the surface, with fracture resulting from a single crack propagating normal to the resultant tensile stress. The appearance of a typical failure is shown in Figure 9.8*b*.

An early reported example of stress–corrosion cracking was in riveted steam boilers. Alkaline boiler water in crevices around the rivets contacted boiler plate surfaces that were in tension (because of internal boiler pressure), with these stresses being accentuated by stress concentration. Some boilers exploded. Mild steel boiler tubes operating with water containing sodium hydroxide have also failed because of stress–corrosion cracking. Other examples of this type of failure include stainless steel aircraft parts exposed to the salt environment of a seacoast (together with elevated operating temperatures in some cases); thin hubs or rims pressed onto an inner member with a heavy interference fit; bridge cables whose steel is inappropriate for the chemicals in the local atmosphere; steel brackets that support heavy static weights; and "season cracking" of brass cartridge cases. These are deep-drawn cylindrical cases having residual tensile stresses in the sharp bottom corner; cracking occurs after storage, before loads have been applied.

The following methods reduce stress–corrosion cracking.

1. Change to a more stress–corrosion–resistant material for the environment involved.
2. Reduce corrosive action, as by providing cathodic protection, using protective coatings on the vulnerable surfaces, or making the environment less corrosive, as by adding inhibitors.
3. Reduce tensile stress, by reducing interference fits, using heavier sections, and annealing (caution: in some situations annealing may render the material *more* susceptible to stress–corrosion cracking), and by shot-peening or hammer-peening vulnerable surfaces.

Peening is of particular practical importance, for it serves to overcome previous surface residual tension and impart helpful residual compressive stresses (see Section 8.14).

A summary of the stress–corrosion performance of several metals and alloys is given in [5a].

9.6 Corrosion Plus Cyclic Stress

The combined action of corrosion and fatigue loading usually causes earlier failure than would be expected from a consideration of these two effects separately. This phenomenon is called *corrosion fatigue*. It occurs with most metals, but most markedly with those having little corrosion resistance. Corrosion fatigue is a complex action, not yet fully understood. A simplified explanation begins with initial corrosion pits which serve as points of stress concentration. Protective films, formed as a result of the corrosion, are usually weak and brittle. Hence, they are ruptured by the imposed cyclic strain. This rupture exposes unprotected metal, which quickly corrodes, forming another film, which is also ruptured by cyclic strain, and so on. Thus, the initial corrosion pit becomes a fatigue crack that propagates more rapidly than can be explained by considering corrosion and cyclic loading separately. As would be expected, corrosion fatigue failures show discoloration of the crack propagation surfaces, whereas ordinary fatigue crack surfaces are corrosion-free (like the surfaces described as "smooth, velvety" in Figure 8.1).

The fatigue strength of corroding parts depends on the *elapsed time*, as well as on the cyclic stress and the corroding environment. The fatigue strength for a given number of stress cycles is obviously greater if these cycles are imposed quickly, without allowing much time for corrosion to occur. Test results tend to support the following generalizations:

1. Corrosion fatigue strengths do *not* correlate with tensile strengths. This is likely, in part, because the stronger metals have a greater sensitivity to corrosion pits ("notches").

2. Medium-alloy steels have only slightly higher corrosion fatigue strengths than carbon steels, and in neither case is corrosion fatigue strength improved by heat treatment.

3. Corrosion-resistant steels, such as those containing chromium, have higher corrosion fatigue strengths than other steels. *Good corrosion resistance is more important than high tensile strength.*

4. Residual tensile stresses are harmful; residual compressive stresses, such as those caused by shot peening, are beneficial.

Remedial measures for corrosion fatigue are similar to those for stress–corrosion cracking: (1) use a more corrosion-resistant material, (2) reduce corrosive action by protective coatings, inhibitors, or cathodic protection, and (3) minimize tensile stresses, and introduce residual compressive stresses.

Much of the experimental data on corrosion fatigue strength of various metals that are still referred to was reported by D. J. McAdam, Jr. [9], the investigator who originally coined the term "corrosion fatigue." Some of McAdam's results are summarized in [6] and [14].

Note that Figure 8.13 gives surface factors for test specimens with *previously* corroded surfaces. These factors serve only as a rough guide and do not apply at all to situations in which the part is subjected to corrosion *while the cyclic stress is applied*.

9.7 Cavitation Damage

Cavitation is the formation of gas bubbles or "cavities" in a liquid that is moving with respect to a nearby solid surface. Bubbles are formed when the liquid pressure drops below its vapor pressure. When these bubbles subsequently collapse at or near the solid surface, pressure waves impinge upon the surface causing local stresses that can be great enough to cause plastic deformation of many metals. Often, metal damage is evident only after repeated bombardment by these pressure waves, much as in the case of damage caused by ordinary metal fatigue.

Cavitation commonly occurs on ship propellers, centrifugal pumps, turbine blades, and other surfaces that encounter high local liquid velocities and large liquid static pressure gradients. The resulting damage to metal surfaces is essentially mechanical. In corrosive environments, however, cavitation can repeatedly damage or remove protective oxide films, thereby increasing galvanic action.

A surface area damaged by cavitation appears roughened, with closely spaced pits. In severe cases, enough material is removed to give the surface a spongy texture.

If it is not feasible to eliminate or reduce cavitation by modifying the liquid composition, velocity, flow pattern, or static pressure, then the most effective means of dealing with cavitation damage is usually to increase surface hardness. Stainless steel is often the most effective material available at reasonable cost. The following materials are listed in decreasing order of resistance to cavitation damage: stellite,[1] 18-8 cast stainless steel, cast magnesium bronze, cast steel, bronze, cast iron, and aluminum. This list is extracted from [4] and [8], which also list other materials.

9.8 Types of Wear

The previous sections in this chapter dealt with surface damage resulting from contact with fluids. The remaining sections discuss contact with another solid. In many instances the resulting surface damage is classed as "wear."

The most common types of wear are *adhesive* wear and *abrasive* wear. These are treated in the next three sections. A third type is *corrosion film* wear, wherein the corroded surface film is alternately removed by sliding and then reformed. A typical example is the wear that may occur on cylinder walls and piston rings of diesel engines burning high-sulfur fuels. An important type of surface deterioration sometimes incorrectly classed as "wear" is *surface fatigue*, discussed in Section 9.14.

All forms of wear are strongly influenced by the presence of a *lubricant*. The information in Section 13.1 on types of lubricants and in Section 13.14 on boundary lubrication is relevant here. The wear rate for an unlubricated bearing can be 10^5 times that for a bearing with boundary lubrication.

In typical well-designed machine components, the initial wear rate on rubbing surfaces during "run in" may be relatively high. As the more pronounced surface

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[1] Trademark of Union Carbide Corporation.

peaks are worn off, causing the actual area of contact to increase, the wear rate decreases to a small constant value. After a period of time the wear rate may again increase because the lubricant is contaminated or surface temperatures are higher.

Reference 10 contains 33 articles dealing with the various aspects of wear and is an excellent reference for further study.

9.9 Adhesive Wear

On a microscopic scale, sliding metal surfaces are never smooth. Although surface roughness may be only a few microinches (or a few hundredths of a millimeter), inevitable peaks (often called "asperities") and valleys occur, as shown in Figure 9.9. Since the contact pressure and frictional heat of sliding are concentrated at the small local areas of contact indicated by the arrows, local temperatures and pressures are extremely high, and conditions are favorable for welding at these points. (*Instantaneous local* temperatures may reach the melting point of the metal, but with temperature gradients so steep that the part remains cool to the touch.) If melting and welding of the surface asperities (at the arrows in Figure 9.9) do occur, either the weld or one of the two metals near the weld must fail in shear to permit the relative motion of the surfaces to continue. New welds (adhesions) and corresponding fractures continue to occur, resulting in what is appropriately called *adhesive wear*. Since adhesive wear is basically a *welding phenomenon*, metals that weld together easily are most susceptible. Loose particles of metal and metal oxide resulting from adhesive wear cause further surface wear because of abrasion.

If the surface asperity welding and tearing cause a transfer of metal from one surface to the other, the resulting wear or surface damage is called *scoring*. If the local welding of asperities becomes so extensive that the surfaces will no longer slide on each other, the resulting failure is called *seizure*. Figure 9.10 shows severe scoring and seizure of differential pinion gears on their shafts. (This unit is used in automotive differentials that allow the two driving wheels to turn at different speeds for going around corners.) Perhaps the best-known examples of seizure occur in engines that continue to operate (but not for long!) after losing their liquid coolant or oil supply. Pistons may seize to the cylinder walls, the crankshaft may seize to its bearings, or both may happen.

Severe adhesive wear is also called *galling*. Mild adhesive wear between piston rings and cylinder walls is often called *scuffing*.
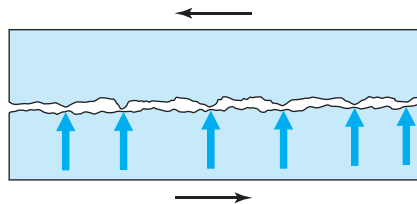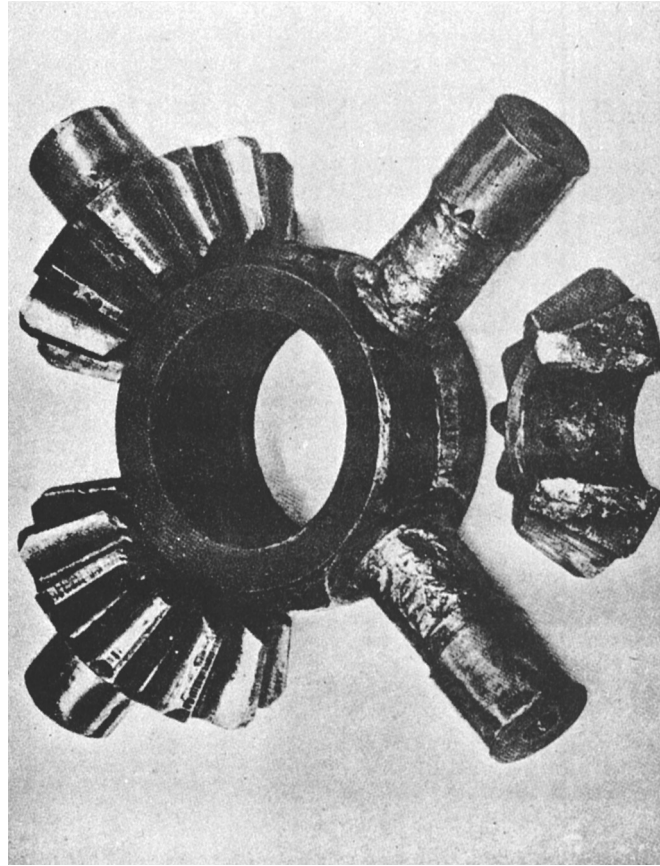

FIGURE 9.9
Greatly enlarged view of two nominally "smooth" rubbing surfaces.

FIGURE 9.10
Results of scoring and seizure in a differential. The broken
pinion gear resulted from seizure to its shaft. (From C. Lipson,
Basic Course in Failure Analysis, Penton Publishing,
Cleveland, 1970.)

When like metals are rubbed together with suitable pressure and velocity,
conditions are ideal for asperity welding because both surfaces have the same
melting temperature. In addition, the cohesive bonds thus formed are normally
stronger than the adhesive bonds between dissimilar welded asperities. For these
reasons, like or metallurgically similar metals should not normally be used
together under conditions likely to cause wear problems. Metallurgically similar
metals are referred to as "compatible." Compatible metals are defined as having
complete liquid miscibility and at least 1 percent solid solubility of one metal in
the other at room temperature. Figure 9.11 shows the degree of compatibility of
various combinations of metals.

In general, the harder the surface (more precisely, the higher the ratio of surface
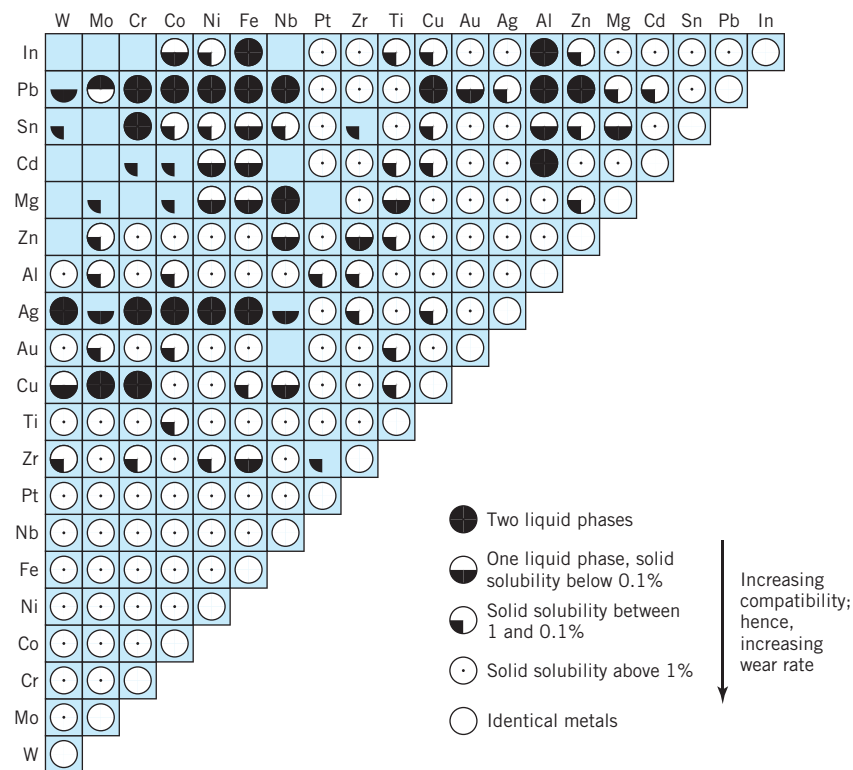hardness to elastic modulus), the greater the resistance to adhesive wear.

FIGURE 9.11

Compatibility of various metal combinations. (From E. Rabinowicz, "Wear Coefficients—Metals," Section IV of [10].)

9.10 Abrasive Wear

The term "wear" most often refers to *abrasive* wear, which is due to the rubbing of abrasive particles on a surface. These particles are typically small and hard and have sharp edges—like grains of sand or particles of metal or metal oxide that rub off a wearing metal surface. Common examples include the wearing down of wood or metal with sand or emery paper or with a grinding wheel, the wearing of shoe leather by scuffing against cement sidewalks, the wearing of a plow blade or earth auger during use, and the removal of metal from the journal surface of a rotating shaft by foreign abrasive particles in the lubricant.

Usually, the harder the surface the more resistant it is to abrasive wear. Hard metal surfaces are produced by heat treatment, flame or induction hardening, carburizing, nitriding, electroplating, flame plating, and other means. Not all these methods are applicable to severe applications because the hardened surfaces must sometimes be at least 3 mm thick to give adequate service life.

In machinery design, it is extremely important to use appropriate oil filters, air cleaners, dust covers, shaft seals, and so on to keep foreign particles away from rubbing metal surfaces.

Sometimes, one of a pair of rubbing members is made relatively soft and is designed to be easily and economically replaced. For example, hard surfaces on rotating shafts are protected by the use of softer, easily replaced bearings and bushings. It is sometimes desirable for the bearing to be sufficiently soft to permit hard abrasive particles to imbed completely so that they do not protrude above the surface and act like abrasive particles on sandpaper. This is one reason why soft babbitt bearings are used with automotive engine crankshafts.

9.11 Fretting

Fretting, also known as *fretting corrosion*, is classed as a form of adhesive wear but usually embraces elements of abrasive wear and corrosion film wear as well. Fretting occurs when surfaces, pressed together, experience slight relative motion. Examples include press fits (as bearings pressed onto shafts) and bolted and riveted connections, where fluctuating loads produce slight relative movement. Other examples are leaf spring interfaces and stacks of sheet metal transported long distances by rail or truck. The relative motion is typically of the order of 0.01 to 0.25 mm. The resulting damage can be mere discoloration of mating surfaces (as with the transported metal sheets), the formation of surface pits (most common), or the wearing away of a millimeter of material (extreme case). The roughness and pitting caused by fretting make the surface more vulnerable to fatigue failure. *Reducing fatigue strength is a major consequence of fretting.*

A widely accepted theory is that the oscillatory motion breaks down natural protective surface films, exposing bare metal surface "peaks" that weld together and are then torn away by the relative motion. With most engineering materials, the surface debris thus formed oxidizes to form powdery abrasive particles which build up and cause continuing wear. With ferrous surfaces the oxide powder is sometimes called "cocoa" because of its brown color. Magnesium and aluminum oxide particles appear black.

Resistance to frettage varies widely in different materials. Cobalt-base hardfacing alloys are among the best. In general, steel-on-steel and cast iron–on–cast iron are good, but interfaces in which one metal is stainless steel or titanium are poor. Brass-on-steel tends to be better than steel-on-steel. Combinations of cast iron with aluminum, magnesium, chrome plate, tin plate, or plastics are poor. The creation of *surface residual compressive stresses* by heat treatment or cold working has proved particularly effective in retarding the propagation of fatigue cracks initiated by fretting. The increased surface hardness resulting from these treatments is probably also beneficial. Low-viscosity, high-tenacity lubricants tend to reduce the intensity of fretting, their main effect apparently being to keep oxygen away from the active interface.

Sometimes fretting can be arrested by increasing surface interface pressure so that relative motion ceases. However, if the relative motion continues, frettage damage will usually increase with the higher pressure.

Additional details concerning fretting corrosion are given in Refs. 4–6, 8, 10, and 13.

9.12 Analytical Approach to Wear

Although the design of machine components from the standpoint of resisting wear remains largely empirical, analytical approaches are now available. The generally recognized "wear equation," which emerged in the 1940s, can be written as

$$\text{Wear rate} = \frac{\delta}{t} = \left(\frac{K}{H}\right)pv \tag{9.1}$$

where

δ = wear depth, mm (or in.)

t = time, s

K = wear coefficient (dimensionless)

H = surface hardness, MPa (ksi) (see footnote 2)

p = surface interface pressure, MPa (ksi)

v = sliding velocity, mm/s (in./s)

For two rubbing surfaces a and b, this equation implies that the rate of wear of surface a is proportional to the wear coefficient (for material a when in contact with material b), inversely proportional to the surface hardness of a, and, assuming a constant coefficient of friction, directly proportional to the rate of friction work.

For a given total compressive force between the surfaces, the volume of material worn away is independent of the area of contact. Thus, another and more commonly used form of the wear equation is
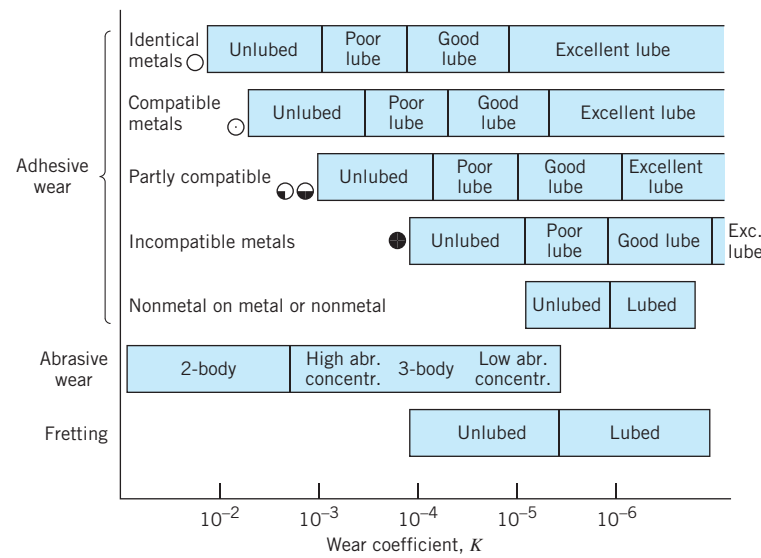
$$W = \frac{K}{H}FS \tag{9.1a}$$

where

W = volume of material worn away, mm^3 ($in.^3$)

F = compressive force between the surfaces, N (kilopounds)

S = total rubbing distance, mm (in.)

The best way to obtain values of the wear coefficient K for a particular design application is from experimental data for the same combination of materials operating under essentially the same conditions, for example, obtaining wear constants for the design of a "new model" from wear data obtained from a similar "old model." In addition, the literature contains values of K for many combinations of materials that have been obtained under laboratory conditions. When we use these values, it is

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[2] Brinell, Vickers, and Knopp hardness values are in kg/mm^2. To convert to MPa or ksi, multiply by 9.81 or 1.424, respectively. For standard test method of determining Knoop and Vickers hardness of materials, see ASTM E384-10e2.

Estimated wear coefficients for various sliding situations. (From E. Rabinowicz, "Wear Coefficients—Metals," Section IV of [10].)

important that the approximate interface temperature and the materials and lubrication of the expected application correspond to those used in the laboratory test.

For a wide variety of sliding systems, wear coefficients range from 10^{-1} to 10^{-8}. Figure 9.12 illustrates ranges of values typically obtained with various combinations of material compatibility (see Figure 9.11), lubrication and wear mode. The values of K pertain to the softer of the two rubbing metals.

Test data for wear coefficients show considerable scatter, typically over a range of plus or minus a factor of 4. For example, if the observed wear coefficient is 100 units, the actual K value will vary from 25 to 400 units. This is perhaps to be expected because adhesive wear tends to be proportional to the fourth or fifth power of the friction coefficient, which itself has considerable scatter.

The following sample problem illustrates the computation of K from experimental data.

SAMPLE PROBLEM 9.2   Determining Wear Coefficients

A pin-on-disk friction testing apparatus (Figure 9.13) involves the unlubricated rounded end of a copper pin of 80 Vickers hardness being pressed with a force of 20 N against the surface of a rotating steel disk of 210 Brinell hardness. The rubbing contact is at a radius of 16 mm; the disk rotates 80 rpm. After 2 hours the pin and disk are weighed. It is determined that adhesive wear has caused weight losses equivalent to wear volumes of 2.7 and 0.65 mm^3 for the copper and steel, respectively. Compute the wear coefficients.

SOLUTION

Known: A cylindrical pin has its end pressed against the flat surface of a rotating disk.

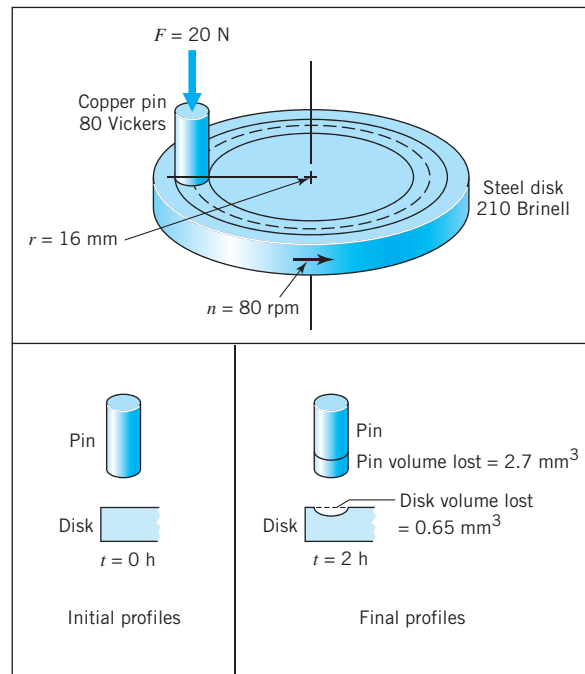**Find:** Determine the wear coefficients.

Schematic and Given Data:

FIGURE 9.13
Pin-on-disk wear testing apparatus for Sample Problem 9.2.

Assumption: Eq. 9.1a is valid.

Analysis:

1. Total rubbing distance in 2 hours,

$$S = 2\pi(16)\frac{\text{mm}}{\text{rev}} \times 80\frac{\text{rev}}{\text{min}} \times 60\frac{\text{min}}{\text{h}} \times 2\text{ h} = 9.65 \times 10^5 \text{ mm}$$

2. Hardness of pin, $H = 9.81(80) = 785$ MPa (copper)
    Hardness of disk, $H = 9.81(210) = 2060$ MPa (steel)

3. From Eq. 9.1a, the wear coefficient,

$$K = WH/FS,$$

$$= \frac{2.7(785)}{20(9.65 \times 10^5)} = 1.10 \times 10^{-4} \quad \text{(for copper)}$$

$$= \frac{0.65(2060)}{20(9.65 \times 10^5)} = 6.94 \times 10^{-5} \quad \text{(for steel)}$$

Comment: The wear volume for the pin is computed as $V_p = \pi d^2 \, \Delta_p/4$ where Δ_p is the linear pin wear and d is the pin diameter. If $d = 4$ mm, then since $V_p = 2.7$ mm^3, we have $\Delta_p = 0.21$ mm. The wear volume for the disk is approximately $V_d = \pi D d \, \Delta_d$ if the worn pin surface remains flat. Here Δ_d is the wear depth in the disk and D is the diameter of the wear track path. With $d = 4$ mm, $D = 32$ mm, and $V_d = 0.65$ mm^3, we have $\Delta_d = 0.0016$ mm. Note that the wear depth in the disk is less than 1/100 that of the linear pin wear.

Because of the need to model the effect of wear on surface geometry in machine and other components, the discretization pressure wear theory was proposed to predict changes in surface geometry and pressure distribution with time [16]. The theory is used for studying contact pressure and wear distribution for bodies in sliding contact and in designing component parts for improved wear resistance. Wear rates are determined in a software program that uses a time-based relationship that couples contact stress or pressure, sliding distances, and experimentally determined wear coefficients. The theory has been used in numerous areas including machine design and biomechanical engineering [17].

In implementing this theory for modeling wear in a machine, it is important that the wear coefficients for the materials involved be appropriate for the specific machine application. Generally, the specimens used to establish wear coefficients should have wear surface similarity with the actual wearing (worn) part. Furthermore, the number of passes for the wear tests to determine wear coefficients need to be related to the pass rate for the actual part [18], [19].

9.13 Curved-Surface Contact Stresses

The theoretical contact between curved surfaces is generally a point or a line (as a ball or cylinder and plane, a pair of mating gear teeth, etc.). When curved *elastic* bodies are pressed together, *finite* contact areas are developed because of deflections. These contact areas are so small, however, that corresponding compressive stresses tend to be extremely high. In the case of machine components like ball bearings, roller bearings, gears, and cam and followers, these *contact stresses* at any specific point on the surface are *cyclically applied* (as with each revolution of a bearing or gear), hence *fatigue failures* tend to be produced. These failures are caused by minute cracks that propagate to permit small bits of material to separate from the surface. This surface damage, sometimes referred to as "wear," is preferably called *surface fatigue*. These failures are discussed more fully in the following section. The present section lays a necessary foundation by considering in more detail the *stresses* caused by pressure plus possible sliding between curved elastic bodies.

Figure 9.14 illustrates the contact area and corresponding stress distribution between two spheres and two cylinders, loaded with force F. By equating the sum of the pressures over each contact area to the force F, we obtain an expression for the maximum contact pressure. The maximum contact pressure, p_0, exists on the
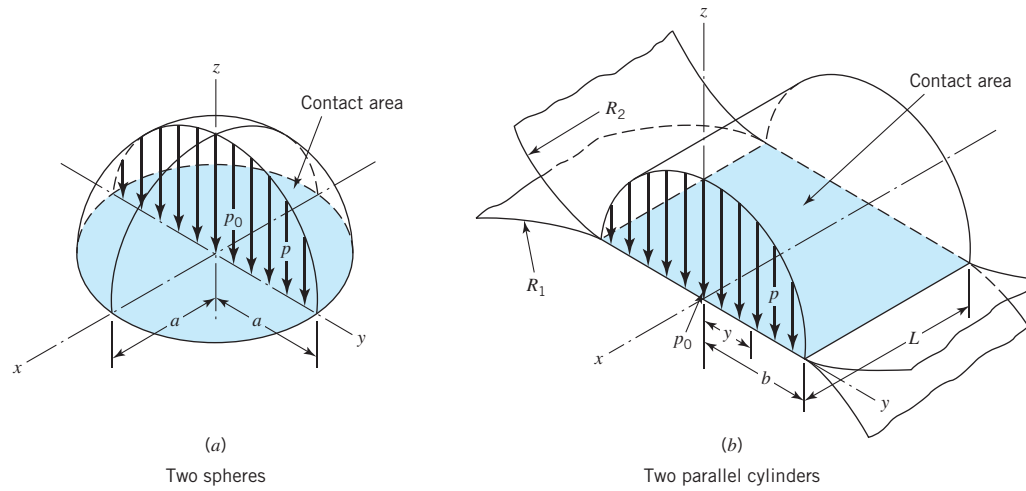
FIGURE 9.14
Contact pressure distribution.

load axis. The area of contact is defined by dimension a for the spheres and b and L for the cylinders. The equations for p_0, a, and b can be simplified by introducing the contact modulus, Δ, which is a function of Young's modulus (E) and Poisson's ratio (v) for the contacting bodies, 1 and 2.

$$\Delta = \frac{1 - v_1^2}{E_1} + \frac{1 - v_2^2}{E_2} \quad (9.2)$$

For two spheres,

$$p_0 = 0.578 \sqrt[3]{\frac{F(1/R_1 + 1/R_2)^2}{\Delta^2}} \quad (9.3)$$

$$a = 0.908 \sqrt[3]{\frac{F\Delta}{1/R_1 + 1/R_2}} \quad (9.4)$$

For a sphere and flat plate, R_2 is infinite; for a sphere and spherical socket, R_2 is negative.

For two parallel cylinders,

$$p_0 = 0.564 \sqrt{\frac{F(1/R_1 + 1/R_2)}{L\Delta}} \quad (9.5)$$

$$b = 1.13 \sqrt{\frac{F\Delta}{L(1/R_1 + 1/R_2)}} \quad (9.6)$$

For a cylinder and flat plate, R_2 is infinite; for a cylinder and cylindrical grove, R_2 is negative.

For other cases of two curved surfaces pressed together (as a wheel rolling on a crowned rail), see Refs. 6, 7, 11, and 12.

Contact pressure p_0 is, of course, also the value of the *surface compressive stress*, σ_z, at the load axis. The original analysis of elastic contact stresses was published in 1881 by Heinrich Hertz of Germany, at age 24. In his honor, the stresses at the mating surfaces of curved bodies in compression are called *Hertz contact stresses*.

The derivation for Eqs. 9.2 through 9.6 assumes that (1) the contact is frictionless; (2) the contacting bodies are elastic, isotropic, homogeneous, and smooth; and (3) the radii of curvature R_1 and R_2 are very large in comparison with the dimensions of the boundary of the surface of contact.

Figure 9.15 shows how the direct compressive stress σ_z diminishes below the surface. It also shows corresponding values of σ_x and σ_y. These compressive stresses result from Poisson's ratio—the material along the load axis that is compressed in the z direction tends to expand in the x and y directions. But the surrounding material does not want to move away to accommodate this expansion, hence the compressive stresses in the x and y directions. Because of symmetry of loading, it can be shown that the x, y, and z stresses plotted in Figure 9.15 are *principal* stresses. Figure 9.16 shows a Mohr circle plot for stresses on the load axis at depth b below the surface for two parallel cylinders. Note that the value of the maximum shear
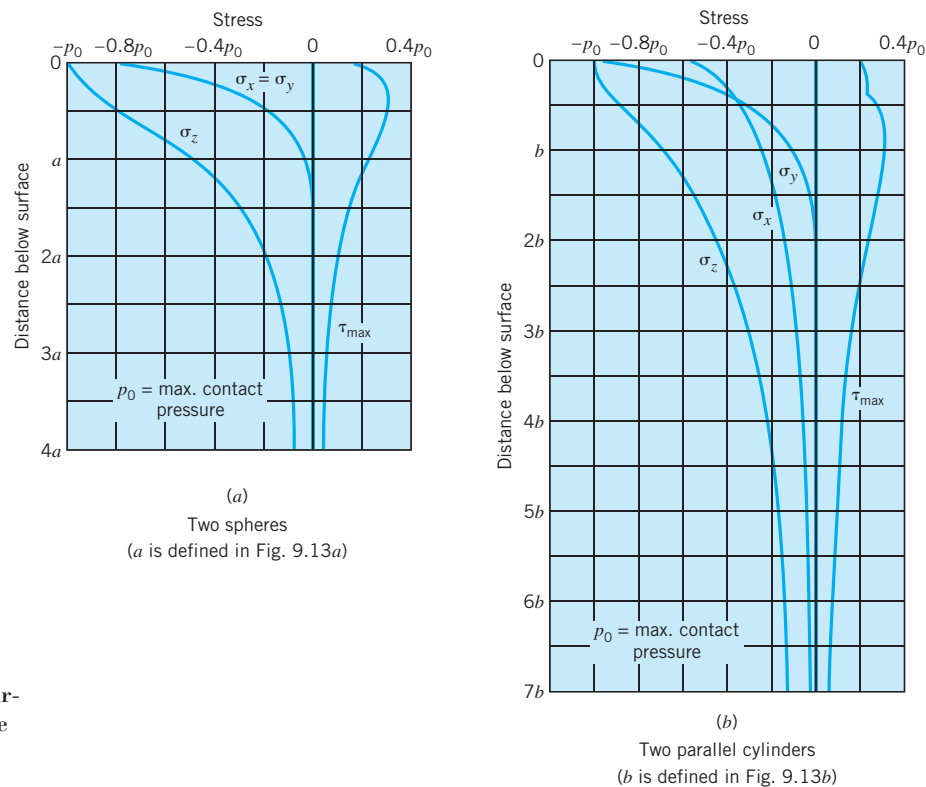

(*a*)

Two spheres
(*a* is defined in Fig. 9.13*a*)

(*b*)

Two parallel cylinders
(*b* is defined in Fig. 9.13*b*)

FIGURE 9.15

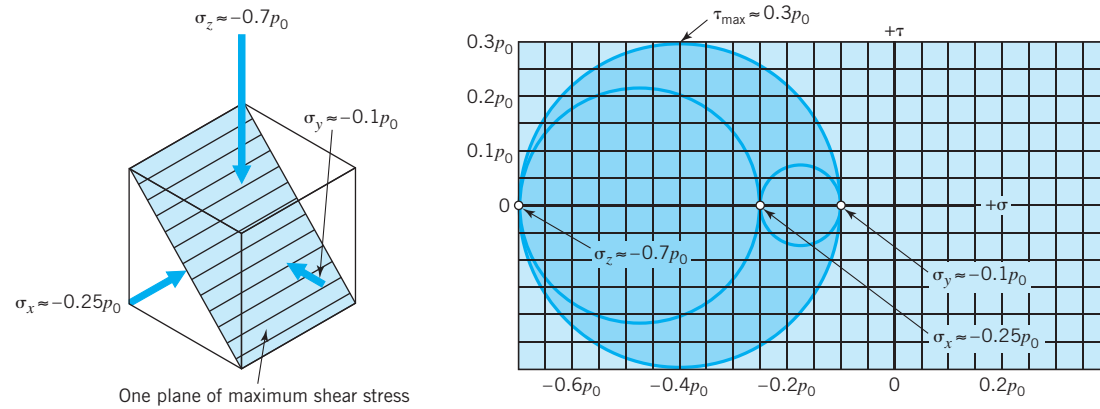**Elastic stresses below the surface, along the load axis (the z-axis; $x = 0$, $y = 0$; for $v = 0.3$).**

Principal element and Mohr circle representation, two cylinders on the load axis, distance b below the surface.

stress, τ_{max}, in Figure 9.16 agrees with the value plotted in Figure 9.15*b*. Other values of τ_{max} plotted in Figures 9.15*a* and *b* can be verified in the same manner.

All stresses previously considered in this section exist along the load axis. Figure 9.17 shows an important shear stress existing below the surface and *displaced* from the load axis. Note that if the cylinders are rotating together in the direction indicated, any point below the surface experiences stresses as shown first at *A* and then *B*. This is a *completely reversed* shear stress, believed to be very significant in connection with subsurface fatigue crack initiation. This stress is greatest at points below the surface a distance of about 0.5*b* (distance *b* is defined in Figure 9.14*b*). As a point at this depth rolls through the contact zone, the maximum values of this shear stress are reached at a distance of about *b* on either side of the load axis.

Most rolling members—mating gear teeth, a cam and follower, and to some extent the rolling members in ball and roller bearings—also tend to *slide*, even if only slightly. The resulting friction forces cause tangential normal and shear stresses that are superimposed on the stresses caused by the normal loading. These tangential stresses are illustrated in Figure 9.18. As any given point on the surface rolls through the contact zone, the tangential shear stresses vary from zero-to-maximum-to-zero, while the normal stresses vary from zero-to-tension-to-compression-to-zero. The presence of a surface tensile stress is undoubtedly important in the propagation of surface fatigue cracks.

Let us conclude this section by summarizing the more important aspects of stresses associated with contacting curved surfaces. First, the maximum contact pressures, and the "flattened" areas of contact, are given by the classical equations of Heinrich Hertz. Below the surface and on the load axis is an important shear stress associated with the "Poisson's ratio" expansion of the compressed material (τ_{max} in Figures 9.15 and 9.16). Below the surface, and to each side of the load axis, is shear stress τ_{xy} (Figure 9.17). This is particularly important in rolling members because it *reverses direction* as any given point below the surface rolls through the contact zone. Some sliding often accompanies rolling and causes both a tangential surface shear stress and a reversed surface tangential stress (Figure 9.18). Two other very important factors affecting stresses in the
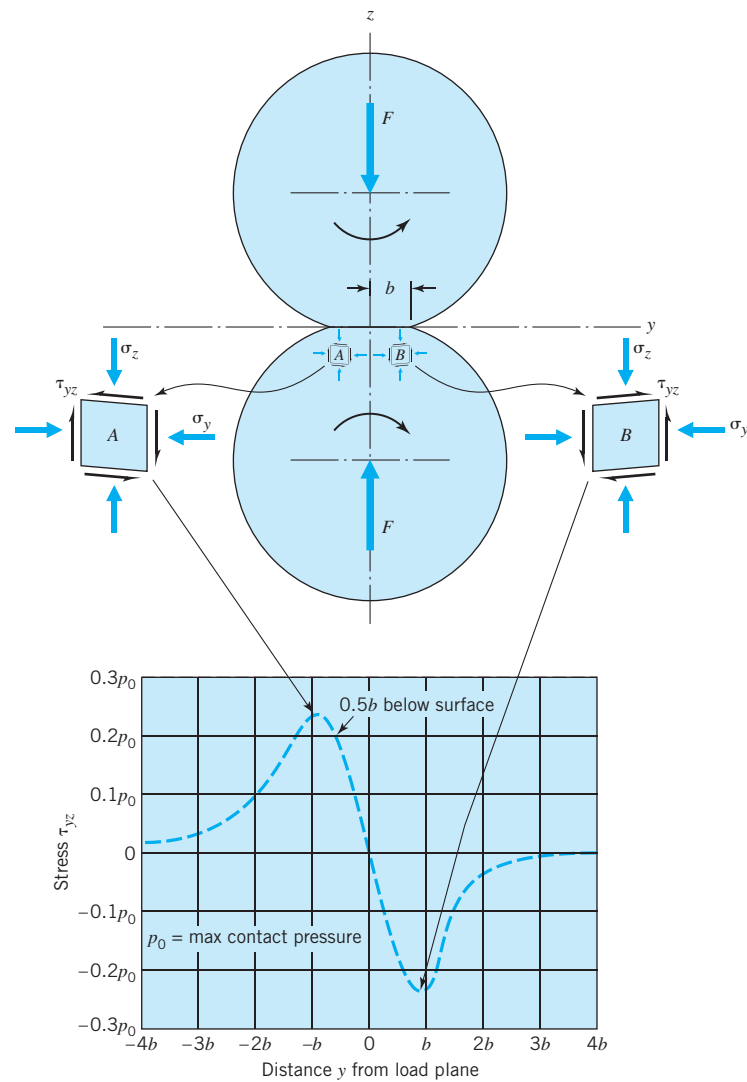
Subsurface shear stress that reverses when rolling through the contact zone. Values plotted are for a depth of $0.5b$ below the surface, and $v = 0.3$. The two parallel cylinders are normally loaded. (Note: τ_{yz} has its maximum value at a depth of $0.5b$ below the surface.) [From J. O. Smith and Chang Keng Liu, "Stresses Due to Tangential and Normal Loads on an Elastic Solid with Application to Some Contact Stress Problems," *J. Appl. Mech.* (March 1953).]

contact region are (1) highly localized heating and thermal expansion caused by sliding friction and (2) the hydrodynamic pressure distribution within the oil film that normally exists in the contact region. Because of these many factors, the maximum Hertz contact pressure (p_0 in Figure 9.14) is not *by itself* a very good index of contact loading severity.
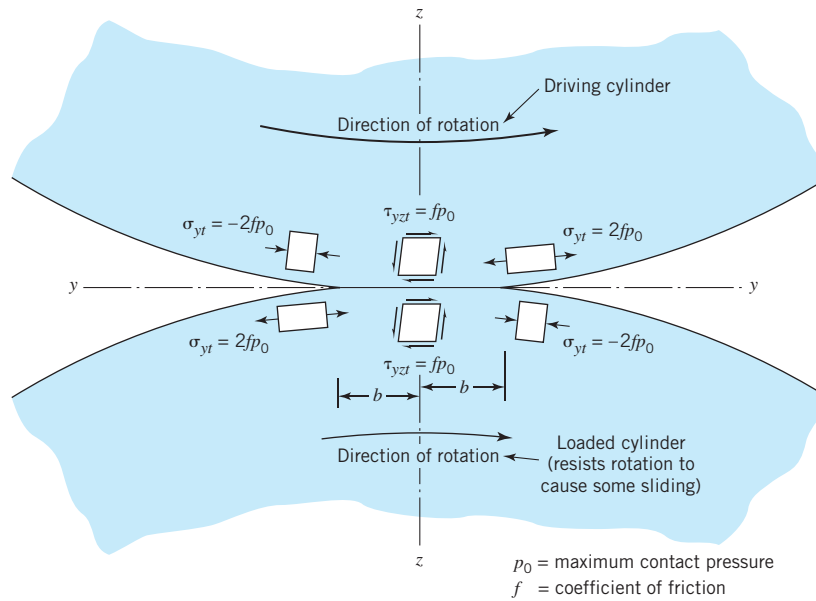
FIGURE 9.18
Tangential normal and shear stresses caused by sliding friction between two parallel cylinders. Maximum values are at the surface, in the locations shown. Note: The subscript t denotes that the stress is due to tangential (frictional) loading.

SAMPLE PROBLEM 9.3   Contact Stresses for Ball and Socket Joints

The ball and socket joint (Figure 9.19a) at the end of a rocker arm has a hardened-steel spherical surface 10 mm in diameter fitting in a hard-bronze bearing alloy spherical seat 10.1 mm in diameter. What maximum contact stress will result from a load of 2000 N?

SOLUTION

Known: A hardened-steel spherical ball of known diameter exerts a known load against a hard-bronze bearing alloy spherical seat of known diameter.

Find: Determine the maximum contact stress.
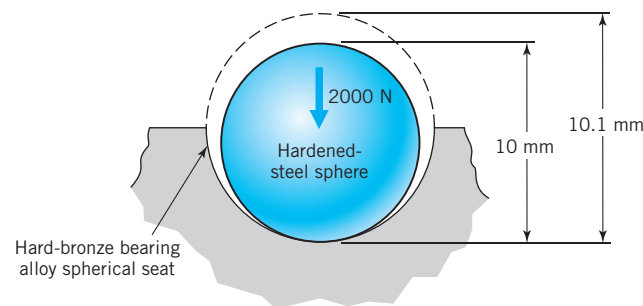
Schematic and Given Data:

FIGURE 9.19a
Ball and socket joint for sample Problem 9.3.

Assumptions:

1. The surfaces of the bodies are frictionless.
2. The bodies are isotropic and homogeneous.
3. The surfaces are smooth and continuous.
4. The radii of curvature R_1 and R_2 are large compared to the dimensions of the contact area.
5. The compressive yield strength of the weaker material is not exceeded.

Analysis:

1. Let body 1 be the steel ball:

$$R_1 = 5 \text{ mm}$$
$$E_1 = 207 \text{ GPa} \quad \text{(Appendix C-1)}$$
$$v_1 = 0.30 \quad \text{(Appendix C-1)}$$

2. Let body 2 be the bronze socket:

$$R_2 = -5.05 \text{ mm}$$
$$E_2 = 110 \text{ Gpa} \quad \text{(Appendix C-1)}$$
$$v_2 = 0.33 \quad \text{(Appendix C-1)}$$

3. From Eq. 9.2

$$\Delta = \frac{1 - v_1^2}{E_1} + \frac{1 - v_2^2}{E_2} = \frac{1 - (0.3)^2}{207 \times 10^9} + \frac{1 - (0.33)^2}{110 \times 10^9}$$
$$= 1.250 \times 10^{-11} \text{ m}^2/\text{N}$$

4. From Eq. 9.3 the maximum contact pressure is

$$p_0 = 0.578 \sqrt[3]{\frac{F(1/R_1 + 1/R_2)^2}{\Delta^2}}$$
$$= 0.578 \sqrt[3]{\frac{2000(1/0.005 + 1/-0.00505)^2}{(1.25 \times 10^{-11})^2}} = 213 \text{ MPa}$$

Comments:

1. For most hard-bronze alloys, 213 MPa would be below the yield strength.
2. For this problem, if $R_1 = R_2$, the contact would be highly conformal (not spot contact), and the Hertz theory is not applicable.
3. The effect of the sphere radius, R_1, and the sphere modulus of elasticity E_1, can be explored by computing and plotting the maximum contact stress for values of modulus of elasticity E_1 of copper, cast iron, and steel for $R_1 = 5.00$ to 5.04 mm. As expected for the steel sphere loaded against the hard-bronze bearing alloy spherical seat, the maximum contact pressure between the sphere and the socket is greatest for all values of R_1. Also, as the radius of the sphere R_1 increases, the contact pressure decreases.
4. The contact between the sphere and seat becomes conformal as the size of the sphere approaches the spherical seat size. When the maximum contacting angle
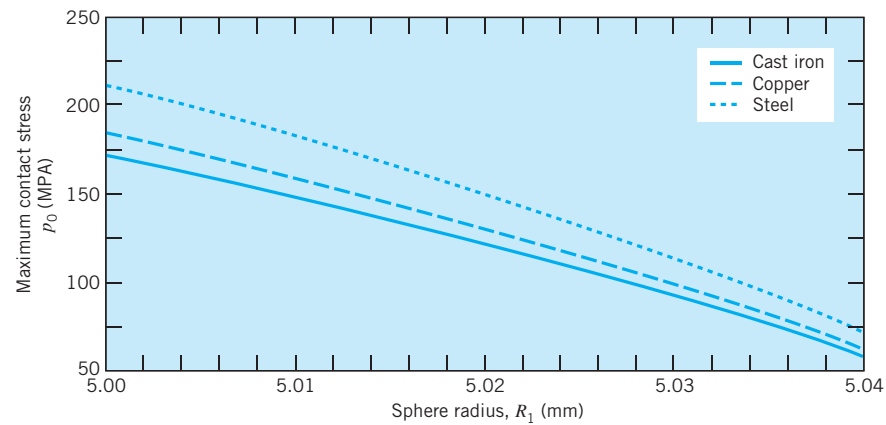
FIGURE 9.19*b*
Contact stress vs. sphere radius for three different sphere materials.

between the sphere and seat is greater than about 15 degrees, the use of Hertz contact analysis to solve the contact problem will yield a low value for the maximum contact pressure. A major assumption in developing the Hertz equations is that dimensions of the contact area are small as compared to the radii of curvature of the contacting surfaces.

5. For a steel ball contacting a bronze *ball* ($R_1 = 5$ mm, $R_2 = 5.05$ mm), $p_0 = 7315$ MPa. Evidently local yielding would take place at the point of contact on the bronze ball.
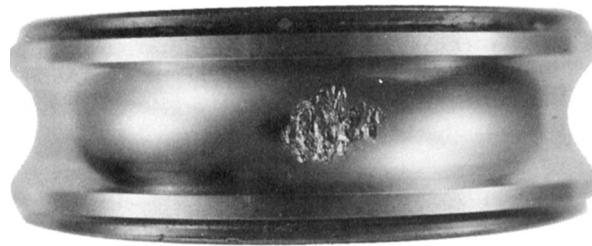
9.14 Surface Fatigue Failures

Surface fatigue failures result from the repeated application of loads that produce stresses in and under the contacting surfaces, as described in the previous section. Cracks initiated by these stresses propagate until small bits of surface material become separated, producing *pitting* or *spalling*. *Pitting* originates with surface cracks, and each pit has a relatively small surface area. *Spalling* originates with subsurface cracks, and the spalls are thin "flakes" of surface material. These types of failure occur commonly in gear teeth, ball and roller bearings, cams and followers, and metal wheels rolling on rails. Typical examples are illustrated in Figure 9.20.

Figure 9.21 shows typical *S–N* curves based on computed elastic Hertz stress (p_0 in Figure 9.14). Note that the degree of sliding generally increases from the parallel rollers (which do not transmit a torque) represented by the top line, to the spur gear teeth corresponding to the bottom line.

The tendency for surfaces to fail in fatigue can obviously be reduced by decreasing loads and decreasing sliding. Better lubrication helps in at least three ways: (1) less friction reduces the surface tangential shear stress and also the tensile stress shown in Figure 9.18; (2) less friction plus improved heat transfer reduce thermal
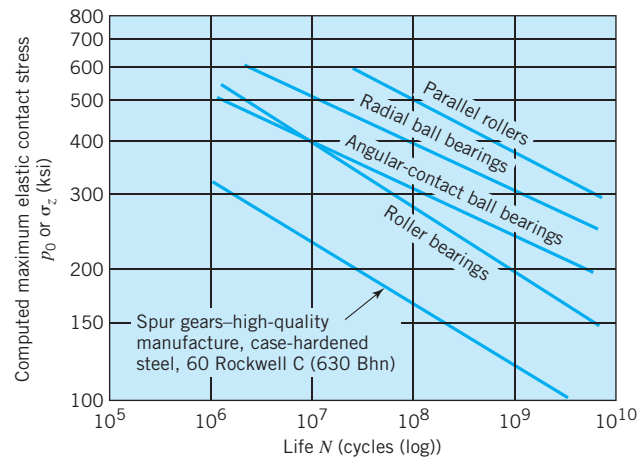
(*a*)
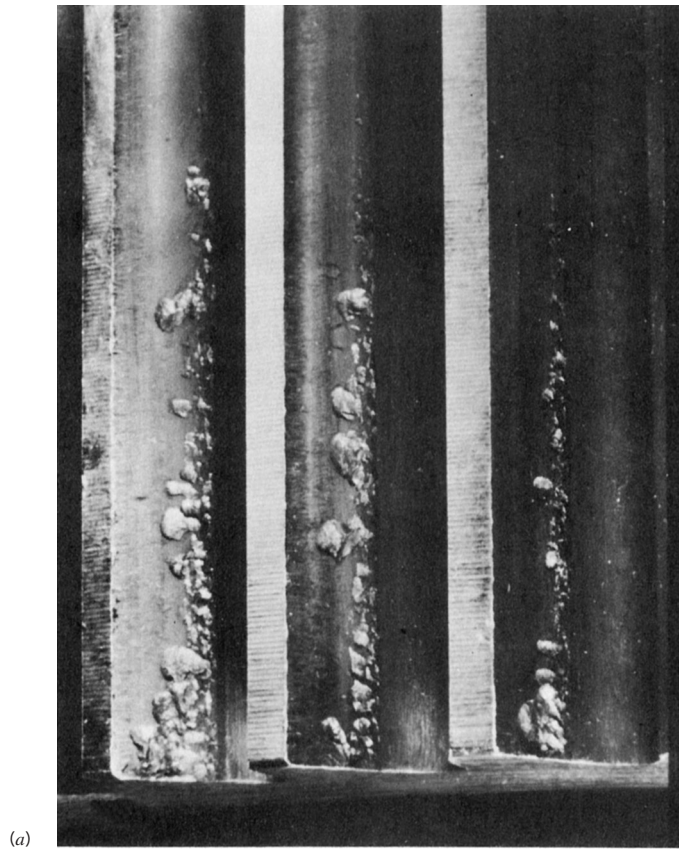
FIGURE 9.20
Surface fatigue failures.
(*a*, Courtesy American
Gear Manufacturers
Association. *b*, Courtesy
New Departure–Hyatt
Bearing Division, General
Motors Corporation.)

(*b*)

FIGURE 9.21
Average *S–N* curves for
contact stresses—rollers,
bearings, and spur gears,
10 percent failure proba-
bility [7].

Computed maximum elastic contact stress p_0 or σ_z (ksi)

Parallel rollers
Radial ball bearings
Angular-contact ball bearings
Roller bearings
Spur gears–high-quality
manufacture, case-hardened
steel, 60 Rockwell C (630 Bhn)

Life *N* (cycles (log))

stresses; and (3) the presence of a good lubricating film usually allows a more favorable distribution of pressure over the contact area.

In general, increased surface hardness increases resistance to surface fatigue. However, the associated increased strength reduces the ability of minute surface imperfections to adjust by wear or surface flow, and thereby reduce localized contact pressures. This is part of the rationale behind the common practice of making one of a pair of mating gears very hard, with the other somewhat softer to allow for "run-in" of the surfaces.

Precise accuracy of surface geometry and extreme surface smoothness are highly beneficial. Exceptions occur when significant sliding is present. Then, surface porosity, or a pattern of minute depressions on one of the mating surfaces, may help by providing tiny reservoirs for holding lubricant.

Compressive residual stresses in the contacting surfaces increase resistance to surface fatigue failure. This is to be expected and follows the general pattern of such stresses discouraging fatigue failure and surface damage.

9.15 Closure

As previously noted, corrosion and wear represent an estimated annual cost (1978) in the United States of some $90 billion. Furthermore, more machine parts *wear* out than break. The reduction of this enormous economic and ecologic burden presents one of the greatest challenges to modern engineering. The solution would seem to require (1) designing to reduce surface damage as much as feasible and (2) providing for the easy replacement of machine components that are most vulnerable to surface deterioration. Almost everyone is familiar with instances in which an entire machine (like a washing machine or refrigerator) was scrapped because it was too costly to replace one or two worn-out parts.

Let us review briefly three key aspects of machine component surfaces.

1. *Smoothness* is important to fatigue strength (recall surface factor C_S in Figure 8.13), to wear resistance, and, to some extent, to corrosion resistance.

2. *Hardness* acts to improve fatigue strength (as in steel, where S'_n in ksi $\approx 250 \times H_B$), to provide resistance to wear, and to prevent cavitation damage.

3. *Surface residual stress* is important, for compressive residual stresses increase fatigue strength, increase resistance to stress corrosion cracking, corrosion fatigue, and surface fatigue (from contact stresses), and decrease damage from fretting corrosion.

An important concept in the modern design of many machine components is that of *choosing different materials for the interior and for the surface*. If the material most suitable for the bulk of the part does not meet the surface requirements, a second material can often be applied to the surface. For example, steel parts can be coated (by electroplating, mechanical plating, hot dipping, cladding, flame spraying, etc.) with zinc, cadmium, chromium, nickel, or other metals to provide desired corrosion resistance. Soft metal parts, or even plastic parts, can be coated with hard, bright surface metal for abrasion resistance and appearance. For extreme hardness, carbides of tungsten and other metals can be commercially applied by flame spraying and other processes. For applications requiring low friction and wear, coatings incorporating fluoroplastics (as Teflon) are commonly applied. Other plastic coatings are used for applications requiring a *high* coefficient of friction (as for brakes, clutches, and

belts). Parts having surfaces subjected to extreme heat can be coated with special high-temperature alloys or ceramic materials. Sometimes the desired coating can be incorporated into a paint-type material, such as corrosion-resistant paints having a pigment of powdered zinc; or wear-resistant coatings consisting of tiny beads of alumina and ceramic in an epoxy resin can be used. Thus it is becoming increasingly feasible to avoid the serious compromises associated with making parts from a single material.

Ecological and health considerations must be taken into account when choosing a coating material and coating process. For example, cadmium in the human body can pose serious danger. Cadmium plating of steel parts has long been extensively used to provide corrosion resistance. (Over 1500 tons were used for this purpose in the United States in 1978, according to the U.S. Bureau of Mines.) Large quantities of spent fluids of high cadmium content are a by-product of cadmium electroplating. Disposal of this waste without polluting water or soil is a problem. The development of safe (and economical) processes for cadmium coating thus becomes an important scientific and engineering challenge.

References

1. Bennett, L. H. *Economics Effects of Metallic Corrosion in the U.S.*, a Report to Congress, National Bureau of Standards, March, 1978.

2. Cocks, F. H. (ed.), *Manual of Industrial Corrosion Standards and Control*, American Society for Testing and Materials, Philadelphia, 1973.

3. Colangelo, V. J., and F. A. Heiser, *Analysis of Metallurgical Failures*, 2nd ed., Wiley, New York, 1987.

4. Fontana, M. G., and N. D. Greene, *Corrosion Engineering*, 3rd ed., McGraw-Hill, New York, 1986.

5. Horger, O. J. (ed.), *ASME Handbook: Metals Engineering—Design*, 2nd ed., McGraw-Hill, New York, 1965. (a) Part 3, Sec. 1.1, "Mechanical Factors Influencing Corrosion," by H. R. Copson. (b) Part 3, Sec. 1.2, "Fretting Corrosion and Fatigue," by G. Sachs and O. J. Horger.

6. Juvinall, R. C., *Engineering Considerations of Stress, Strain, and Strength*, McGraw-Hill, New York, 1967.

7. Lipson, C., and R. C. Juvinall, *Handbook of Stress and Strength*, Macmillan, New York, 1963.

8. Lipson, C., *Wear Considerations in Design*, Prentice-Hall, Englewood Cliffs, N.J., 1967.

9. McAdam, D. J., Jr., "Corrosion Fatigue of Metals as Affected by Chemical Composition, Heat Treatment, and Cold Working," *Trans. ASTM*, **11** (1927).

10. Peterson, M. B., and W. O. Winer (ed.), *Wear Control Handbook*, The American Society of Mechanical Engineers, New York, 1980.

11. Roark, R. J., and W. C. Young, *Formulas for Stress and Strain*, 5th ed., McGraw-Hill, New York, 1975.

12. Timoshenko, S., and J. N. Goodier, *Theory of Elasticity*, 3rd ed., McGraw-Hill, New York, 1970.

13. Uhlig, H. H., and R. W. Revie, *Corrosion and Corrosion Control: An Introduction to Corrosion Science and Engineering,* 4th ed., Wiley, New Jersey, 2008.

14. Van Vlack, L. H., *Elements of Materials Science and Engineering*, 6th ed., Addison-Wesley, Reading, Mass., 1989.

15. Rabinowicz, E., *Friction and Wear of Materials*, 2nd ed., Wiley, New York, 1996.

16. Marshek, K. M. and H. H. Chen, "Discretization Pressure-Wear Theory for Bodies in Sliding Contact," *Journal of Tribology*, Vol. 111, pp. 95–100, 1989.

17. Maxian, T. A., T. D. Brown, D. R. Pedersen, and J. J. Callaghan, "A Sliding-Distance-Coupled Finite Element Formulation for Polyethylene Wear in Total Hip Arthroplasty," *Journal of Biomechanics*, Vol. 29, pp. 687–692, May 1996.

18. Burr, B. H., and K. M. Marshek, "O-Ring Wear Test Machine," *Wear*, Vol. 68, pp. 21–32, April 1981.

19. Burr, B. H., and K. M. Marshek, "An Equation for the Abrasive Wear of Elastomeric O-Ring Materials," *Wear*, Vol. 81, pp. 347–356, October 1982.

Problems ···

Sections 9.2–9.4

9.1   In 1824, Sir Humphry Davy proposed protecting the copper sheathing on the ocean-going HMS Samarang using iron anodes. Explain why this would be effective.

9.2   Aluminum plates are fastened together with brass rivets. The aluminum plates have a total exposed area of 1.5 ft.^{2} and the rivets have a total exposed area of 2.5 in.^{2}. The environment involves moisture and some salt.
          (a)   Which metal will corrode?
          (b)   If twice as many rivets are used, what effect would this have on the total rate of corrosion?

9.3   Square metal plates having a total exposed area of 10.75 ft.^{2} are fastened together with rivets having a total exposed area of 15.5 in.^{2}. The environment involves moisture and some salt. Consider two cases: (1) iron plates with nickel–copper alloy rivets, and (2) nickel–copper alloy plates with iron rivets.
          (a)   For each case, which metal will corrode?
          (b)   How do the rates of corrosion compare for the two cases?
          (c)   If half as many rivets were used, what influence would this have on the total rate of corrosion?

9.4   Lead sheet is pop-riveted with special bronze fasteners. The total exposed area of the sheet is 100 times that of the fasteners. The environment for the assembly is seawater.
          (a)   Which metal will corrode?
          (b)   If half as many fasteners are used, what influence would this have on the total rate of corrosion?
          (c)   How could corrosion be reduced?

9.5   Galvanized steel sheet metal is fastened together with copper rivets. The galvanized steel sheet has an area of 1.2 ft^2 and the rivets have a total exposed area of 2 in.^{2}. The environment contains moisture and some salt.
          (a)   Which metal will corrode?
          (b)   If half as many rivets are used, what effect would this have on the total rate of corrosion?
          (c)   How could corrosion be reduced?

9.6D   Search www.corrosion-doctors.org, and under the "Information Modules" section select "Corrosion by Environments." Choose one of the listed topics and write a summary of the information covered. Include if costs are addressed, types of materials affected, what type of corrosion can be expected, and how to deter the effects of corrosion.

9.7D   Review the web site http://www.corrosionsource.com. (a) What types of corrosion phenomena can be identified by visual observation? (b) What methods of controlling corrosion are suggested?

9.8   An assembly comprised of circular AISI 301 stainless steel plates having a total exposed area of 1.5 m^2 are bolted together with chromium-plated steel cap screws having a total exposed area of 110 cm^2. The environment contains moisture, and possibly some salt (see Figure P9.8).
          (a)   Which metal will corrode?
          (b)   If half as many bolts are used, what influence would this have on the total rate of corrosion?
          (c)   How could corrosion be reduced?

Chromium-plated steel cap screws
Total exposed area = 110 cm^2

301 Stainless steel plates
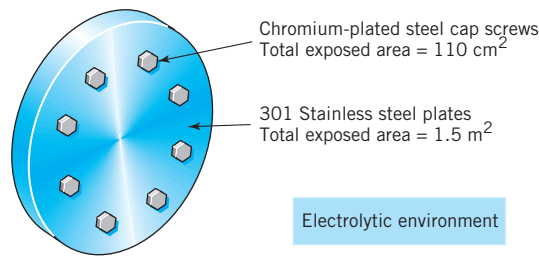Total exposed area = 1.5 m^2

Electrolytic environment

FIGURE P9.8

9.9   Repeat Problem 9.8, except use titanium cap screws.

9.10   Metal plates having a total exposed area of 1 m^2 are fastened together with rivets having a total exposed area of 100 cm^2. The environment contains moisture, and possibly some salt. Consider two cases: (1) steel plates with copper rivets, and (2) copper plates with steel rivets.

    (a)   For each case, which metal will corrode?

    (b)   How do the rates of corrosion compare for the two cases?

    (c)   If twice as many rivets are used, what influence would this have on the total rate of corrosion?

9.11D Some plumbing codes require that an electrical insulator be used when copper tubing is connected to steel pipe. With the aid of a simple sketch, explain the rationale behind this requirement.

9.12D A pickup truck tailgate cable having a breaking strength of 4000 lb is fabricated from 7 × 19 braided carbon steel wire. To prevent corrosion, the 5-mm-diameter cable is galvanized and covered with a weather resistant heat shrink tube made of cross-linked polyolefin. The ends of the tailgate cable are sealed with epoxy during manufacturing. Because of its geometry and specific end fixtures, the cable bends and twists when the pickup truck tailgate is raised and lowered. The twisting and bending opens and closes the seven cable wire bundles located within the polyolefin tube. List and then comment on the possible reasons why the galvanized cable might corrode and break within a few years of initial use and describe what could be done to improve the design (see Figure P9.12D).
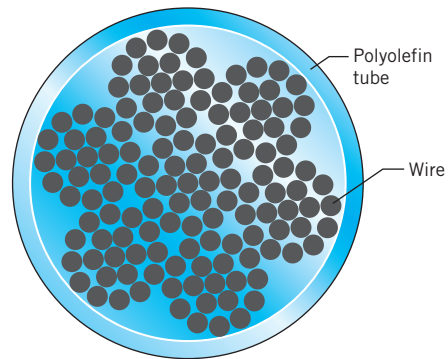

Polyolefin tube

Wire

FIGURE P9.12D
Cross section of tailgate cable—seven bundles of 19 wires.

9.13D Corrosion of the internal steel surfaces of the crankcase of a particular engine is a problem. Someone suggests replacing the steel oil drain plug with one made of magnesium. You recommend that the steel plug be retained, but that one end of a small magnesium rod be embedded in the inside surface of the plug (see Figure P9.13D). Explain, briefly.
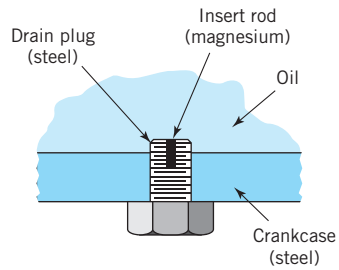
9.14D   Illustrate design details to reduce corrosion from:

(a)   atmospheric corrosion in structural members, corners, welded joints, storage tanks;

(b)   concentration cell corrosion in liquid containers, baffles, pipes, and connections liquid containers (e.g., water heater); and

(c)   galvanic corrosion in joints and connections (rivets, bolts, and nuts) of dissimilar materials.

9.15D   Write a report titled *Mechanism of Corrosion* addressing six basic causes of corrosion: (1) direct, (2) complex, (3) galvanic, (4) concentrated, (5) dezincification, and (6) fatigue and stress corrosion. Explain what can be done to overcome or minimize each.

Section 9.12

9.16   Figure P9.16 shows a small pin pressed against a rotating disc. Describe how the friction coefficient between the pin and the disc could be measured. Give one use for such an apparatus.
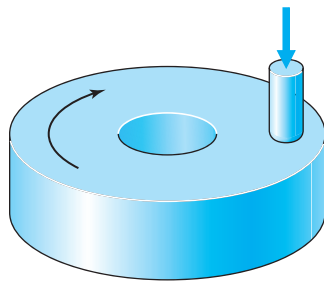

FIGURE P9.16

9.17   Figure P9.17 shows two thin-walled cylinders where the top, constrained cylinder is pressed in an axial direction against the bottom, rotating cylinder. Describe how the frictional torque and the specimen temperature could be measured. Give one use for such an apparatus.
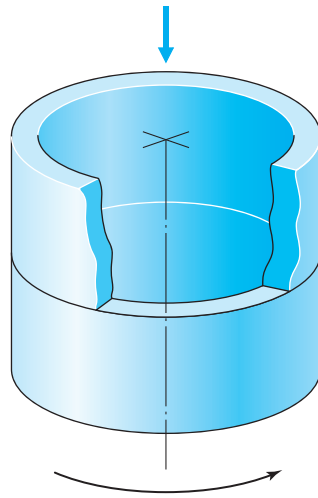
FIGURE P9.17

9.18   Figure P9.18 shows a rotating cylinder pressed against a second rotating cylinder. The cylinders rotate in opposite directions as shown. Describe how such an apparatus might be used.
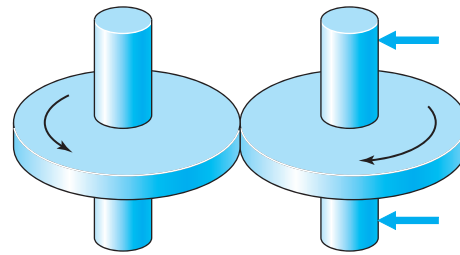

FIGURE P9.18

9.19   A latching mechanism has steel mating surfaces of 100 and 300 Bhn rubbing back and forth over a distance of 30 mm each time the latch is operated. Lubrication is questionable (the surfaces are supposed to get a drop of oil every few months). The latch is operated an average of 30 times per day, every day (see Figure P9.19). Estimate the volume of metal that will wear away from the softer steel member during one year of use if the compressive load between the surfaces is 100 N.
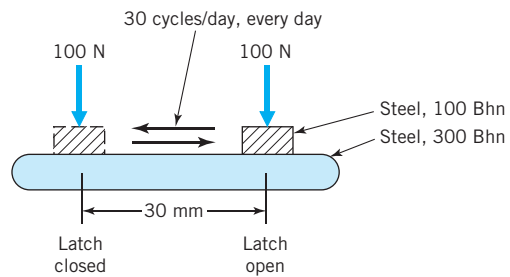

FIGURE P9.19

9.20   Reconsider Problem 9.19 but use a rubbing distance of 20 mm. Estimate the volume of metal that will wear away for each of the steel mating surfaces. All other conditions are the same as in Problem 9.19.

9.21   Reconsider Problem 9.19, but estimate the volume of metal that will wear away for each of the steel mating surfaces, both of 300 Bhn. All other conditions are the same as in Problem 9.19.

9.22   Repeat Sample Problem 9.2, except use a rotating disk made of wrought-aluminum alloy 2014-T6 having a 135 Brinell hardness.

9.23   Repeat Sample Problem 9.2, except use a pin made of wrought-aluminum alloy 2011-T3 having a 95 Brinell hardness.

9.24   A steel part of 550 Bhn rubs back and forth over a distance of 3 in. in the slot of a 150 Bhn steel link. The link and part are components in a scissor mechanism used to raise and lower an automobile window. The sliding surfaces are unlubricated. The window is to operate an average of 2000 times per year. Estimate the volume of metal that will wear away from the softer steel link during one year if the compressive load between the surfaces is 20 lb.

Sections 9.13 and 9.14

9.25   Figure P4.1 in Chapter 4 (*Problems*) shows a 0.5-in.-diameter ball loaded in compression by a 4000 lb force against the left end of a bar where the cross section is 1 in. $\times$ 1 in. The balls are hardened steel and the steel bar has a yield strength of 50 ksi. What maximum contact stress will result from the load of 4000 lb?

9.26   Figure P4.2 in Chapter 4 (*Problems*) shows a 0.25-in.-diameter ball loaded in compression by a 1000 lb force against the left end of a bar where the cross section is 1 in. $\times$ 1 in. The balls are hardened steel and the steel bar has a yield strength of 50 ksi. What maximum contact stress will result from the load of 1000 lb?

9.27   The ball and socket joint at the end of a rocker arm has a hardened-steel spherical surface of 10-mm diameter fitting in a hard-bronze bearing alloy spherical seat of 10.2-mm diameter. What maximum contact stress will result from a load of 2000 N?

9.28D   Reconsider Problem 9.27, but compute and plot the maximum contact stress for loads from 1800 N to 2000 N.

9.29   Figure P9.29 shows a Geneva indexing mechanism used, for example, on the indexing heads of machine tools. Each time the driving arm makes one revolution, the Geneva wheel (for the four-slot design illustrated) turns 90°. The arm supports a rolling cylindrical hardened-steel pin that fits into the Geneva wheel slots. The pin is to have the same length and diameter. The wheel is made of heat-treated alloy cast iron ($E = 140$ GPa, $v = 0.25$). For a design contact stress of 700 MPa, determine the smallest acceptable pin diameter if the design overload torque (normal torque times safety factor) applied to the arm is 60 N $\cdot$ m.
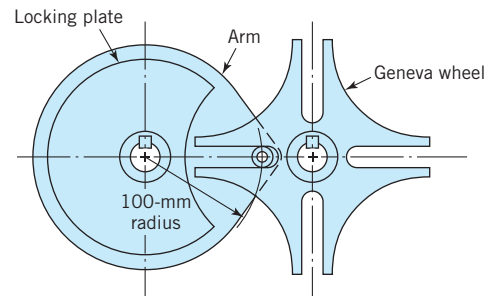
FIGURE P9.29

9.30　Two mating steel spur gears are 20 mm wide, and the tooth profiles have radii of curvature at the line of contact of 10 and 15 mm. A force of 250 N is transmitted between them.

(a)　Compute the maximum contact pressure and the width of contact.

(b)　How deep below the surface is the maximum shear stress, and what is its value?

[Ans.: (a) 275 MPa, 0.058 mm; (b) 0.023 mm, 83 MPa]

9.31　Repeat Problem 9.30 using a steel pinion and a cast-iron gear.

9.32　In a traction drive, a 1.0-in.-diameter cylindrical roller is preloaded against a 3.0-in.-diameter cylindrical roller. The steel rollers are 1.0 in. wide and the preload force is 50 lb. The axes of the cylinders are parallel. Calculate the maximum contact pressure and the width of contact. Also determine the maximum value of the subsurface shear stress.

9.33　Power is transmitted between two steel rollers pressed together, as in Figure 9.17. Loading is such that the maximum contact pressure is 2 GPa and the width of contact 1 mm. There is slight slippage, and the coefficient of friction is estimated to be 0.3.

(a)　What is the maximum completely reversed shear stress, τ_{yx}, and how far on either side of the load line does it occur?

(b)　What is the maximum value of reversed tensile stress developed at the surface?

(c)　What is the maximum value of shear stress developed at the surface?

(d)　Explain briefly the kinds of surface deterioration that might occur?

[Ans.: (a) 0.46 GPa, 0.45 mm; (b) 1.2 GPa; (c) 0.6 GPa]

9.34　A 15-mm-diameter, 20-mm-long steel roller is subjected to a load of 150 N per axial millimeter, as it runs on the inside of a steel ring of inside diameter 75 mm. Determine the value of the maximum contact pressure and the width of the contact zone.

9.35　A 25-mm-diameter cylindrical roller is preloaded against a 75-mm-diameter cylindrical roller in a traction drive. The steel rollers are 25 mm wide and the preload force is 200 N. The axes of the cylinders are parallel. Calculate the maximum contact pressure, the width, and the area of contact. Also determine the maximum value of the subsurface shear stress (see Figure P9.35).
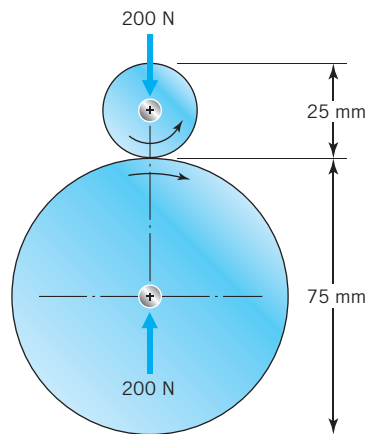

FIGURE P9.35