3.10 Tribology, Lubrication, and Bearing Design

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Introduction

Tribology, the science and technology of contacting surfaces involving friction, wear, and lubrication, is extremely important in nearly all mechanical components. A major focus of the field is on friction, its consequences, especially wear and its reduction through lubrication and material surface engineering. The improper solution of tribological problems is responsible for huge economic losses in our society, including shortened component lives, excessive equipment downtime, and large expenditures of energy. It is particularly important that engineers use appropriate means to reduce friction and wear in mechanical systems through the proper selection of bearings, lubricants, and materials for all contacting surfaces. The aim of this section is to assist in that endeavor.

Sliding Friction and its Consequences

Coefficient of Friction

If two stationary contacting bodies are held together by a normal force W and a tangential force is applied to one of them, the tangential force can be increased until it reaches a magnitude sufficient to initiate sliding. The ratio of the friction force at incipient sliding to the normal force is known as the static coefficient of friction, f_s. After sliding begins, the friction force always acts in the direction opposing motion and the ratio between that friction force and the applied normal force is the kinetic coefficient of friction, f_k.

Generally, f_k is slightly smaller than f_s and both coefficients are independent of the size or shape of the contacting surfaces. Both coefficients are very much dependent on the materials and cleanliness of the two contacting surfaces. For ordinary metallic surfaces, the friction coefficient is not very sensitive to surface roughness. For ultrasmooth or very rough surfaces, however, the friction coefficient can be larger. Typical friction coefficient values are given in Table 3.10.1. Generally, friction coefficients are greatest when the two surfaces are identical metals, slightly lower with dissimilar but mutually soluble metals, still lower for metal against nonmetal, and lowest for dissimilar nonmetals.

TABLE 3.10.1 Some Typical Friction Coefficients[a]

	Static Friction Coefficient f_s		Kinetic Friction Coefficient f_k	
Material Pair	**In Air**	**In Vacuo**	**In Air, Dry**	**Oiled**
Mild steel vs. mild steel	0.75	—	0.57	0.16
Mild steel vs. copper	0.53	0.5 (oxidized) 2.0 (clean)	0.36	0.18
Copper vs. copper	1.3	21.0	0.8	0.1
Tungsten carbide vs. copper	0.35	—	0.4	—
Tungsten carbide vs. tungsten carbide	0.2	0.4	0.15	—
Mild steel vs. polytetrafluoroethylene	0.04	—	0.05	0.04

[a] The friction coefficient values listed in this table were compiled from several of the references listed at the end of this section.

The kinetic coefficient of friction, f_k, for metallic or ceramic surfaces is relatively independent of sliding velocity at low and moderate velocities, although there is often a slight decrease in f_k at higher velocities. With polymers and soft metals there may be an increase in the friction coefficient with increasing velocity until a peak is reached, after which friction may decrease with further increases in velocity or temperature. The decrease in kinetic friction coefficient with increasing velocity, which may become especially pronounced at higher sliding velocities, can be responsible for friction-induced

vibrations (stick–slip oscillations) of the sliding systems. Such vibrations are an important design consideration for clutches and braking systems, and can also be important in the accurate control and positioning of robotic mechanisms and precision manufacturing systems.

Wear

Wear is the unwanted removal of material from solid surfaces by mechanical means; it is one of the leading reasons for the failure and replacement of manufactured products. It has been estimated that the costs of wear, which include repair and replacement, along with equipment downtime, constitute up to 6% of the U.S. gross national product (Rabinowicz, 1995). Wear can be classified into four primary types: sliding wear, abrasion, erosion, and corrosive wear. Owing to its importance, wear and its control have been the subject of several handbooks (Peterson and Winer, 1980; Blau, 1992), which the interested reader may consult for further information.

Types of Wear. Sliding wear occurs to some degree whenever solid surfaces are in sliding contact. There are two predominant sliding wear mechanisms, adhesion and surface fatigue. *Adhesive wear* is caused by strong adhesive forces between the two surfaces within the real area of contact. It results in the removal of small particles from at least one of the surfaces, usually the softer one. These particles can then transfer to the other surface or mix with other material from both surfaces before being expelled as loose wear debris. Adhesive wear can be particularly severe for surfaces which have a strong affinity for each other, such as those made from identical metals. *Surface fatigue wear* occurs when repeated sliding or rolling/sliding over a wear track results in the initiation of surface or subsurface cracks, and the propagation of those cracks produces wear particles in ductile materials by a process that has been called delamination. With brittle materials, sliding wear often occurs by a *surface fracture* process.

After an initial transition or "running-in" period, sliding wear tends to reach a steady state rate which is approximated by the following Archard (or Holm/Archard) wear equation:

$$V = K * W * s/H \tag{3.10.1}$$

where V = volume of worn material, K = dimensionless wear coefficient, s = sliding distance, W = normal load between the surfaces, and H = hardness of the softer of the two contacting surfaces.

The dimensionless wear coefficient gives an indication of the tendency of a given material combination to wear; relative wear coefficient values are given in Figure 3.10.1. In general, wear coefficients are highest for identical metals sliding without lubrication, and wear is decreased by adding a lubricant and by having material pairs which are dissimilar.

Abrasive wear occurs when a hard, rough surface slides against a softer surface (*two-body abrasion*) or when hard particles slide between softer surfaces (*three-body abrasion*). This process usually results in material removal by plowing or chip formation, especially when the abraded surface is metallic; surface fracture can occur during abrasion of brittle surfaces. In fact, abrasion mechanisms are similar to those of grinding and lapping, which could be considered as intentional abrasion. Consideration of the cutting and plowing processes shows that abrasive wear obeys the same equation (3.10.1) as sliding wear (Archard, 1980; Rabinowicz, 1995). Typical wear coefficients for abrasive wear are given in Figure 3.10.1. Since the relative size, hardness, and sharpness of the abrading particles, or surface asperities, also affect abrasive wear rates, the wear coefficients for abrasion must include recognition of those factors (Rabinowicz, 1995).

Erosion occurs when solid particles or liquid droplets impinge on a solid surface. When impingement is on a ductile metallic surface, the wear process is similar to that caused by abrasion, and is dominated by plastic deformation. Brittle surfaces, on the other hand, tend to erode by surface fracture mechanisms. The material removal rate is dependent on the angle of attack of the particles, with erosion reaching a peak at low angles (about 20°) for ductile surfaces and at high angles (90°) for brittle materials. In either case, the wear rate is proportional to the mass rate of flow of the particles and to their kinetic energy; it is inversely proportional to the hardness of the surface and the energy-absorbing potential (or toughness)

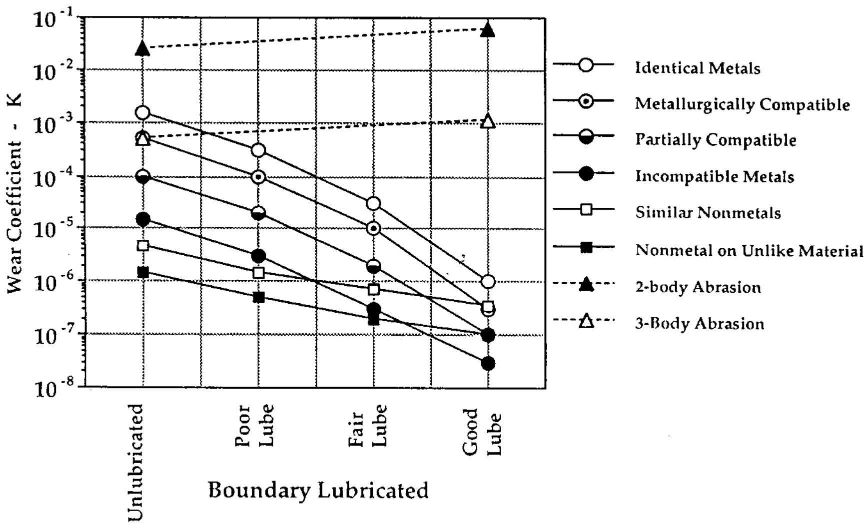

FIGURE 3.10.1 Typical values of wear coefficient for sliding and abrasive wear. (Modified from Rabinowicz, 1980, 1995.)

of the impinged surface (Schmitt, 1980). Although erosion is usually detrimental, it can be used beneficially in such material removal processes as sandblasting and abrasive water jet machining.

Corrosive wear results from a combination of chemical and mechanical action. It involves the synergistic effects of chemical attack (corrosion) of the surface, followed by removal of the corrosion products by a wear mechanism to expose the metallic surface, and then repetition of those processes. Since many corrosion products act to protect the surfaces from further attack, the removal of those films by wear acts to accelerate the rate of material removal. Corrosive wear can become particularly damaging when it acts in a low-amplitude oscillatory contact, which may be vibration induced, in which case it is called *fretting corrosion.*

Means for Wear Reduction.
The following actions can be taken to limit sliding wear:

- Insure that the sliding surfaces are well lubricated. This can best be accomplished by a liquid lubricant (see sub-section on effect of lubrication on friction and wear), but grease, or solid lubricants such as graphite or molybdenum disulfide, can sometimes be effective when liquid lubricants cannot be used.
- Choose dissimilar materials for sliding pairs.
- Use hardened surfaces.
- Add wear-resistant coatings to the contacting surfaces (see the following subsection).
- Reduce normal loads acting on the contact.
- Reduce surface temperatures. This is particularly important for polymer surfaces.

To reduce abrasive wear:

- Use hardened surfaces.
- Add a hard surface coating.
- Reduce the roughness of hard surfaces that are in contact with softer surfaces.
- Provide for the removal of abrasive particles from contacting surfaces. This can be done by flushing surfaces with liquid and/or filtering liquid coolants and lubricants.
- Reduce the size of abrasive particles.

To reduce erosion:

- Modify the angle of impingement of solid particles or liquid droplets.
- Provide for the removal of solid particles from the stream of fluid.
- Use hardened surfaces.
- Use tough materials for surfaces.
- Add protective coating to surfaces.