
CHAPTER 7

FRICTION, LUBRICATION, AND WEAR

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7.1 INTRODUCTION

Sliding friction is primarily a surface phenomenon. Consequently it depends very markedly on surface conditions, such as roughness, degree of work hardening, type of oxide film, and surface cleanliness.^{4,6,11} In general, in unlubricated sliding the roughness has only a secondary effect, but surface contamination can have a profound influence on friction (and wear), particularly with surfaces that are nominally clean. Because of this the account given here concentrates mainly on the mechanisms involved in friction.^{4,11,20a} In this way the reader may be better able to assess the main factors involved in any particular situation. Tables of friction values are given, but they must be used with caution. Very wide differences in friction may be obtained under apparently similar conditions, especially with unlubricated surfaces.

7.2 DEFINITIONS AND LAWS OF FRICTION

7.2.1 Definition

The friction between two bodies is generally defined as the force at their surface of contact which resists their sliding on one another. The friction force F is the force required to initiate or maintain motion. If W is the normal reaction of one body on the other, the coefficient of friction

$$\mu = F/W \quad (7.1)$$

7.2.2 Static and Kinetic Friction

If the force to initiate motion of one of the bodies is F_s and the force to maintain its motion at a given speed is F_k , there is a corresponding coefficient of static friction $\mu_s = F_s/W$ and a coefficient of kinetic friction $\mu_k = F_k/W$. In some cases, these coefficients are approximately equal; in most cases $\mu_s > \mu_k$.

7.2.3 Basic Laws of Friction

The two basic laws of friction, which are valid over a wide range of experimental conditions, state that:⁴

1. The frictional force F between solid bodies is proportional to the normal force between the surfaces, i.e., μ is independent of W .
2. The frictional force F is independent of the apparent area of contact.

These two laws of friction are reasonably well obeyed for sliding metals whether clean or lubricated. With polymeric solids (plastics) the laws are not so well obeyed: in particular, the coefficient of friction usually decreases with increasing load as a result of the detailed way in which polymers deform.

7.3 SURFACE TOPOGRAPHY AND AREA OF REAL CONTACT

7.3.1 Profilometry and Asperity Slopes

When metal surfaces are placed in contact they do not usually touch over the whole of their apparent area of contact.^{4,11} In general, they are supported by the surface irregularities which are present even on the most carefully prepared surfaces. Such roughnesses are usually characterized by means of a profilometer in which a fine stylus runs over the surface and moves up and down with the surface contour. The movement is measured electrically and may be recorded digitally for future detailed analysis by appropriate interfaced display units.²⁸ These units can provide information (see below) concerning the mean asperity heights, the distribution of peaks, valleys, slopes, asperity-tip curvatures, correlation lengths, and other features. Some commercial units display not only the essential parameters but also some which are redundant or even pointless. For visualization of the surface topography it is convenient to display the stylus movements on a chart. Since changes in height are generally very small compared with the horizontal

distance traveled by the stylus, it is usual to compress the horizontal movement on the chart by a factor of 100 or more. As a result the chart record appears to suggest that the surface is covered with sharp jagged peaks.³⁰ In fact, when allowance is made for the difference in vertical and horizontal scales, the average slopes are rarely more than a few degrees (see Fig. 7.1).³⁰

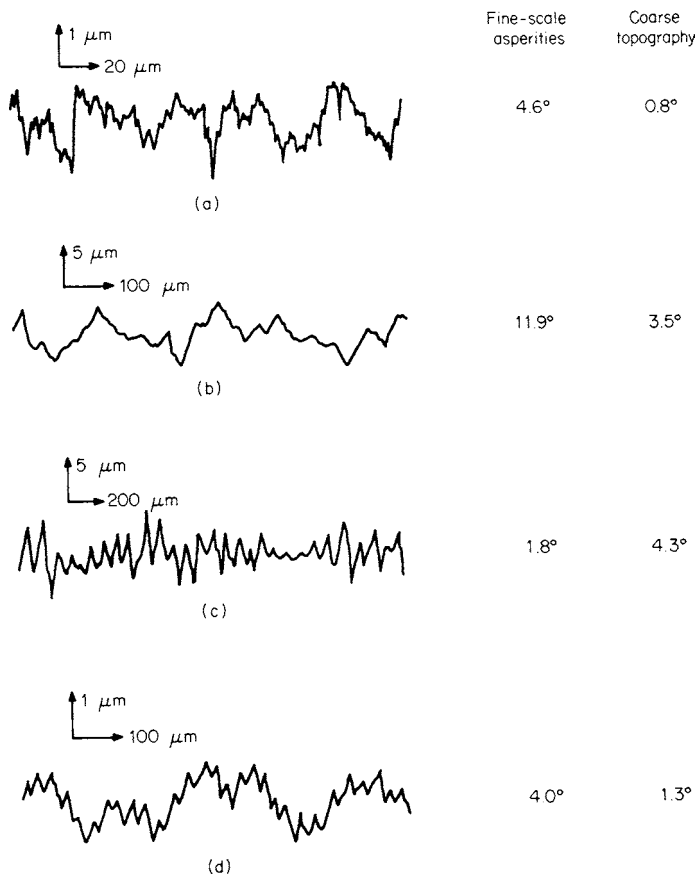


FIG. 7.1 Profilometry traces of surfaces¹⁶ showing the average surface slopes of the fine-scale asperities and of the coarser topography. Surface treatments are (a) ground; (b) shot peened; (c) turned; (d) diamond turned.

7.3.2 Elastic and Plastic Deformation of Conical Indenters

The characterization of surface topographies and the detailed way in which the asperities deform under contact have become the subject of a number of specialized studies of varying degrees of sophistication.^{28,30} We consider here the simplest case, in which the individual asperity is represented by a right circular cone of a slope θ (semiapical angle $90^\circ - \theta$). If the cone is pressed against a smooth, flat, nondeformable surface

and if it deforms elastically, the mean contact pressure p is independent of the load and is given by

$$p = (E \tan \theta)/2(1 - \nu^2) \tag{7.2}$$

where E is Young's modulus and ν is Poisson's ratio of the cone material.²⁹ Ignoring the problem of infinite stresses at the cone tip we may postulate that plastic deformation of the cone will occur when p equals the indentation hardness H of the cone,* that is, when

$$(E \tan \theta)/H = 2(1 - \nu^2) \approx 2 \tag{7.3}$$

Thus the factors favoring elastic deformation are (1) smooth surfaces, that is, low θ , and (2) high hardness compared with modulus, that is, a low value of E/H .* We may at once apply this to various materials to show the conditions of surface roughness under which the asperities will deform elastically (Table 7.1). The results show that with pure metals the surfaces must be extremely smooth if plastic deformation is to be avoided. By contrast, ceramics and polymers can tolerate far greater roughnesses and still remain in the elastic regime. From the point of view of low friction and wear, elastic deformation is generally desirable, particularly if interfacial adhesion is weak (see below). Further, on this model the contact pressure is constant, either $(E \tan \theta)/2(1 - \nu^2)$ for elastic deformation or H for plastic deformation. Thus the area of contact will be directly proportional to the applied load.

TABLE 7.1 Mean Asperity Slope for Conical Asperity Marking Transition from Elastic to Plastic Deformation

Material	Ratio E/H	Critical asperity slope for plastic deformation
Pure metals (Annealed)	200–400	$> \frac{1}{2}^\circ$
Pure metals (Work-hardened)	70–100	1°
Alloys in hardened state	30–50	2°
Ceramics	20–30	5°
Diamond	8–10	10°
Thermoplastics (Below T_g)	5	$> 20^\circ$
Cross-linked plastics	3–5	$> 20^\circ$

7.3.3 Elastic and Plastic Deformation of Real Surfaces

Real surfaces are conveniently described by two main classes of representation, each of which requires two parameters.

Random or Stochastic Process. Here the profile is treated as a two-dimensional random process and is described by the root-mean roughness (see below) and the distance

*The indentation hardness for a conical asperity depends on the cone angle, but for shallow asperities ($80^\circ < \theta < 90^\circ$) the variation in H is small compared with $E \tan \theta$ in Eq. (7.3).

over which the autocorrelation function decays to a certain fraction of its initial value. This is sometimes referred to as the “correlation distance,” though it is not quite the same thing. This representation is extremely powerful but not so convenient conceptually for the purposes of this section.

Statistical Height Description. Here the two most important parameters are:

1. The radius of curvature β of the tip of the asperities (sharp-pointed conical asperities are unrealistic). This quantity may be treated as approximately constant for a fixed surface or it may be given a distribution of values.
2. The center-line average R_a , or alternatively the root-mean-square σ of the asperity heights (see Fig. 7.2). If in any length L of the surface the distance of any point from the mean is y ,

$$R_a = \frac{1}{L} \int_0^L y \, dL \tag{7.4}$$

$$\text{and } \sigma = \left(\frac{1}{L} \int_0^L y^2 \, dL \right)^{1/2} \tag{7.5}$$

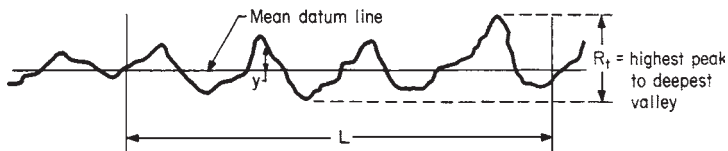


FIG. 7.2 Typical surface profile indicating the main parameters used to describe the heights of the surface roughnesses.²⁸

For roughnesses resembling sine functions $\sigma \approx 1.1R_a$ and for gaussian roughnesses $\sigma \approx 1.25R_a$. In engineering practice it is usual to use the center-line average R_a to specify surface roughness. However, in topographical theories it is more useful to use the rms value σ . (Note that in some conventions the symbol for the rms value is R_q .) However, it is clear that a measure of the mean surface height does not include such features as the spacing between significant peaks. This is particularly important for surfaces which have been milled or planed or turned, for here the topography is very different along or across the direction of machining. The random-process analyses specifically include a correlation distance between asperity peaks as well as a distribution of radii of curvature of the asperity tips. The sampling length is also of great importance.²⁸

If an individual asperity is pressed against a hard smooth surface under a load ω and if it deforms elastically, the area of contact is²⁹

$$A = \pi \{ \frac{3}{4} \omega \beta [(1 - \nu^2)/E] \}^{2/3} \tag{7.6}$$

Thus for each asperity A is proportional to $\omega^{2/3}$ and the contact pressure increases as $\omega^{1/3}$. The overall behavior of the real surface then depends on the way in which the asperities deform as the total load is increased. Clearly, existing asperity contacts will grow in size while new asperities will come into contact. Some of the initial asperities may reach a contact pressure exceeding the elastic limit and plastic flow will occur.

Greenwood and Williamson⁸ showed that, with surfaces for which the asperity heights followed an exponential distribution, the total area of contact, even if some asperities undergo elastic and others plastic deformation, will be directly proportional to the applied load.^{26,28} Physically this means that the distribution of asperity-contact areas remains almost constant so that increasing the load merely increases the number of contacts proportionately. However, real surfaces do not show an exponential distribution. The distribution is more nearly gaussian.* The detailed behavior now depends in the Greenwood-Williamson model on (1) the *surface topography* which can be described by the square root of α/β ; (2) the deformation properties of the material as represented by the ratio E'/H , where $E' = E/(1 - \nu^2)$ and H is the contact pressure at which plastic deformation occurs. For a spherical asperity, plastic deformation is initiated when the contact pressure is about $H_c/3$, where H_c is the Vickers indentation hardness, and gradually increases with further deformation.²³ Thus H is not a crisp constant. However, to a good approximation the situation is described analytically in terms of the plasticity index ψ where

$$\psi = \frac{E'H}{(\sigma/\beta)^{1/2}} \tag{7.7}$$

The analysis shows that if $\psi < 0.6$, the deformation will be elastic over an enormous load range. The mean asperity contact pressure increases somewhat as the load is increased, but the change is not large: it is of order $0.3E(\sigma/\beta)^{1/2}$ over a large load range, so that the area of contact is very nearly proportional to the load. For extremely smooth surfaces the true contact pressure turns out to be between 0.1 and $0.3H$.²⁵

For most engineering surfaces $\psi > 1$: the deformation is now plastic over an enormous range of loads and the true contact pressure is close to H . The area of contact is again proportional to the load.

The elastic and plastic regimes are shown in Fig. 7.3 for a gaussian distribution of roughnesses on a series of solids of different hardnesses. For a given surface finish the deformation is elastic if the nominal pressure is below each line. If it passes across the line, a fraction of the asperities will begin to deform plastically. This fraction will increase with increasing load until the major part of the contact becomes plastic. It will be noted that with aluminum ($H = 40 \text{ kg/mm}^2$), a nominal pressure of only 4 kg/mm^2 will give predominantly plastic deformation for even the smoothest surface. Only with ball-bearing steel ($H = 900 \text{ kg/mm}^2$) is the contact predominantly elastic even for relatively rough surfaces.²⁵ Similar results have been obtained with a stochastic treatment of surface asperities.

We conclude that for plastic deformation the true contact pressure will be equal to H . For elastic contact, over an extremely wide range it will lie between $0.1H$ and $0.3H$; indeed, it is difficult to envisage any type of asperity distribution involving elastic deformation for which contact pressure is less than about $0.1H$. This provides limiting values to the true area of contact A for the most diverse situations; for metals it will lie between W/H (plastic) and $10W/H$ (elastic), where W is the applied load.

Finally, we may note that $(\sigma/\beta)^{1/2}$ is a direct measure of the average slope of the asperity. In fact, for sine-wave asperities, it is roughly equal to θ . Thus the results obtained in the topographical model assuming spherical asperities [Eq. (7.7)] merge with the results deduced for conical asperities [Eq. (7.3)]. We may also note that if the surface roughness is characterized by a correlation length ℓ and rms asperity height σ (stochastic treatment), the average asperity slope is $2.3\sigma/\ell$.

*Note that the tail of a gaussian is approximately exponential, so that the highest asperities would first deform in the way described below.

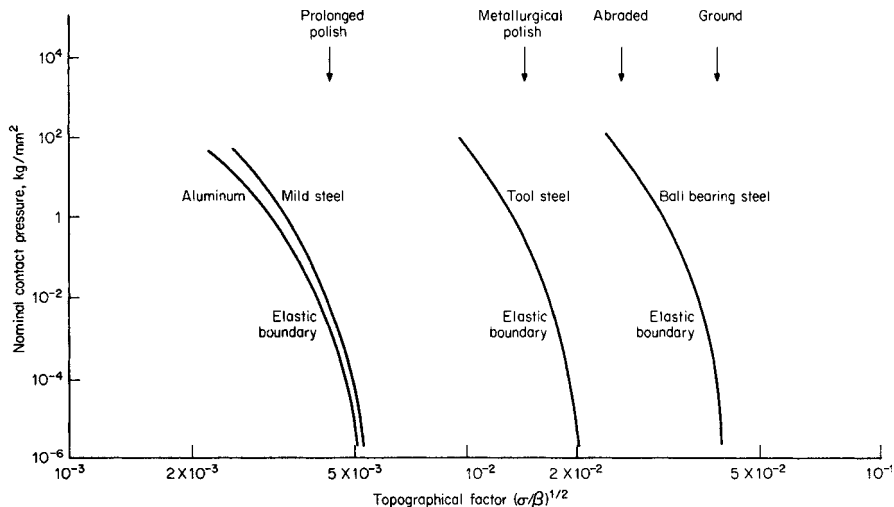


FIG. 7.3 Graph showing the nominal pressure at which the transition from elastic to the onset of plastic deformation occurs for a flat metal of specified roughness pressed on to a flat ideally smooth hard surface.¹² The materials are aluminium ($H = 40 \text{ kg}\cdot\text{mm}^{-2}$); mild steel ($H = 120 \text{ kg}\cdot\text{mm}^{-2}$); tool steel ($H = 400 \text{ kg}\cdot\text{mm}^{-2}$); ball-bearing steel ($H = 900 \text{ kg}\cdot\text{mm}^{-2}$).

7.4 FRICTION OF CLEAN METALS

7.4.1 Theory of Metallic Friction

Friction involves three major factors: (1) the area of true contact A between the surfaces, (2) the nature of the adhesion or bonding at the regions of real contact, and (3) the way in which the junctions so formed are sheared during sliding.

We have already seen that over a wide range of experimental conditions, A is proportional to the applied load and independent of the size of the bodies. For clean surfaces the adhesion that occurs at these regions is a process resembling the cold welding of metals. Consequently strong junctions are formed at the interface. Then if s is the specific shear strength of the interface, the force to produce sliding is

$$F = As + P$$

where P is a deformation or ploughing term which arises if a harder surface slides over a softer one. In general, for unlubricated surfaces, the adhesion term As is very much larger than the deformation term P , so that $F = As$. Thus the friction is proportional to the load and independent of the size of the bodies. This mechanism also explains the type of adhesive wear and surface damage which occurs between unlubricated surfaces. If the surfaces are contaminated, the adhesion is weaker and the amount of surface plucking and transfer—that is, the wear—is much less. The friction will also be smaller, but the two laws of friction still apply. However, the deformation term P may become more important relative to the adhesion term.

If metal surfaces are thoroughly cleaned in a vacuum, it is almost impossible to slide them over one another.^{4,6} An attempt to do so causes further deformation at the regions of contact. The surfaces, being clean, adhere strongly wherever they touch, so that marked junction growth occurs (see Sec. 7.4.2 on microdisplacements before sliding).

TABLE 7.2 Static Friction of Metals (Spectroscopically Pure) in Vacuum (Outgassed) and in Air (Unlubricated)

Conditions	Metals											
	Ag	Al	Co	Cr	Cu	Fe	In	Mg	Mo	Ni	Pb	Pt
μ , metal on itself in vacuo	S*	S	0.6	1.5	S	1.5	S	0.8	1.1	2.4	S	4
μ , metal on itself in air	1.4	1.3	0.3	0.4	1.3	1.0	2	0.5	1.9	1.7	1.5	1.3

*S signifies gross seizure ($\mu = 10$).

The resistance to motion increases the harder the surfaces are pulled, and complete seizure may readily occur (top row, Table 7.2). Hydrogen and nitrogen generally have little effect, but the smallest trace of oxygen or water vapor produces a profound reduction in friction by inhibiting the formation and growth of strong metallic junctions. With most metals in air the surface oxide film serves a similar role, and the friction μ is in the range 0.5 to 1.3 (second row, Table 7.2).

The results in Table 7.2 are for spectroscopically pure metals.⁴ The friction values depend crucially on the state of surface cleanliness. Thus, measurements carried out in even better vacuum will give higher values than those quoted in the table.⁶

Small amounts of impurities do not have a marked effect on the friction if (1) they do not produce a second phase, (2) they do not diffuse to the surface and dominate the

TABLE 7.3 Static Friction of Unlubricated Metals and Alloys Sliding on Steel in Air*

Metal or alloy	μ_s
Aluminum (pure)	0.6
Aluminum bronze	0.45
Brass (Cu 70%, Zn 30%)	0.5
Cast iron	0.4
Chromium (pure)	0.5
Constantan	0.4
Copper (pure)	0.8
Copper-lead (dendritic: Pb 20%)	0.2
Copper-lead (nondendritic: Pb 27%)	0.28
Indium (pure)	2
Lead (pure)	1.5
Molybdenum (pure)	0.5
Nickel (pure)	0.5
Phosphor-bronze	0.35
Silver	0.5
Steel (C 0.13%, Ni 3.42%)	0.8
Tin (pure)	0.9
White metal (tin-base): (Sb 6.4%, Cu 4.2%, Ni 0.1%, Sn 89.2%)	0.8
White metal (lead base): (Sb 15%, Cu 0.5%, Sn 6%, Pb 78.5%)	0.5
Wood's alloy	0.7

*The values are for sliders of pure metals and alloys sliding over 0.13 percent C, 3.42 percent Ni normalized steel. The results on mild steel are essentially the same.

surface properties, and (3) they do not appreciably modify the nature of the oxide film. The friction values obtained in air will depend on the extent to which the surface oxide is ruptured by the sliding process itself. Indeed, with metals in air, especially in the absence of lubricant films, the removal of the surface oxide either by an adhesion or ploughing (abrasion) mechanism—and its reformation—often play an important part in both the friction and wear mechanisms.

For softer metals, pickup occurs onto the harder surface and with repeated traversals of the same track, the sliding becomes characteristic of the softer metal sliding on itself.

The data of Tables 7.3–7.5 show that the friction does not vary monotonically with the hardness and is not greatly dependent on it. The reason is that with softer metals the area of contact A is large for a given load, but the interface is weak and therefore s is small. Conversely with hard metals A is small but s is large. Consequently the product $F = As$ is scarcely affected by the hardness. However, the friction of hard metals is, on the whole, somewhat less than that of softer metals. This is partly because of the reduced ductility of the metal junctions, which restricts junction growth, but mainly because the harder substrate provides greater support to the surface oxide film (see results for copper-beryllium alloy in Table 7.5). The friction also depends on the nature and strength of the oxide film itself. With ferrous alloys the homogeneity of the alloy is at least as important a factor, since heterogeneous materials will give weakened junctions.

TABLE 7.4 Static Friction of Unlubricated Ferrous Alloys Sliding on Themselves in Air*

Alloy	VPN kg/mm ²	μ_s
Pure iron	150	1–1.2
Normalized steel (C 0.13%, Ni 3.42%)	170	0.7–0.8
Austenitic steel (Cr 18%, Ni 8%)	200	1
Cast iron (pearlitic)	200	0.3–0.4
Ball race steel (Hoffman)	900	0.7–0.8
Tool steel (C 0.8%, containing carbides)	900	0.3–0.4
Chromium plate (hard bright)	1000	0.6

*The values indicate the effect of structure and the lack of correlation with hardness.⁴

TABLE 7.5 Static Friction of Hard Steel on Beryllium Alloy in Air*

Condition	Approximate VPN, kg/mm ²	μ_s
As quenched	120	1
Fully aged	410	0.4
Overaged	200	0.9–1

*The values are for a hard-steel slider (VPN 464 kg/mm²) on beryllium alloy (Be 2%, Co 0.25%). They show the effect of heat treatment.

7.4.2 Microdisplacements before Sliding^{4,11}

When surfaces are placed in contact under a normal load and a tangential force F is applied, the combined stresses produce further flow in the junctions long before gross sliding occurs. On a microscopic scale the surfaces sink together, increasing the area

of contact; at the same time a minute tangential displacement occurs. As the tangential force is increased this process continues until a stage is reached at which the applied shear stress is greater than the strength of the interface. Junction growth comes to an end and gross sliding takes place. The tangential force has its critical value F_s . The tangential displacements before sliding are always very small. The values given below correspond to the stage where F has reached 90 percent of the value necessary to produce gross sliding ($F = 0.9F_s$). The results are for a hemispherically tipped conical slider on a flat, finely abraded surface of the same metal. As a crude approximation these tangential displacements are proportional to the square root of the normal load (Table 7.6).

TABLE 7.6 Microdisplacements before Gross Sliding⁴

Surfaces	Vicker's hardness kg/mm ²	Tangential displacements at $F = 0.9F_s, 10^{-4}$ cm		
		1-g load	100-g load	10,000-g load
Indium	1	30	100	
Tin	7	1	20	200
Gold	19	0.5	5	
Platinum	117		1	60
Mild steel	280		1	8

7.4.3 Breakdown of Oxide Films

If the surface deformation produced during sliding is sufficiently small, the surface oxide may not be ruptured so that all the sliding may occur within the oxide film itself. The junctions formed in the oxide film are often weaker than purely metallic junctions, so that the friction may be appreciably less than when the oxide is ruptured. Since the shearing process occurs within the oxide film, the surface damage and wear are always considerably reduced. The criterion for "survival" of the oxide film is that it should be sufficiently soft or ductile compared with the substrate metal itself, so that it deforms with it and is not easily ruptured or fractured. Thus the oxide normally present on copper is not easily penetrated, whereas aluminum oxide, being a hard oxide on a soft substrate, is readily shattered during sliding, and even at the smallest loads there is some metallic interaction (Table 7.7). Thicker oxide films often provide more effective protection to the surfaces. Thus with anodically oxidized surfaces of aluminum or aluminum alloys,

TABLE 7.7 Breakdown of Oxide Films Produced during Sliding

Metal	Vickers hardness, kg/mm		Load, g, at which appreciable metallic contact occurs, g
	Metal	Oxide	
Gold	20		0
Silver	26		0.003
Tin	5	1650	0.02
Aluminum	15	1800	0.2
Zinc	35	200	0.5
Copper	40	130	1
Iron	120	150	10
Chromium plate	800	2000	> 1000

the sliding may be entirely restricted to the oxide layer. Similarly, with very hard metal substrates, such as chromium, the surface deformation may be so small that the oxide is never ruptured.⁴

In Table 7.7 the breakdown is detected by electrical conductance measurements. The results are for a spherical slider on a flat, electrolytically polished surface. The actual breakdown loads will depend on the geometry of the surfaces and on the thickness of the oxide film. The values given in this table provide a relative measure of the protective properties of the oxide film normally present on metals prepared by electrolytic polishing.

7.4.4 Friction of Metals after Repeated Sliding

Much of the earlier basic work on the friction of metals dealt with single traversals of one body over the other. This emphasized the initial deformation and shearing at the interface and tended to give prominence to plastic deformation even if the surfaces were covered with a thin protective film of oxide (see Sec. 7.4.3). In practical systems where repeated traversals take place, work hardening and gradual surface conformity may occur; the asperities may achieve a state of plastic-elastic shakedown and the deformation may be quasi-elastic. Such a condition can never be achieved with thoroughly clean surfaces but with engineering surfaces, in air, where oxide films form this may be the more common mode.

Friction is then primarily due to shearing of oxide layers which can reform if worn away. A small part of the friction may also arise from deformation losses. In the presence of effective lubrication the friction is due to the viscous shearing of the lubricant (see Sec. 7.5). In both cases the asperities are subjected to repeated loading-unloading cycles and, even in the state of plastic-elastic shakedown, they will gradually fail by fatigue. At this stage the surfaces are worn out (see Sec. 7.6).

7.4.5 Friction of Hard Solids

The friction of hard solids in air is generally small, partly because they lack ductility and partly because of the presence of surface films. Further, there is some evidence that with covalent solids the adhesion at the interface will generally be weaker than the cohesion within the solid itself. Higher frictions are observed if the surface films are removed and/or if the sliding occurs at elevated temperatures; with covalent solids, this will favor the formation of strong interfacial bonds (see Table 7.8).

7.4.6 Friction of Thin Metallic Films

If soft metal films of suitable thickness are plated onto a hard metal, the substrate supports the load, while sliding occurs within the soft film. This can give very low coefficients of friction which persist up to the melting point of the surface film. Copper-lead-bearing alloys function in this way. Note, however, that the shear properties of the metallic film may depend on the contact pressure.

Table 7.9 gives typical friction values for thin films of indium, lead, and copper (10^{-3} to 10^{-4} cm thick) deposited on various metal substrates. The other sliding member is a steel sphere 6 mm in diameter. In air, lead films have been found to show remarkable viability.

A very effective low-friction, low-wear combination for sliding electrical contacts consists of a thin flash of gold on plated rhodium.

TABLE 7.8 Friction of Very Hard Solids

Unbonded "hard metals"*			
Material	Coefficient of friction, μ_s		
	In air at 20°C	Outgassed and measured in vacuo	
		20–1000°	Comments
Boron carbide	0.2	0.9	Rises rapidly above 1800°C
Silicon carbide	0.2	0.6	
Silicon nitride	0.2		
Titanium carbide	0.15	1.0	Rises rapidly above 1200°C
Titanium monoxide	0.2	0.6	
Titanium sesquioxide	0.3		
Tungsten carbide	0.15	0.6	Rises rapidly above 1000°C
Diamond and sapphire†			
Surfaces and conditions			μ_s
Diamond on self:			
In air at 20°C, clean and lubricated			0.05–0.15
Outgassed at 1000°C and measured in vacuo at 20°C			0.5
Surface films worn away be repeated sliding in high vacuum ⁶			0.9
Diamond on steel:			
In air at 20°C, clean and lubricated			0.1–0.15
Sapphire on self:			
In air at 20°C, clean			0.2
Outgassed at 1000°C and measured in vacuo at 20°C			0.9
Sapphire on steel			
In air at 20°C, clean and lubricated			0.15–0.2

*Carbides, oxides, and nitrides sliding on themselves in air.

†Diamond shows marked frictional anisotropy. On the cube face {100}, $\mu_s = 0.05$ along the edge direction <100>. As with sapphire, lubrication has little effect in air.⁴

TABLE 7.9 Static Friction of Thin Metallic Films, Unlubricated Room Temperature, in Air, Spherical Steel Slider Diameter 6 mm⁴

Load, g	Coefficient of static friction, μ_s			
	Indium film on steel	Indium film on silver	Lead film on copper	Copper film on steel
4000	0.07	0.1	0.18	0.3
8000	0.04	0.07	0.12	0.2

7.4.7 Friction of Polymers

The friction of polymers is fairly adequately explained in terms of the adhesion theory of friction. There are, however, three main differences from the behavior of metals. First, Amontons' laws are not accurately obeyed; the coefficient of friction tends to decrease with increasing load; it also tends to decrease if the geometric contact area is decreased. Second, if the surfaces are left in contact under load, the area of true contact may increase with time because of creep and the starting friction may be correspondingly larger. Third, the friction may show changes with speed which reflect the viscoelastic properties of the polymer, but the most marked changes occur as a result of frictional heating.²⁷ Even at speeds of only a few meters per second, the friction of unlubricated polymers can, as a result of thermal softening, rise to very high values.

TABLE 7.10 Friction of Steel on Polymers, Room Temperature, Low Sliding Speeds*

Material	Condition	μ
Nylon	Dry	0.4
Nylon	Wet (water)	0.15
Perspex (Plexiglas)	Dry	0.5
PVC	Dry	0.5
Polystyrene	Dry	0.5
Low-density polythene (No plasticizer)	Dry or wet (water)	0.4
Low-density polythene (With plasticizer)	Dry or wet (water)	0.1
High-density polythene (No plasticizer)	Dry or wet (water)	0.15
Soft wood	Natural	0.25
Lignum vitae	Natural	0.1
PTFE† (low speeds)	Dry or wet (water)	0.06
PTFE (high speeds)	Dry or wet (water)	0.3
Filled PTFE (15% glass fiber)	Dry	0.12
Filled PTFE (15% graphite)	Dry	0.09
Filled PTFE (60% bronze)	Dry	0.09
Rubber (polyurethane)	Dry	1.6
Rubber (isoprene)	Dry	3–10
Rubber (isoprene)	Wet (water-alcohol solution)	2–4

*The slider is 0.13% carbon, 3.42 percent Ni normalized steel. Mild steels give essentially the same result.

†Polytetrafluoroethylene.

On the other hand, at extremely high speeds the friction may fall again because of the formation of a molten lubricating film (see Table 7.10). With very soft rubbers, sliding may occur by a type of ruck moving through the interface so that motion resembles the movement of a caterpillar.

7.4.8 Shear Properties of Thin Polymer Films

The shear strengths of thin films of polymer trapped between hard surfaces have been studied experimentally.⁵ (See Table 7.11.) It is found that s depends to some extent on speed and temperature, but most markedly on contact pressure p . To a first approximation

$$s = s_0 + \alpha p \tag{7.8}$$

where s_0 is the shear strength at negligibly small pressure and α is a coefficient which is approximately constant for a given material. This has an interesting relation to the friction coefficient of polymers sliding on themselves or on harder solids.¹

Under a load W , the true area of contact A is given by $A = W/p$, where p is the true contact pressure acting on the polymer. The frictional force, ignoring the deformation term, is $F = As = (W/p)s = (W/p)(s_0 + \alpha p)$. Consequently,

TABLE 7.11 Shear Properties of Solid Polymer Films at Room Temperature (Low Speeds)⁵

Polymer	$s_0, 10^7 \text{ N/m}_2$	α	μ_s^*
Polytetrafluoroethylene (PTFE)			0.1
High-density polyethylene (HDPE)			0.25
Low-density polyethylene (LDPE)			0.6
Polystyrene (PS)			1.4
Polyvinyl choride (PVC)			0.45
Polymethyl methacrylate			2.00
Plexiglas, Perspex			
Stearic acid			0.15
Calcium stearate			0.10

*See Table 7.9.

[†] s_0 is too large to be neglected in Eq. (7.9).

$$\mu_s = F/W = s_{0p} + \alpha \tag{7.9}$$

The first term is usually small compared with the second, so that

$$\mu_s \approx \alpha \tag{7.10}$$

7.4.9 Kinetic Friction

Kinetic friction is usually smaller than static. The behavior is complicated by frictional heating which may produce structural changes near the surface or influence oxide formation. At speeds of a few meters per second, these effects are not as marked as at very high speeds (compare Tables 7.12 and 7.13), but they may be significant. The results in Table 7.12 are for stationary sliders rubbing on a mild steel disk in air. The materials are grouped in descending order of friction.

At very high sliding speeds the friction generally falls off because of the formation of a very thin molten surface layer which acts as a lubricant film. Other factors may

TABLE 7.12 Kinetic Friction of Unlubricated Metals at Speeds of a Few Meters per Second

Slider	μ_k
Nickel, mild steel	0.55–0.65
Aluminum, brass (70:30), cadmium, magnesium	0.4–0.5
Chromium (hard plate), steel (hard)	0.4
Copper, copper-cadmium alloy	0.3–0.35
Bearing alloys:	
Tin-base	0.46
Lead-base	0.34
Phosphor-bronze	0.34
Copper-lead (Pb 20)	0.18
Nonmetals:	
Brake materials (resin-bonded asbestos)	0.4
Garnet	0.4
Carbon	0.2
Bakelite	0.13
Diamond	0.08

TABLE 7.13 Kinetic Friction of Unlubricated Metals at Very High Sliding Speeds

Surface	Duration of experiment, s	Coefficient of friction, μ_k			
		9 m/s	45 m/s	225 m/s	450 m/s
Bismuth	1–10	0.25	0.1	0.05	—
Lead	1–10	0.8	0.6	0.2	0.12
Cadmium	1–10	0.3	0.25	0.15	0.1
Copper	1–10	>1.5	1.5	0.7	0.25
Molybdenum	1–10	1	0.8	0.3	0.2
Tungsten	1–10	0.5	0.4	0.2	0.2
Diamond	1–10	0.06	0.05	0.1	~ 0.1
Bismuth	10^{-3}	0.25	0.1	0.05	0.3
Lead	10^{-3}	0.7	0.5	0.2	0.3
Copper	10^{-3}	—	0.25	0.15	0.1
Steel (mild)	10^{-3}	—	0.2	0.1	0.08
Nylon	10^{-3}	0.4	0.25	0.1	0.08

*Up to 600 m/s.

also be involved. For example, with steel sliding on diamond, the friction first diminishes and then increases, because at higher speeds steel is transferred to the diamond so that the sliding resembles that of steel on steel.^{4,6} In some cases the solids may fragment at these very high speeds, particularly if they are of limited ductility. Again, if appreciable melting occurs, the friction may increase at high speeds because of the viscous resistance of the liquid interface: this occurs with bismuth.

The results in Table 7.13 are for a rapidly rotating sphere of ball-bearing steel rubbing against another surface in a moderate vacuum.⁴ The friction is roughly independent of load over the load range examined (10 to 500 g). However, it may depend critically on the duration of sliding, since cumulative frictional heating may greatly change the sliding conditions. The duration in the upper part of the table is about 1 to 10 s; in the lower part where a special rebound technique was used⁵ the duration was about 10^{-3} s.

7.4.10 New Tribological Materials: Composites, Ceramics

Because most lubricating oils oxidize and form gums at temperatures above 250°C, considerable effort has been expended in developing high-temperature materials which are self-lubricating over a wide temperature range. One very promising approach is the formation of composite surfaces by plasma spraying, electrodeposition, or by “ion-plating.” It is now possible to deposit almost any required material onto any substrate and to achieve strong adhesion to the substrate. Ceramics are particularly effective as low-friction, low-wear surfaces for operation at elevated temperatures. They may be made less brittle and tougher by incorporating other constituents during deposition. In some cases the additives act as binders, as in cermets, or as solid lubricants or structural modifiers. Ceramics are often covalent solids. As a result, when ceramics slide on one another, the interfacial adhesion is weaker than the cohesion in the bulk, so that sliding should occur at the interface itself. If they are extremely brittle, interfacial sliding may be regarded as a Type II fracture. The friction will be small compared with metals. The wear will also be smaller unless shear produces interfacial fragmentation. In general some ductility is desirable. However, at very high temperatures interfacial covalent bonding may be activated, the solids may become more ductile, and the behavior will begin to resemble that of metals.²¹

7.5 LUBRICATION

7.5.1 Hydrodynamic or Fluid Lubrication

If a convergent wedge of fluid can be established between surfaces in relative motion it will, because of its viscosity Z , generate a hydrodynamic pressure in the fluid film.^{7,18} If there is no solid-solid contact, the whole of the resistance to motion is due to the viscous shear of the fluid. In journal bearings the bearing has a radius of curvature a little bigger than that of the journal (by about one part in 1000). The journal acquires a position which is slightly eccentric relative to the bearing so that lubricant is squeezed through the converging gap between the surfaces. Under properly designed conditions, the hydrodynamic pressure built up in the lubricant film is sufficient to support the normal load W . The friction is very low ($\mu_k \approx 0.001$) and there is, in principle, no wear of the solid surfaces.

Journal bearings operate under average pressures P of order 10^6 to 10^7 N/m² and speeds of revolution N of the order of 100 r/min. For a journal of radius R , diameter D , length L , radial clearance c , the torque G to overcome the viscous resistance of the lubricant in a full bearing may be calculated fairly reliably, simply by assuming that the journal and bearing run concentrically:

$$G = (4\pi^2 R^3 L / 60c) ZN \tag{7.11}$$

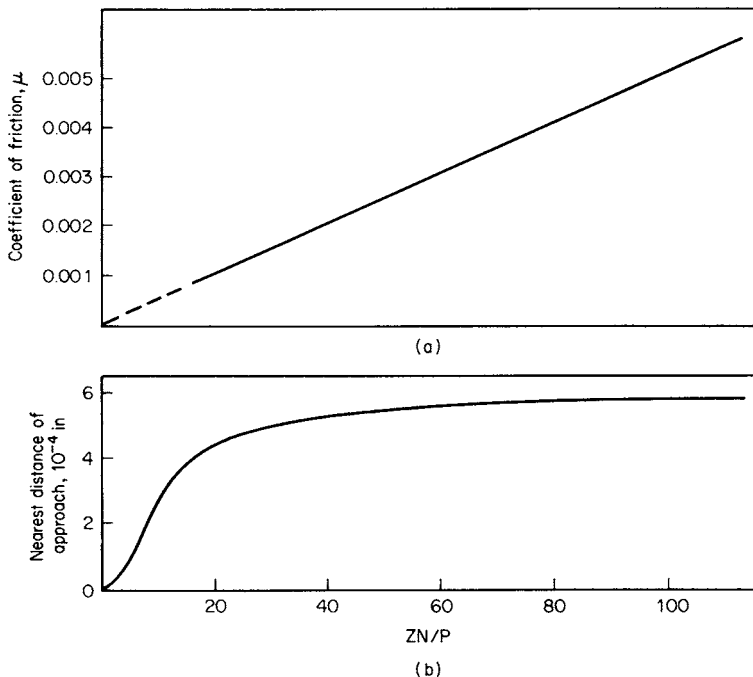


FIG. 7.4 Hydrodynamic lubrication between journal and bearing¹⁸: (a) friction and (b) distance of nearest approach. The dimensionless parameter ZN/P is in mixed units, with Z in centipoise, N in r/min, and P in lb/in².

Since the nominal pressure $P = W/2RL$, and the couple G may be written $G = \mu WR$, we obtain

$$\mu = (2\pi^2/60)(R/c)(ZN/P) \tag{7.12}$$

where N is in revolutions per minute and all the other parameters are in consistent units.

Results for a typical full oil bearing are shown in Fig. 7.4a for $R = 15$ mm and $R/c = 1000$. Evidently μ is very small and can be reduced by working at very low values of ZN/P . However, there is a limit to this. As ZN/P diminishes, the distance h_{\min} of nearest approach (Fig. 7.4b) diminishes in order to maintain adequate convergence of the lubricant film. The film may then become smaller than the surface roughness and penetration of the film may occur. In engineering practice in oil bearings, the average film thickness is of order 10^{-3} cm, and in air bearings perhaps 10 times smaller. Figure 7.5 shows the distance of nearest approach (h_{\min}) for a full bearing (of infinite length) and for a full bearing of length $L = 2R$. The quantities are dimensionless and may therefore be used for both oil and air bearings if self-consistent units are used. This implies that in English units, all lengths should be in inches, forces (and loads) in pound-force, viscosity in reyns, where $1 \text{ reyn} = 6.9 \times 10^6 \text{ cP}$. In SI units, all forces should be in newtons, viscosity in pascals per second, where $1 \text{ Pa/s} = 10^3 \text{ cP}$. In both systems N should be in revolutions per second. For further design charts, see Ref. 18.

In hydrodynamic lubrication (HL) it is essential to maintain an adequate value of h_{\min} relative to surface roughness. The most important properties of the oil are its viscosity,

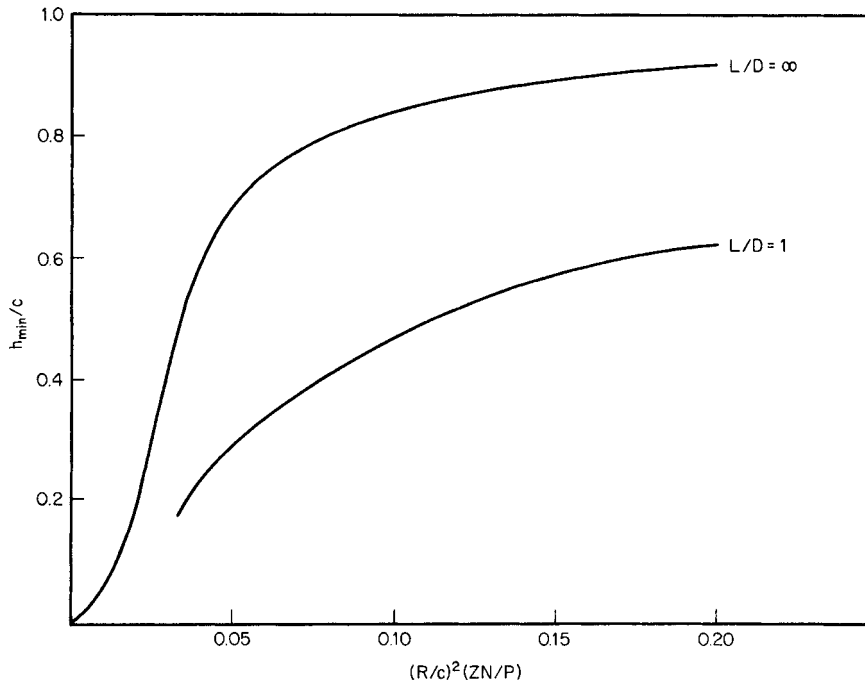


FIG. 7.5 Nondimensional graphs showing the distance of nearest approach (h_{\min}) for a full journal and bearing.

its viscosity temperature dependence, and its chemical stability, especially stability against oxidation.¹⁷

7.5.2 Elastohydrodynamic Lubrication

In normal hydrodynamic lubrication, the hydrodynamic pressures developed in the oil film are too small to produce appreciable elastic deformation of the bearing. However, if rubber bearings are used, appreciable elastic deformation may occur and there may be a significant change in the geometry of the convergent film.⁷ The hydrodynamic equations must then be combined with the equations for elastic deformation. If both surfaces are metallic and the contact pressures are high (as in rolling-element bearings or in the contact between gear teeth), there may again be sufficient elastic deformation to produce a significant change in the geometry of the contacting surfaces. A new feature is that with most lubricating oils the high pressures produce a prodigious increase in the viscosity of the oil. Thus at contact pressures of 30, 60, and 100 kg/mm² (such as may occur between gear teeth), the viscosity of a simple mineral oil is increased 200-, 400-, and 1000-fold, respectively. The harder the surfaces are pressed together, the harder it is to extrude the lubricant. As a result, effective lubrication may be achieved under conditions where it would normally be expected to break down. The film thickness in elastohydrodynamic lubrication (EHL) is of order 10^{-5} cm (0.1 μm), so that for safe operation, surface finish and alignment are of great importance. A full and detailed account of EHL is given in Chap. 15. It will be observed that the EHL film can show elastic, viscous, and viscoelastic properties. At sufficiently high contact pressures where the lubricant solidifies (that is, below its glass transition temperature), the oil behaves as a solid wax and its shear behavior is essentially that of a plastic solid.

7.5.3 Boundary Lubrication

Under severe conditions the EHL film may prove inadequate. Metallic contact and surface damage may occur, particularly if the oil-film thickness is too small relative to surface roughness. It is then found that the addition of a few percent of a fatty acid, alcohol, or ester may significantly improve the lubrication even if the thickness of the lubricant film is no larger than 100 \AA (10^{-2} μm) or so. This is the regime of boundary lubrication (BL).⁹ Radioactive tracer experiments show that while a good boundary lubricant may reduce the friction by a factor of about 20 (from $\mu \approx 1$ to $\mu \approx 0.05$), it may reduce the metallic transfer by a factor of 20,000 or more. Under these conditions the metallic junctions contribute very little to the frictional resistance. The friction is due almost entirely to the force required to shear the lubricant film itself. For this reason two good boundary lubricants may give indistinguishable coefficients of friction, but one may easily give 50 times as much metallic transfer (i.e., wear) as the other. Thus with good boundary lubricants the friction may be an inadequate indication of the effectiveness of the lubricant.⁴

In boundary lubrication the film behaves in a manner resembling EHL. There is, however, one marked difference. Because most boundary additives are adsorbed at the surface to form a condensed film or react with the surface to form a metallic soap, they are virtually solid; they do not depend on high contact pressures to achieve the load-bearing capacity of an EHL film. They are able to resist penetration by surface asperities (and here their protective properties may be enhanced by the high contact pressures), and thus they provide protection which cannot be achieved with ordinary EHL films. If, however, the temperature is raised, the boundary film may melt or it may dissolve in the superincumbent bulk fluid, and lubrication may then become far less effective (see Fig. 7.6).

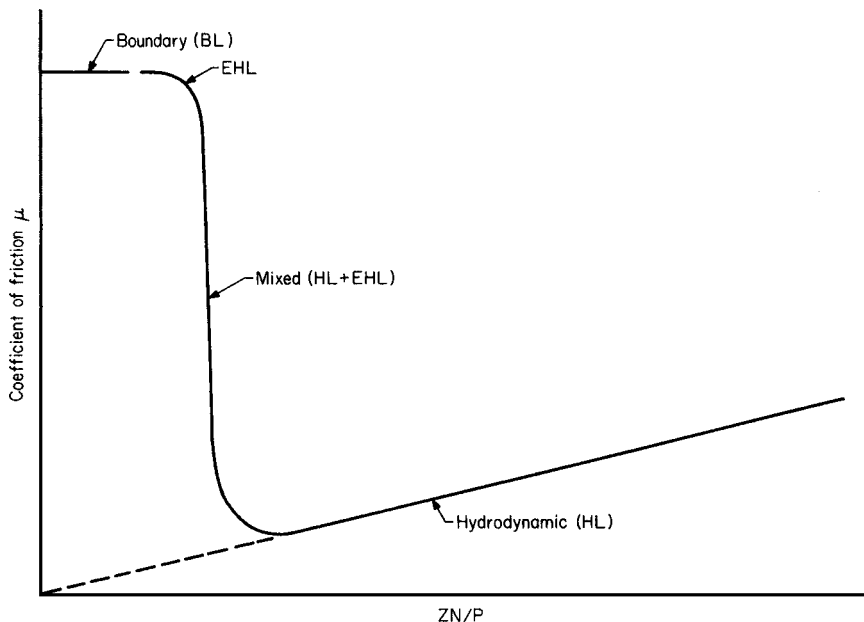


FIG. 7.6 Lubrication of a journal bearing showing the regimes of hydrodynamic (HL), elastohydrodynamic (EHL), and boundary lubrication (BL).

In the older literature the transition from HL to BL was referred to as the regime of “mixed” lubrication. We now recognize that HL gradually merges into EHL and that this then merges into BL. The coefficient of friction with good boundary lubricants ($\mu = 0.05$ to $\mu = 0.1$) is indeed similar to that observed in EHL.

In view of the nature of boundary films it is not surprising to find that their shear behavior resembles that of thin polymeric films.⁵ The shear strength s per unit area of film again depends to some extent on speed and temperature, but so long as it is solid it is affected most by the contact pressure p . We find

$$s = s_0 + \alpha p$$

where α for long-chain fatty acids or esters is of order 0.05 to 0.08 and s_0 is very small (see Tables 7.14 to 7.16).

Another approach is to form a protective film by chemical attack, a small quantity of a suitable reactive compound being added to the lubricating oil. The most common materials are additives containing sulfur or chlorine or both. Phosphates are also used. The additive must not be too reactive, otherwise excessive corrosion will occur; only when there is danger of incipient seizure should chemical reaction take place. The earlier work suggested that metal sulfides and chlorides were formed and the results in Table 7.17 are based on idealized laboratory experiments in which metal surfaces were exposed to H_2S or HCl vapor and the frictional properties of the surface examined. The results show that the films formed by H_2S give a higher friction than those formed by HCl . However, in the latter case the films decompose in the presence of water to liberate HCl , and for this reason chlorine additives are less commonly used than sulfur additives.

The detailed behavior of commercial additives depends not only on the reactivity of the metal and the chemical nature of the additive but also on the type of carrier

TABLE 7.14 Static Friction of Pure Metals Sliding on Themselves in Air and When Lubricated with 1 Percent Fatty Acid in Mineral Oil (Room Temperature)⁴

Metal	Coefficient of friction, μ_s	
	Unlubricated	Lubricated
Aluminum	1.3	0.3
Cadmium	0.5	0.05
Chromium	0.4	0.34
Copper	1.4	0.10
Iron	1.0	0.12
Magnesium	0.5	0.10
Nickel	0.7	0.3
Platinum	1.3	0.25
Silver	1.4	0.55

TABLE 7.15 Lubrication of Mild Steel Surfaces by Various Lubricants (Room Temperature)⁴

Lubricant	μ_s
None	0.6
Vegetable oils	0.08–0.10
Animal oils	0.09–0.10
Mineral oils:	
Light machine	0.16
Heavy motor	0.2
Paraffin	0.18
Extreme pressure	0.10
Oleic acid	0.08
Trichloroethylene	0.3
Ethyl alcohol	0.4
Benzene	0.5
Glycerine	0.2

TABLE 7.16 Friction of Metals Lubricated with Certain Protective Films⁴

Protective film	Coefficient of friction μ_s	Temperature up to which lubrication is effective
PTFE (Teflon)	0.05	320°C
Graphite	0.07–0.13	600°C
Molybdenum disulfide	0.07–0.1	800°C

TABLE 7.17 Effect of Sulfide and Chloride Films on Friction of Metals⁴

Metal	Coefficient of friction, μ_s				
	Clean	Sulfide films		Chloride films	
		Dry	Covered with lubricating oil	Dry	Covered with lubricating oil
Cadmium on cadmium	0.5	—	—	0.3	0.15
Copper on copper	1.4	0.3	0.2	0.3	0.25
Silver on silver	1.4	0.4	0.2	—	—
Steel on steel (0.13% C, 3.42% Ni)	0.8	0.2	0.05	0.15	0.05

fluid used (e.g., aromatic, naphthenic, paraffinic). Further, the chemical reactions which occur are far more complicated than originally supposed. With sulfurized additives, oxide formation appears to be at least as important as sulfide formation. With phosphates the surface reaction is still the subject of dispute.² The most widespread phosphate is zinc dialkyldithio phosphate (ZDP), and in most applications it provides a low coefficient of friction ($\mu < 0.1$) up to elevated temperatures.

7.6 WEAR

7.6.1 Laws of Wear

Although the laws of friction are fairly well substantiated, there are no satisfactory laws of wear. In general, it is safe to say that wear increases with time of running and that with hard surfaces the wear is less than with softer surfaces, but there are many exceptions, and the dependence of wear on load, nominal area of contact, speed, etc., is even less generally agreed upon. This is because there are many factors involved in wear and a slight change in conditions may completely alter the importance of individual factors or change their mode of interaction.^{26,31}

7.6.2 Mild and Severe Wear¹⁰

One of the most general characteristics of metallic wear, both for clean and for lubricated surfaces, is that below a certain load the wear is small (mild wear); above this load it rises catastrophically to values that may be 1000 or 10,000 times greater ("severe wear"). In severe wear, which occurs most readily with unlubricated surfaces, the wear is mainly due to adhesion and the shearing of the intermetallic junctions so formed.^{4,26} If the junctions are very strong, shearing takes place a short distance from the interface; lumps of metal are torn out of one or both of the surfaces and these later appear as wear fragments. This often occurs in the sliding of similar metals since the junctions at the interface are highly work-hardened. If the junctions are weaker than one surface but stronger than the other, fragments will be torn out of the softer metal and the wear will generally be lower. This often occurs in the sliding of dissimilar metals. In this regime of severe wear the wear of various metallic pairs may vary by a factor of say 100 to 1, although the friction may be substantially the same.

Mild wear occurs with metals in the presence of suitable oxide films.^{4,10} If the surface deformation is below a critical value, the oxide retains its integrity and the shearing occurs in the oxide film itself. The wear rate is very small and the oxide is able to reform. Mild wear also occurs with lubricated surfaces.

If wear is due to interfacial adhesion and the shearing of junctions, it may be shown on a simple model that wear is proportional to the load, is not greatly dependent on the nominal area, and is little affected by the sliding speed if frictional heating is not excessive.⁴ The wear volume Z per unit distance of sliding may be written as

$$Z = K(W/3p) \quad (7.14)$$

where Z is in cubic millimeters per millimeter (or cubic centimeters per meter), the load W is in kilogram-force, and p , the yield pressure or indentation hardness of the softer of the two bodies, is in kilograms per square millimeter. In the earlier work the quantity K was regarded as the fraction of friction junctions which produce a wear fragment. More recent work suggests that it may be more meaningful to regard it as a measure of the rate at which subsurface fatigue causes cracking and the release of a wear fragment, often in the form of a flake (delamination).²² Table 7.18 shows wear rates of different materials in combination.

There are some combinations of friction pairs in which the interfacial adhesion is weak and sliding appears to occur truly at the interface (e.g., polyethylene on steel). Minute wear rates may then be regarded as long-term fatigue of surface asperities. A similar situation appears to occur in the wear of lubricated metals.

TABLE 7.18 Wear Rates of Various Combinations of Materials

Surfaces	Hardness p , kg/mm ²	K (calculated)
Similar metals, 0.01 cm/s:		
Cadmium	20	10^{-2}
Zinc	38	10^{-1}
Silver	43	10^{-2}
Mild Steel	160	10^{-2}
Dissimilar metals, 0.01 cm/s:		
Cadmium on mild steel	—	10^{-4}
Copper on mild steel	—	10^{-3}
Platinum on mild steel	—	10^{-3}
Mild steel on copper	—	4×10^{-4}
Similar metals, 180 cm/s:		
Mild steel	190	7×10^{-3}
Hardened tool steel	850	10^{-4}
Sintered tungsten carbide	1300	10^{-6}
On hard tool steel, 180 cm/s:		
Brass 60 : 40	90	6×10^{-4}
Silver steel	320	6×10^{-5}
Beryllium copper	210	4×10^{-5}
Stellite 1	690	5×10^{-5}
Nonmetals on hard steel, 180 cm/s:		
PTFE (Teflon, Fluon)	5	2×10^{-6}
Perspex (Plexiglas)	20	7×10^{-6}
Bakelite (poor)	5	7×10^{-6}
Bakelite (good)	30	7×10^{-7}
Polythene	2	1×10^{-7}

7.6.3 Effect of Environment

The surrounding atmosphere can have a marked effect on friction, and in many cases air or oxygen or water vapor reduce the wear rate. However, this is not always the case. If, for example, the metal oxide is hard and the conditions favor abrasive wear, the continuous formation of oxidized wear fragments may lead to a large increase in wear rate. With ferrous materials in air, the atmospheric nitrogen may play an important part. Frictional heating and rapid cooling can produce martensite, but with low-carbon steels, surface hardening can still occur by reaction with nitrogen. When these hard surface films are formed the wear generally decreases.¹⁰

7.6.4 Effect of Speed

The main effect of speed arises from increased surface temperatures.⁴ Four of the most important consequences are:

1. High hot-spot temperatures increase reactivity of the surfaces and the wear fragments with the environment.
2. Rapid heating and cooling of asperity contacts can lead to metallurgical changes which can change the wear process.
3. High temperatures may greatly increase interdiffusion and alloy formation.
4. Surface melting may occur. In some cases, if melting is restricted to the outermost surface layers, the friction and wear may become very low.

7.6.5 Wear by Abrasives

Wear by hard abrasive particles is very common in running machinery. Measurements of the wear rate Z on abrasive papers show that the abrasion resistance $1/Z$ increases almost proportionally with the hardness of the metal.¹² This is shown in Fig. 7.7. The surfaces are grooved by the abrasive particles, but the wear is mainly in the form of fine shavings. It has been estimated that the amount of wear corresponds to about 10 percent of the volume of the material displaced in the grooves.³

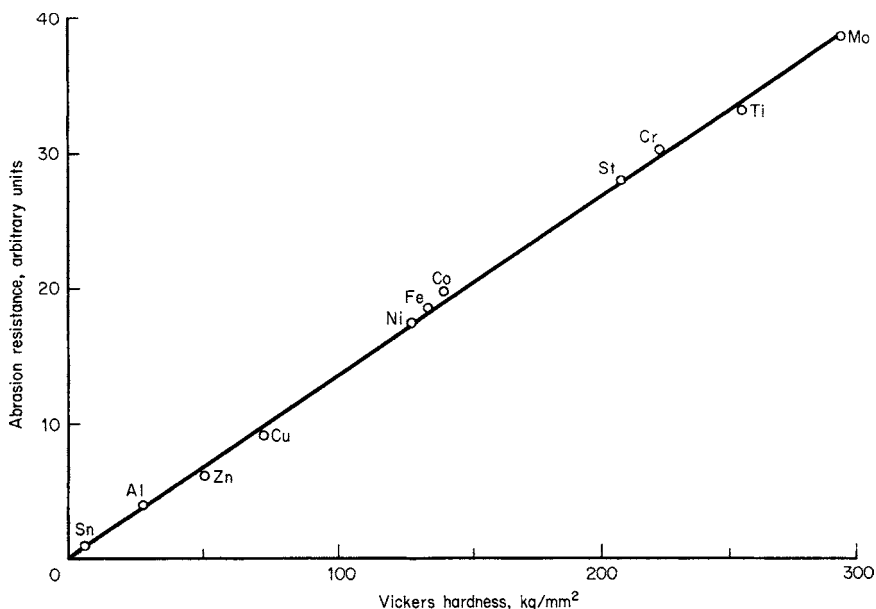


FIG. 7.7 Variation of abrasion resistance (reciprocal of wear rate) as a function of hardness for metals rubbed under standard conditions on dry abrasive paper. (The symbol St refers to 1.2 percent carbon steel.)

7.6.6 Wear Behavior of Specific Materials

There are many current publications, proceedings of conferences, etc., which deal with the wear of specific materials.^{13a,13b,21,26,27,31} In addition, there are individual papers which deal, for example, with the wear of aluminum, carbon brushes,¹⁴ bronze bearings,¹⁵ steel,²⁰ and polymers.¹³

7.6.7 Identification of Wear Mechanisms

The following are possible ways of identifying wear mechanisms in a particular piece of machinery:

1. Examination of the wear debris (collected, for example, from the lubricating oil): large lumps imply adhesive wear; fine particles, oxidative wear; chiplike particles, abrasive wear; flakelike particles, delamination wear.

2. Examination of the worn surfaces: heavy tearing implies adhesive wear; scratches imply abrasive wear; burnishing indicates nonadhesive wear.
3. Metallographic examination of the surface and subsurface structure. This may reveal the type of deformation produced by the sliding process, the generation of subsurface cracks, incipient delamination, etc.

REFERENCES

1. Amuzu, J. K. A., B. J. Briscoe, and M. M. Chaudhri: "Frictional Properties of Explosives," *J. Phys. D. Appl. Phys.*, vol. 9, pp. 133–143, 1976.
2. Barcroft, F. T., K. J. Bird, J. F. Hutton, and D. Parks: "The Mechanism of Action of Zinc Thiophosphates as Extreme Pressure Additives," *Wear*, vol. 77, pp. 355–382, 1982.
3. Battacharya, S.: "Wear and Friction of Aluminum and Magnesium Alloys and Brasses," "Wear of Materials," ASME, New York, p. 40, 1981.
4. Bowden, F. P., and D. Tabor: "Friction and Lubrication of Solids," Clarendon Press, Oxford, England, part 1, 1954; part 2, 1964.
5. Briscoe, B. J., and D. Tabor: "Shear Properties of Polymeric Films," *J. Adhesion*, vol. 9, pp. 145–155, 1978.
6. Buckley, D. H.: "Surface Effects in Adhesion, Friction, Wear and Lubrication," Elsevier Publishing Co., Amsterdam, The Netherlands, 1981.
7. Cameron, A. (ed.): "Principles of Lubrication," Longman, Inc., New York, 1966.
8. Greenwood, J. A., and J. B. P. Williamson: "The contact of nominally flat surfaces," *Proc. Roy. Soc. London*, vol. A295, pp. 300–319, 1966.
9. Hardy, Sir W. B.: "Collected Scientific Papers," Cambridge University Press, Cambridge, England, 1936.
10. Hirst, W.: "Basic Mechanisms of Wear," *Proc. Lubrication and Wear, Proc. Inst. Mech. Eng.*, vol. 182 (3A), pp. 281–292, 1968.
11. Kragelsky, I. V., M. N. Dobychin, and V. S. Komalov: "Friction and Wear-Calculation Methods" (in English), Pergamon Press, Oxford, England, 1982.
12. Kruschov, M. M.: "Principles of Abrasive Wear," *Wear*, vol. 28, pp. 69–88, 1974.
13. Lancaster, J. K.: "Friction and Wear," in "Polymer Science, a Materials Science Handbook," A. D. Jenkins ed., North Holland Publishing Co., Amsterdam, The Netherlands, pp. 960–1046, 1972.
- 13a. "Selecting Materials for Wear Resistance," Third International Conference on Wear of Materials, ASME, San Francisco, 1981.
- 13b. Ludema, K. C.: The Biennial Wear Conferences organized by ASME.
14. McNab, I. R., and J. L. Johnson: "Brush Wear," in "Wear Control Handbook," ASME, New York, p. 1053, 1980.
15. Murray, S. F., M. B., Peterson, and F. Kennedy: "Wear of Cast Bronze Bearings," INCRA Project 210, International Copper Research Association, New York, 1975.
16. Neale, M. J. (ed.): "Tribology Handbook," Butterworth & Company, London, 1973.
17. Norton, A. E.: "Lubrication," McGraw-Hill Book Company, Inc., New York, p. 24, 1942.
18. O'Connor, J. J., and J. Boyd: "Standard Handbook of Lubrication Engineering," McGraw-Hill Book Company, Inc., New York, 1978.
19. Rabinowicz, E.: "Friction and Wear of Materials," John Wiley & Sons, Inc., New York, 1965.
20. Salesky, W. J.: "Design of Medium Carbon Steels for Wear Applications," "Wear of Materials," ASME, New York, p. 298, 1981.
- 20a. Singer, I. L., and H. M. Pollock: "Fundamentals of Friction: Micoscopic and Microscopic Processes," Proceedings of a NATO Conference, 1991, Kluwer Academic Publishers, Dordrecht, The Netherlands, 1992.

21. Suh, N. P., and N. Saka (eds.): "International Conference on Fundamentals of Tribology," MIT Press, Cambridge, Mass., 1978.
22. Suh, N. P.: "The Delamination Theory of Wear," *Wear*, vol. 25, pp. 111–124, 1973.
23. Tabor, D.: "Hardness of Metals," Cambridge University Press, Cambridge, England, 1951.
24. Tabor, D.: "A Simplified Account of Surface Topography and the Contact between Solids," *Wear*, vol. 32, pp. 269–271, 1975.
25. Tabor, D.: "Interaction between Surfaces: Adhesion and Friction," chap. 10 in "Surface Physics of Materials," vol. II, J. M. Blakely (ed.), Academic Press, New York, 1975.
26. Tabor, D.: "Wear—A Critical Synoptic View," *J. Lub. Technol.*, vol. 99, pp. 387–395, 1977.
27. Tanaka, K., and Y. Uchiyama: "Friction and Surface Melting of Crystalline Polymers," in "Advances in Polymer Friction and Wear, Polymer Science and Technology," 5A and 5B, pp. 499–532, H. H. Lee (ed.), Plenum Press, Inc., New York, 1974.
28. Thomas, T. R. (ed.): "Rough Surfaces," Longman, Inc., New York, 1982.
29. Timoshenko, S., and J. N. Goodier: "Theory of Elasticity," McGraw-Hill Book Company, Inc., New York, 1951.
30. Whitehouse, D. J., and M. J. Phillips: "Discrete Properties of Random Surfaces," *Phil. Trans. Roy. Soc. (London)*, vol. 290, pp. 267–298, 1976.
31. Winer, W. O. (ed.): "Wear Control Handbook," ASME, New York, 1980.

