CHAPTER 20
LUBRICATION

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20.1 FUNCTIONS AND TYPES OF LUBRICANT

Whenever relative movement takes place between two surfaces in contact, there will be resistance to movement. This resistance is called the *frictional force,* or simply *friction.* Where this situation exists, it is often desirable to reduce, control, or modify the friction.

Broadly speaking, any process by which the friction in a moving contact is reduced may be described as *lubrication.* Traditionally this description has presented no problems. Friction reduction was obtained by introducing a solid or liquid material, called a *lubricant,* into the contact, so that the surfaces in relative motion were separated by a film of the lubricant. Lubricants consisted of a relatively few types of material, such as natural or mineral oils, graphite, molybdenum disulfide, and talc, and the relationship between lubricants and the process of lubrication was clear and unambiguous.

Recent technological developments have confused this previously clear picture. Friction reduction may now be provided by liquids, solids, or gases or by physical or chemical modification of the surfaces themselves. Alternatively, the sliding components may be manufactured from a material which is itself designed to reduce friction or within which a lubricant has been uniformly or nonuniformly dispersed. Such systems are sometimes described as "unlubricated," but this is clearly a matter of terminology. The system may be unconventionally lubricated, but it is certainly not unlubricated.

On the other hand, lubrication may be used to modify friction but not specifically to reduce it. Certain composite brake materials may incorporate graphite or molybdenum disulfide, whose presence is designed to ensure steady or consistent levels of friction. The additives are clearly lubricants, and it would be pedantic to assert that their use in brake materials is not lubrication.

This introduction is intended only to generate an open-minded approach to the processes of lubrication and to the selection of lubricants. In practice, the vast majority of systems are still lubricated by conventional oils or greases or by equally ancient but less conventional solid lubricants. It is when some aspect of the system makes the use of these simple lubricants difficult or unsatisfactory that the wider interpretation of lubrication may offer solutions. In addition to their primary function of reducing or controlling friction, lubricants are usually expected to reduce wear and perhaps also to reduce heat or corrosion.

In terms of volume, the most important types of lubricant are still the liquids (oils) and semiliquids (greases). Solid lubricants have been rapidly increasing in importance since about 1950, especially for environmental conditions which are too severe for oils and greases. Gases can be used as lubricants in much the same way as liquids, but as is explained later, the low viscosities of gases increase the difficulties of bearing design and construction.

20.2 SELECTION OF LUBRICANT TYPE

A useful first principle in selecting a type of lubrication is to choose the simplest technique which will work satisfactorily. In very many cases this will mean inserting a small quantity of oil or grease in the component on initial assembly; this is almost never replaced or refilled. Typical examples are door locks, hinges, car-window winders, switches, clocks, and watches.

This simple system is likely to be unsatisfactory if the loads or speeds are high or if the service life is long and continuous. Then it becomes necessary to choose the lubricant with care and often to use a replenishment system.

The two main factors in selecting the type of lubricant are the speed and the load. If the speed is high, then the amount of frictional heating tends to be high, and low-viscosity lubricants will give lower viscous friction and better heat transfer. If the loads are high, then low-viscosity lubricants will tend to be expelled from the contact. This situation is summarized in Fig. 20.1.

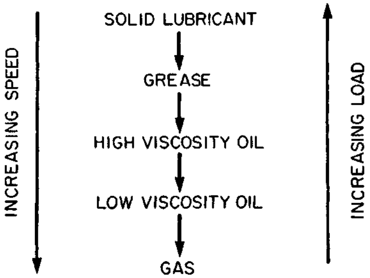


FIGURE 20.1 Effect of speed and load on choice of lubricant type. *(From Ref. [20.1].)*

It is difficult to give precise guidance about the load and speed limits for the various lubricant types, because of the effects of geometry, environment, and variations within each type, but Fig. 20.2 gives some approximate limits.

Some other property of the system will sometimes restrict the choice of lubricant type. For example, in watches or instrument mechanisms, any lubricant type could meet the load and speed requirements, but because of the need for low friction, it is normal to use a very low-viscosity oil. However, for open gears, wire ropes, or chains, the major problem is to prevent the lubricant from being thrown off the moving parts, and

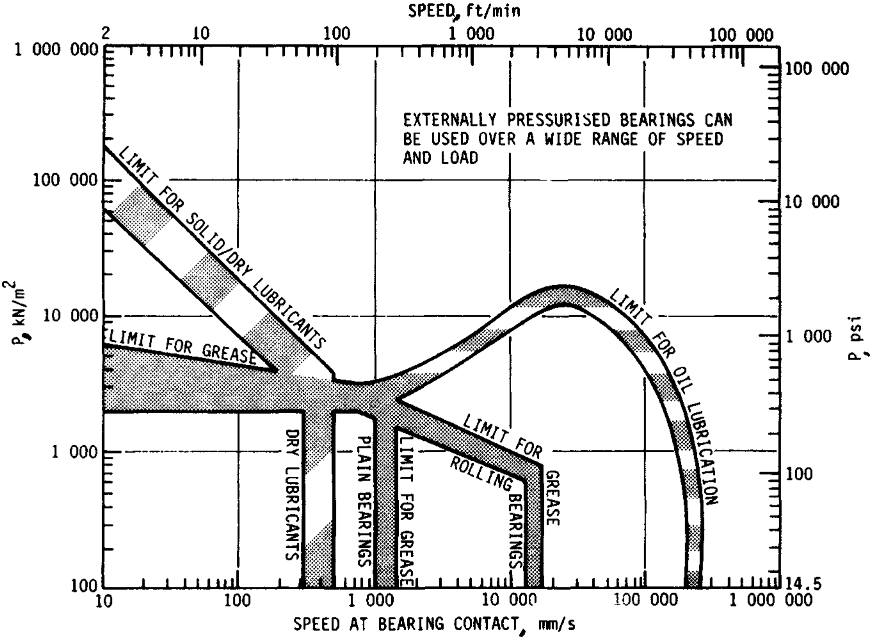


FIGURE 20.2 Speed and load limitations for different types of lubricants. *(From Ref. [20.2].)*

it is necessary to use a "tacky" bituminous oil or grease having special adhesive properties.

In an existing system the geometry may restrict the choice of lubricant type. Thus, an unsealed rolling bearing may have to be lubricated with grease because oil would not be retained in the bearing. But where the lubrication requirements are difficult or particularly important, it will usually be essential to first choose the lubricant type and then design a suitable system for that lubricant. Some very expensive mistakes have been made, even in high technology such as aerospace engineering, where systems that could not be lubricated have been designed and built.

20.3 LIQUID LUBRICANTS: PRINCIPLES AND REQUIREMENTS

The most important single property of a liquid lubricant is its viscosity. Figure 20.3 shows how the viscosity of the lubricant affects the nature and quality of the lubrication. This figure is often called a *Stribeck curve*, although there seems to be some doubt as to whether Stribeck used the diagram in the form shown.

The expression $\eta N/P$ is known as the *Sommerfeld number*, in which η is the lubricant viscosity, N represents the relative speed of movement between the counterfaces of the bearing, and P is the mean pressure or specific load supported by the bearing. Of these three factors, only the viscosity is a property of the lubricant. And if N and P are held constant, the figure shows directly the relationship between the coefficient of friction μ and the lubricant viscosity η.

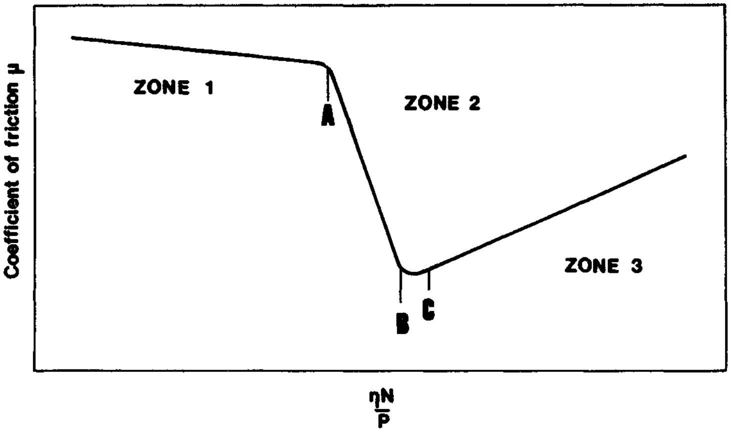


FIGURE 20.3 Effect of viscosity on lubrication.

The graph can be conveniently divided into three zones. In zone 3, the bearing surfaces are fully separated by a thick film of the liquid lubricant. This is, therefore, the zone of *thick-film* or *hydrodynamic lubrication,* and the friction is entirely viscous friction caused by mechanical shearing of the liquid film. There is no contact between the interacting surfaces and therefore virtually no wear.

As the viscosity decreases in zone 3, the thickness of the liquid film also decreases until at point *C* it is only just sufficient to ensure complete separation of the surfaces. Further reduction in viscosity, and therefore in film thickness, results in occasional contact between asperities on the surfaces. The relatively high friction in asperity contacts offsets the continuing reduction in viscous friction, so that at point *B* the friction is roughly equal to that at *C*.

Point *C* is the ideal point, at which there is zero wear with almost minimum friction, but in practice the design target will be slightly to the right of *C*, to provide a safety margin.

With further reduction in viscosity from point *B*, an increasing proportion of the load is carried by asperity contact, and the friction increases rapidly to point *A*. At this point the whole of the bearing load is being carried by asperity contact, and further viscosity reduction has only a very slight effect on friction.

Zone 1, to the left of point *A*, is the zone of *boundary lubrication.* In this zone, chemical and physical properties of the lubricant other than its bulk viscosity control the quality of the lubrication; these properties are described in Sec. 20.5.

Zone 2, between points *A* and *B*, is the zone of mixed lubrication, in which the load is carried partly by the film of liquid lubricant and partly by asperity interaction. The proportion carried by asperity interaction decreases from 100 percent at *A* to 0 percent at *C*.

Strictly speaking, Fig. 20.3 relates to a plain journal bearing, and *N* usually refers to the rotational speed. Similar patterns arise with other bearing geometries in which some form of hydrodynamic oil film can occur.

The relationship between viscosity and oil-film thickness is given by the Reynolds equation, which can be written as follows:

$$\frac{\partial}{\partial x}\left(h^3\frac{\partial P}{\partial x}\right)+\frac{\partial}{\partial z}\left(h^3\frac{\partial P}{\partial z}\right)=\eta\left(6U\frac{\partial h}{\partial x}+6h\frac{\partial U}{\partial x}+12V\right)$$

where h = lubricant-film thickness
P = pressure
x, z = coordinates
U, V = speeds in directions x and z

Fuller details of the influence of lubricant viscosity on plain journal bearings are given in Chap. 19.

In nonconformal lubricated systems such as rolling bearings and gears, the relationship between lubricant viscosity and film thickness is complicated by two additional effects: the elastic deformation of the interacting surfaces and the increase in lubricant viscosity as a result of high pressure. The lubrication regime is then known as *elastohydrodynamic* and is described mathematically by various equations.

For roller bearings, a typical equation is the Dowson-Higginson equation:

$$h_{\min} = \frac{2.65(\eta_o U)^{0.7} R^{0.43} \alpha^{0.54}}{E^{0.03} p^{0.13}}$$

where η_o = oil viscosity in entry zone
R = effective radius
α = pressure coefficient of viscosity

Here U represents the speed, p a load parameter, and E a material parameter based on modulus and Poisson's ratio.

For ball bearings, an equivalent equation is the one developed by Archard and Cowking:

$$h_{\min} = \frac{1.4(\eta_o U \alpha)^{0.74} E^{0.074}}{R^{0.74} p^{0.074}}$$

For such nonconformal systems, a diagram similar to Fig. 20.3 has been suggested in which zone 2 represents elastohydrodynamic lubrication. It is difficult to think of a specific system to which the relationship exactly applies, but it may be a useful concept that the lubricant-film thickness and the friction in elastohydrodynamic lubrication bridge the gap between thick-film hydrodynamic lubrication and boundary lubrication.

A form of microelastohydrodynamic lubrication has been suggested as a mechanism for asperity lubrication under boundary conditions (see Sec. 20.5). If this suggestion is valid, the process would probably be present in the zone of mixed lubrication.

Where full-fluid-film lubrication is considered necessary but the viscosity, load, speed, and geometry are not suitable for providing full-fluid-film separation hydrodynamically, the technique of *external pressurization* can be used. Quite simply, this means feeding a fluid into a bearing at high pressure, so that the applied hydrostatic pressure is sufficient to separate the interacting surfaces of the bearing.

Externally pressurized bearings broaden the range of systems in which the benefits of full-fluid-film separation can be obtained and enable many liquids to be used successfully as lubricants which would otherwise be unsuitable. These include aqueous and other low-viscosity process fluids. Remember that the lubricant viscosity considered in Fig. 20.3 and in the various film-thickness equations is the viscosity under the relevant system conditions, especially the temperature. The viscosity of all liquids decreases with increase in temperature, and this and other factors affecting viscosity are considered in Sec. 20.4.

The viscosity and boundary lubrication properties of the lubricant completely define the lubrication performance, but many other properties are important in service. Most of these other properties are related to progressive deterioration of the lubricant; these are described in Sec. 20.6.

20.4 LUBRICANT VISCOSITY

Viscosity of lubricants is defined in two different ways, and unfortunately both definitions are very widely used.

20.4.1 Dynamic or Absolute Viscosity

Dynamic or *absolute viscosity* is the ratio of the shear stress to the resultant shear rate when a fluid flows. In SI units it is measured in pascal-seconds or newton-seconds per square meter, but the centimeter-gram-second (cgs) unit, the centipoise, is more widely accepted, and

$$1 \text{ centipoise (cP)} = 10^{-3} \text{ Pa} \cdot \text{s} = 10^{-3} \text{ N} \cdot \text{s/m}^2$$

The centipoise is the unit of viscosity used in calculations based on the Reynolds equation and the various elastohydrodynamic lubrication equations.

20.4.2 Kinematic Viscosity

The *kinematic viscosity* is equal to the dynamic viscosity divided by the density. The SI unit is square meters per second, but the cgs unit, the centistoke, is more widely accepted, and

$$1 \text{ centistoke (cSt)} = 1 \text{ mm}^2/\text{s}$$

The centistoke is the unit most often quoted by lubricant suppliers and users.

In practice, the difference between kinematic and dynamic viscosities is not often of major importance for lubricating oils, because their densities at operating temperatures usually lie between 0.8 and 1.2. However, for some fluorinated synthetic oils with high densities, and for gases, the difference can be very significant.

The viscosities of most lubricating oils are between 10 and about 600 cSt at the operating temperature, with a median figure of about 90 cSt. Lower viscosities are more applicable for bearings than for gears, as well as where the loads are light, the speeds are high, or the system is fully enclosed. Conversely, higher viscosities are selected for gears and where the speeds are low, the loads are high, or the system is well ventilated. Some typical viscosity ranges at the operating temperatures are shown in Table 20.1.

The variation of oil viscosity with temperature will be very important in some systems, where the operating temperature either varies over a wide range or is very different from the reference temperature for which the oil viscosity is quoted.

The viscosity of any liquid decreases as the temperature increases, but the rate of decrease can vary considerably from one liquid to another. Figure 20.4 shows the

TABLE 20.1 Typical Operating Viscosity Ranges

Lubricant	Viscosity range, cSt
Clocks and instrument oils	5–20
Motor oils	10–50
Roller bearing oils	10–300
Plain bearing oils	20–1500
Medium-speed gear oils	50–150
Hypoid gear oils	50–600
Worm gear oils	200–1000

change of viscosity with temperature for some typical lubricating oils. A graphical presentation of this type is the most useful way to show this information, but it is much more common to quote the viscosity index (VI).

The *viscosity index* defines the viscosity-temperature relationship of an oil on an arbitrary scale in comparison with two standard oils. One of these standard oils has

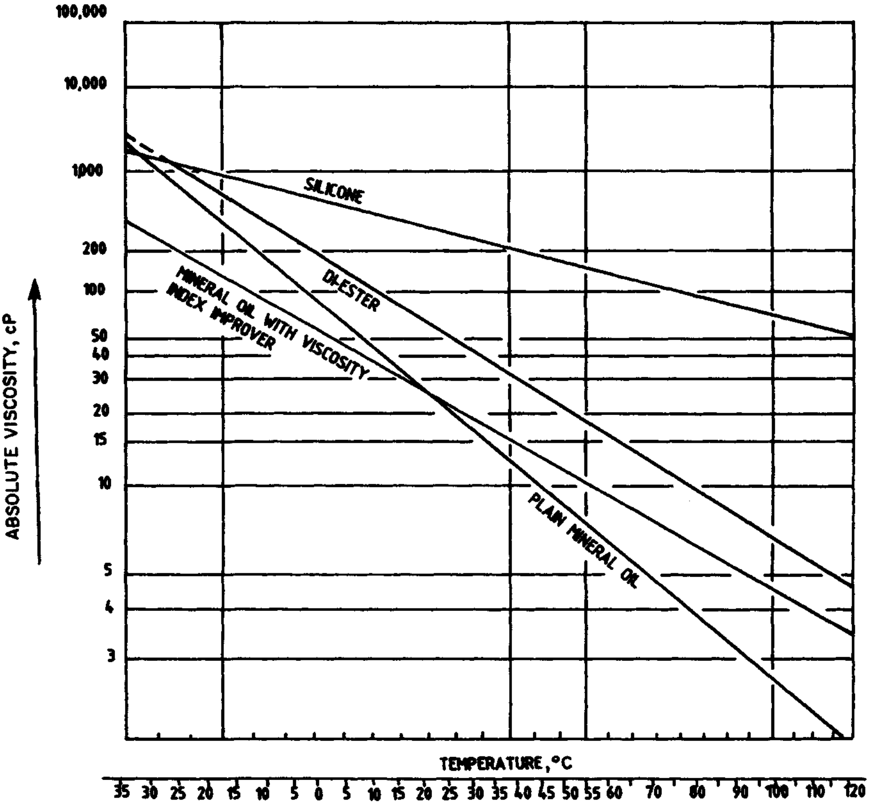


FIGURE 20.4 Variation of viscosity with temperature.

a viscosity index of 0, representing the most rapid change of viscosity with temperature normally found with any mineral oil. The second standard oil has a viscosity index of 100, representing the lowest change of viscosity with temperature found with a mineral oil in the absence of relevant additives.

The equation for the calculation of the viscosity index of an oil sample is

$$\mathrm{VI} = \frac{100(L - U)}{L - H}$$

where U = viscosity of sample in centistokes at 40°C, L = viscosity in centistokes at 40°C of oil of 0 VI having the same viscosity at 100°C as the test oil, and H = viscosity at 40°C of oil of 100 VI having the same viscosity at 100°C as the test oil.

Some synthetic oils can have viscosity indices of well over 150 by the above definition, but the applicability of the definition at such high values is doubtful. The viscosity index of an oil can be increased by dissolving in it a quantity (sometimes as high as 20 percent) of a suitable polymer, called a *viscosity index improver.*

The SAE viscosity rating scale is very widely used and is reproduced in Table 20.2. It is possible for an oil to satisfy more than one rating. A mineral oil of high viscosity index could meet the 20W and 30 criteria and would then be called a 20W/30 multigrade oil. More commonly, a VI improved oil could meet the 20W and 50 criteria and would then be called a 20W/50 multigrade oil.

Note that the viscosity measurements used to establish SAE ratings are carried out at low shear rate. At high shear rate in a bearing, the effect of the polymer may

TABLE 20.2 1977 Table of SAE Oil Ratings

SAE no.	Maximum viscosity at −18°C, cP	Viscosity at 100°C, cSt	
		Minimum	Maximum
		Engine oils	
5W	1 250	3.8	
10W	2 500	4.1	
20W†	10 000	5.6	
20	.....	5.6	<9.3
30	.....	9.3	<12.5
40	.....	12.5	<16.3
50	.....	16.3	<21.9
		Gear oils	
75	3 250		
80	21 600		
90	.....	14	<25
140	.....	25	<43
250	.....	43	

†15W may be used to identify 20W oils which have a maximum viscosity of 5000 cP.

disappear, and a 20W/50 oil at very high shear rate may behave as a thinner oil than a 20W, namely, a 15W or even 10W. In practice, this may not be important, because in a high-speed bearing the viscosity will probably still produce adequate oil-film thickness.

Theoretically the viscosity index is important only where significant temperature variations apply, but in fact there is a tendency to use only high-viscosity-index oils in the manufacture of high-quality lubricant. As a result, a high viscosity index is often considered a criterion of lubricant quality, even where viscosity index as such is of little or no importance.

Before we leave the subject of lubricant viscosity, perhaps some obsolescent viscosity units should be mentioned. These are the *Saybolt viscosity* (SUS) in North America, the *Redwood viscosity* in the United Kingdom, and the *Engler viscosity* in continental Europe. All three are of little practical utility, but have been very widely used, and strenuous efforts have been made by standardizing organizations for many years to replace them entirely by kinematic viscosity.

20.5 BOUNDARY LUBRICATION

Boundary lubrication is important where there is significant solid-solid contact between sliding surfaces. To understand boundary lubrication, it is useful to first consider what happens when two metal surfaces slide against each other with no lubricant present.

In an extreme case, where the metal surfaces are not contaminated by an oxide film or any other foreign substance, there will be a tendency for the surfaces to adhere to each other. This tendency will be very strong for some pairs of metals and weaker for others. A few guidelines for common metals are as follows:

1. Identical metals in contact have a strong tendency to adhere.
2. Softer metals have a stronger tendency to adhere than harder metals.
3. Nonmetallic alloying elements tend to reduce adhesion (e.g., carbon in cast iron).
4. Iron and its alloys have a low tendency to adhere to lead, silver, tin, cadmium, and copper and a high tendency to adhere to aluminum, zinc, titanium, and nickel.

Real metal surfaces are usually contaminated, especially by films of their own oxides. Such contaminant films commonly reduce adhesion and thus reduce friction and wear. Oxide films are particularly good lubricants, except for titanium.

Thus friction and wear can usually be reduced by deliberately generating suitable contaminant films on metallic surfaces. Where no liquid lubricant is present, such a process is a type of dry or solid lubrication. Where the film-forming process takes place in a liquid lubricant, it is called boundary lubrication.

Boundary lubricating films can be produced in several ways, which differ in the severity of the film-forming process and in the effectiveness of the resulting film. The mildest film-forming process is adsorption, in which a layer one or more molecules thick is formed on a solid surface by purely physical attraction. Adsorbed films are effective in reducing friction and wear, provided that the resulting film is sufficiently thick. Figure 20.5 shows diagrammatically the way in which adsorption of a long-chain alcohol generates a thick film on a metal surface even when the film is only one molecule thick.

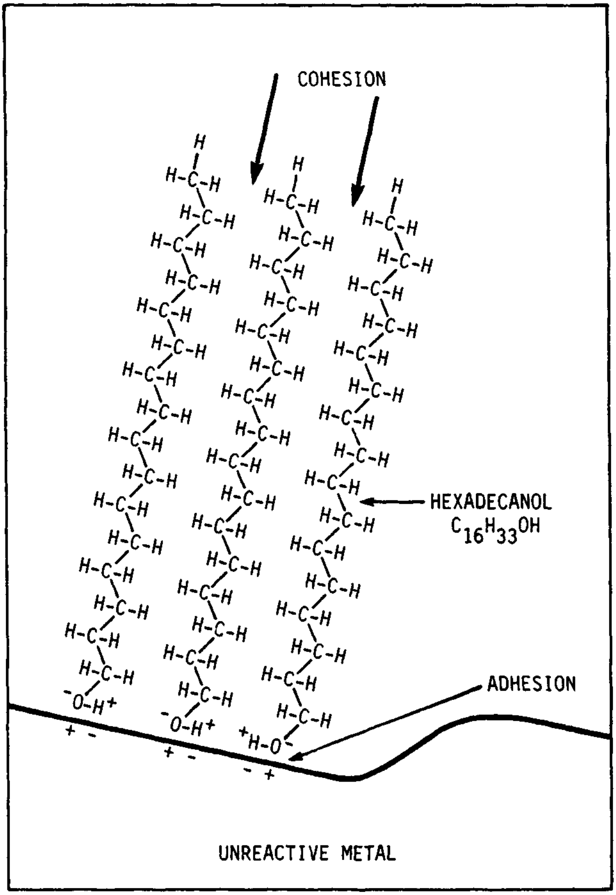


FIGURE 20.5 Representation of adsorption of a long-chain alcohol. *(From Ref. [20.3].)*

Mineral oils often contain small amounts of natural compounds which produce useful adsorbed films. These compounds include unsaturated hydrocarbons (olefines) and nonhydrocarbons containing oxygen, nitrogen, or sulfur atoms (known as asphaltenes). Vegetable oils and animal fats also produce strong adsorbed films and may be added in small concentrations to mineral oils for that reason. Other mild boundary additives include long-chain alcohols such as lauryl alcohol and esters such as ethyl stearate or ethyl oleate.

Adsorbed boundary films are removed fairly easily, either mechanically or by increased temperature. A more resistant film is generated by chemisorption, in which a mild reaction takes place between the metal surface and a suitable compound. Typical chemisorbed compounds include aliphatic ("fatty") acids, such as oleic and stearic acids. A chemisorbed film is shown diagrammatically in Fig. 20.6.

Even more resistant films are produced by reaction with the metal surface. The reactive compounds usually contain phosphorus, sulfur, or chlorine and ultimately

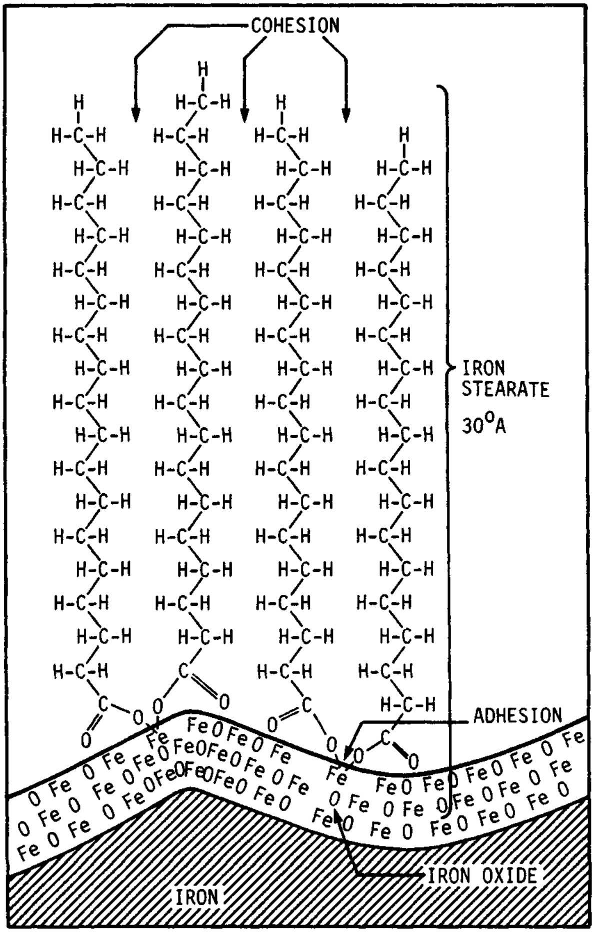


FIGURE 20.6 Representation of chemisorption of a long-chain aliphatic acid. *(From Ref. [20.3].)*

produce films of metal phosphide, sulfide, or chloride on the sliding surface. These reactive additives are known as *extreme-pressure,* or EP, additives.

The processes by which modern boundary lubricant additives generate surface films may be very complex. A single additive such as trixylyl phosphate may be initially adsorbed on the metal surface, then react to form a chemisorbed film of organometallic phosphate, and finally, under severe sliding or heating, react to form metal phosphate or phosphide.

All these boundary lubricant compounds have corresponding disadvantages. As a general rule, they should be used only where the conditions of use require them. The mild, adsorbed compounds have the least undesirable side effects. They are more readily oxidized than the usual mineral-base oils and, as a result, have a higher tendency to produce corrosive acidic compounds and insoluble gums or lacquers. However, these effects are not serious, and mild antiwear additives are widely used in small quantities where sliding conditions are not severe, such as in hydraulic fluids and turbine oils.

The stronger chemisorbed additives such as fatty acids, organic phosphates, and thiophosphates are correspondingly more reactive. They are used in motor oils and gear oils. Finally, the reactive sulfurized olefines and chlorinated compounds are, in fact, controlled corrodents and are used only where the sliding conditions are very severe, such as in hypoid gearboxes and in metalworking processes.

Boundary lubrication is a very complex process. Apart from the direct film-forming techniques described earlier, there are several other effects which probably make an important contribution to boundary lubrication:

1. *The Rehbinder effect* The presence of surface-active molecules adjacent to a metal surface decreases the yield stress. Since many boundary lubricants are more or less surface-active, they can be expected to reduce the stresses developed when asperities interact.
2. *Viscosity increase adjacent to a metal surface* This effect is controversial, but it seems probable that interaction between adsorbed molecules and the free ambient oil can result in a greaselike thickening or trapping of oil molecules adjacent to the surface.
3. *Microelastohydrodynamic effects* The interaction between two asperities sliding past each other in a liquid is similar to the interaction between gear teeth, and in the same way it can be expected to generate elastohydrodynamic lubrication on a microscopic scale. The increase in viscosity of the lubricant and the elastic deformation of the asperities will both tend to reduce friction and wear. However, if the Rehbinder effect is also present, then plastic flow of the asperities is also encouraged. The term *microrheodynamic lubrication* has been used to describe this complex process.
4. *Heating* Even in well-lubricated sliding there will be transient heating effects at asperity interactions, and these will reduce the modulus and the yield stress at asperity interactions.

Boundary lubrication as a whole is not well understood, but the magnitude of its beneficial effects can be easily seen from the significant reductions in friction, wear, and seizure obtained with suitable liquid lubricants in slow metallic sliding.

20.6 DETERIORATION PROBLEMS

In theory, if the right viscosity and the right boundary properties have been selected, then the lubrication requirements will be met. In practice, there is one further complication—the oil deteriorates. Much of the technology of lubricating oils and additives is concerned with reducing or compensating for deterioration.

The three important types of deterioration are oxidation, thermal decomposition, and contamination. A fourth long-term effect is reaction with other materials in the system, which is considered in terms of compatibility. Oxidation is the most important deterioration process because over a long period, even at normal atmospheric temperature, almost all lubricants show some degree of oxidation.

Petroleum-base oils produced by mild refining techniques oxidize readily above 120°C to produce acidic compounds, sludges, and lacquers. The total oxygen uptake is not high, and this suggests that the trace compounds, such as aromatics and asphaltenes, are reacting, and that possibly in doing so some are acting as oxidation inhibitors for the paraffinic hydrocarbons present. Such mildly refined oils are not much improved by the addition of antioxidants.

More severe refining or hydrogenation produces a more highly paraffinic oil which absorbs oxygen more readily but without producing such harmful oxidation products. More important, however, the oxidation resistance of such highly refined base oils is very considerably improved by the addition of suitable oxidation inhibitors.

Most modern petroleum-base oils are highly refined in order to give consistent products with a wide operating-temperature range. Antioxidants are therefore an important part of the formulation of almost all modern mineral-oil lubricants.

The commonly used antioxidants are amines, hindered phenols, organic phosphites, and organometallic compounds. One particularly important additive is zinc diethyl dithiophosphate, which is a very effective antioxidant and also has useful boundary lubrication and corrosion-inhibition properties.

If no oxygen is present, lubricants can be used at much higher temperatures without breaking down. In other words, their thermal stability is greater than their oxidative stability. This effect can be seen for mineral oils in Table 20.3. To prevent contact of oxygen with the oil, the system must be sealed against the entry of air or purged with an inert gas such as nitrogen. Some critical hydraulic systems, such as those in high-speed aircraft, are operated in this way.

In high-vacuum systems such as spacecraft or electron microscopes, there is no oxygen contact. But in high vacuum an increase in temperature tends to vaporize the

TABLE 20.3 Range of Temperature Limits in Degrees Celsius for Mineral Oils as a Function of Required Life

	Life, h				
Oil condition	1	10	10^2	10^3	10^4
Thermal stability limit; insignificant oxygen present	415 to 435	385 to 405	355 to 375	320 to 340	290 to 310
Limit dependent on amount of oxygen present and presence or absence of catalysts	190 to 415	170 to 385	140 to 355	155 to 320	90 to 290
Limit imposed by oxidation where oxygen supply is unlimited; for oils containing antioxidants	175 to 190	155 to 170	125 to 140	100 to 115	80 to 90
Limit imposed by oxidation where oxygen supply is unlimited; for oils without antioxidants	155 to 165	130 to 140	95 to 110	65 to 80	35 to 50
Lower temperature limit imposed by pour point; varies with oil source, viscosity, treatment, and additives	−65 to 0	−65 to 0	−65 to 0	−65 to 0	−65 to 0

SOURCE: Ref. [20.2].

oil, so that high thermal stability is of little or no value. It follows that oxidative stability is usually much more important than thermal stability.

Compatibility of lubricating oils with other materials in the system is complex, and Table 20.4 lists some of the possible problems and solutions. Compatibility problems with synthetic lubricants are even more complicated; these are considered further in the next section.

20.7 SELECTING THE OIL TYPE

So far most of the information in this chapter has been related to mineral oils. For almost 150 years the availability, good performance, variety, and cheapness of mineral oils have made them the first choice for most applications. They still represent over 90 percent of total lubricant use, but many other liquids are used successfully as lubricants and can provide special features which make them the best choice in particular situations.

Table 20.5 shows the most important types of lubricating oil and their advantages and disadvantages as compared with mineral oils. The natural oils comprise a wide variety of compounds of vegetable or animal origin, consisting mainly of organic esters. They all have better low-friction and boundary lubrication properties than mineral oils, but lower thermal and oxidative stability. Before mineral oils became generally available, natural oils and fats were the most common lubricants, and several are still widely used because their properties make them particularly suitable for special applications, as shown in Table 20.6.

The diesters were the first synthetic lubricating oils to be used in large quantities. Their higher thermal and oxidative stability made them more suitable than mineral

TABLE 20.4 Examples of Compatibility Problems and Possible Solutions

Problem	Solution
1. Attack by mineral oils on natural rubber	Change to nitrile rubber or neoprene
2. Attack by synthetic oils on natural rubber, nitrile, or other rubber	Change to suitable rubber for specific oil, e.g., Viton, resin-cured butyl, or EPR
3. Attack by synthetic oils on plastics or paints	Change to resistant plastics such as PTFE, polyimide, polysulfone, or polyphenylene sulfide
4. Corrosion by dissolved water	Use rust-inhibitor additives such as sulfonates
5. Corrosion by acidic degradation products	Use corrosion inhibitors such as ZDDP, or increase antioxidants to reduce degradation
6. Corrosion by additives of copper alloys or mild steel	Use less powerful EP additives, or change to corrosion-resistant metals
7. Corrosion by synthetic oils	Change to more resistant metals or platings

TABLE 20.5 Advantages and Disadvantages of Main Nonmineral Oils

Oil type	Comparison with mineral oils	
	Advantages	Disadvantages
1. Vegetable oil	Good boundary lubrication; does not cause carburization of steel in metalforming	Decomposes readily to give high viscosity or sludges and lacquers
2. Diesters, hindered esters	Higher temperature stability; high viscosity index	Some attack on rubbers and plastics
3. Polyglycol	Miscibility with water; decomposes without producing solid degradation products	Low maximum temperature
4. Silicones	High temperature stability; resistance to chemicals	Poor boundary lubrication for steel on steel
5. Phosphate ester	Fire resistance; very good boundary lubrication	Attack on rubbers and plastics; poor temperature stability
6. Chlorinated diphenyls	Fire resistance; chemical stability; boundary lubrication	Poor viscosity index; attack on plastics and copper alloys
7. Fluorocarbon	Excellent temperature and chemical stability	Price; poor viscosity index

TABLE 20.6 Some Uses of Natural Oils and Fats

Oil type	Uses
1. Rapeseed oil	*a.* To reduce friction in plain bearings where oil-film thickness is inadequate by addition of 5% to 10% to mineral oil
	b. In metal forming to give low friction and EP properties without staining or carburizing
	c. Has been used as lubricant in continuous casting
2. Castor oil	*a.* As low-viscosity hydraulic fluid for compatibility with natural rubber
	b. To give low viscous drag and good boundary lubrication in racing car engines and early aircraft engines
3. Tallow	*a.* For low friction in metal forming
4. Sperm oil	*a.* For outstanding boundary lubrication in metal cutting especially in sulfurized form; now virtually obsolete because of whale protection laws

oils for gas-turbine lubrication, and by about 1960 they were almost universally used for aircraft jet engines. For the even more demanding conditions of supersonic jet engines, the more complex ester lubricants such as hindered phenols and triesters were developed.

Phosphate esters and chlorinated diphenyls have very low-flammability characteristics, and this has led to their wide use where critical fire-risk situations occur, such as in aviation and coal mining. Their overall properties are mediocre, but are sufficiently good for use where fire resistance is particularly important.

Other synthetic fluids such as silicones, chlorinated silicones, fluorinated silicones, fluorinated hydrocarbon, and polyphenyl ethers are all used in relatively small quantities for their high-temperature stability, but all are inferior lubricants and very expensive compared with mineral oils.

Several types of water-containing fluid are used in large quantities, and these are listed in Table 20.7. They are used almost entirely to provide either fire resistance or superior cooling.

Mineral oils can be considered as the normal, conventional oils, and alternative types are used only when they can offer some particular advantage over mineral oils. Table 20.8 summarizes the selection of oil type in relation to the special properties required.

It is difficult to give precise high-temperature limits for the use of specific oil types, because the limiting temperature depends on the required life and the amount of degradation which is acceptable. Even for water-containing lubricants, the upper temperature limit may be from 50 to 85°C depending on the required life, the degree of ventilation, and the amount of water loss which is acceptable. Table 20.9 summarizes the temperature limits for a few synthetic oils, but the limits shown should be considered only approximate.

Serious incompatibility problems can occur with lubricating oils, especially with nonmetallic materials such as rubber seals and hoses. Table 20.10 lists some satisfactory and unsatisfactory materials for use with various lubricants.

TABLE 20.7 Some Water-Containing Lubricants

Oil type	Applications
1. Invert emulsions (water in mineral oil)	Used as hydraulic fluids for fire resistance, e.g., in coal mining. Good lubricating properties.
2. Dilute emulsions (5% mineral oil in water)	Used for fire resistance and cheapness where good lubrication properties not needed (e.g., roof jacks in coal mining).
3. "Soluble" oils (about 1% oil in water)	Used for their good cooling properties in metal cutting and grinding operations.
4. Water/Polyglycol	Used for fire resistance where increased viscosity and lack of solid degradation products are required.
5. "Synthetic" Coolants (solutions of boundary additives in water)	Used for excellent cooling and stability in metal cutting operations.

TABLE 20.8 Choice of Oil Type for Specific Properties

Property required	Choice of oil type
1. Wide range of viscosities	Mineral oil; silicone; polyglycol
2. Good boundary lubrication	Natural oil or fat; mineral oil with suitable additives; ester; phosphate ester
3. Long life	Mineral oil; silicone; fluorocarbon; ester; polyphenyl ether
4. High temperature stability	Polyphenyl ether; fluorocarbon; silicone; ester
5. Fire resistance	Emulsions; fluorocarbon; fluorosilicone; chlorinated biphenyl; phosphate ester
6. Cheapness	Emulsions; mineral oil

20.8 LUBRICATING GREASES

Lubricating greases are not simply very viscous oils. They consist of lubricating oils, often of quite low viscosity, which have been thickened by means of finely dispersed solids called thickeners. The effect of the thickeners is to produce a semirigid structure in which the dispersion of thickener particles is stabilized by electric charges. The liquid phase is firmly held by a combination of opposite electric charges, adsorp-

TABLE 20.9 Range of Temperature Limits in Degrees Celsius for Some Synthetic Oils as a Function of the Required Life

Name of lubricant; type of limit	Life, h				
	1	10	10^2	10^3	10^4
Polyphenyl ethers; thermal stability limit	545	520	490	455	425
Polyphenyl ethers; oxidation limit	350	330	305	280	260
Silicones; thermal stability limit	280 to 290	260 to 275	240 to 260	220 to 245	200 to 230
Esters and silicones; oxidation limit	225 to 260	215 to 245	200 to 240	185 to 220	175 to 210
Phosphate esters; thermal and oxidative limit	160	145	130	110	100
Polyphenal ethers; pour-point limit	0	0	0	0	0
Silicones and esters; pour-point limit	−60	−60	−60	−60	−60

SOURCE: Ref. [20.2].

TABLE 20.10 Some Compatible and Incompatible Materials for Different Oil Types

Oil type	Rubbers and plastics	
	Satisfactory	Unsatisfactory
1. Natural oils	Most rubbers, including natural rubber; most plastics	SBR rubber; highly plasticized polyethylene and polypropylene
2. Mineral oil	Nitrile rubber; neofrene; Viton; EPR; most unplasticized plastics	Natural rubber; SBR; highly plasticized plastics; polyurethanes
3. Esters	High nitrile; Viton; nylons; PPS; polyethersulfones	Natural rubber; SBR; low nitrile; polyacrylates; polyurethanes
4. Silicones	High nitrile; Viton; nylons; PPS	Natural rubber; silicone rubber; plasticized plastics
5. Phosphate ester	Resin-cured butyl rubber; EPR; PPS	Most other rubbers; many plastics

tion, and mechanical trapping. As a result, the whole grease behaves as a more or less soft solid, and there is only a very slight tendency for the oil to flow out of the grease.

Greases can probably be made from any type of lubricating oil, but in practice the majority are based on mineral oils, and only a few other base oils are of any real importance. Diesters have been used to produce greases for higher and lower temperatures than greases based on mineral oils are suitable for. Silicones are used for higher temperatures again, and fluorinated hydrocarbons for even higher temperatures; both these types are also used because of their chemical inertness, but the total quantities are relatively small. Phosphate esters have been used for fire resistance, and vegetable oils for compatibility with foodstuffs; but, again, the quantities are very small.

The most commonly used thickeners are soaps, which are salts of organic acids with calcium, sodium, lithium, or aluminum. The soaps take the form of fibrous particles which interlock to give a high level of stiffness at low soap concentrations. Many other substances which have been used as grease thickeners tend to be more spherical and have to be used at higher concentrations than soaps to achieve the same degree of thickening.

Most of the additives used in lubricating oils are also effective in greases. And some, such as the solid lubricants graphite and molybdenum disulfide, are much more effective in greases than in oils.

Table 20.11 lists some of the many different components which may be used in greases. The possible combinations of these components, and their different proportions, lead to an infinite range of grease formulations. In practice, a typical grease consists of a mineral oil in which are dispersed about 10 percent of a soap thickener, about 1 percent of antioxidant, and small amounts of other additives such as corrosion inhibitors, antiwear or extreme-pressure agents, and structure modifiers.

The most important physical characteristic of a grease is its relative hardness or softness, which is called *consistency*. Consistency is assessed by measuring the dis-

TABLE 20.11 Some Components Used in Grease Manufacture

Base oils	Thickeners	Additives
Mineral oils	Sodium soap	Antioxidants
Silicones	Lithium soap	EP additives
Diesters	Aluminum soap	Corrosion inhibitors
Chlorinated silicone	Lithium complex	Metal deactivators
Fluorocarbons	Aluminum complex	Tackiness additives
Phosphate esters	Bentonite clay	Water repellants
	PTFE	Structure modifiers
	Indanthrene dye	

tance in tenths of a millimeter to which a standard metal cone penetrates the grease under a standard load; the result is known as the *penetration.* A widely used classification of greases is that of the American National Lubricating Grease Institute (NLGI), and Table 20.12 shows the relationship between NLGI number and penetration.

TABLE 20.12 NLGI Grease Classification

NLGI number	Worked penetration at 25°C
000	445–475
00	400–430
0	355–385
1	310–340
2	265–295
3	220–250
4	175–205
5	130–160
6	85–115

The consistency of a grease varies with temperature, and there is generally an irregular increase in penetration (softening) as the temperature increases. Eventually a temperature is reached at which the grease is soft enough for a drop to fall away or flow from the bulk of the grease; this is called the *drop point.* The drop point is usually taken to be the maximum temperature at which the grease can be used in service, but several factors confuse this situation:

1. The drop point is measured in a standard apparatus which bears no resemblance to any service equipment, so that the correlation with service use may be poor.
2. Some greases will never give a drop point because chemical decomposition begins before the thickener structure breaks down.
3. A grease may be a satisfactory lubricant above its drop point, although then it will behave like an oil rather than a grease.

4. Some greases can be heated above their drop points and will again form a grease when cooled, although normally the re-formed grease will be markedly inferior in properties.

At high temperature greases will decompose thermally or oxidatively in the same way as lubricating oils. In addition, the grease structure may break down, as explained previously, or the thickener itself may decompose. Table 20.13 depicts the general effects of temperature on lubricating greases.

A grease behaves as an extreme form of non-Newtonian fluid, and its viscous properties change when it is sheared in a feed line or a bearing. Occasionally the viscosity increases with small shear rates, but more commonly the viscosity decreases as the shear rate increases, until eventually the viscosity reaches that of the base oil. For this reason, the viscosity of the base oil may be important if the grease is to be used in high-speed equipment.

The mechanism by which a grease lubricates is more complicated than that for an oil, and it depends partly on the geometry of the system. Some part of the total grease fill distributes itself over the contacting surfaces and is continually sheared in the same way as an oil. This part of the grease performs the lubricating function, giving either hydrodynamic lubrication or boundary lubrication according to the load, speed, and effective viscosity.

The remainder of the grease is swept out of the path of the moving parts and remains almost completely static in the covers of a bearing or the upswept parts of a gearbox. Because of the solid nature of the grease, there is virtually no circulation or exchange between the static, nonlubricating portion and the moving, lubricating portion.

In a plain bearing or a closely fitting gearbox, a high proportion of the grease fill is being continuously sheared at the contacting surfaces. In a roller bearing or a spa-

TABLE 20.13 Temperature Limits in Degrees Celsius for Greases as a Function of Required Life

	Life, h				
Grease; type of limit	1	10	10^2	10^3	10^4
Synthetic greases; oxidation limit with unlimited oxygen present	275 to 285	255 to 265	225 to 240	200 to 225	175 to 200
Synthetic greases; drop-point limit with inorganic thickeners	250	250	250	250	250
Mineral-oil greases; upper limit imposed by drop point depends on thickener; oxidation dependent on amount of oxygen present	80 to 200	80 to 200	80 to 200	80 to 200	80 to 200
Mineral greases; oxidation limit with unlimited oxygen	185 to 200	160 to 175	135 to 150	110 to 125	85 to 100
Mineral greases; lower limit imposed by high torque	−50 to −10	−50 to −10	−50 to −10	−50 to −10	−50 to −10
Synthetic greases; lowest limit imposed by high torque	−70 to −80	−70 to −80	−70 to −80	−70 to −80	−70 to −80

SOURCE: Ref. [20.2]

cious gearbox, a small proportion of the grease is continuously sheared and provides all the lubrication, while the larger proportion is inactive.

If a rolling bearing or gearbox is overfilled with grease, it may be impossible for the surplus to escape from the moving parts. Then a large quantity of grease will be continuously sheared, or "churned," and this causes a buildup of temperature which can severely damage the grease and the components. It is, therefore, important with grease lubrication to leave a void space which is sufficient to accommodate all the surplus grease; in a ball bearing, this could be more than 60 percent of the total space available.

The static grease which is not involved in lubrication may fulfill two useful functions: It may provide a very effective seal against the ingress of dust or other contaminants, and it can prevent loss of base oil from the grease fill. In addition, the static grease may form a reservoir from which to resupply the lubricated surfaces if the lubricating portion of the grease becomes depleted.

If the void space in the system is large, i.e., in a large bearing or gearbox, then usually it is desirable to use a stiffer grease to avoid the surplus grease "slumping" into the moving parts and being continuously churned. The advantages and disadvantages of grease lubrication are summarized in Table 20.14.

The selection of a grease for a specific application depends on five factors: speed, load, size, temperature range, and any grease feed system. For average conditions of speed, load, and size with no feed system, an NLGI no. 2 grease would be the normal choice, and such a grease with a mineral-oil base is sometimes known as a multipurpose grease. The effect of the various factors on selection can then be summarized in a few paragraphs.

1. *Speed* For high speeds, a stiffer grease, NLGI no. 3, should be used except in plain bearings, where no. 2 would usually be hard enough. For lower speeds, a softer grease such as no. 1 or no. 0 should be used.

TABLE 20.14 Advantages and Disadvantages of Grease Lubrication

Advantages
1. Maintain effective lubricant film on surfaces during a shutdown
2. Provide useful squeeze-film lubrication
3. Give effective sealing of rolling bearings
4. Maintain a reserve supply of lubricant in the vicinity of the bearing
5. Reduce contamination problems compared with oil
6. Provide an effective carrier for solid lubricants for antiseize or highly loaded situations
Disadvantages
1. Ineffective cooling
2. Limitations on bearing speed
3. Possible incompatibility with other similar greases
4. Lower oxidation resistance
5. Poorer storage stability

2. *Load* For high loads, it may be advantageous to use EP additives or molybdenum disulfide. Because higher loads will lead to higher power consumption and therefore higher temperature, a stiffer grease such as no. 3 or a synthetic-base oil may help.
3. *Size* For large systems, use a stiffer grease, no. 3 or no. 4. For very small systems, use a softer grease, such as no. 1 or no. 0.
4. *Temperature range* The drop point should be higher than the maximum predicted operating temperature. For sustained operation at higher temperatures, a synthetic-base oil may be necessary. For very high temperatures, about 230°C, one of the very expensive fluorocarbon greases may be required.
5. *Feed systems* If the grease is to be supplied through a centralized system, usually it is desirable to use one grade softer than would otherwise be chosen (i.e., use a no. 0 instead of a no. 1 or a no. 00 instead of a no. 0). Occasionally a particular grease will be found unsuitable for a centralized feed because separation occurs and the lines become plugged with thickener, but this problem is now becoming less common.

20.9 SOLID LUBRICANTS

Any solid material can act as a solid lubricant provided that it shears readily and smoothly when interposed between sliding surfaces. Some of the wide range of solids which can be used are listed in Table 20.15.

TABLE 20.15 Materials Used as Solid Lubricants

Layer-lattice compounds	
Molybdenum disulfide	Graphite
Tungsten diselenide	Tungsten disulfide
Niobium diselenide	Calcium fluoride
Graphite fluoride	
Polymers	
PTFE	PTFCE
PVF_2	FEP
Acetal	Polyimide
Polyphenylenesulfide	Polysulfones
Metals	
Silver	Gold
Tin	Lead
Barium	Gallium
Other inorganics	
Boron nitride	Molybdenum trioxide

There are many other desirable properties, including the following:

1. Ability to adhere to one or both of the bearing surfaces to ensure retention in the contact area
2. Chemical stability over the required temperature range in the particular environment
3. Sufficient resistance to wear
4. Nontoxicity
5. Easy application
6. Economy

Most of the available materials are eliminated by these requirements, and in practice almost all solid lubrication in engineering is provided by three materials—graphite, molybdenum disulfide, and polytetrafluoroethylene (PTFE).

Solid lubricants can be used in several different forms, such as loose powder, adhering powder, bonded film, or solid block. In the form of a solid block, the material is often called a *dry* bearing material rather than a solid lubricant.

20.9.1 Graphite

Graphite is probably the oldest known of the three main solid lubricants, and it has ceased to be the dominant one since about 1950. It is a grayish black crystalline form of carbon in which the atoms are arranged hexagonally in monatomic layers. The strong chemical bonds between the carbon atoms give strength to the layers, so that they resist bending or fracture and can carry useful loads. The bonds between the layers are relatively weak, and so the layers slide easily over each other and can be easily separated.

When graphite is used as a lubricant, the crystals orient themselves so that the layers are parallel to the bearing surfaces. The layers then adhere fairly well to the bearing surfaces, but slide easily over each other to give low friction.

The low shearing forces, and therefore the low friction, are not an inherent property of the graphite but are strongly influenced by the presence of moisture or certain other adsorbents. If graphite is used in a very dry atmosphere, the crystal layers have quite high interlayer bonding forces, and the friction and wear are high.

The biggest advantage of graphite over molybdenum disulfide and PTFE is its electrical conductivity, and it is almost universally used as a component in electric brushes. Its coefficient of friction varies from 0.05 at high loads to 0.15 at low loads, and these low values are maintained to over 500°C in air.

In block form, graphite has quite high structural integrity. It is commonly used in an impure form as graphitized carbon, in which the degree of crystallization can vary from 30 to over 80 percent of that of crystalline graphite. The frictional and structural properties and abrasiveness vary with the purity and degree of graphitization, and graphite technology is complex.

Graphite can be used in block form, as free powder, or as a coating deposited from dispersion in a liquid. It adheres readily to many solid surfaces, but probably its strength of adhesion is generally lower than that of molybdenum disulfide.

20.9.2 Molybdenum Disulfide

Molybdenum disulfide has also been known as a solid lubricant for centuries, but because it is similar in appearance, it has often been confused with graphite. Its use has increased enormously since about 1950, and for high-technology applications it is now generally preferred to graphite. In crude form, molybdenum disulfide is found naturally, sometimes in very large quantities, as molybdenite, the most common ore of molybdenum.

Like graphite, molybdenum disulfide is a dark gray crystalline material with a hexagonal layer-lattice structure. The bond strengths within the layers are very high, whereas those between layers are very low. The load-carrying capacity normal to the crystal planes is therefore high, and the shear strength parallel to the crystal layers is very low.

Unlike graphite, molybdenum disulfide does not require the presence of adsorbed moisture or other vapors to give low interplanar strength. Its low friction is therefore an inherent property which is maintained in high vacuum and in dry atmospheres.

Molybdenum disulfide starts to oxidize significantly above 350°C in oxygen and 450°C in air, but the main oxidation product is molybdic oxide, which is itself a fair high-temperature lubricant. In high vacuum the disulfide is said to be stable to 1000°C, and it outgasses (evaporates) very slowly, so that it has been widely used in space.

The adhesion to metals and many other solid surfaces is excellent, and durable coatings can be produced on metal surfaces by burnishing (a coating of loose powder is rubbed into the surface to give a very thin, shiny, and strong film). The powder may be applied free or from dispersion in a volatile liquid. Durable coatings can also be obtained by sputtering, but this technique is expensive and is not widely used.

Bonded coatings are widely used, in which molybdenum disulfide powder is incorporated in almost any effective adhesive, including many polymers, natural resins, or molten solids. The performance of the softer bonded coatings is also improved if they are carefully burnished before use. The coefficient of friction of burnished films varies from 0.02 to about 0.12. But for bonded films the friction depends on the nature of the binder and the percentage composition, and it can vary from 0.02 to about 0.3.

Molybdenum disulfide is often added to oils or greases to give high load-carrying capacity, especially at low running speeds. There is also strong evidence that the addition of up to 2 percent to vehicle engine oils produces a small but significant fuel savings without any apparent disadvantages.

At one time molybdenum disulfide suffered considerable criticism, especially for reported corrosion of steels and aluminum. Some of this may have been due to its use in conjunction with graphite. Some was certainly caused by failure to understand that solid lubricants, unlike oils and greases, do not normally protect against corrosion. It is probably fair to say that molybdenum disulfide is now well understood and that, when properly used, it is a very valuable solid lubricant.

20.9.3 Polytetrafluoroethylene

Abbreviated PTFE, polytetrafluoroethylene is a polymer produced from ethylene in which all the hydrogen atoms have been replaced by fluorine atoms. This fluorination produces a material of very high chemical stability and low intermolecular bond strength, while the polymerization of an ethylene-type molecule gives long, straight molecular chains.

The result is a white solid which consists of masses of parallel long-chain molecules that slide easily past one another. This leads to the same sort of low shear strength parallel to the chains which is found in molybdenum disulfide and to a high load-carrying capacity normal to the chains, but significantly lower than that of molybdenum disulfide.

PTFE is often used in the form of solid components, occasionally in bonded coatings, and very rarely as free powder. In addition, it has been used very successfully in composites, and two types are particularly effective.

The coefficient of friction of pure PTFE varies from 0.02 at high load to about 0.1 at low load. It is a rather soft solid, so that its load-carrying capacity is limited and its wear rate is high. It therefore needs reinforcement for use in highly loaded bearings. One successful form of reinforcement is to incorporate the PTFE in the pores of a sintered metal, especially bronze. In one composite, further reinforcement is obtained by dispersing fine particles of lead in the PTFE.

A second, and probably even more successful, form of reinforcement is by means of strengthening fibers. Glass fiber or carbon fiber can be incorporated in solid PTFE components, but the resulting high structural strength is obtained at the cost of an increase in the coefficient of friction to between 0.06 and 0.2. An alternative technique is to interweave PTFE fibers and reinforcing fibers of glass, metal, rayon, or other synthetics. Some of the resulting composites have outstanding strength with low wear rate and low friction.

PTFE can be used in air to about 250°C, but in high vacuum it outgasses slowly, and so it is used in spacecraft only in well-shielded locations.

Because of its high chemical stability, PTFE can be used safely in oxygen systems and in many types of chemical plants. It is nontoxic in almost all situations and is therefore used in the pharmaceutical and food industries, even in situations where low friction is not required, and as the nonstick lubricant in domestic cooking utensils.

20.9.4 Miscellaneous Solid Lubricants

Other solid lubricants are used to a relatively minor degree, in situations where they have specific advantages. They can be classified in three broad categories: inorganics, polymers, and metals.

The inorganics include a number of materials similar to molybdenum disulfide, known generally as the lubricating dichalcogenides. None of these occurs naturally, and the synthetic materials are relatively expensive. Tungsten disulfide has a higher oxidation temperature, and both tungsten disulfide and tungsten diselenide oxidize more slowly than molybdenum disulfide. Niobium diselenide has better electrical conductivity and has been used in electric contact brushes, but in fact molybdenum disulfide composites have been shown to be equally satisfactory.

Other inorganics have been used for their much higher temperature limits, and these include molybdic oxide, boron nitride, graphite fluoride, and calcium fluoride.

The low friction and chemical inertness of PTFE make it difficult to bond to other materials, and two other fluorinated polymers have been recommended for their better bonding behavior: polyvinylfluoride (PVF_2) and polytrifluorochloroethylene (PTFCE). But in both cases the advantages of better bonding and slightly higher structural strength are offset by higher friction.

For higher temperatures, polyimide, polysulfones, and polyphenylene sulfide can be used unlubricated. Other polymers, such as nylons, acetals, and phenolics, are occasionally used unlubricated where sliding speeds are low, but they require lubrication by oil, grease, or water for really useful performance.

Silver, gold, and tin have useful antigalling properties in slow sliding, but metallic coatings are mainly used as lubricants only in high vacuum, where silver, gold, barium, gallium, and lead have all been used successfully.

20.10 GAS LUBRICATION

Gases can be used to provide full-fluid-film lubrication in the same ways as liquids in hydrodynamic and externally pressurized bearings. The physical laws governing behavior are the same for both liquids and gases, but the very low viscosities of gases lead to considerable practical differences in their use, especially in self-pressurizing, or "gas-dynamic," bearings:

1. Operating speeds are much higher to compensate for low viscosity.
2. Surface finish and precision must be better because of the much smaller lubricant-film thickness.
3. Lubricant flow rate is higher for the same pressure differential.
4. Load-carrying capacity is generally low.

As a result, gas bearings tend to be small, high-speed, and lightly loaded, with tight tolerances and high-quality surface finishes. The overall design and manufacturing cost is high, and they are mainly used in high-technology applications.

Any gas or vapor can be used provided that it is chemically stable under the operating conditions and does not attack any of the system materials. If no chemical change takes place, there is no upper temperature limit to the use of a gas, and the viscosity increases as temperature increases.

Air is the most common gas used in gas lubrication. Nitrogen or helium may be used where inertness is important. Otherwise, any gas which is available can be used, especially if it is available at high enough pressure for external pressurization.

Some of the advantages of gas lubrication are high precision, very low friction, cleanliness, and ready availability of lubricant. The greatest potential advantage is the wide temperature range. In theory, it should be possible to design a gas bearing to operate from –250 to +2000°C. The corresponding disadvantages include the demanding design and construction requirements, the low load-carrying capacity, and the need for a very clean gas supply. Examples of important applications of gas bearings are dentists' air-turbine drills, high-precision grinding spindles, and inertial gyroscopes.

20.11 LUBRICANT FEED SYSTEMS

In many lubricated components, no feed system is needed, because the initial lubricant fill is sufficient to last the required life. A feed system becomes necessary when the lubricant must be replaced or replenished, for one of the following reasons:

1. The temperature is too high, so that the lubricant must be removed and replaced by a fresh charge of cooler lubricant.
2. Lubricant becomes depleted by leakage or creepage and must be topped up.
3. Lubricant decomposes and must be replaced with a fresh charge.
4. Lubricant becomes contaminated and must be replaced with clean material.

Where the rate of loss or deterioration is relatively low, it will be sufficient to provide a facility for occasional topping up by means of an oil can or a grease gun, provided that access to the lubricated component is available. Where this occasional manual topping up is not adequate, a lubricant feed system will be needed. It is beyond the scope of this chapter to describe the whole range and design of lubricant feed systems available. It is only possible to give a brief description of the main types and the factors involved in selecting them.

20.11.1 Internal Circulation

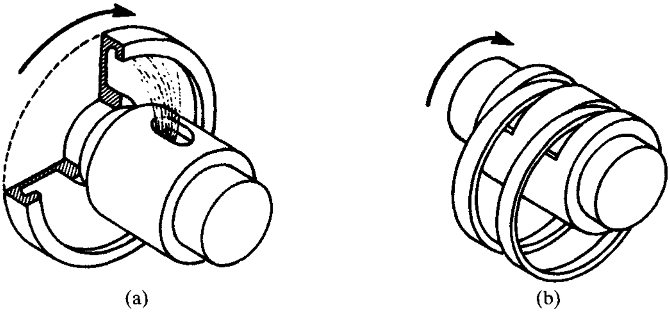
One obvious way to reduce oil temperature, slow down the increase in contamination, and increase the life is simply to increase the quantity of oil supplied in the initial fill. This requires an increase in the volume of space available for oil or, in other words, the creation of an oil reservoir or sump adjacent to the lubricated bearings or gears.

Circulation of the oil can be ensured by arranging for the moving parts to dip below the surface of the oil. But they should not be completely submerged because the resulting viscous drag and churning of the oil lead to excessive power consumption and heating. For slow-moving components this problem is not serious, but for high speeds the depth of immersion is critical, and the following guidelines are useful:

1. Gears should be immersed to twice the tooth height. In a vertical train, the oil level should be just below the shaft of the lowest gear.
2. Rolling bearings should be immersed to halfway up to the lowest rollers or balls.
3. Crankshafts should be immersed so that the oil level is just above the big-end bearings at their lowest point.
4. The oil level should be higher for slow operation than for higher-speed systems.

Oil is carried by the partly submerged components to contacting surfaces and is also spread by splashing. Where transfer by these two mechanisms is inadequate, the oil feed can be improved by the use of rings or disks, as shown in Fig. 20.7. Both operate by providing a larger surface with higher peripheral speed to transfer the oil, but they do not cause excessive viscous drag because they are both uniform in shape.

Disks have an advantage over rings in that they can be designed to propel oil axially as well as radially, and this is particularly useful for bearing lubrication. Usually plain bearings cannot be adequately lubricated by partial immersion in oil unless the oil flow is augmented by a ring or a disk. If a weir is incorporated, part of the splashed oil can be trapped and directed to critical locations.



(a) (b)

FIGURE 20.7 Ring and disk lubrication. (*a*) Disk; (*b*) ring. *(From Ref. [20.1].)*

20.11.2 Topping Up Systems

Where the main problem is loss of oil by leakage or creep, it may be sufficient to set up a wick or drip feed to provide a small-scale supply. Wicks or pads consist of porous or permeable materials such as felt which transfer oil by capillary action to the bearing surfaces. The pads may form a path from a reservoir to the bearing or may simply contain a small initial oil fill to increase the quantity available and feed it slowly to the bearing. This latter approach is commonly used in small electric motors.

Drip feeds consist of small reservoirs mounted above the bearing or gears and equipped with a feed tube with some form of flow regulation and usually a sight glass. They can be used to provide a much higher flow rate than a wick.

20.11.3 Centralized Total-Loss Systems

Wick and drip feeds are examples of total-loss systems, in which no attempt is made to collect the oil after feeding it to the bearings or gears. Far more sophisticated total-loss systems can be used to supply oil or grease to a number of separate components.

The requirements of centralized total-loss systems are basically very simple. A typical system consists of a reservoir, a single pump to pressurize a manifold, and a number of controllers, each regulating the feed to a single lubrication point. Alternatively, the flow to several lines may be controlled by a multipiston pump, in which individual single-cylinder piston pumps are operated by cams on a common camshaft immersed in the lubricant. The number of outlets can vary from one to several hundred.

The main advantage of centralized total-loss systems is that they reduce the labor required where a large number of components need relubricating. They are also valuable where the lubrication points are not readily accessible. Their disadvantages are that they do not provide any form of cooling or removal of contaminants, and there is no recovery of used lubricant.

20.11.4 Oil Mist or Fog Systems

One type of total-loss system which has become widely used in recent years is oil mist or fog, in which fine droplets of oil are carried by a stream of air from a reservoir to a bearing or gears. The mist or fog of oil in air is produced by passing the airstream through the reservoir at low speed and low pressure. The oil is usually formulated to have low surface tension. The resulting dispersion of oil droplets is passed through steel, copper, or plastic pipes to the vicinity of the lubricated component. Passage through fine nozzles, or reclassifiers, then increases the linear flow rate to something over 45 meters per second (m/s) and thus causes the oil droplets to coalesce, producing a flow of liquid oil to the lubrication point.

Oil mist and fog systems have two advantages over other total-loss systems in that the oil supply rate can be very low, resulting in a clean system, and the airflow gives a significant amount of cooling.

20.11.5 Oil-Circulation Systems

The most sophisticated centralized systems are those in which the lubricant is collected after use and returned to the reservoir for recirculation. The basic requirements of such a system are a reservoir, a pump, possibly a flow divider or proportioner, feed lines, and return lines.

In practice a full-circulation system is likely to be more complex and to include many of or all the following components:

Multiple or divided reservoirs
Heaters
Coolers
Oil-level warning devices
Full-flow filtration to protect the pump
Bypass filtration
Pressure switches and alarms
Water separators
Chip detectors
Sampling points
Sight glass

Circulation systems give a high degree of control over the quality and quantity of oil supplied to each component, enabling the cleanliness and the temperature of the oil to be controlled. Their only disadvantage is their complexity and therefore their cost.

20.12 LUBRICANT STORAGE

The storage of lubricants, like that of any other class of goods, depends first on making rational decisions about the number of varieties and the quantities which it is necessary to store. The special factors which then need to be considered in storing lubricants are as follows:

1. Lubricants are an integral part of the precision components in which they are used. They must therefore be treated as precision components and protected carefully against contamination by dirt, water, or other materials. Never store them in the open.
2. Because most lubricants are liquids, they have no characteristic shapes, and it is very easy to use the wrong lubricant in a machine. This is always undesirable and sometimes catastrophic. So it is important to label lubricant containers carefully and to control their issue and use.
3. Some lubricants deteriorate in storage, and it is important to use supplies in proper rotation and ensure that storage lives are not exceeded.
4. Many lubricants are flammable, and special precautions are necessary to reduce fire risk.
5. Lubricants are slippery, and spillages can cause accidents. Floor gratings and drainage channels should be supplied, and absorbent powders or granules kept available to absorb spilled oil.
6. Oil drums are very convenient and satisfactory containers for storing lubricants, but water can collect in the recessed top and enter even through sealed apertures to contaminate the contents. Drums should always be stored horizontally and never upright.

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