Advanced Diploma in Engineering and Technology

EAL

EMTA Awards Limited

Maintenance of Mechanical Systems

Unit 29.2

(Lubrication)

The Principles of Lubrication

Whenever the surfaces of two bodies are in contact, the force of friction will resist relative motion between them. The operation of almost all industrial equipment relies on the relative motion of separate machine elements and lubrication is necessary to overcome the effects of the friction forces. To lubricate means ‘to make smooth and slippery’, and thus the application of a lubricant helps to reduce the effect of friction. Friction causes energy to be wasted in the form of heat and causes the rubbing surfaces to wear. The introduction of a lubricant separates the surfaces in contact and thus reduces the effects of friction although friction can never be entirely eliminated.

The basic purposes of lubrication are to:

- reduce friction
- reduce wear
- dampen shock
- cool moving elements
- prevent corrosion
- seal out dirt

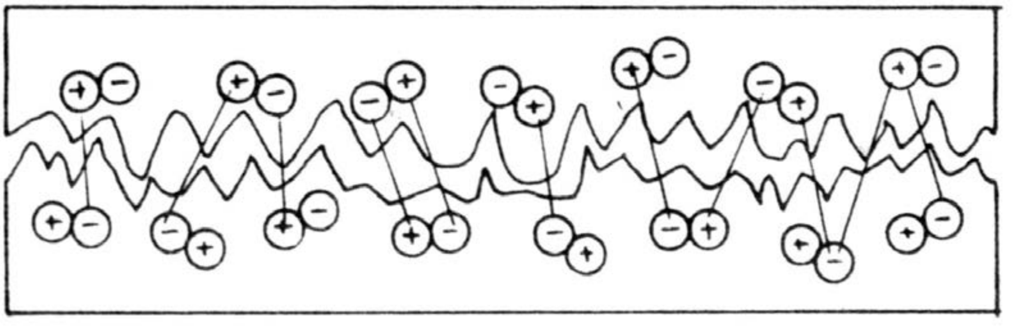
Friction

The force of friction always opposes relative motion between two bodies regardless of the shape. Friction not only exists between solids but also between liquids and solids and between gases and solids. However, we are only concerned here with friction between solids.

Causes of Friction

Molecular attraction

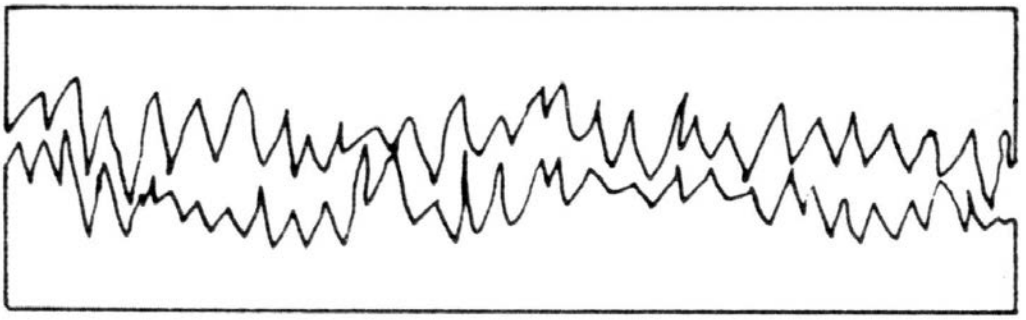
The molecules of a substance are held together by electromagnetic forces between positively and negatively charges atoms as shown below. These forces can also act across the boundary of two substances in contact. Hence the negatively charged atoms of one substance attract the positively charged atoms of the other and vice versa. This molecular attraction increases as the surfaces in contact become smoother and theoretically two perfectly flat surfaces can not be separated once they come into contact except by mechanical means.



Electromagnetic Forces of Attraction

Interlocking of asperities

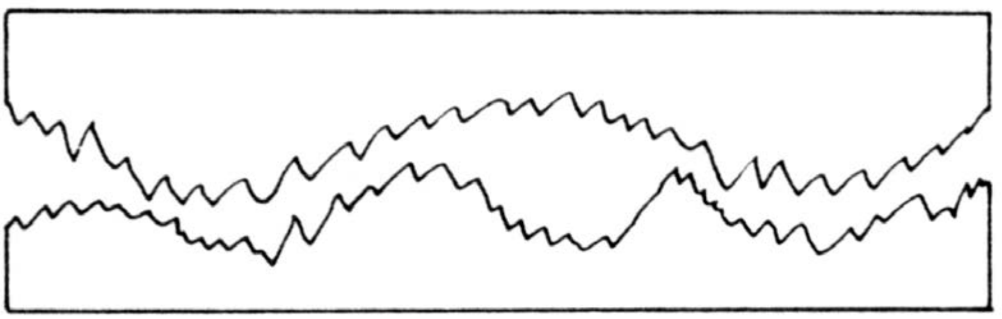
When viewed under a microscope even the smoothest surface is seen to contain a series of peaks and valleys **(asperities)**. When the surfaces are in contact with each other, these asperities interlock and cause resistance to relative motion.



Interlocking Asperities

Surface waviness

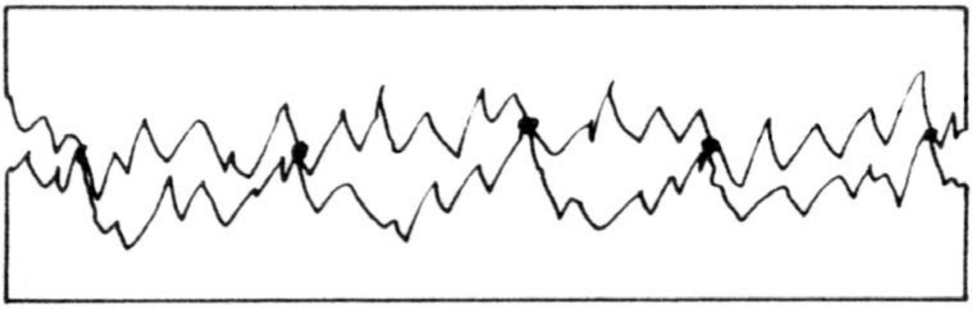
No surface is, in fact, perfectly flat but contains an element of waviness on which the irregularities referred to above are superimposed, as shown below.



Surface Waviness

Local welding

Because it is only the tips of the asperities that come into contact, the actual area of contact is much less than the total surface area. This means that the force between the surfaces, instead of being carried by the whole surface area, is only carried by that part in actual contact. Hence the pressure developed on these areas is extremely high and often can be sufficient to generate enough heat to cause the surfaces to melt and stick together as shown below. In order for the surfaces to move relative to each other, it is necessary for these welds to be broken.



Local Welds

Friction force

The amount of friction developed, that is, the size of the friction force, depends on:-

- the type of frictional system.
- the nature and condition of the surfaces.
- The normal force between the surfaces.

$$F = \mu N$$

where:-

F = force of friction

μ = coefficient of friction

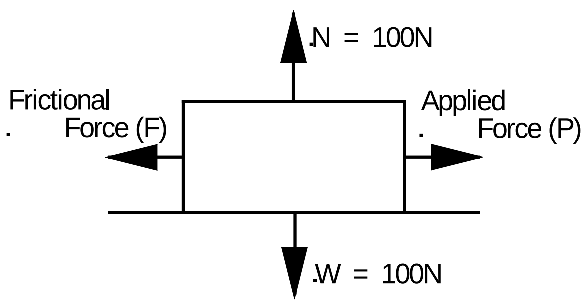
N = normal reaction between the surfaces

The lower the value of 'μ' the more easily the surfaces will slip over one another. This can be seen in the table below giving values of the coefficient of friction of different surfaces in contact.

Material	μ
Wood on Wood (Dry)	0.25 - 0.5
Metal on Wood (Dry)	0.2 - 0.6
Metal on Metal (Dry)	0.15 - 0.3
Metal on Metal (oiled)	0.07 - 0.08
Clutch/Brake Lining	0.3 - 0.55

Example

A block of metal has a weight of 100 newtons and is resting on a horizontal metal surface. The coefficient of friction between the metal surfaces is 0.2. What force is required to start moving the block?



$$F_{max} = \mu N = 0.2 \times 100 = 20 \text{ N}$$

Re-capping

When an object, such as a block of wood, is placed on a floor and sufficient force is applied to the block, the force being parallel to the floor, the block slides across the floor. When the force is removed, motion of the block stops; thus there is a force which resists sliding. This force is called **dynamic** or **sliding friction.** A force may be applied to the block which is insufficient to move it. In this case, the force resisting motion is called the **static friction.** Thus there are two categories into which a frictional force may be split:

1. ***dynamic or sliding friction force which occurs when motion is taking place***

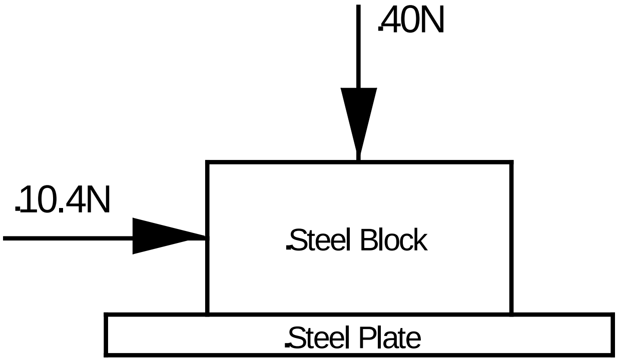
2. ***static friction force which occurs before motion takes place***

Note

The value of dynamic coefficients of friction are lower than those values for static coefficients of friction.

Example

A block of steel requires a force of 10.4N applied parallel to a steel plate to keep it moving with constant velocity across the plate. If the normal force between the block and the plate is 40N, determine the dynamic coefficient of friction.



As the block is moving at constant velocity, the force applied must be that required to overcome frictional forces, i.e.

the frictional force , F = 10.4N

the normal force is 40N.

Therefore:

$$F = \mu N$$

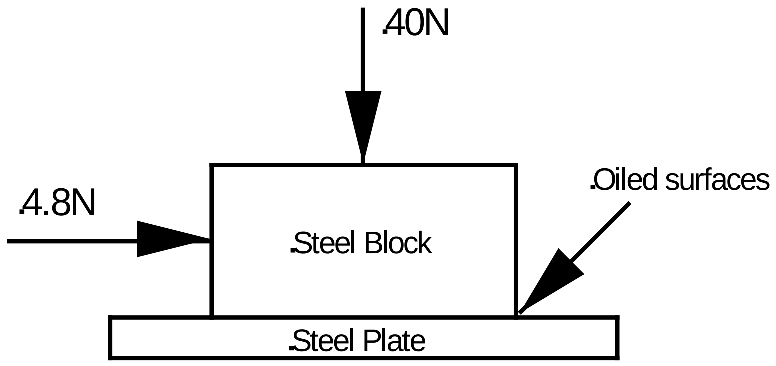
Transposing this equation in terms of 'μ' we get:

$$\mu = \frac{F}{N} = \frac{10.4}{40} = 0.26$$

i.e. the dynamic coefficient of friction in this situation is 0.26

Example

Still considering the last example the steel block and the steel plate are now lubricated and the dynamic coefficient of friction falls to 0.12. Find the new value of force required to push the block at a constant speed.



The normal force depends on the weight of the block and remains unaltered at 40N. The new value of the dynamic coefficient of friction is 0.12.

Using:

$$F = \mu N = 0.12 \times 40 = 4.8 \text{ N}$$

The block is sliding at constant velocity, thus the force required to overcome the frictional force is also **4.8N**, i.e. the require applied force is **4.8N.**

Example

The normal force between two surfaces is 100N and the dynamic coefficient of friction is 0.4. Calculate the force required to maintain a constant speed of sliding.

The normal force between two surfaces is 50N and the force required to maintain a constant speed of sliding is 25N. Calculate the dynamic coefficient of friction for this situation.

Example

The maximum force which can be applied to an object without sliding occurring is 60N, and the static coefficient of friction is 0.3. Calculate the normal force between the two surfaces.
The coefficient of friction of a brake pad and a steel disc is 0.82. Determine the normal force between the pad and the disc if the frictional force required is 1025N.

Types of Friction

There are three types of friction that can exist between solids.

Static Friction

When a force is applied in order to move one surface with respect to another there is a certain minimum force required before movement can be achieved. The friction force resisting motion can be calculated from the relationship:-

$$F = \mu_s N$$

Where:- μ_s Is the coefficient of static friction.

Dynamic Friction

Once motion occurs, the force required to maintain it reduces and is less than the force required to initiate motion. This force can also be calculated from the relationship:-

$$F = \mu_d N$$

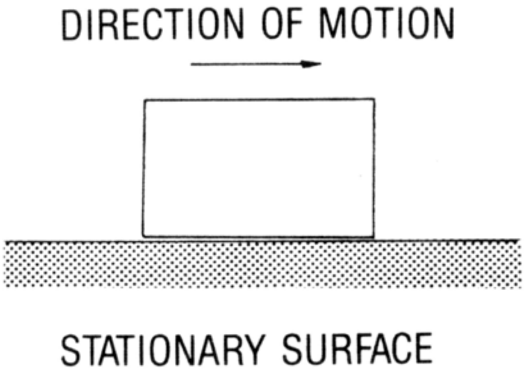
Where:- μ_d Is the coefficient of dynamic

The coefficient of dynamic friction is always less than the coefficient of static friction for any two surfaces because of the increased adhesion due to local welding that occurs when the surfaces are stationary. These coefficients are determined by experiment and common values can be found from engineering tables.

Dynamic friction is the main concern in the case of machine elements and there are two types to consider:-

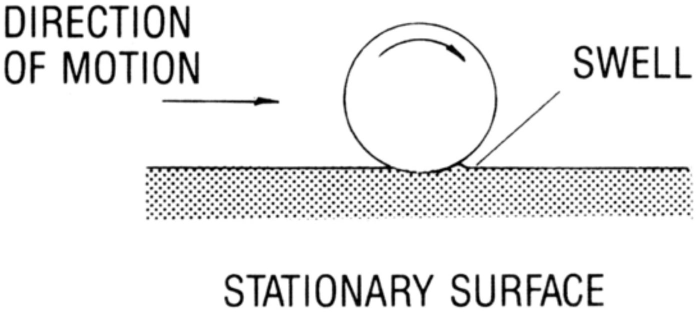
Sliding Friction

This is the commonly understood situation giving rise to friction involving one surface sliding over another. This is the type of friction which occurs in plain bearings, cylinders, slides and cross heads, etc.



Rolling Friction

This is a rather different form of friction and to understand how it arises we must consider what happens when a ball, roller or wheel rolls across a surface. Although it is not usually visible to the naked eye some deformation of the opposing elements occurs with the result that a 'swell' in the surface occurs ahead of the rolling element as shown below:-



The swell causes resistance to motion and this can be reduced, as with rolling element bearings, by making the surfaces as hard as possible in order to resist deformation.

Effects of Friction

There are two major effects of friction which have consequences for machine elements and which lubrication is intended to overcome. Much of the energy that is used to overcome the force of friction is converted to heat. If this heat is not dissipated, but is allowed to build up, the moving elements may fuse together or ‘seize up’.

The other effect of friction, which also uses up energy, is ***wear***. The constant rubbing of one surface on another causes a physical change to occur to the topography of the surfaces and this may ultimately lead to a stage where the elements concerned can no longer perform their function effectively. The analysis of wear patterns is an important step in the troubleshooting process and in the assessment of the lubricant effectiveness.

Wear

Wear can be defined as’ the transformation of matter by use’ and it results in the diminishing of the dimensions of machinery parts. Mechanical wear is the most important of four types of wear which convert useful material into useless debris. The others are chemical ***(corrosion),*** bacteriological ***(decay)*** and electrolytic ***(metal removal).*** Mechanical wear is primarily caused by the relative motion of the surfaces in physical contact and is a complex process often occurring as a result of some combination of the following:-

Adhesive Wear

The two surfaces in contact bear on the tips of the asperities which results in local welding and causes surface wear. When relative motion takes place, a shearing process occurs. Sometimes the local welding is so strong that instead of shearing taking place at the surface, grain displacement occurs, creating pits and graters. This known as ***'galling'.*** Adhesion is the most fundamental type of wear and occurs according to the nature of the opposing surfaces.

Abrasive Wear

Abrasion occurs when particles of hard material become trapped between the surfaces or when hard particles are embedded in or attached to an opposing surface. The hard particles remove metal from the softer material rather like a grinding operation. The hard particles may be present in the materials or may accumulate due to the shearing action between the surfaces. Abrasive particles may also enter the space between the surfaces from external sources.

Fatigue

Fatigue failure is caused by repetitive or cyclic stresses which weaken a material and cause failure to occur at a level of stress well below the normal strength of the material. This can happen in rolling element bearings due to the cycling effect of the rolling elements, and in plain bearings due to the fluctuating load patterns. Fatigue first affects the sub-surface region and ultimately causes cracks to appear on the surface of the material. As the process progresses the surface begins to flake off. When this condition becomes severe it is known as ***'spalling'.***

Fretting

Fretting often known as false brinelling, is a type of corrosion which occurs when there is a slight, imperceptible motion between two surfaces in contact. The source of such motion is usually vibration. The surface of the area of contact deteriorates and break down to form oxides. This problem is sometimes encountered when machinery is transit, and the vibration of the carrier is transmitted to rolling element bearings. The slight motion between the rolling elements and the raceway can be sufficient to cause fretting to occur. The problem of fretting can be solved by eliminating the relative motion or plating the surface with non-oxidising materials, rather than by lubrication. In the example given above, barring the machine over from time to time may avoid the problem.

The Theory of Lubrication

The purpose of lubrication is to reduce the friction between two contacting surfaces in relative motion by introducing a lubricant between the surfaces. In theory, any substance, whether it be liquid, solid or gaseous, may act as a lubricant, although in practice only a limited number of materials have the properties necessary to act as effective lubricants.

Lubricants work by creating special conditions between the surfaces in contact. There are four main types of lubricant film conditions that can exist:-

Dry Friction

When surfaces are clean and dry and no lubricant exists, the condition is referred to as dry friction. This condition gives rise to the greatest frictional resistance to motion.

Boundary Friction

In this condition a thin layer of lubricant is present but significant metal-to-metal contact still exists. Hence part of the load is taken by the lubricant, but most is still taken by the surface high spots. This condition, when used to combat heavy loading, is known as extreme pressure lubrication.

Metal-film lubrication

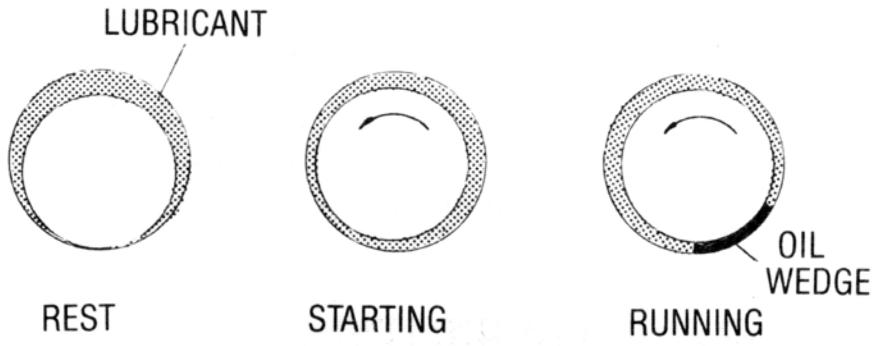
This is an intermediate condition between boundary and full-film lubrication in which the lubricant layer is thicker than in boundary lubrication, but some metal-to-metal contact still exists.

Full-film lubrication (also called thick-film)

This is the condition in which the moving surfaces are completely separated by the lubricant film. This can occur in three different

Hydrostatic – When the lubricant is supplied under pressure from an outside source e.g., a pump or gravity feed.

Hydrodynamic – In which the pressure develops due to the resistance of the lubricant itself. This is the type of lubrication that occurs in a plain bearing and can best be understood by examining how the lubricant film forms in that situation, this is shown below in the illustrations.



While at rest the journal sits on the bottom of the bearing as shown. On start-up it climbs up the side of the bearing and establishes a lubricant film which, as it develops, forces the journal over to the other side of the bearing where it rides on a wedge of lubricant. As the lubricant is drawn into the wedge by the action of the journal it is compressed, and the pressure developed keeps the metal surfaces apart. As the velocity of the journal increases, the wedge builds up and forces the journal and bearing closer to a concentric relationship.

Elastohydrodynamic – This form of lubrication is associated with rolling friction and involves a combination of the effects of elasticity of the surfaces in contact and the lubricant characteristics. When a ball or a roller contacts a raceway, both surfaces deform slightly but return to their original shape when the element moves on, due to the elasticity of the materials. As the rolling element climbs out of the depression lubricant is drawn into the space between the element and the raceway, and a hydrodynamic film is formed similar to that in a plain bearing.

In engineering applications such as plain bearings it is desirable to achieve full-film lubrication to provide maximum separation of the surfaces. Where loads are very high this may not be possible, and the use of extreme pressure lubricants may be needed in order to maintain boundary lubrication.

For components where positional accuracy is essential, such as ways and slides, full-film lubrication is undesirable and boundary lubrication is preferred because metal-to-metal contact involved ensures more precise positioning of the components.

Lubricant Selection

The selection of a lubricant is determined by the following factors:

Load – the load on a bearing will determine the pressure that the lubricant will have to work against.

Speed – as operating speeds increase the lubricated surfaces will tend to wear faster.

Temperature – the operating temperature may affect the properties of the lubricant.

Environment – the lubricant may be required to cope with the presence of water or corrosive materials.

Lubricant selection should normally be left to those who are expert in the field. However, as a general rule it is worth remembering that for plain journal bearings:

- *for light loads and high speeds – use a lubricant of low viscosity; and*
- *for high loads and low speeds – use a lubricant of high viscosity.*

The decision of whether to use oil or grease as the lubricant will depend on the operating conditions.

The following comparative advantages should be taken into account:

Oil provides cooling
feeds more easily and can be fed from a central supply
washes away dirt
can also lubricate other elements such as gears
absorbs less torque.

Grease allows simpler bearing designs
Provides better sealing against dirt
Is easier to contain and seal
Allows longer periods without attention.

Methods of Application

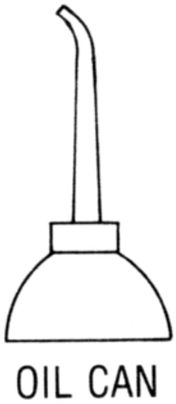
The golden rule of lubrication is said to be: ***'Good lubrication depends on the right lubricant being available in the right quantity at the right time.'*** For this to be achieved the technician must be aware of a number of basic principles governing the application of lubricants.

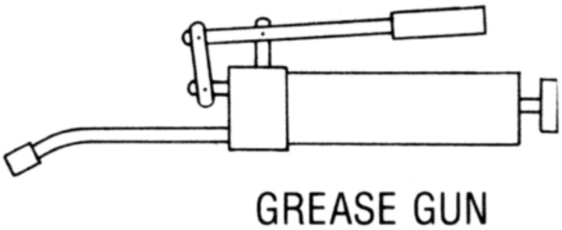
- Cleanliness is vital. Lubricating equipment must be kept free of dirt and other contaminants.
- Lubricants are not necessarily interchangeable and as a general rule should not be mixed. Before changing lubricant the equipment should be cleaned out.
- An excess of lubricant, especially grease, will cause excessive heat to build up and eventual breakdown of the lubricant.
- Lubricant filters or strainers should always be changed at the recommended time.
- The selection of lubricant for a particular application should be left to qualified personnel if possible.
- Inadequate lubrication can often be identified by the operating condition of the bearing, especially its temperature. As a general rule, if a bearing is too hot to hold a hand on it, then lubrication may be inadequate and should be investigated.
- Lubricants are potentially hazardous materials and should be stored regarding safety and effect of the environment.

There are four basic methods by which lubricants can be applied and these are selected according to design criteria and the demands of the equipment.

Manual Application

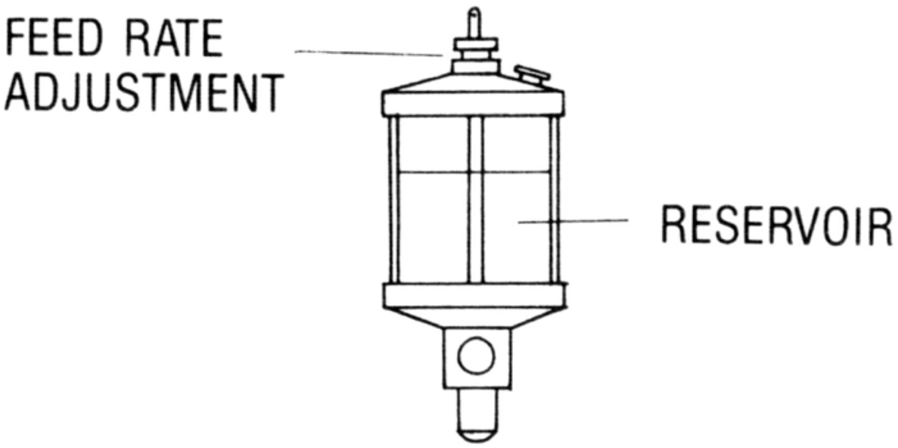
Whether the lubricant is liquid, semi-solid or solid the simplest method of application is by hand. An oil can may be used for liquid lubricant, a grease gun for grease and a brush or spray gun for solid lubricant.





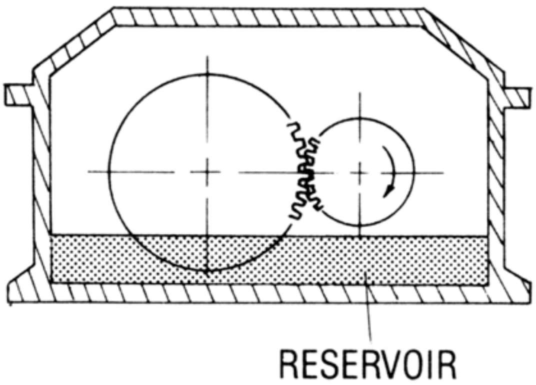
Gravity

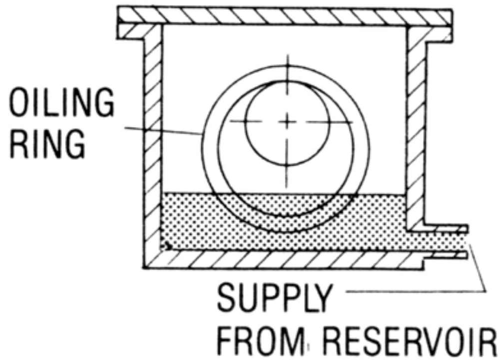
This method is only suitable for liquid lubricants and is sometimes referred to as drip-feed oiling. There are various types of drip-feed oilers and they usually include some method of feed regulation.



Splash Lubrication

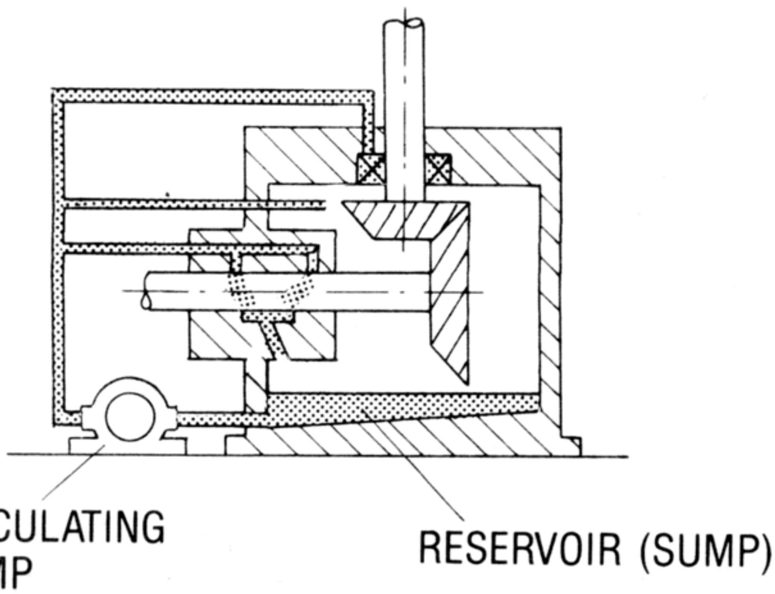
Splash lubrication relies on the components requiring lubrication being partially immersed in an oil sump so that they pick up oil as they rotate. The oil picked up in the process may also be deposited on the shaft bearings and other components. A variation on this method is the ring-type oiler which uses a steel or brass ring which rotates with the shaft and picks up oil which it deposits on the upper surface of the shaft. Examples of these methods are shown below.





Pressure Lubrication

Many industrial applications, especially where loads are heavy and operating speeds are high, require a pressurised system to ensure that an adequate supply of lubricant can be maintained. This usually takes the form of a circulating system such as that shown below.



Characteristics and Properties

There are four basic types of lubricant:

- liquid
- semi-solid or plastic
- solid
- gaseous

and they can be classified according to their source:

- animal
- vegetable
- mineral

Most lubricants are mineral based and are obtained from petroleum by refining processes and further purification and blending. Petroleum and petroleum products belong to a group of chemicals known as 'hydrocarbons' because they are compounds of the elements hydrogen and carbon in varying combinations.

Animal fats come from common animals such as cattle, sheep, pigs and fish and are melted down to remove impurities. Vegetable oils are produced by squeezing vegetables and seeds (e.g. soyabean and rapeseed) to produce pulp and juice and then further refined to remove impurities. Animal and vegetable oils are less stable than mineral oils and break down more easily. Lubricants are classified according to their properties and several standard tests are applied to common types of lubricants, such as oils and greases, n order to determine their properties.

Criteria for measuring the properties of oils

The properties of lubricating oils are measured by the following criteria:

Viscosity – This is the single most important characteristic and refers to the ‘thickness of a fluid and is also described as resistance to flow. Viscosity is affected by temperature and decreases with increasing temperature. There are various ways of measuring viscosity, all of which are based on the time taken for a fixed volume of oil to pass through a standard orifice under standard conditions. ***The SI unit is the centistoke (cSt).***

Viscosity Index – The rate of change of viscosity with temperature is known as the viscosity index. It is normally desirable for the viscosity of a lubricant to remain the same over a wide range of temperatures. A high viscosity index indicates such a property whereas a low viscosity index indicates that the oil tends to thin out rapidly with increasing temperature.

Flash Point – This is the temperature at which the vapour of a lubricant will ignite.

Fire Point – This is the temperature, higher than the flash point, required to form sufficient vapour from the lubricant to cause it to burn steadily.

Pour Point – This is the low temperature at which the lubricant becomes so thick that it ceases to flow.

Oxidation Resistance – When hydrocarbons are exposed to the atmosphere, especially at increased temperatures, they tend to absorb oxygen. This causes a chemical change in the oil that makes it useless for lubricating purposes.

Emulsification – An emulsion, e.g., a mixture of water and oil, is undesirable because it has poor lubricating properties. Emulsification is a measure of the tendency of an oil to mix intimately with water. Demulsibility measures the readiness of an oil to separate from water in an emulsion.

Criteria for measuring the properties of greases

The properties of greases, being semi-solid rather than liquid, are measured by a separate set of criteria:

Hardness – Because greases are semi-solid, they can be considered as ranging from hard to soft. These ratings are based of the results of a penetration test and the standard gradings used by the National Grease Institute (US) are as follows:

NLGI No.	Consistency	ASTM worked penetration at 25^0C (77^0F) 10^{-1}mm
000	Very fluid	445 – 475
00	Fluid	400 – 430
0	Semi fluid	355 – 385
1	Very soft	310 – 340
2	Soft	265 – 295
3	Semi firm	220 – 250
4	Firm	175 – 205
5	Very firm	130 – 160
6	hard	85 - 115

Dropping Point – This is the temperature at which the grease will change from semi-solid to liquid i.e., the melting point.

Pumpability – This is a measure of the ease with which the grease will flow through a system.

Water Resistance – This determines whether or not a grease will dissolve in water. This property is important where there is a likelihood

Stability – This property determines the ability of a grease to retain its characteristics with time. Some greases become soft and thin after being in use for a while.

Liquid Lubricants

Rather than classifying lubricants according to their composition, it is more useful for industrial purposes to classify them according to their application. There are several commonly recognised categories.

Circulating Oils

These oils are designed to circulate through a closed system such as a crankcase or hydraulic circuit. Because they remain in the system for some time, they normally include a range of additives such as anti-oxidants, anti-foam agents, rust inhibitors, etc.

Gear Oils

Gear oils are required to handle the relatively high pressures that develop between gear teeth and to dampen the shock of impact. They are generally required to have high viscosity although they are often required to lubricate bearings as well and must be able to transfer heat. ***They are normally classified as follow:***

Grade	Viscosity (cSt)
Light	140 – 160
Medium	200 – 240
Heavy	420 – 500
Light E.P.	60 – 75
Heavy E.P.	300 – 360
Cling type gear shield	200 - 240

The oils in the first group are designed for gears running in enclosed spaces and lubricated by splash or pressure systems. The extreme pressure type of oils are particularly used where tooth loads are high, such as hypoid gears used in automotive transmissions. Cling type oils are used for open gears and are specially compounded to resist being thrown off as the gears move. Gear oils often contain anti-wear additives where tooth loads are expected to be heavy.

Machine and Engine Oils

These are general purpose oils suitable for once-through systems and were originally designed for the external operating parts of machinery that could be oiled with cans or cups. They are commonly used on plain bearings and for slides and ways. Viscosities range from 35 – 200 cSt. They should not be used in situations where sludge may form.

Spindle Oils

These are very carefully refined, high quality oils designed to lubricate the spindles of the textile industry and to lubricate delicate instruments and other sensitive equipment. They are usually straight mineral oils with low viscosities ranging from 1 – 25 cSt.

Refrigeration Oils

Oils used for lubricating refrigeration equipment are special straight minerals with low pour point and free of wax and moisture. They range in viscosity from 15 – 120 cSt and are usually non-foaming.

Steam Cylinder Oils

These are special purpose oils, formulated by compounding mineral oils with animal oils, and sprayed into the steam or applied directly to the walls of steam cylinders. The animal oils help to ensure that they adhere to the surfaces they are supposed to lubricate. Viscosities are high and range from 20 – 35 cSt at 100^0C (210^0F). [500 – 1300 cSt at 38^0C (100^0F)].

Special Purpose Oils

Several special purpose oils are available for particular applications, not necessarily associated with lubrication.

These include:

- Fire resistant oils
- Cutting oils
- Heat treatment oils

General Purpose Oils

In recent years manufacturers have developed a range of multipurpose oils which meet multiviscosity or multigrade specifications. These are primarily used for lubricating automotive engines and transmissions and can withstand the variation between summer and winter conditions.

The above categories are only general, and many oils are suited to more than one particular application. The categories are listed merely as a guide and the selection of lubricants should be referred to the supplier.

Greases

Categories of Greases

Soap-thickened mineral oils

These are the most used greases and are classified according to the type of soap base used to thicken the oil.

Calcium-based – The most important general-purpose greases. They do not dissolve in water and are limited to applications below 70^0C (160^0F).

Sodium-based – General purpose greases with a high dropping point of 150^0C (300^0F). They can be used for parts near a heat source.

Barium-based – General purpose greases suitable for temperatures up to 135^0C (275^0F) but less suitable for low temperature applications due to the high soap content.

Lithium-based – Have good water resistance and stability and are suitable for both low temperature -50^0C (-60^0F) and high temperature 150^0C (300^0F) applications.

Strontium-based – Have good resistance to water washing and to corrosion from substances such as salt water. They can also operate up to 175^0C (350^0F)

Aluminium-based – Have a particular advantage that they adhere well to the surfaces they are supposed to lubricate.

Complex – Greases whose basic ingredients have been fortified, modified or treated in some way in order to achieve high performance in a particular application.

Mixed-base – Combine the advantages of two or more different soap bases.

Multipurpose – The advantages of these greases is that they reduce the number of types of grease required in a particular industrial situation and also reduce the possibility of using an inappropriate grease. They are usually either barium or lithium-based and combine the properties of specialised greases

Mineral oils mixed with solids

These are heavy greases used to lubricate rough-fitting components which operate under high pressure or at low speed such as conveyor systems.

Heavy asphaltic-type oils

Although these are thick oils they are classified as greases and are used to lubricate open gearing and wire ropes. They are painted on when hot, and cool to form a protective coating.

Extreme pressure greases

These are designed to give improved load carrying capacity in rolling element bearings and gears. Various types of additives are used to improve the film-strength (resistance to rupture) of the grease. They are often lithium-based and contain further additives to improve lubricity ***(oiliness).***

Roll-neck greases

These are specialised greases used for lubricating plain bearings in rolling mill equipment and are usually used in block form which is cut to shape to fit the bearing.

Synthetic oil-based greases

Various synthetic fluids are used to produce greases with special characteristics not easily attainable with mineral oils.

The fluids used include:

Chlorofluorocarbon polymers, dibasic acid esters, polyglycols, silicones and polyphenol ethers.

The silicone-based greases are particularly useful because they are suitable for a wide temperature range and are resistant to oxidation. For this reason they are often used in sealed-for-life bearings.

Applications of Greases

Ways and Slides

The greases used for ways and slides are usually sodium-based of consistency NLFG No. 1 or 2.

Plain Bearing Greases

Greases can be used for the lubrication of plain bearings operating at low speeds up to about 400 rpm. Grease has a tendency to work its way out of the ends of the bearing so it must be regularly replaced, especially as speeds increase. Most of the soap-based greases can be used for lubricating plain bearings. Lithium-based grease is one of the most versatile.

Rolling Element Bearing Greases

Greases used for rolling element bearings must be free of contaminant and chemically active elements that may attack the bearing or the seal, and they must also maintain consistency in operation. Most general-purpose greases are suitable depending on the particular conditions.

Solid Lubricants

Solid lubricants, such as graphite and molybdenum disulphide, may be used as additives for oil and grease or may be used alone in their dry state where oils and greases do not perform satisfactorily. Solid lubricants may have advantages over oils and greases where:

- Bearings are inaccessible or likely to be missed by routine maintenance.
- The use of liquid lubricants may cause product contamination.
- There is a tendency for galling or seizing to occur.
- Operating temperatures are either too low or too high for oils and greases.
- Fretting corrosion is a possibility.
- Vacuum conditions exist which tend to cause evaporation of most substances.
- The lubricant is exposed to nuclear radiation which causes ionisation of organic compounds and change in viscosity.

The most satisfactory method of application for solid lubricants in the dry state is spraying or dipping. They may also be brushed on, but care must be taken to ensure that film thickness is even. When applied in this way they are usually used in a bonded form using a 'binder' which helps the lubricant to adhere to the surface. Phenolic resins are often used for this purpose.

Molybdenum disulphide in its powdered form is often used on metal forming dies and on threaded parts. Bolts that have been lubricated can be tightened closer to strength limits and undone more easily.

Additives

The wide variation in the requirements of modern machinery is beyond the ability of straight oils and greases to handle and a range of additives has been developed to improve lubricant properties.

The most common types of additives are:

Oxidation inhibitors – These are designed to prevent the chemical breakdown of lubricants and the formation of acids.

Detergents and dispersants – Detergents help to keep surfaces clean by preventing the formation of dirt particles. Dispersants keep the dirt particles in suspension by enveloping the dirt particles and preventing them from adhering to the metal surfaces.

Rust and corrosion inhibitors – These prevent or retard the formation of rust and also protect metal parts against corrosion by contaminants.

Pour point depressants – These are used to ensure that the lubricant will maintain its ability to flow at low temperatures.

Viscosity index improvers – These are added to reduce the effect of changes in temperature on viscosity.

Anti-foam agents – These help to break up the air bubbles that tend to form in a circulating or a hydraulic system.

Anti-friction compounds – Oiliness and lubricity of the lubricant are increased in order to reduce the coefficient of friction between the rubbing surfaces.

Anti-wear agents – These also reduce friction and wear due to scoring, seizing, and rubbing.

Extreme pressure agents – These are used primarily in gear oils and help to cushion the shock between gear teeth at high loads.

Emulsifiers – These keep water away from contact surfaces by forming an oil film around water particles.

Emulsion breakers – When an emulsion is undesirable an emulsion breaker is used to help the oil and water separate more easily.

Adhesive compounds – These ensure that lubricants adhere to surfaces and prevent then being thrown off by centrifugal force or turbulence. A range of organic and inorganic substances is used to achieve these various effects and individual manufacturers of lubricants have their own particular formulae.