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Some Factors Affecting the Movement of Oil in Miniature Ball Bearings

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ABSTRACT

The transport of oil in films less than one micron thick is controlled largely by surface chemical forces, because the gravitational forces operating on such films are one to three orders of magnitude smaller than the surface forces available. Oils spread largely as a result of capillary forces in scratches or submicroscopic irregularities, and because of surface-tension gradients produced by evaporation of volatile components, by adsorption of surface active components, or by differences in surface temperature. Although centrifugal fields intensify inertial effects until they become a significant factor for oil movement in operating bearings, surface chemical forces remain important in gyro bearings which operate on minimum amounts of oil. Hydrodynamic wedge effects join surface chemical forces in the circulation of oil to and from porous separators.

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SOME FACTORS AFFECTING THE MOVEMENT OF OIL IN MINIATURE BALL BEARINGS

INTRODUCTION

The rate and extent of spreading of liquid drops on solid surfaces have practical importance for such varied problems as lubrication, paint application, metal cleaning, agricultural sprays, the action of chemical-warfare agents and disinfectants, and adhesive joints. In spite of this importance, a large proportion of the research that has been done on wetting and spreading by liquids has concerned situations in which the liquid forms a finite contact angle with a plane solid surface. This work has defined the conditions under which spreading is thermodynamically possible (1a). There has been relatively little study of rates of spreading for oils that spread on solid surfaces or of the factors which can alter such rates. This report will summarize, in a qualitative way, what these factors are, and point out their significance for the lubrication of miniature ball bearings.

OIL TRANSPORT

Given a spreading oil, i.e., one that forms a zero contact angle, there are many factors that influence the rate of spreading. It is a familiar fact that oils such as silicones and polybutenes are notorious spreaders, while some others spread only moderately. There is a general impression that oils of low surface tension are the most vigorous spreaders, but critical examination of surface tension and spreading rate data reveal so many exceptions that the generalization is almost useless.

Viscosity

One of the factors that influences spreading rates is obviously the viscosity of the oil. When one deals with an oil film one micron thick, it turns out that if the surface of the oil film moves at the rate of 1 cm/hr the shear gradient is 36 reciprocal seconds. If the oil film is only 0.1 micron thick the shear gradient is 360 sec^{-1}. With a 100-centistoke oil the force required to maintain this rate of 1 cm/hr at the surface of a 0.1-micron film would be 360 dynes/cm^2. The gravitational forces available to promote movement of such a film are of the order of hundredths of a dyne. One hundredth of a dyne would produce a surface velocity in the film of a tenth of a micron per hour, or nine millimeters per year.

The actual drainage of a film on a vertical plate is described by the Jeffreys' equation (2),

$$h = \sqrt{\frac{x\nu}{gt}} .$$

This equation relates the thickness h to the distance x below the upper edge of the film, the time of drainage t, and the kinematic viscosity ν. It can be seen that film thickness at a specified point on the draining plate decreases as the square root of the time, and for different oils, will be proportional to the square roots of their viscosities. Figure 1 shows graphically the prediction of the Jeffreys' equation for the drainage of V78 gyro oil on a smooth vertical surface. The curves show the thickness h of the residual film

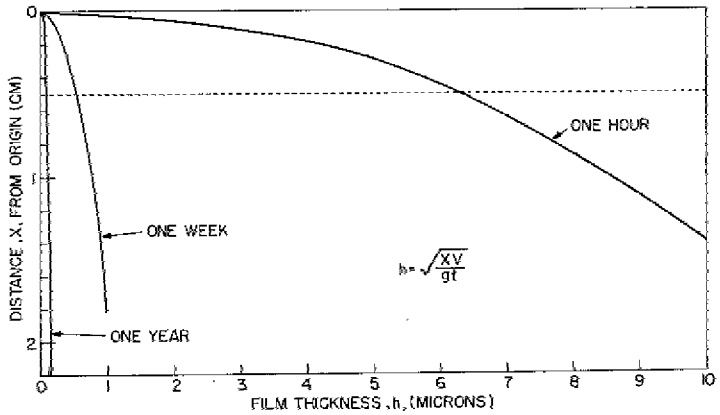


Fig. 1 - Drainage of oil films according to the Jeffreys equation

after three different drainage periods. The film of oil retained on surfaces five millimeters below the highest point wet by the oil, as shown by the dotted line, approaches 0.1 micron thickness after a few months of drainage.

A centrifugal field of 100 g can increase oil drainage by a factor of ten. At 1600 g the rate will be increased 40 fold, but drainage will still be very slow below 0.1 micron thickness.

This approximate limiting thickness for draining V78 films is confirmed by microscope examination of the oil films remaining on miniature bearing surfaces after one to two years of operation. A film of about 0.1 micron remains on bearings at failure. It is not available oil, but it is the essential substrate required before other oil can move over the surface rapidly enough to maintain bearing lubrication.

Surface-Tension Gradients

In miniature bearings, where oil-film thicknesses have usually been less than one micron, much larger forces than those due to gravity are required if we are to observe ready oil transport. For example, the rapid loss of oil from the bearings of stored synchros is difficult to understand unless forces more powerful than gravity are involved. Surface diffusion accounts for some spreading, but it is too slow a process to account for many observed spreading phenomena. It has recently been shown that surface-chemical mechanisms can increase spreading rates by orders of magnitude (1b,1c).

One of these mechanisms was revealed by an attempt to check the Jeffreys equation for some oils. A metal plate was immersed in a beaker of the oil, which was lowered away from the plate, and film thicknesses were recorded by photographing the interference bands shown by the film. Figure 2 shows what happened. In this figure the dashed lines show the profile to have been expected from the Jeffreys equation. Almost every oil, instead of draining away from the original boundary, started spreading upwards. Often the film profile showed a distinct bead of liquid near the leading edge. These spreading films, from 0.1 to 1 micron thick, moved upward against gravity at rates several times greater than the rate of downward movement expected from simple drainage. The results are not easily related to oil viscosities or surface tensions; some of the most viscous of the materials examined gave unusually high spreading rates.

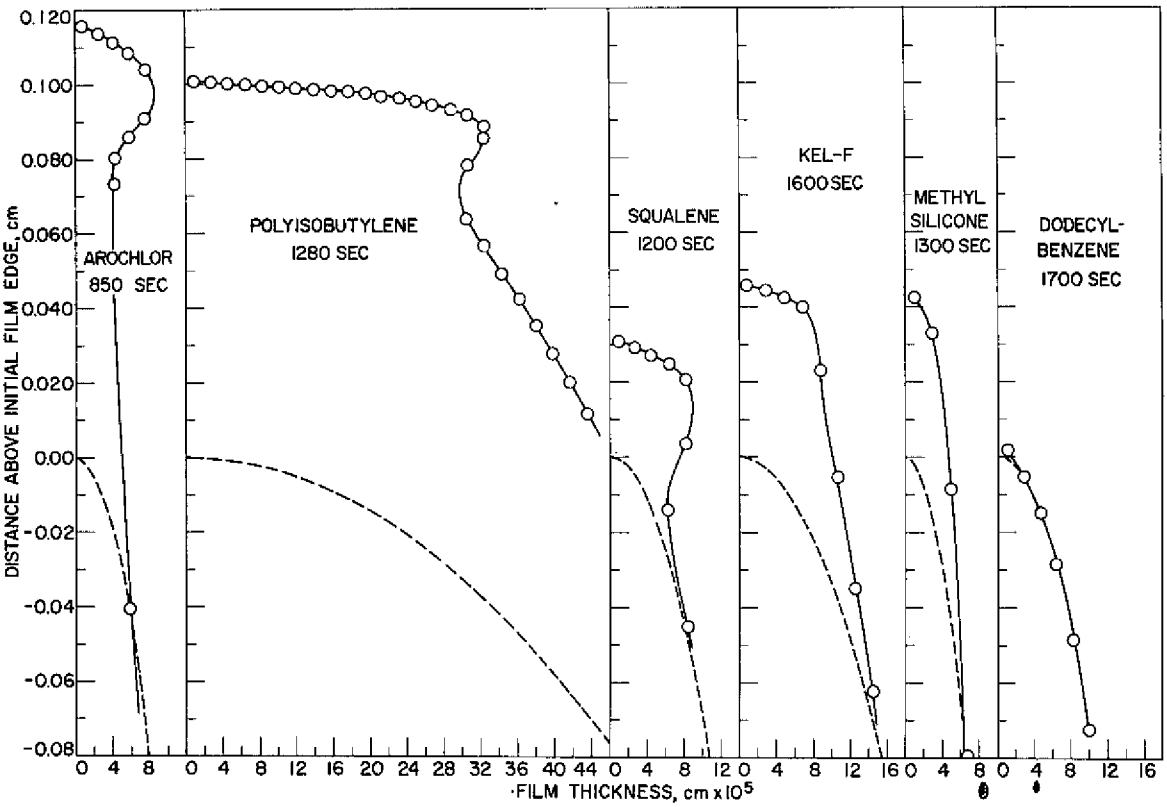


Fig. 2 - Drainage profiles obtained for actual oils at the times specified. The dashed lines show the profiles to have been expected from the Jeffreys equation for drainage on a vertical plate.

The anomalies were explained when several of the oils were redistilled in a molecular still. The purified fraction collected after a forerun of light ends had been removed turned out to obey the Jeffreys equation precisely. A drop of it on a horizontal surface of polished metal showed a zero contact angle, but it spread so slowly that a quick examination would have classed it as a nonspreading oil. The surface tension of the more volatile forerun was found to be lower than that of the pure main fraction. This fact provides a ready explanation of the effect, which is illustrated by Fig. 3. When the edge of the oil film diffuses over the adjacent metal the more volatile material of low surface tension evaporates, so that the surface tension of the remaining film is higher than that of the main body of liquid. This increase creates a surface-tension gradient, which causes a surface flow from low towards high surface tension. This flow entrains the oil beneath by viscous coupling, as shown in the figure, so that bulk liquid is pulled out over the thin film. As new thin film is formed, the process continues. The process is an example of what is called the Marongoni effect (3,4).

From the drainage experiments shown in Fig. 2, it is clear that the vigorous spreaders are those liquids that are known to contain a range of molecular weights, and in which surface tensions are less for the more volatile components, e.g., the silicones and polybutenes. This explanation also takes care of the case of impure polyamylnaphthalene (Fig. 4), which appears to drain from the plate more rapidly than required by the Jeffreys equation (indicated by dashed lines). In this case the more volatile molecules are those containing fewer amyl groups substituted on the naphthalene. Since the proportion of aromatic content is higher in this volatile fraction, it will have a higher surface tension; thus evaporative depletion will lower the surface tension of the liquid at the

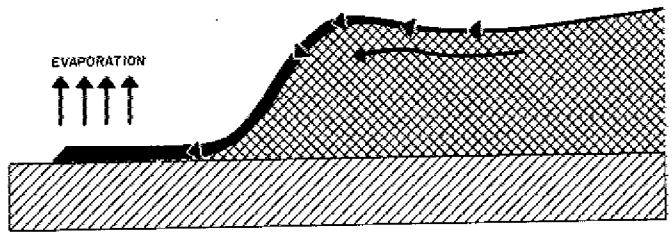


Fig. 3 - Diagram illustrating the increased spreading rate caused by an evaporation-induced surface-tension gradient. As a volatile component of low surface tension is exhausted from the thin edge of the film, the surface tension rises. The weight of the line defining the surface is here made proportional to the increase in surface tension.

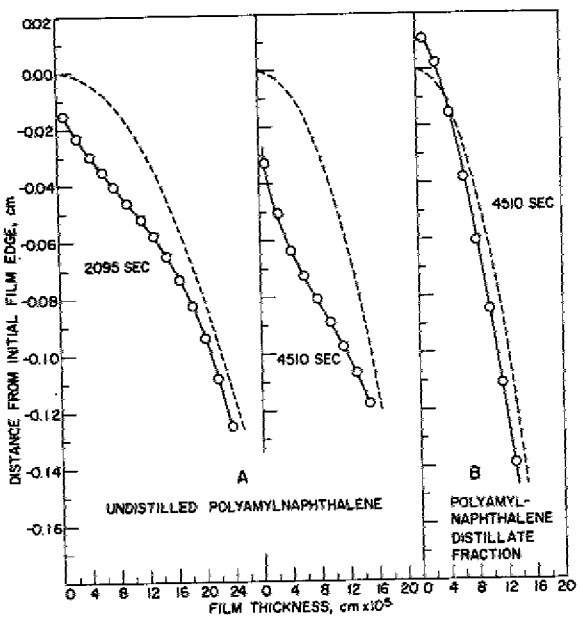


Fig. 4 - Drainage behavior of polyamylnaphthalene

margin, creating a reverse surface-tension gradient which promotes surface flow downwards from the boundary.

Surface-tension gradients can be produced in other ways than by loss of a volatile component. The surface tension of a liquid falls as the temperature rises. The change per degree is small, but over a long period a difference of even a tenth of a dyne will cause oil-migration. Larger gradients than this may occur near miniature bearings if the external environment is cooler than the sealed unit, so that heat flows along a shaft from the bearing to a cooler point. The effects of a large temperature gradient are shown in Fig. 5. Here the temperature-induced surface-tension gradient has heaped the oil up at the ends of the level plate. An interesting example of surface-tension flow induced by temperature effects alone has been noted in thin films of silicone liquids on horizontal glass or metal plates heated to 400°C. Because of the great difference between the temperature of the plate and the air above it, there is a sharp vertical temperature gradient in the liquid film. The surface of any thin spot in the film will be hotter and have a lower surface tension than thicker portions near it. Consequently the film is unstable, and the liquid draws up into small droplets, distributed over a much thinner film on which they nevertheless show zero contact angles. The droplets spread as soon as the temperature is lowered.

Capillary Effects

An equally important mechanism for oil spreading, however, is flow in open capillaries. By open capillaries are meant scratches or depressed channels in the surface

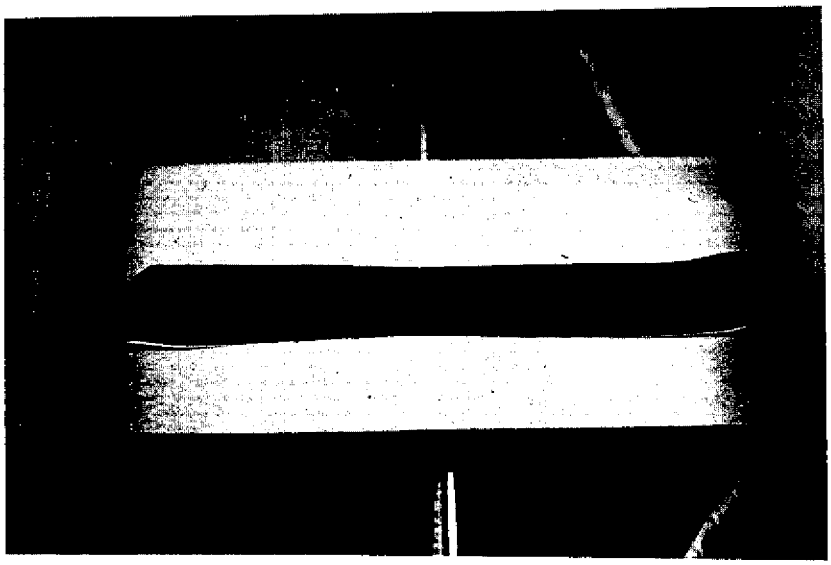


Fig. 5 - The effect of temperature-induced surface-tension gradients on the distribution of an oil film on a centrally heated metal plate

which are small enough so that the flow of liquid along them is dictated by surface chemical rather than gravitational forces. These channels may have many shapes, but it is convenient to discuss the case of V-shaped grooves, which can be generalized to explain the more complex cross sections.

Except when the metal has been plowed or flowed during fabrication, the sides of such grooves are likely to form obtuse angles with each other. The sharper angles will be found on ground surfaces, and the more obtuse on polished surfaces, where the "groove" is frequently ten times as wide as it is deep. Such a groove doesn't look much like a capillary hazard, but it must be remembered that the actual feature is less than 1000 Å wide. When a liquid enters a scratch this small its surface resembles that of a small cylinder laid into the capillary, as in Fig. 6. The less liquid there is in the capillary the greater the curvature of its surface. For the small grooves of interest the radii of curvature are often less than one micron.

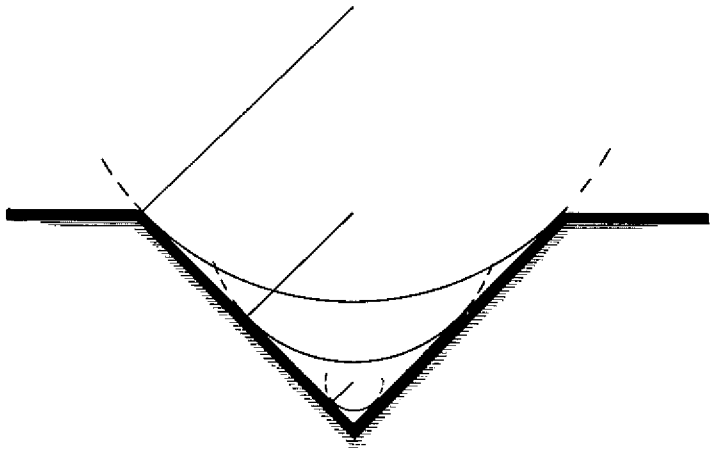


Fig. 6 - Diagram illustrating the decrease in radius of curvature with decreasing amount of liquid in a "V" groove

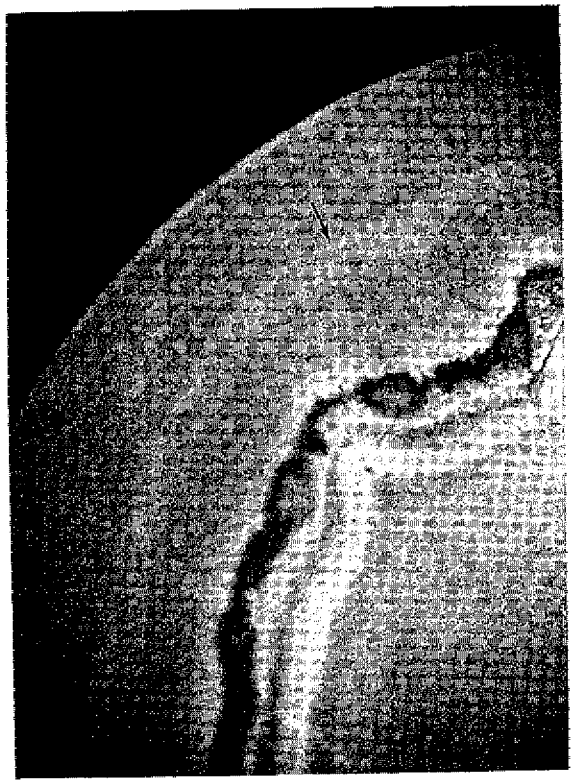


Fig. 7 - Breath pattern showing the advance of silicone oil in capillary scratches (see arrow). The margin of the three-day-old drop is defined by the irregular band in the lower right quadrant.

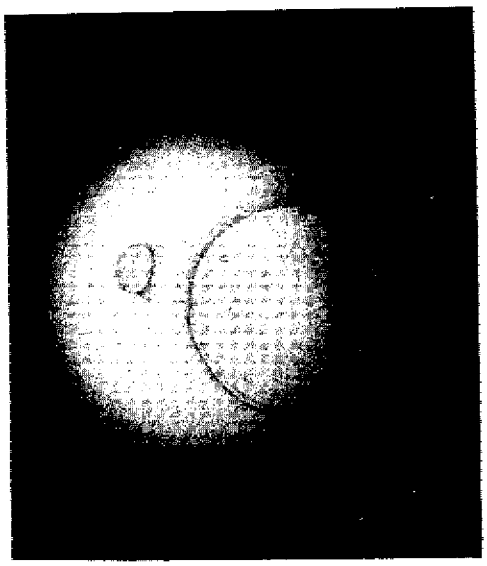


Fig. 8 - The use of a test droplet (left) to detect the invisible film of oil which spreads ahead of an oil drop by flow in open capillaries (finishing scratches)

When the surface tension of the liquid operates on this curvature the effect is to reduce the pressure within the liquid below atmospheric, just as it does at the meniscus of a conventional capillary tube. In the tube the reduced pressure causes the familiar capillary rise. The reduction in pressure is greater the greater the curvature of the surface. A small scratch which intersects a liquid boundary will be completely filled with liquid at the intersection, but less than filled at more distant points. Because of the difference in curvature at the two locations there is an actual difference in pressure within the liquid, and the liquid flows along the scratch much as it would in a closed pipe with a pressure differential. In a small scratch such differences in pressure within the liquid between the completely filled point and the advancing tip may easily amount to several pounds per square inch. These forces become inoperative when the capillary is completely filled, but surface diffusion from the scratches takes some of the oil away, and the capillary process continues until the entire surface between the micro-scratches is covered with a film of oil.

Each step in this spreading may be followed by observing the breath patterns formed around the drop on a cold surface. Figure 7 shows such a breath pattern around a silicone drop which has been resting on a metal plate for three days. The advance of oil along invisible scratches can also be detected by placing a test droplet of a higher-surface-tension oil near the zone of capillary spreading, as in Fig. 8. Here the surface tension gradient produced at the contact between the spreading oil and the test droplet causes the liquid of the latter to flow away from the invisible film, producing a flat on the contact side. It should be noted that even non-spreading oils, which make a finite contact angle on the plane metal surface, will spread in a capillary scratch if the contact angle is less than 90 degrees. Of course the process may be less vigorous in such cases.

It is when capillary spreading and surface-tension gradients combine forces that spreading becomes spectacular. This combination is usually found when oils spread strongly. Capillary spreading and surface diffusion create the ultrathin films from which the volatile

low-surface-tension component escapes by evaporation. Surface flow then pulls bulk liquid forward over the thin films. This action in turn fills new sections of the open capillaries, and the process continues. One of the most unusual and spectacular examples of this combination of capillary advance abetted by surface-tension gradients occurs with pure diester or aromatic hydrocarbon oils, to which a trace of a silicone has been added. In theory, the silicone should adsorb at the drop edge to form a low-energy surface over which the oil does not spread, and in fact the drop appears nonspreading when it is deposited. Within 15 minutes, however, evidence of unusually active capillary flow in scratches appears. Within a few hours the extraordinary pattern shown in Fig. 9 emerges. Here the dark lines are the interference bands formed by the oil layer. Oil has flowed out from the nonspreading drop to fill a reticulated pattern of previously invisible finishing scratches. It has not only filled the scratches, it has heaped oil up into beads and ridges at various places in the network. The thickness of these films can be estimated by counting the interference bands.

The explanation of this peculiar flow is as follows. As the silicone-containing oil spread along the scratches by capillary action, the trace of silicone it contained was adsorbed onto the walls of the scratch. Removal of the silicone raised the surface tension of the oil progressively as it got further away from the drop. The surface-tension gradient thus produced took over from the capillary action, pulling oil out along bank-full capillaries and actually heaping it up into droplets or ridges. These became nonspreading as traces of silicone from the main drop finally arrived and adsorbed on the metal at the drop edge. When the flow had equalized surface tensions in the satellite drops with that in the main drop, spreading ceased and the pattern remained stable for weeks.

It is interesting to turn these ideas about flow in open capillaries toward oil flow through packed spheres in which the interstices are incompletely filled with oil. Figure 10

Fig. 9 - Effect of a trace of silicone on the spreading of an ester oil in capillary scratches. Interference pattern with mercury green light.

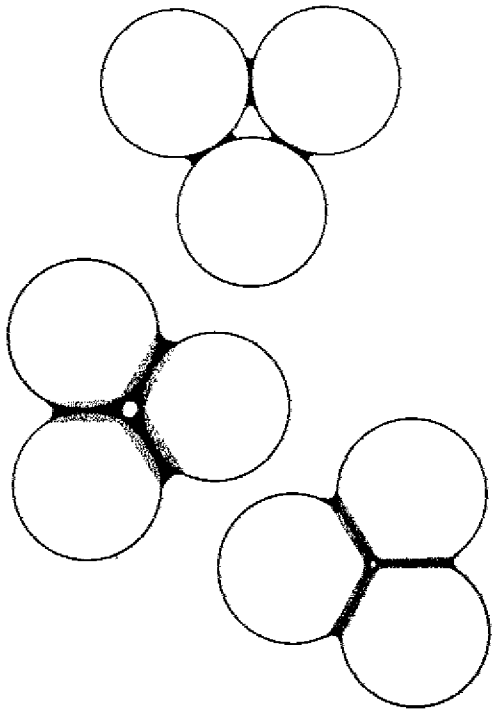


Fig. 10 - Diagrams for capillary retention of oil about contact points of close-packed spheres. Top, nondraining isolated annuli; center, drainable oil at higher oil loading; below, effect of deforming spheres at contact points to favor drainage.

represents three different situations. The three balls at the top are wet with oil, and the excess oil is held in annular wedges surrounding the ball-to-ball contacts. These open capillaries are completely isolated from each other, so oil cannot be drawn from one to another or to the surface of the array by capillary gradients. Oil can pass from one annulus to the next only when the oil loading is great enough to cause the curved surfaces bounding the oil in each annulus to intersect, as in the center diagram. If, however, the spheres are slightly deformed by pressure, as in the lower set, the annuli will intersect at a much lower oil loading, and oil can migrate under capillary gradients.

In the sintered compacts used to form Nylasint separators the dimensions of the pores between the nylon spheres are so small that oil is unlikely to be more than 0.1 micron away from a solid surface at any point in the pore. Capillary flow is therefore extremely slow because of viscous drag. Measurement of the oil remaining in the structure at bearing failure confirms this slow rate of flow; the oil in the micropores appears to be almost completely unavailable for bearing operation. The oil in the large-scale pores between Nylasint clusters, on the other hand, may be several microns away from a solid surface, and flows readily under the available pressure or surface-tension gradients. Attention should also be directed to one other important example of the overriding importance of capillary forces on oil distribution in a bearing. When the oil supply runs low and active wear begins at the edge of the ball track, the wear particles accumulate nearby in a ridge that is a rough version of the close-packed spheres we have just talked about. Powerful capillary forces then draw all the movable oil nearby into the wear debris, thus accelerating race wear until catastrophic failure intervenes. Even an isolated particle of wear debris on the surface can immobilize several times its own volume of oil in the annulus which surface tension forms around the base of the particle.

Capillary forces must also affect the movement of oil in a ball-bearing race as the ball passes over it. Figure 11 shows schematic nonscale sketches of the situation to be expected about an oil-covered ball rolling in an oil-covered race. The upper sketch shows an exaggeration of the oil annulus in elevation and the lower in plan. Oil must accumulate ahead of the ball, so the distribution is unsymmetrical. More importantly, the liquid ahead of the ball will develop a convex curvature as oil is squeezed into it, and that in the rear will have an extremely small radius of concave curvature. The pressure in the front bead will therefore be greater than atmospheric, while that at the rear of the ball will be less than atmospheric. As a consequence there will be a flow of oil in the annulus in the sense shown by the arrows in the lower sketch. The volume of the flow will depend upon the amount of oil present, but it will be greater than would result from centrifugal effects alone. The oil in the traveling annulus will be in approximate equilibrium with the two zones of thicker oil film on each side of the ball track. There will be similar zones of thicker oil around the ball at each side of its rolling track. Excess

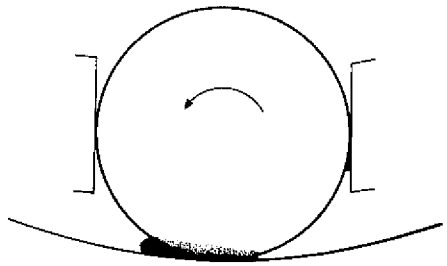
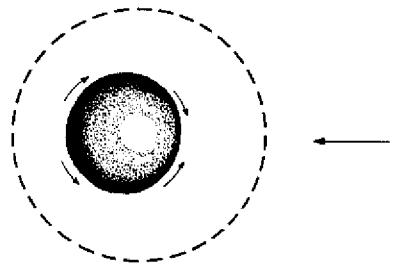


Fig. 11 - Schematic of oil distribution about contact points in a ball bearing



oil transferred to the ball from the retainer will be partly accumulated in these zones and partly in the traveling annulus.

The observed circulation of oil from the ball into the porous separator and out again to the ball probably depends primarily on the pressures created in the hydrodynamic wedge film between ball and separator face. In the upper illustration, the direction of rotation would create extra pressure in the lower section of the film and subatmospheric pressure in the upper section. This pressure differential would maintain a continuous flow along separator pore channels paralleling the contact area. In addition, the curvature of the exposed edges of the oil film will again lead to surface-tension-induced pressures which will augment the flow produced by hydrodynamic effects. Surface tension can therefore be added to the other agencies, such as centrifugal acceleration, gravity, and bearing movements, which mediate the movement of oil in a ball bearing.

CONCLUSIONS

The information on spreading presented in this report is of major significance for the lubrication of instruments, miniaturized components, and miniature ball bearings. This is true because the amounts of lubricant which such bearing parts can hold have small masses when compared with the surface-tension forces acting on them or with the rates at which oil can be depleted from critical points by the flow processes described. The rate of evaporative loss of the lubricant, which may be negligible in bulk applications, is also enormously magnified in importance when the surface area exposed is multiplied by a factor of one hundred or more as a result of spreading. In such a case the lubricant may be evaporated as rapidly as it spreads, so that spreading continues at a nearly constant rate until exhaustion of the lubricant. On the other hand, it is probable that insufficient attention has been given to the role of the degree and orientation of surface roughness in securing capillary replenishment of oil between sliding surfaces that depend for lubrication on lateral feed of oil from adjacent "idle" surfaces.

The considerations presented here about the movement of oil in miniature bearings can be applied to larger bearings in space applications, because the absence of a

gravitational field allows surface chemical forces to dominate the movement of much larger volumes of liquid.

There are other significant deductions that follow from the results of these spreading studies:

1. One-component synthetic oils such as pure esters should be less susceptible to spreading over smooth surfaces than petroleum oils or silicones, which contain more volatile components of lower surface tension.

2. The spreading tendency of a lubricant can be repressed without sacrifice of zero contact angle by incorporating a mi' or amount of a slightly more volatile oil of higher surface tension, although the effect will diminish with time.

3. Because of the open-capillary effect on ground, machined, or production polished surfaces, significant long-term spreading losses must be anticipated from all small commercial bearings unless they are lubricated with a nonspreading oil or protected by low-energy barrier films over which oil cannot spread. This Laboratory has reported on the use of such films (5).

4. The tendency of oil to move away from hot spots must be taken into account whenever conditions exist that cause heat to be generated at the actual load-bearing point in a bearing. Unless provision is made for a liberal and positive resupply of oil, one must anticipate progressive lubricant starvation and increasing heat generation until catastrophic failure occurs.

In the spray application of thin coatings, it is important that the droplets spread quickly to cover any bare islands remaining on the surface; the results of this study point the way to formulations in which a high spreading rate is assured by mixing solvents of suitable volatility and surface tension. Similar considerations apply to the spraying of disinfectants and insecticides.

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