tive. Moreover, the temperature seems to have but a negligible effect on the resistance of treated oil, Fig. 7.

It also has been found that, for given film thickness, the resistive behavior of treated oil is almost unaffected by the removal and reappearance of potential, even if it exceeds the breakdown value. For the same gap and applied potential, oil-resistance values under d-c potential are noted to be, in general, lower than those obtained with a-c potential.

The increase in strength of the additive in the mixture (up to 4 per cent) is found to lead to a related increase in the value of the breakdown voltage, i.e., to an extension in the range of ohmic resistance behavior of the oil, and a reduction in the rate of change of oil resistance with film thickness, Fig. 7.

In the course of tests run on the rotating-disk testing machine [2], it was found necessary to extend the film resistance-thickness characteristic to include film-thickness values up to 0.005 in. Such a calibration curve is shown in Fig. 8.

The effect of film extent on both sides of the line of nearest approach in the following manner:

The bath was first filled with oil to a level much higher than that of the intermediate plane between the disks, the current passing through the film being measured for given gap and applied potential. The oil was thereafter drained till the bath became empty. The current then flowing in the short oil film suspended between the disks was found to remain exactly the same as that measured before. This would imply that for such thin film the current flows in the region closest to the line of nearest approach.

An alternative additive, namely, naphthalene tetrachloride in the strength of 1 per cent, was investigated; however, no effect on the electrical behavior of the oil could be detected. On increasing the strength to 1.5 per cent, the additive was found to form a layer of precipitate on the disks, and no reliable results could be obtained.

The results of tests conducted on the stationary-disk apparatus described previously, were applied to the running-disk machine [2], the lubricating oil, Castrolite 20 A, being admixed with 4 per cent sodium-petroleum sulphonate, a-c or d-c potential (not exceeding 0.75 and 1.25 volts, respectively) being applied across the gap between specimen disks. Fortunately, no difficulty due to previous electrical history of the oil was encountered in the running machine on account of the continuous replenishment of oil therein.

It should be noted that the curves relating film thickness to film resistance are obtained for idle films under no pressure, films which do not exactly conform to conditions prevailing in the rotating-disk machine [2]. Test results obtained, however, on this latter machine show similar resistive behavior of the oil film as that obtained for the stationary disk apparatus.

Conclusion

The measurement of oil-film thickness by electrical conductivity method would lead to unreliable results should straight mineral oil be used.

The treatment of oil with certain additives is found, however, to impart to the oil fundamental favorable features which render it quite suitable for use with this method of measurement.

Admixing Castrolite 20 A oil with sodium-petroleum sulphonate (in the strength of up to 4 per cent) greatly increases its electrical conductivity and extends its range of ohmic-resistance behavior for the same gap and applied potential. The additive seems to relieve the oil almost completely from its dependence on the electrical history and temperature. The resistive behavior of treated oil, for a given film thickness, is found to be almost unaffected by the removal and reappearance of potential, even if it exceeds the breakdown value. The additive also makes more gradual the rate of change of resistance with film thickness for the same applied potential.

Eventually, a reliable relationship between the oil-film resistance and the oil-film thickness would emerge and, consequently, the method of electrical conductivity could be applied successfully to the measurement of oil-film thickness between gear teeth.

References


Discussion

C. M. Allen

The authors are to be complimented on their unique approach to solving the age-old problem of measuring lubricant film thickness of a static and dynamic sliding-rolling system. The authors not only confirm the results of earlier workers but go beyond them in the business of electrical measurement of lubricant film thicknesses.

The data presented in Figs. 7 (a and b) are convincing proof that the effects of temperature between 50 and 190 F are negligible. This appears to be true for variable concentrations of additive, at least between 2 and 4 per cent.

Of interest also, is the comparative results showing the a-c and d-c electrical potentials. Invariably, the indicated resistance of a given oil film is greater using a-c than for d-c. However, at thin films of the order below 200 microrinches the two begin to coincide. The discussor considered a considerable number of minimum oil-film-thickness experiments on full cylindrical sleeve bearings from a number of years ago. The a-c method of determining minimum lubricant film thickness was selected because it was felt that the d-c methods might not provide as realistic data. The thought was that as the electrical impulse passed through or punctured the oil film the d-c potential would have a tendency to keep the film punctured as the film thickness increased slightly. In contrast, the a-c method alternately punctured the film but permitted the puncture to heal between cycles. If this is true, one would expect to have higher indicated resistance with a-c than with d-c. It should be added that attempts to make the results precisely quantitative were not particularly fruitful. When attempts were made and published, the results were politely criticized as they should have been because no data were available at that time concerning the effects of shear, pressure, and temperature of the film. Later on, a new approach to the problem was made and was moderately successful. The oils used were petroleum base and no additives were used.

The present authors are urged to provide an enlarged plot of oil-film resistance versus film thickness in the range of zero to 200 microrinches. It is in this region that many rolling and sliding-rolling machine elements operate; e.g., bearings and gears. This regime is of primary importance, since this is the region approaching nonhydrodynamic lubrication, say at film thicknesses below 50 microrinches. It would not be surprising if the electrical resistance method were found to coincide with these films.

The authors are to be complimented on this approach and are urged to provide additional results on the effects of friction and temperature on these films.

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the voltmeter will only average the indicated resistance or potential. A multitude of instantaneous zero-resistance points. The cathode-conductivity methods employed by the authors ran into difficulty in this zone because many localized asperities will protrude-

in this zone because many localized asperities will protrude—difficulty in this zone because many localized asperities will protrude—difficulty in this zone because many localized asperities will protrude—difficulty in this zone because many localized asperities will protrude. The recent results presented by Rogers, Siripongse, and Cameron in the August 1 issue of Engineering also appear to offer some new data and hope for electrical detection of oil-film thickness. Within the range of their experimental data, the effects of shear, pressure, and apparently temperature do not appear to hamper interpretations of their d-c discharge potential on film thickness. However, no data are presented for film thicknesses below 150 microinches.

M. D. Hersey

The authors are to be congratulated on establishing a relation between film-thickness and electrical resistance, capable of leading to the useful results reported in their companion paper. In effect, they have removed the difficulty previously associated with the application of Ohm's law. It would therefore be of interest to compare their findings with calculation. An approximation may be offered by treating the circumference of each disk as a parabola near the line of centers, and assuming that all the elements of current flow are parallel to that line. The total resistance \( R \) may then be expressed by integration in terms of the resistivity of the oil \( \rho \), the film-thickness \( h_0 \) at the point of nearest approach, disk diameter \( D \), axial length \( L \) of the film at right angles to the motion, and its breadth \( B \), or extent at right angles to the line of centers. Thus

\[
R = \frac{\rho}{4L} \left( \frac{h_0}{D} \right)^{1/5}
\]

where \( A \) denotes the angle whose tangent is \( B/(2Dh_0)^{1/5} \). As \( B \) approaches zero, Equation (1) approaches the limiting form

\[
R = \rho h_0 / BL
\]

This agrees with the known expression for the resistance of a rectangular block of height \( h_0 \) and cross-section \( BL \).

It would be of value to have numerical data on the extent \( B \) of the film remaining in suspension after draining the bath. We should expect that \( B \) will depend on the surface tension and viscosity of the oil and the motion of the disks. A comparison of Equation (1) with Fig. 7 indicates that \( B \) decreases with increasing \( h_0 \). Equation (1) seems to confirm the fact that the resistance is but slightly affected by the film extent when \( B \) is sufficiently great, but the formulas presuppose a knowledge of \( B \).

Ragnar Holm

A condition for the reliability of the method is that the lubricant has a resistivity \( \rho \) that does not depend on the thickness of the film. A judgment on this condition has to be based on calculations of the following type.

Let us assume ideally smooth rings with parallel axes; thickness \( h_0 \); radius \( r \); shortest gap \( h \). It is readily shown that the gap at a point \( x \) (see Fig. 9) is approximately \( x^2/r + h \). Thus the total resistance across the film is approximately

\[
R = \frac{1}{2} \frac{h}{\rho} \left[ \int_{x=0}^{\infty} \frac{dx}{x^2/r + h} \right]^{-1} = \frac{\rho}{\pi b} \frac{h}{r}
\]

Fig. 10 shows that the calculated \( R \) plotted against \( h \) is represented by a curve of another type than was measured. I would like to hear the author's comments concerning the discrepancy between theory and measurement.

H. Blok

The electrical resistance method was perhaps the first ever to be tried with some degree of success for measuring thickness of lubricant films. But, as the authors have pointed out, this method, owing to certain drawbacks, has become increasingly unpopular. The authors deserve much merit for reviving the method by introducing the artifice of an additive that decreases the electrical resistance of the test oil by several orders of magnitude, and thereby removes what have previously been perhaps the worst drawbacks of the method.

There remains, however, one important question, that is, about the correctness of the authors' interpretation of the resistances measured in their various tests in terms of minimum film thicknesses. This question is all the more important because their concurrent paper is also subject to it.

In this connection it should be observed that the authors' calibration measurements have been done with unloaded disks, in an attempt to find minimum film thickness for films between disks that were loaded, sometimes rather heavily. Therefore it should be taken into account that, even at equal minimum film thickness, an unloaded film between two disks, or other curved surfaces, will have a geometry that may be quite different from that obtaining with a loaded film. The reason is to be sought in the elastic deformations that loaded rubbing surfaces will undergo in their region of closest approach. Particularly at the heaviest loads applied in the authors' tests (see also their concurrent paper) local elastic flattening of the disk surfaces in their region of closest approach must have been considerable. Then the gap, occupied by the lubricant film between the surfaces, in that region was no longer bounded by the originally circular arcs, but rather by two nearly parallel plane surfaces.

Unless the authors should be able to show that, even at the highest loads applied in their tests, elastic flattening was unappreciable, their conversion of the resistance measurements in terms of minimum film thickness would appear to be open to some doubt. As can easily be shown, the authors' minimum film thickness calculated from their data for the electrical resistance of their test oil and the dielectric constant of the oil used would be 2.5 microns instead of 20 microns.

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See, for instance, H. Schering and R. Vieweg, "Über die Beurteilung der Lagerbeanspruchung nach elektrischen Messungen," Zeitschrift für Angewandte Chemie, vol. 90, 1956, pp. 1119-1125; see also the many references given in this paper to earlier work.

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thickness would otherwise be on the high, that is, optimistic side.

Perhaps a better approximation to the actual minimum film thicknesses could be obtained by assuming, at least for high enough loads, the gap between the disks to be planar parallel and to have a width, measured along the periphery of the disks, equal to that of the contact area that would occur according to Hertz’s theory for no oil at all. This method, approximate as it is, might well result in estimates of minimum film thickness that are more reliable than the present ones, even though one would neglect edge effects such as occur on either side of the supposedly planar parallel gap owing to the curving away of the disk surfaces. The electrical resistivity of the test oil, which would be needed in carrying out such an estimate, might be determined from any suitable resistivity test.\textsuperscript{12} There might also be a possibility of finding the electrical resistivity from the authors’ calibration measurements with the unloaded disks. Then a formula should be available that relates the electrical resistance measured to the gap thickness (minimum film thickness), the radii of the disks, and the electrical resistivity of the oil. Such a formula was, in fact, developed by Schering and Vieweg (see the first reference of this discussion) for their case of a cylindrical journal bearing where one cylindrical “electrode” (the bearing surface) enveloped another (the journal), at least partially. The formula for the present case, where the cylindrical electrodes are external to each other, can be found by essentially the same method, which, for instance, can be derived from potential theory by using the technique of conformal mapping. But more direct determinations of the electrical resistivity of the oil are also conceivable,\textsuperscript{12} so that one is not wholly dependent on the authors’ calibration measurements and on the formula involved.

Calibration measurements on disks during running, as a supplement to the present measurements on stationary disks, could perhaps be performed by using a technique in which a beam of x-rays is projected onto one side of the disks and the remaining radiation intensity is measured on the other side, that is, where what is left of the beam emerges from the film. As soon as some such calibration would be available, one could further rely on the much more convenient method of the authors.

It is hoped that the authors will succeed in developing their ingenious and attractive method to the extent where any reasonable doubt about its reliability is removed.

\textsuperscript{12} J. L. van der Minne and A. Klinkenberg, “Electrical Statics in the Petroleum Industry. The Prevention of Explosion Hazards,” Elsevier, Amsterdam, Holland, 1958. In this book many additives are mentioned that, like the petroleum sodium sulphate used by the authors, decrease the electrical resistivity of petroleum products. Some of these additives might perhaps be suitable also for the authors’ purpose.

**Authors’ Closure**

The authors wish to thank contributors to discussion for their kind comments, interest, and criticism.

In reply to the points raised by Mr. Allen, we would like to point out that the method of electrical conductivity was primarily developed and used by the authors for measuring hydrodynamic films between rotating disks (simulating gear teeth)\textsuperscript{2}. We do agree, however, in that the development of suitable measuring technique for film thicknesses in the range zero to 200 microinches is essential for the study of conditions approaching boundary lubrication. Such technique would evidently necessitate more sensitive instruments. It is fortunate that wider choice of additives has recently become available.\textsuperscript{13}

Analytical treatments of the problem of electric current flow through the oil film between disks, such as those mentioned by Professor Hersey and Mr. Holm, are based on assumptions that may, in part, be not quite valid.

Experiment, as mentioned in the text of the paper, implies that, for thin films encountered in the tests, current flows in the region closest to the line of nearest approach. In other words, the extent of the effective oil film through which current flows is extremely small to the extent that the actual disk surface profile across current flow—whether parabolic as assumed by Professor Hersey, circular as worked out by Mr. Holm, or even flat due to plastic deformations under externally applied load—plays a negligible role in oil-film resistance. Consequently the resistance would be expected to have simply a linear relationship with film thickness.

At relatively small gaps, however, it is feasible to expect that relative proportions of particles of the insulating oil and those of the conductive additive in the mixture, through which current passes, would have a more significant effect on film resistance, as would the resistance at the boundary layer.

At relatively large gaps, on the other hand, the oil-film suspended between the disks may narrow down to the extent that the effective core area, through which current flows, may be reduced thus leading to increase in the rate of change of resistance with oil-film thickness.

It is believed that through intensive study of factors, such as those outlined, that theory may be brought in closer agreement with experiment.

The authors are particularly indebted to Professor Blok for his valuable suggestions regarding further development and elaboration of their method, which suggestions will be carefully considered in relevant future work.