Contact Resistance Measurements in Mixed Lubrication

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Measurements of electrical resistance have been widely used to characterize the state of lubrication in mixed film, high pressure, lubricated contacts. Such measurements are relatively easy to carry out and are usually thought to provide at least an approximate indication of the extent to which the surfaces are separated by a film of lubricant. However, it has been difficult to relate these measurements to other commonly-used indicators of the state of lubrication, such as the oil film thickness or the coefficient of friction.

With the recent development of the spacer layer imaging method, it has become possible to acquire instantaneous film thickness maps of rough surfaces in rolling-sliding, lubricated contact. It has also proved possible to obtain electrical contact resistance (ECR) measurements from effectively the same system, by coating a glass disk with a thin, conductive layer, and also to measure friction using the same test set-up.

This has made it possible, for the first time, to directly investigate the relationship between electrical contact resistance and experimentally measured film thickness and friction coefficient.

KEY WORDS

Elastohydrodynamic Lubrication; Mixed Lubrication; Oil Film Thickness; Electrical Contact Resistance; Friction; Spacer Layer Imaging, Optical Interferometry, ECR; EHD

INTRODUCTION

The regime of mixed boundary/fluid film lubrication or "mixed lubrication" has become steadily more important in recent years in response to a progressive tendency for machine components to be designed for and to operate with thinner and thinner lubricant films. It is thus of great interest both to understand this lubrication regime and also its practical influence on aspects of performance such as friction, wear and scuffing.

Experimentally, one of the oldest and potentially most promising techniques for studying mixed lubrication has been time-resolved, electrical contact resistance (ECR) measurement across rubbing contacts in order to quantify the extent and duration of asperity collision events. This approach has the considerable advantage that, as well as being quite simple to implement, it can, in principle, be applied to real components in operating machines, to provide an indication as to the prevailing lubrication regime.

Examination of the literature indicates that this electrical contact resistance approach has not fulfilled its early promise and is still of limited use in research or development work. One of the main reasons for this is the problem of interpretation. To be quantitatively useful, contact resistance measurements need to be related to corresponding lubricant film thicknesses. Unfortunately details of the lubricant film thickness distribution in the mixed lubrication contact of rough surfaces have not been available.

The authors have recently developed an optical technique for mapping film thickness in mixed lubrication conditions. This provides the opportunity for directly relating film thickness and electrical contact measurements in the same mixed film systems. The aims of the work described in this paper were;

(a) to measure time-resolved, electrical contact resistance between a steel ball and a coated, glass disk, a contact similar to that used in optical work.
(b) to correlate measurements obtained from such a system to in-contact film thickness measurements
(c) to show how the two can be related to friction measurements in mixed film lubrication.

BACKGROUND

The study of mixed lubrication has been a topic of research interest for many years and there has been a great deal of both modeling and experimental work carried out in the field. Previous experimental work will be reviewed in this paper. Reviews of theoretical studies of mixed lubrication have been provided by Cheng (1), Chang (2) and Spikes (3).

Experimentally there have been three main approaches, based respectively on time-resolved, electrical contact resistance, optical interferometry and friction measurement.

The first use of time-resolved ECR to study mixed lubrication was by Furey (4). He employed a high speed oscilloscope to detect the ECR across the lubricated contact between a fixed ball and a rotating cylinder, and showed that the electrical resistance was composed of a rapid fluctuation between very low and very high resistance states. Furey suggested that these two states represented pure metallic asperity contact and full fluid film contact

respectively, and demonstrated that the fraction of time for which there was low resistance varied from 100% to zero as the contact moved from boundary to elastohydrodynamic lubrication.

This approach was considerably extended by Tallian and co-workers (5), using a four-ball machine. Tallian analyzed the ECR trace to determine two characteristic ECR parameters, the average fractional time with no electrical contact and the average number of electrical contact events per unit time. He then developed a contact model, based on measured surface topography, to relate these two values to the ratio of lubricant film thickness to out-of-contact surface roughness and thus operating conditions such as entrainment speed and lubricant viscosity. Tallian's initial work neglected the influence of contact pressure on surface topography, but he subsequently took this into account using a plastic asperity deformation approach (6). In the same year, Johnson and co-workers showed that Tallian's ECR measurements also fitted an elastic asperity deformation model (7).

Subsequent advances have been due to Leather et al. (8), who showed how the occurrence of simultaneous asperity contact events could be treated statistically and Palacios (9), who investigated the evolution of the electrical contact resistance with running-in time using a four ball machine contact.

Both Tallian's and Palacios' work showed a convincing correlation between the main ECR parameters and estimated film thickness. However despite this, the technique does not appear to have become widely-used, and most workers have preferred to employ simple monitoring of mean contact resistance as a qualitative indicator of the presence of a lubricating film.

One limitation of all the ECR work carried out to date, which may explain its lack of widespread application, is that it has never been possible to be sure of the actual lubricant film thickness present in the system under study. The useful application of time-resolved ECR presupposes that some asperity-asperity contact events are taking place, i.e. the existence of rough surface, mixed lubrication. Unfortunately, there are no reliable equations for predicting film thickness, and in particular film thickness distribution, in such contacts. A second problem is that it is not clear what a low resistance, "contact" event actually represents in terms of film thickness; whether it is true metallic contact or simply a very thin film through which electrical tunneling or discharge can occur. Tallian (4) suggests that this film may be less than 10 nm, but it has not been possible to determine its true value, nor its dependence on applied voltage or lubricant chemistry.

A second technique used for studying mixed film lubrication has been optical interferometry. In this, one surface is made of an optically-transparent material such as glass or sapphire, coated with a very thin, semi-reflective, metallic layer, while the second is a reflective, normally steel ball. When light is shone through the disk into the contact, the extent of optical interference depends upon the thickness of lubricant film present. This technique is generally employed with smooth ball and disk surfaces, to measure the elastohydrodynamic film-forming properties of lubricants. However a number of authors have used it with rough balls, to investigate the influence of roughness on film formation, e.g. Jackson (10), Cusano (11), Kaneta, (12), de Silva, (13), and Tondor, (14).

Most optical interferometric investigations of rough surfaces have been made in conditions where there was a quite thick lubricant film over the whole contact, including the asperities, and are thus not applicable to mixed lubrication and thus ECR studies, where there is some asperity contact. Recently, however, the interferometric technique has been extended to measure very thin films by using a spacer layer of transparent silica deposited on top of the semi-reflecting metallic layer (15). This enables mean film thickness to be measured as a function of entrainment speed for rough ball surfaces down to less than 5 nm lubricant film thickness as described by Guangteng and Spikes (16). In the last two years, this approach has been developed still further, to produce maps of film thickness across rough surface ball on flat contacts, Guangteng et al. (17), (18).

An alternative optical method for looking at mixed lubrication has been described by Liang and Linqing (19), who used a total internal reflection method to estimate the extent and distribution of asperity contact in a glass/steel contact.

The third main approach to studying thin film, mixed lubrication has been to measure friction coefficient in rolling/sliding contacts as a function of operating conditions such as speed and load. The measurement of variation of friction with entrainment speed produces a Stribeck-type curve. This can be used both to delineate the boundaries of fluid film versus mixed and boundary lubrication, (10), (3) and also to test theories relating friction and thus load-sharing to rough surface contact mechanics and lubrication, (7).

The three experimental approaches outlined above are complementary and ideally all three should be used in parallel, at least at the research level, to improve our understanding of mixed lubrication. The ability to measure film thickness distribution in thin film contacts provides an important opportunity in this respect. Because quite detailed maps of film thickness are attainable, down to just a few nanometers, it is possible to obtain statistical information of film thickness distribution in rough surface contact. This should be directly applicable to interpreting friction curves and time-resolved ECR measurements and the latter might then be used to monitor real machine components, where optical interferometry is not possible.

One problem which has to be resolved before such parallel measurements can be made is that thin film optical interferometry requires a transparent silica-coated surface whereas ECR measurements have always been carried out between a pair of opaque, metallic solid bodies. In the current paper, the possibility of taking ECR measurements from a thin chromium layer on a glass disk is therefore explored.

TEST METHOD AND MATERIALS

Electrical Contact Resistance Method

The aim of this study was to correlate directly electrical contact resistance with lubricant film thickness maps and with friction measurements for effectively the same lubricated contact system. The optical film thickness mapping method, which is described below, employs a glass disk on steel ball system. The

glass disk is coated with a very thin, semi-reflecting chromium layer on top of which is sputtered a silica layer. The actual contact is thus one of a steel ball surface on silica flat.

Clearly such a contact cannot be used for ECR measurements since silica does not conduct electricity. It was therefore decided to employ a glass disk from the same batch as those used in film thickness work but coated with a thin layer of chromium, thick enough to electrically conduct but too thin to significantly influence contact stresses and thus lubricant film thickness.

Figure 1 shows a schematic diagram of the test set-up. A steel ball is loaded and driven against the underside of the chromium-coated glass disk. A 16 mV voltage is applied to the periphery of the chromium layer while the steel ball is held at earth. The electrical resistance measurement from across the contact is smoothed using a simple circuit with time contact 10 μm, amplified, digitized and then captured using a microcomputer. In the tests carried out, the chromium layer had thickness 10 to 20 nm, giving an electrical resistance between ball contact position and the disk edge of 20 kΩ. Electrical contact resistance was sampled at 40 kHz.

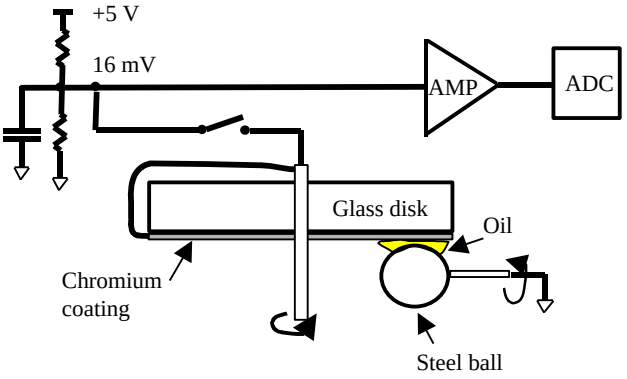

Figure 1 — Schematic diagram of ECR ball-on-disk test method

The test protocol was as follows. The test rig was assembled using a cleaned ball and disk and the load was applied. Contact resistance was measured in the loaded, dry contact to provide a baseline "full-contact" reading. The contact was then lubricated and the rolling speed raised in a series of steps, sampling ECR at each speed.

Spacer Layer Imaging Method

The spacer layer imaging method (SLIM) used in this study is fully described by Cann et al. (21). The test setup is shown schematically in figure 2. A lubricated contact is formed between a steel ball and the flat surface of a glass disk, as in the ECR measurements. The surface of the disk in contact with the ball is coated with a very thin, semi-reflective layer of chromium, on top of which is a transparent spacer layer of silica, about 400 nm thick. White light is shone through the glass disk into the contact, where some is reflected back from the chromium layer while some passes through the silica and any oil film present, before being reflected back from the steel ball. Since they have traveled different distances, upon recombination the two beams interfere optically at values of wavelength dependent upon the path difference and thus the film thickness. The result is a colored, interference image of the contact.

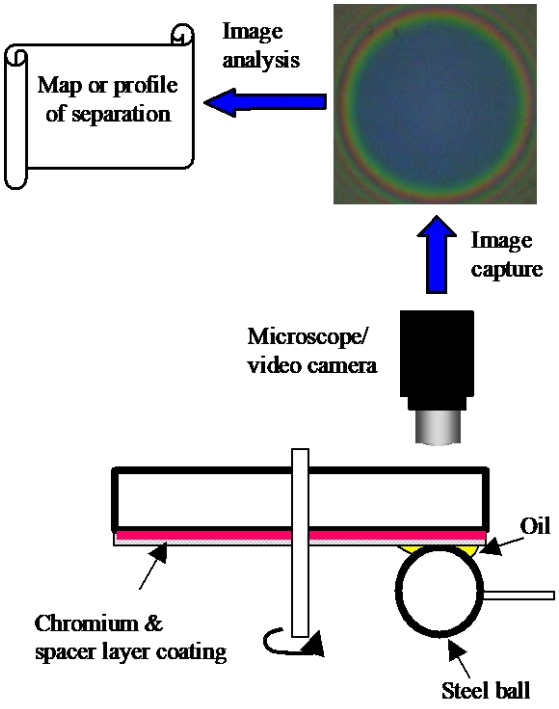

Figure 2 — Diagram of spacer layer imaging method

This interference image is detected by a CCD camera and frame-grabbed by a microcomputer for analysis. Since the RGB color at each pixel position depends upon the oil and spacer layer film thickness at that location in the contact, by using an appropriate calibration it is possible to convert the interference image map across the contact into a film thickness one. The calibration procedure and accuracy of the technique have been described by Guangteng and co-workers (22).

The images obtained in this study contained 256 x 256 film thickness values and, with the magnification employed, each pixel represented an approximately 1.3 μm square region of the contact. The Hertzian contact diameter was approximately 300 μm.

The test protocol was as follows. Ball, disk and test chamber were thoroughly cleaned and interference images were then taken from a loaded, stationary contact to obtain the local spacer layer thickness, plus a mean value of any in-contact separation in the stationary contact due to roughness. Motion was then started and interference images captured from the lubricated contact at a range of rolling speeds. An electronic shutter on the camera was set to capture images within a time period of 1/10000 of a second. Over

this time interval, at a surface speed of 0.1 m/s, an asperity under observation will travel 10 μm.

Friction Measurement Method

Friction was measured using an uncoated glass disk/steel ball contact, with the glass disk originating from the same batch as the coated ones used in ECR and film thickness work. The test rig was very similar to that used in ECR and film thickness measurements and shown in figure 1, except that the disk was fastened to its driving shaft by a support incorporating a load cell. This was able to measure the torque applied by the disk on the shaft and thus enabled the friction force at the ball/disk contact to be determined. Tests were carried out by monitoring friction over a series of mean rolling speeds at fixed slide roll ratio.

Test Materials and Conditions

In this study, the glass disks and smooth steel balls employed had out-of-contact surface roughnesses of 6 and 15 nm rms respectively. Rough balls were obtained by premature removal from the standard bearing finishing procedure. They has isotropic, random roughness with two different roughness levels. The topographical characteristics of the three types of ball studied are listed in table 1. Both rough and smooth balls had radius 19 mm and the elastic modulus of the steel balls was 207 GPa and that of the glass disk was 75 GPa.

TABLE 1 — ROUGHNESS OF STEEL BALLS

Ball type	Roughness (rms, μm)	Composite roughness (μm)	Mean Slope (cut-off 0.8 mm)
Smooth	0.015	0.016	0.9º
Rough-1	0.060	0.060	2.2º
Rough-2	0.095	0.095	3.4º

All experiments described in this paper were made using an additive-free, polyalphaolefin lubricant. This had a dynamic viscosity, η, of 0.0238 Pa.s and an effective pressure-viscosity coefficient, α, of 11.3 GPa^{-1} at 25 °C.

For all tests, the ball and disk were ultrasonically cleaned, first in toluene and then in analytical grade acetone. The test chamber was also rinsed in toluene and acetone. All tests were carried out at a load of 18 N, corresponding to a mean Hertz pressure of 0.49 GPa, and at room temperature of between 20 and 22 °C.

The ECR tests were carried out in nominally pure rolling with the ball driving the freely-rotating disk. Friction measurements were made at a fixed slide-roll ratio of +10%. (Slide roll ratio in this paper is defined as sliding speed divided by mean rolling speed, being positive when the ball is travelling faster than the disk). Film thickness measurements were made both in nominally pure rolling and at +10% slide roll ratio

RESULTS

ECR Results

Figure 3 shows typical ECR traces for the smooth ball, at 0.02 m/s and 0.2 m/s rolling speed. Also shown on the figures is the contact resistance level for the static contact. The resistance scale is arbitrary, with the highest value representing the full, applied 16 mV, and the static contact value corresponding to 0 mV.

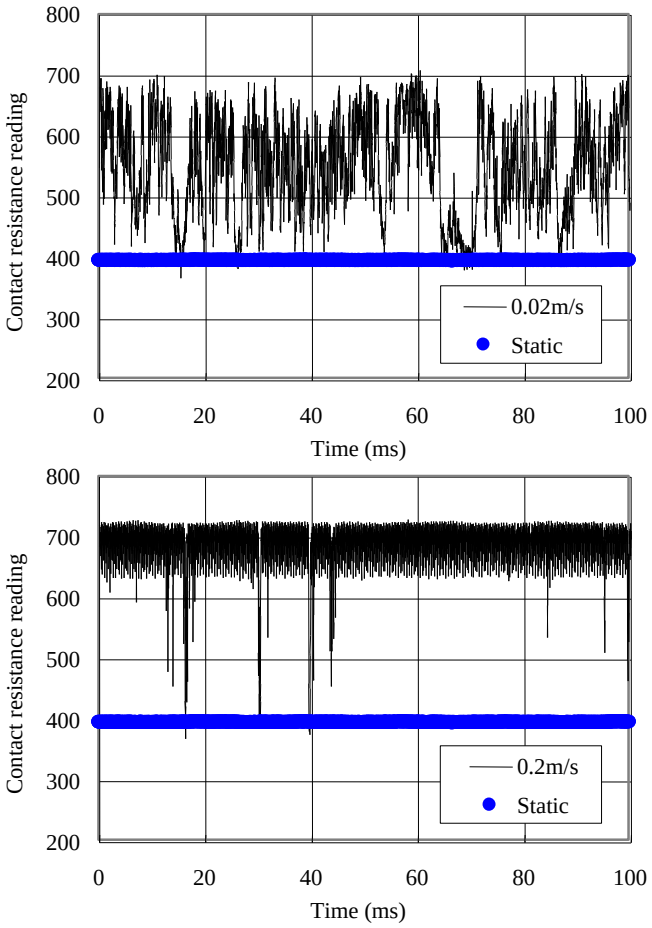

Figure 3 — ECR traces for smooth ball at 0.02 and 0.2 m/s rolling speeds

At the higher speed, the resistance remains high except for just a few excursions to lower values. The 100 unit fluctuation of the high resistance values over time represents variation in electrical resistance around the disk due to the way that the circumferential circuit wire was attached to the chromium film at the periphery of the disc. At the lower speed, the resistance fluctuates, spending much of its time at intermediate to low resistance, indicating considerable asperity "contact". Figures 4a and 4b show results for the rough-1 and rough-2 balls at 0.2 m/s, for comparison with the smooth ball case in figure 3b. As the ball roughness increases, the proportion of low resistance operation increases.

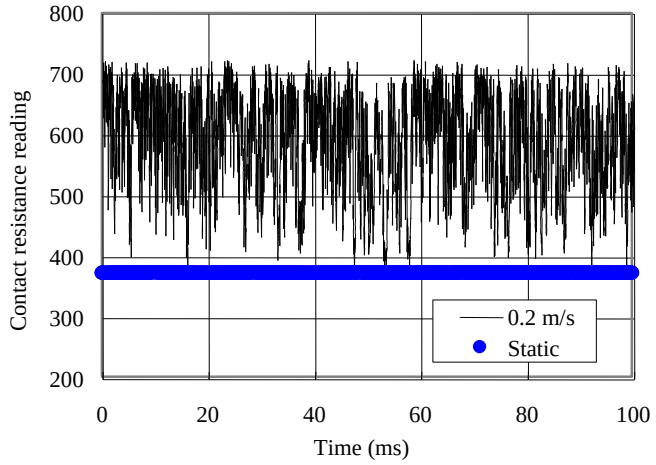

Figure 4a — ECR trace for rough-1 ball at 0.2 m/s rolling speed

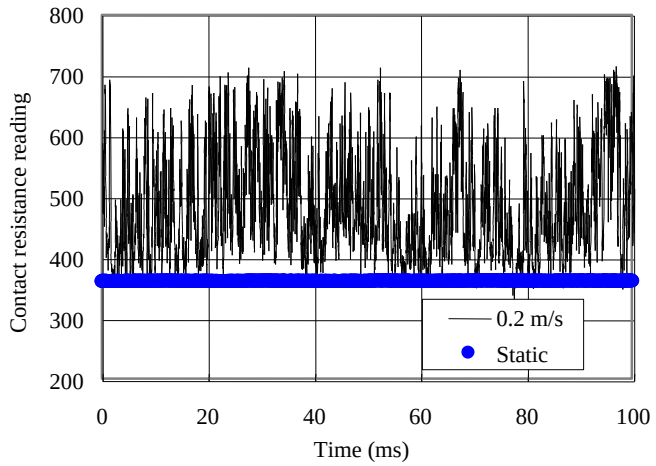

Figure 4b — ECR trace for rough-2 ball at 0.2 m/s rolling speed

Figure 5 shows the distribution of ECR values for several rolling speeds for a smooth ball.

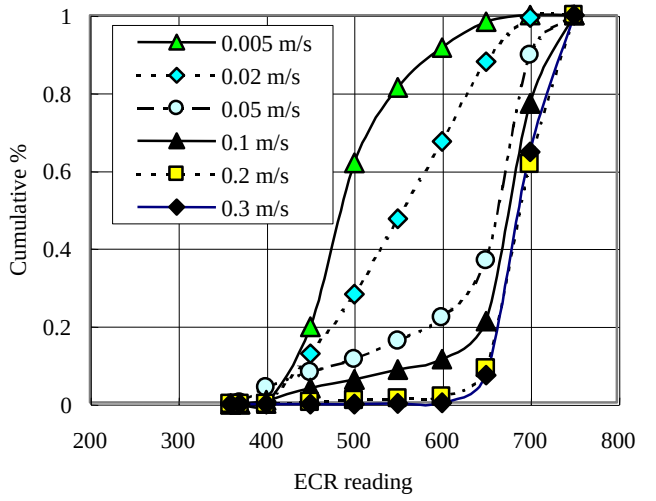

Figure 5 — Cumulative ECR distributions for smooth ball at various rolling speeds

The evolution from primarily low resistance to primarily high contact resistance as the speed increases is clearly seen. Since the signal does not fluctuate instantaneously between full and zero contact, it is necessary to define a discriminator level, i.e. some level of electrical resistance value which represents "no-contact" as opposed to "in-contact". Tallian and Palacios took discriminator levels of 20% and 44% above the full-contact base line respectively. In the current work, values lower than 600 on the scale used are taken to represent in-contact. Once such a value has been decided it is possible to determine the proportion of in-contact and no-contact time for a given condition and figure 6 shows how the fraction of electrical in-contact time varies with rolling speed for the three types of ball. As expected, rougher balls show higher proportions of in-contact time than smoother ones at a given entrainment speed and thus film thickness.

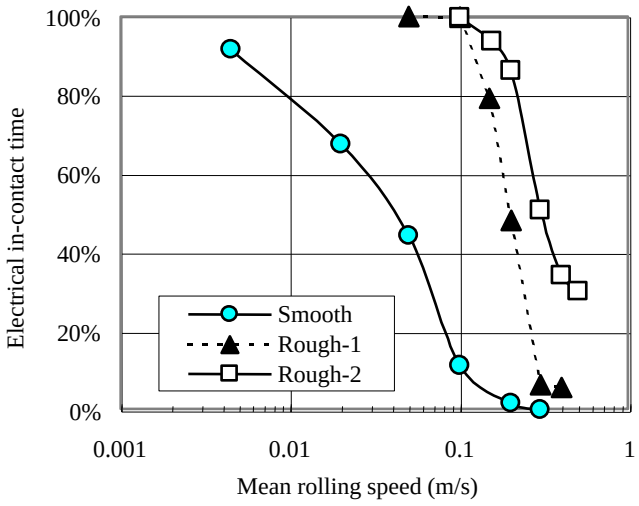

Figure 6 — Influence of rolling speed on percentage electrical in-contact time

Film Thickness Results

Figure 7 overleaf shows typical film thickness maps obtained using spacer layer imaging from the contact of a rough ball (rough-1), both stationary and at three different rolling speeds. It can be seen that, even in the stationary contact, there is not full conformity, and that the film thickness increases with rolling speed.

To quantify the extent of thin film "asperity" contact, film thickness maps such as those in figure 7 were analyzed to produce film thickness distributions over the central region of the contact. (The region analyzed was a circular zone spanning 0.65 of the Hertzian contact). Figure 8 shows a typical cumulative distribution for a rough-1 ball at a mean rolling speed of 0.14 m/s.

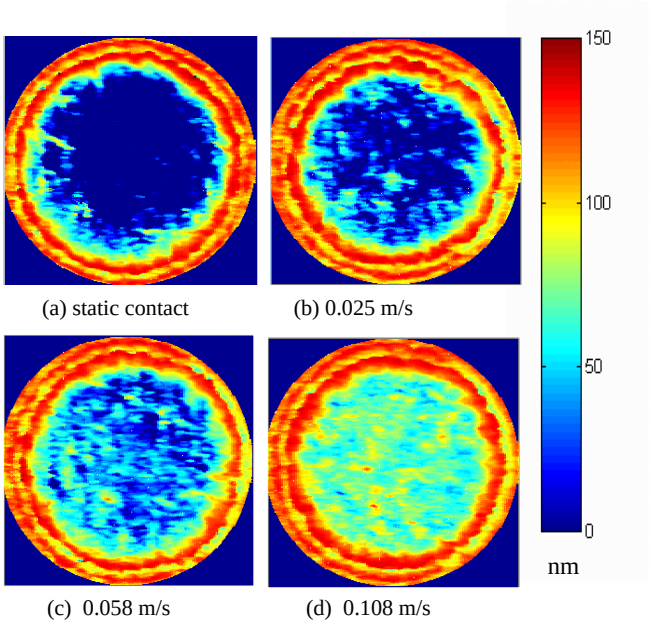

Figure 7 — Film thickness maps for rough-1 balls in static contact and at three mean rolling speeds

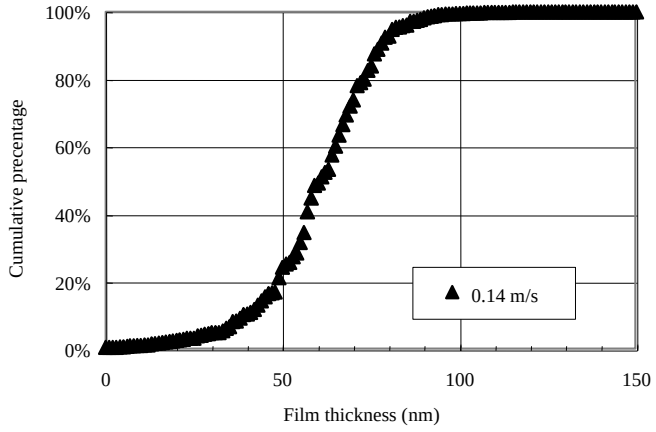

Figure 8 — Cumulative plot of film thickness distribution in a rough-1 ball/disk contact at 0.14 m/s mean rolling speed

From the point of view of interpreting ECR, of particular interest is the proportion of the contact having film thickness below a certain, threshold value which just permits electrical conduction. Figure 9 shows how the percentage of the contact lying below three selected film thickness values varies with mean rolling speed for a rough-1 ball.

The figure includes both nominally pure rolling (square symbol) and +10% slide roll ratio (triangular symbol) results and it can be seen that there is no significant difference between the two. There is considerable scatter in the results, partly from deficiencies in repeatability of the technique used (22) but largely due to the stochastic nature of the surface roughness being studied. However the three film thickness thresholds clearly give quite different distributions. These are further discussed below.

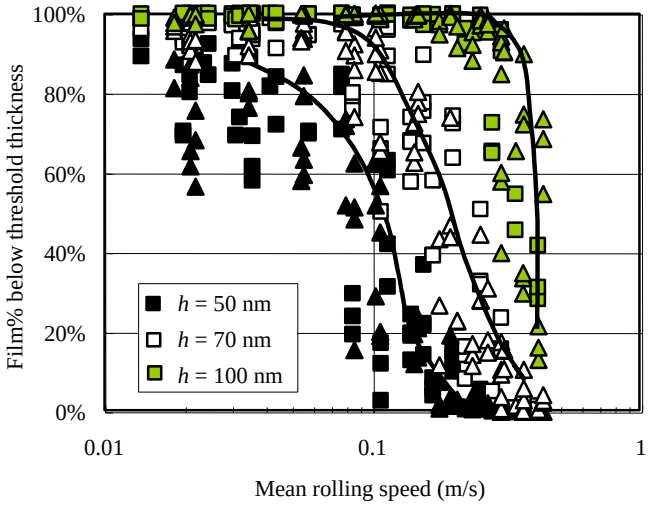

Figure 9 — Influence of rolling speed on percentage lubricant film below a threshold thickness, *h* (squares = pure rolling, triangles = +10% slide roll ratio)

Friction Results

Figure 10 shows how friction coefficient varies with mean rolling speed for the three roughness balls, all at 10% slide roll ratio.

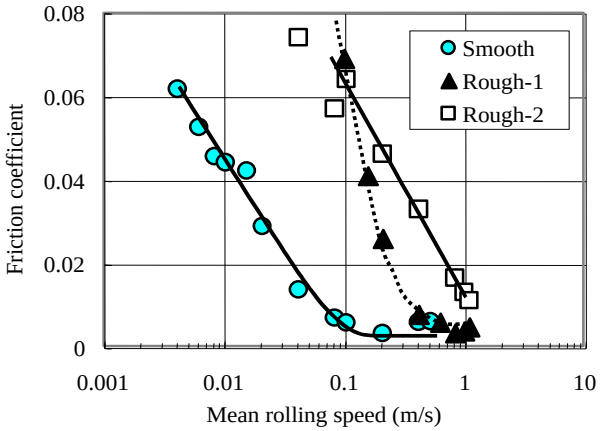

Figure 10 — Dependence of friction coefficient on mean rolling speed for the three different roughness balls at +10% slide roll ratio

The smooth and rough-1 ball show the transition from low friction, EHD lubrication to higher friction mixed lubrication as the rolling speed and thus lubricant film thickness is reduced, as reported by other studies (3), (23). The friction values for full-film lubrication are quite low because PAO has a low EHD traction coefficient and also because of the relatively low slide roll ratio and contact pressure employed. The rough-2 ball barely enters the

full film regime even at the highest speed and thus shows no leveling out at a low friction value.

DISCUSSION

Because both ECR and film thickness were measured as a function of mean rolling speed, it is possible to cross-plot the two to see how ECR features vary with mean film thickness. Figure 11 plots the percentage of electrical in-contact time versus mean central film thickness for the three different roughness balls. There is clearly little correlation between the three plots. Figure 12 shows the same data plotted in terms of the lambda ratio, i.e. the ratio of film thickness to out-of-contact root mean square (rms) roughness. Again there is little correlation between the behavior of the three different roughness balls.

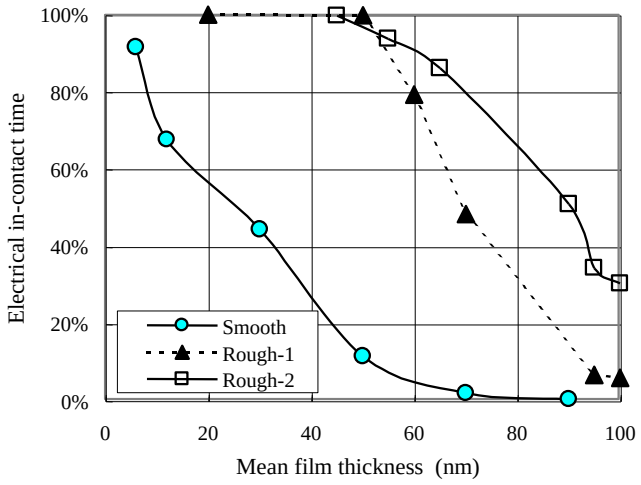

Figure 11 — Cross-plot of electrical in-contact time % versus mean central film thickness

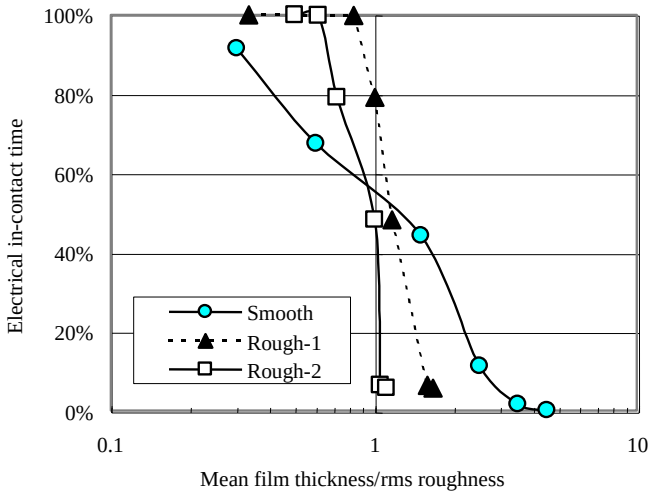

Figure 12 — Cross-plot of electrical in-contact time % versus lambda ratio

Figure 13 shows a plot of percentage electrical in-contact versus the difference between film thickness and rms. This produces a rather better correlation. This form of plot results in negative values of the abscissa, presumably because, in practice, in-contact roughness is considerably less than the out-of-contact values used. However, since in-contact roughness is likely to be related in some systematic way to the out-of-contact value, the broad correlation does suggest that electrical contact occurs when the film thickness lies below some critical value.

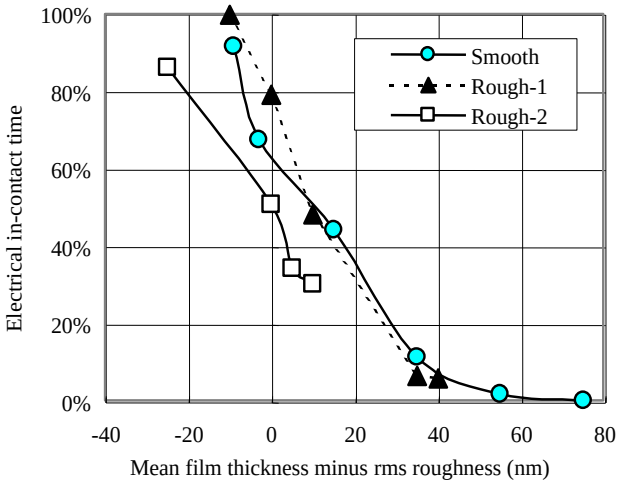

Figure 13 — Cross-plot of electrical in-contact time % versus (mean central film thickness minus rms roughness)

In this context, a comparison of figures 6 and 9 is revealing. Figure 6 includes a plot showing how the percentage of electrical in-contact time falls with rolling speed for a rough-1 ball. Figure 9 shows how the percentage of film thickness below three critical threshold values falls with rolling speed for the same ball roughness. It appears that a threshold film thickness of 70 nm in figure 9 most closely matches the shape of the decay curve of electrical contact time, with both curves crossing the 50% line at a mean rolling speed of ≈ 0.1 m/s. This suggests that electrical contact may occur for the PAO studied when the lubricant film thickness between opposing asperities falls below about 70 nm.

CONCLUSIONS

A technique has been developed for measuring time-resolved electrical contact resistance (ECR) across a lubricated steel ball on chromium-plated, glass disk contact. This makes it possible to carry out parallel ECR, film thickness and friction measurements on essentially the same lubricated contact.

The use of spacer layer imaging to produce film thickness maps across the contact can be used to directly interpret ECR in terms of film thickness distribution. This suggests that, for the polyalphaolefin studied, the effective electrical "in-contact" threshold selected corresponds to a film separation of about 70 nm.

The work carried out to date has been quite preliminary and confined to just one test fluid and three ball roughnesses. However

the authors believe the combination of the spacer layer imaging, ECR and friction measurement experimental techniques, especially after further refinement, holds considerable promise in furthering our understanding of mixed lubrication and in enhancing the usefulness of the ECR technique as an experimental tool.

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