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# **An investigation into mixed lubrication conditions using electrical contact resistance techniques**

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## **Abstract**

Electrical contact resistance (ECR) techniques are widely used to study mixed-elastohydrodynamic lubrication conditions, where direct asperity contact takes place alongside conditions of very thin lubricant films.

This paper presents the use of the ECR technique to study realistic mixed-EHL contacts, identifying the high frequency variation of instantaneous contact resistance on a repeatable basis between two superfinished surfaces. The variation of mean ECR measurements with operating conditions for ground surfaces in contact is investigated, and it is shown that they are strongly related to the lubricant film thickness and lambda ratio. Thermal effects are considered and shown to be highly influential on both the mean and instantaneous contact resistance. The influence of load on contact resistance is also investigated.

**Keywords:** Elastohydrodynamic, Mixed, Roughness, Resistance

## **1. Introduction**

Electrical contact resistance techniques have long been used to investigate conditions within lubricated contacts of one form or another. Bowden and Tabor carried out early work [1] to investigate the actual area of contact between both stationary and sliding surfaces. Courtney-Pratt and Tudor [2] used the electrical contact resistance method to investigate the lubricant conditions between piston ring and cylinder liner wall of a running internal combustion engine. They found that low resistance conditions corresponded to poor lubrication where the fluid film broke down and direct contact (and hence abrasive wear) occurred between the contacting surfaces. Use of an oscilloscope synchronised with the stroke of the engine allowed the variation of contact resistance with stroke to be examined, demonstrating that lubricant film breakdown occurred at points during the stroke under all conditions investigated.

Lane and Hughes [3] investigated the variation in contact resistance over the meshing cycle for a pair of spur gears. They found that whilst the variation in contact resistance depended on load, in all cases the resistance was lowest at points of highest sliding, and highest at the pitch point where there was no relative sliding between the surfaces. Whilst investigating the use of disk machines to simulate gear tooth contacts at particular points within the meshing cycle, Crook [4] measured the

contact resistance between test disks at various stages of a “running in” process, where he found that initial metal-to-metal asperity contact events were greatly reduced as the surfaces were modified by the running in. Crook also investigated the transient variation of contact resistance, which he found to vary rapidly between high and low levels, a characteristic he attributed to fluctuating levels of asperity interaction within the contact. The mean contact resistance was found to depend on load, speed and surface temperature of the disks – Crook explained this by recognising that each parameter influences generation of the hydrodynamic oil film between the surfaces.

The well-known paper by Furey [5] concerned experimental work using a ball on cylinder tribometer, used to investigate lubricated contacts. The instantaneous contact resistance was found to vary rapidly between very low and infinite levels, suggesting that the nature of metallic contact in the experiment was intermittent. Furey proposed that the time-averaged value of electrical contact resistance was, therefore, an indication of the percentage of time for which metallic contact occurred.

Talian et al. [6] showed transient electrical contact resistance traces obtained using a four ball test rig. They developed two representative parameters based on an analysis of these traces - the average fractional time with no electrical contact, and the average number of electrical contact events per unit time. They then presented a theoretical relationship between electrical contact resistance and the ratio between lubricant film thickness and surface roughness. This approach was later extended to include the effects of contact pressure on surface geometry, using a plastic asperity deflection model [7].

Further enhancements have been reported by Leather [8] and Palacios [9]. Leather developed advanced statistical techniques for dealing with the occurrence of simultaneous asperity contact, whilst Palacios investigated running-in using a four ball machine with the electrical contact resistance technique.

Hornig [10] used electrical contact resistance measurements to infer the level of metallic contact in a disc on pad machine used to investigate the transition from boundary to mixed lubrication. Guangteng *et al.* [11] directly investigated the relationship between electrical contact resistance and experimentally measured film thickness, by using a ball on disk test rig equipped with both contact resistance and the spacer layer imaging method optical interferometry measurements. They found that the mean electrical contact resistance (assumed, like Furey, to be related to the percentage of time for which metallic contact occurred) was inversely proportional to measured film thickness, under a range of operating conditions. They also presented the transient variation of electrical contact resistance and found it to fluctuate rapidly, with noticeable occurrences of intermediate levels of contact resistance between the high levels associated with full film lubrication and the low levels usually associated with asperity contact.

Lugt *et al.* [12] used mean electrical contact resistance parameters to indicate the separation of surfaces in disk machine tests designed to investigate the running in of surfaces as part of an investigation into roller bearing surface finish. They found the contact voltage (when the disks are used as part of a resistance network) to be directly proportional to the level of separation (and hence metallic contact) between the surfaces. Lord and Larsson [13] also conducted running-in experiments, using a ball on disc tribometer fitted with electrical contact resistance measuring equipment. In their tests, electrical contact resistance between ball and disc gradually increased

with time during running in experiments, suggesting gradual modification of surface topography. They also investigated the effects of the surface finishing method, and of lubricant formulation, on the levels of metallic contact between surfaces, as indicated by their electrical contact resistance measurements.

Various researchers have demonstrated the value of contact resistance techniques in investigating levels of metallic contact and asperity interaction under mixed lubrication conditions. However most workers, with the exception of notable early works [2, 4, 5], have used *mean* contact resistance levels as an indicator of conditions within the lubricant film. The current paper reports development of the approach to use modern high-speed data acquisition hardware so as to allow a detailed investigation of the transient variation of contact resistance as rough surfaces move through the contact in a series of disc machine experiments. The overall objective is to provide experimental measurements for comparison with transient 3D mixed EHL analyses of the contact conditions using surface roughness information taken from the experimental disks. The programme involves investigation of surface roughness modification during the initial running-in process, and validation of the breakdown of the inter asperity lubricant film appearing in the mixed EHL analysis. The focus here is on the latter aspect which requires high resolution transient knowledge of the asperity contacts occurring.

## 2. Twin Disc test rig

The rig used is a power-recirculating two disc machine, following the general concept presented by Merritt [14], and originally constructed to investigate micropitting. Figure 1 shows the general layout of the test rig, with the disks, shafts and loading arrangement visible.

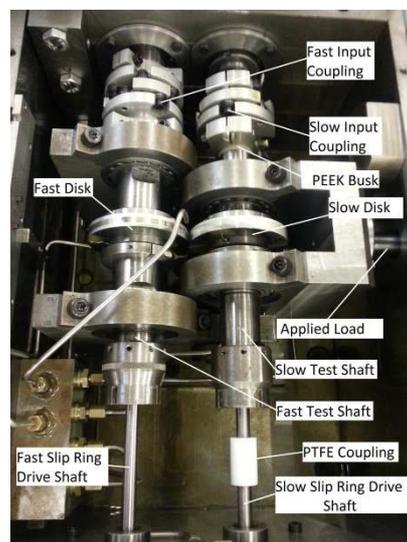


Figure 1: General view of test head

The test discs are made from a case-carburised and hardened alloy steel to Rolls-Royce specification 6010, with a hardness of around HV 840, and are 76.2mm in diameter with a crown radius of 304.8mm in the axial direction. This gives a self-aligning elliptical contact with an aspect ratio of approximately 4:1, where the major axis of the ellipse is parallel to the shaft axis. The test disks are

finished by axial grinding, in order to give a surface with directionality similar to that of gear teeth, with a roughness average value (Ra) of approximately 0.4 $\mu$ m. Some discs were subject to a further superfinishing process, which reduced the Ra further to below 0.1 $\mu$ m. Lubricant was sprayed onto the discs at both the inlet and outlet of the contact. For this work, the lubricant was a naval gearing oil to specification OEP-80 as the investigation is part of a collaborative investigation of micropitting in gears that has used the lubricant in gear tests. OEP-80 is a performance specification, the actual lubricant being a gear oil with a nominal viscosity of 68 centistokes at 40°C, containing a proprietary EP additive package.

The hydraulic loading mechanism allows up to 8kN to be applied to the discs with a corresponding maximum contact pressure of 2.1 GPa. The test discs are mounted on hardened steel shafts, which are gear connected to produce a rolling/sliding contact. In the work presented here, the gear ratio was chosen such that the resulting slide / roll ratio was 0.25. The shafts are supported in rolling element bearings, and the slower shaft is connected to the drive gear via a quill shaft, which incorporates a strain-gauged reduced section in order to measure traction at the EHL contact. Parasitic friction (including bearing friction and windage) is carefully measured as part of the rig calibration process, and this can be used to compensate the total measured friction in order to give the traction force at the contact.

The rig is driven by a 5.5kW electric motor, which is controlled by the rig control computer via a variable frequency drive, to provide stepless control of fast shaft speed between 200 and 3000 rpm, which equate to entraining velocities between 0.71 and 10.64 m/s. As well as the friction measurement, thermocouples are embedded 3mm below the disk running tracks, in order to provide a measurement of disk temperature. A knowledge of these temperatures is important as it is the mean surface temperature at the entrance to the EHL contact which determines the lubricant viscosity at the entrance to the EHL contact in the film-forming zone. The embedded thermocouples are connected to the rig data acquisition system via high-speed silver/graphite slip rings.

In order to allow measurement of electrical contact resistance between the discs, the slower shaft is electrically isolated from the rest of the test rig. This is achieved by using silicon-nitride rolling elements in the pivot bearings of the yoke which supports the slow shaft, and by using a PEEK bush to isolate the shaft from its driving gear. In addition, slip ring connections are made using PTFE links to avoid grounding. The disks are connected to the data acquisition system via slip rings as part of a potential divider circuit as shown in Figure 2.

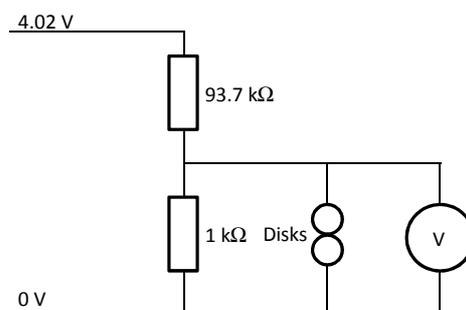


Figure 2: General layout of electrical resistance circuit

The voltage across the test discs, as measured by the data acquisition system, varies in this circuit between 0mV when there is a dead short between the test discs, and 43mV when the resistance between the discs is infinite. Thus, low voltage levels are associated with significant metallic contact between the discs, whereas high contact voltages are indicative of full film lubrication. The term metallic contact used here would include circumstances where there is no effective lubricant film separating the surfaces and any surface tribofilm has a low electrical resistance. The contact voltage is sampled by a data acquisition card at a frequency of 1.25MHz, which is necessary to capture the rapidly fluctuating conditions as reported earlier [5,6]. By using a shaft encoder connected to the faster shaft, the data acquisition system is able to capture electrical contact voltage values at high frequency corresponding to one complete rotation of the faster disc. The high frequency measurements are filtered to remove electrical noise, using a 50 kHz low pass 3<sup>rd</sup> order Butterworth filter. This was chosen as it does not attenuate the signal in the pass band. The filtered data can then be either investigated in detail, or averaged to provide a mean contact voltage measurement, which is stored every rotation. Friction, load and disc temperatures are recorded at a lower frequency by a separate data acquisition card within the control computer and stored every ten fast disc rotations.

### **3. Results and Discussion**

#### **3.1 Superfinished experiments to assess repeatability**

In order to assess the repeatability and significance of the high frequency contact voltage measurements, a pair of superfinished discs was installed into the disc machine. They were initially run at a maximum Hertzian contact pressure of 1.5 GPa, and a fast disk speed of 200 rpm giving an entrainment velocity of 0.71 m/s, as part of a separate study into running-in. The surface topography was assessed at regular intervals using a portable profilometer, until stable surface micro-geometry was achieved. At this point, the discs were run for a period of time at a maximum contact pressure of 1.4GPa and an entraining velocity of 1.42 m/s, whilst high frequency contact voltage measurements were recorded for subsequent rotations of the fast shaft, with acquisition being triggered to start at the same angular disc position using the shaft encoder. The shafts are geared together at a gear ratio 7:9 so that the same sections of both fast and slow discs are in contact every nine rotations of the faster shaft. Thus, a comparison may be made between the contact voltage due to the same portions of surface in contact, in order to assess the repeatability of the contact voltage signal. Figure 3 shows two portions of contact voltage traces, representing some 20 degrees of fast disk rotation, taken nine rotations apart.

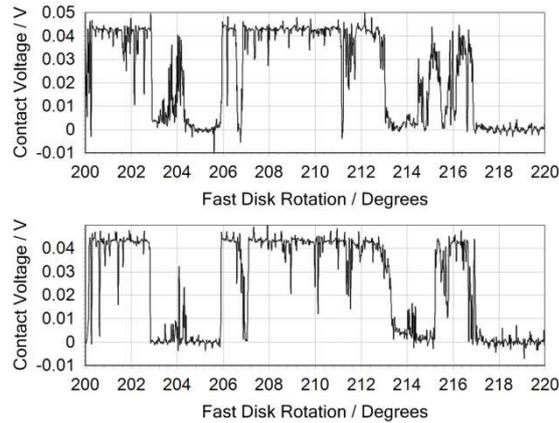


Figure 3: Comparison of superfinished surface contact voltage traces

It is clear from Figure 3 that the electrical contact voltage signal shows characteristic behaviour similar to that reported by previous workers [2, 4, 5] in that it oscillates rapidly, and shows intermediate levels between the 43 mV (full film conditions) and 0 mV (high levels of metallic contact) levels. The intermediate contact voltage levels are interesting and may be associated with extremely thin lubricant films having a lower resistance, or light asperity interaction where some form of tribo-film remains on the surface and true metallic contact is not achieved. For the two traces, the mean contact voltage recorded is 18.6 mV and 19.7 mV respectively. The overall form of the two contact voltage traces is very similar, with some differences of detail. Whilst these are not thought to be significant, they may be related to transient load fluctuations caused by the hydraulic loading system, as evidenced by the slight differences in mean signal level. Consideration must also be given to the small amount of noise visible in the traces, particularly where the signal appears to fluctuate above the 43 mV maximum and below the 0 mV minimum. These are residual noise spikes resulting from filtering of the high frequency electrical noise (due to the inverter drive). After experimentation with the cut-off frequency for the filter, it was found that any lower cut-off (to remove more of the noise) also resulted in degradation of the actual contact voltage signal. In order to further investigate repeatability, traces were captured for every ninth rotation of the fast shaft and used to produce Figure 4. In Figure 4 the measured contact voltage over  $30^\circ$  of rotation is illustrated as a colour coded line for each of the captured fast shaft rotations. The colour coded lines are plotted next to each other in terms of the time at which each line was captured. It is clear from Figure 4 that the contact voltage shows a strong level of repeatability, as illustrated by the evident horizontal banding. In this figure all the contact resistance lines correspond to the same relative positions of the disk surfaces.

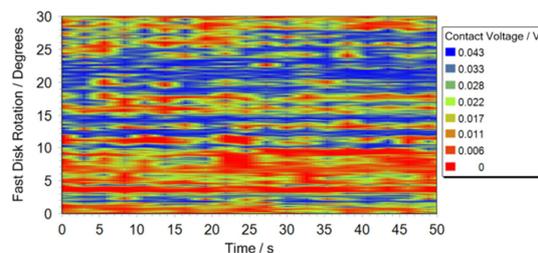


Figure 4: Variation of contact voltage with time for superfinished discs, plotted with every ninth rotation of the fast disc

In contrast Figure 5 shows the corresponding plot obtained when the traces were captured for every tenth rotation of the fast shaft. The horizontal banding is now not apparent and the discs are clearly not in phase at all the times plotted. Figure 5 does however contain evidence of particularly aggressive asperities on one surface or the other repeatedly penetrating the lubricant film, regardless of the corresponding portion of counterface surface.

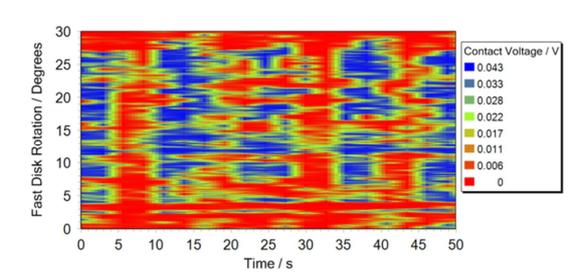


Figure 5: Variation of contact voltage with time for superfinished discs, plotted with every tenth rotation of the fast disc

### 3.2 Mean contact voltage levels in ground disk experiments

Having established the repeatability of the electrical contact measurements, the test rig was fitted with ground disks, with Ra values of 0.38 and 0.35  $\mu\text{m}$  for the fast and slow disks, respectively. These were again run in using the procedure outlined in section 3.1. Once the surfaces had stabilised, the fast and slow disks were found to have Ra values of 0.27 and 0.23  $\mu\text{m}$ , respectively. A typical 1 mm section of profile trace from the fast disc is shown in Figure 6.

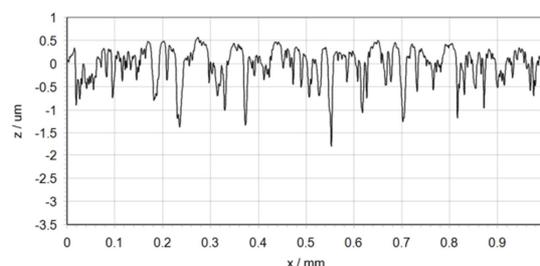


Figure 6: Surface profile for fast ground disk

A range of speed-varying experiments was now carried out, in which the load was fixed at a particular value of either 1.0, 1.1, 1.2, 1.3 or 1.4 GPa. Initially, the lubricant was circulated through the test head in order to heat the rig to the lubricant temperature of 50°C. The disks were then rotated at a fast shaft speed of 200 rpm, and the load applied. The speed was held constant for 300 seconds, and increased to 300 rpm for a further 300 seconds. The overall sequence of speeds, all held constant for 300 seconds, was 200, 300, 400, 500, 750, 1000, 1500, 2000 rpm. Upon reaching 2000 rpm, this speed sequence was then repeated in reverse order, until the disc speeds once again

reached 200 rpm. A typical result for a speed varying experiment with a load of 1.4 GPa may be seen in Figure 7.

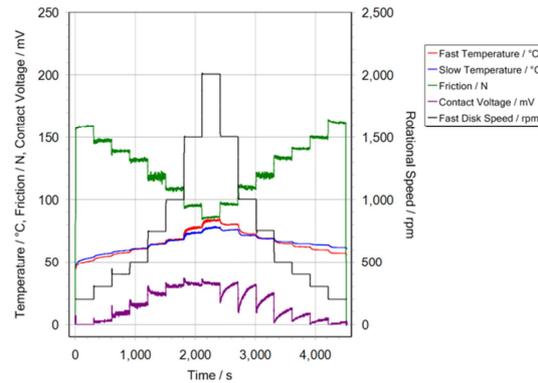


Figure 7: Speed-varying experiment, where  $p_0 = 1.4$  GPa

The mean electrical contact voltage behaviour, averaged over each complete rotation, shows a number of interesting characteristics. In general, as expected, the contact voltage is higher as the entrainment speed increases generating thicker lubricant films and giving less asperity interaction. At low speeds, the contact voltage is at or near 0 mV, indicating continuous levels of metallic contact. At higher speeds, the contact voltage levels are far nearer the 43 mV level which corresponds to full film conditions with no metallic contact. However, in this experiment, even at the highest speeds, full film conditions are not reached. For example, during the 2000rpm speed stage, the maximum contact voltage is around 38 mV, suggesting that intermittent metallic contact is still taking place when the most aggressive asperities pass through the contact.

A more detailed consideration of the measured mean contact voltage demonstrates the effect of disc temperature. For example, when the speed is increased, the contact voltage initially shows a sharp increase, after which it gradually falls to a quasi-steady state level towards the end of the 300 seconds speed stage. This may be explained by inspection of the disc temperature traces. Whilst these temperatures are measured some 3 mm below the surface, their behaviour is indicative of the trends in mean disc surface temperature. When the speed is increased, the temperatures are initially at the steady level achieved at the end of the previous speed stage. Thus, the effect of increased entrainment is to increase the film thickness and reduce the instance of metallic contact, increasing the measured contact voltage. However, the increase in speed means that a higher level of shear heating is being generated in the lubricant film, leading to a gradual rise in temperature of the disk surfaces over the speed stage until a new steady state condition is reached. This rise in temperatures leads to an effective decrease in the lubricant viscosity at the inlet to the contact, since this is driven by the surface temperatures at the inlet, which in turn decreases the thickness of the lubricant film, leading to a reduction in contact voltage levels.

This thermal-lag effect is more apparent in the speed stages in the speed reducing part of the test. Here, the surfaces are initially at the higher steady state temperatures achieved in the previous speed stage. When the entrainment speed is reduced, the film thickness reduces accordingly and increased levels of metallic contact occur, leading to the rapid drop observed in contact voltage. At this stage, there is now less heat being generated in the oil film, and the disc surface temperatures

gradually reduce until they reach a new equilibrium temperature. During this gradual reduction in temperature the viscosity increases and the lubricant film recovers, reducing metallic contact and giving a steadily increasing contact voltage measurement.

Thus it becomes clear from consideration of Figure 7, that any attempt to correlate mean contact voltage levels with contact conditions must take account of time-dependent thermal effects in order to give meaningful results. A comparison of, for example, the two 1000 rpm speed stages shows very different mean contact voltage behaviour which can only be reconciled when the differences in contact temperatures are considered.

In order to assess the combined effect of load, speed and temperature on mean metallic contact levels, the lambda ratio was calculated. This was taken as:

$$\Lambda = \frac{h_c}{\sqrt{R_{q1}^2 + R_{q2}^2}}$$

where  $h_c$  is the calculated central film thickness, and  $R_{q1}$  and  $R_{q2}$  are the root mean square roughnesses of the two disc surfaces, measured as  $0.36\mu\text{m}$  and  $0.31\mu\text{m}$  for the fast and slow discs respectively. The central film thickness was used since it is more meaningful in the context of a contact with significant mixed lubrication than the commonly used minimum film thickness, and is calculated using the formula presented by Chittenden *et al.* [15]. For this calculation, the lubricant properties are calculated at the mean disc temperatures, taken over the final 60 seconds of each speed stage. Note that these temperatures are measured 3 mm below the disk surfaces which will achieve a higher temperature. The mean contact voltage values may be seen plotted against lambda ratio in Figure 8.

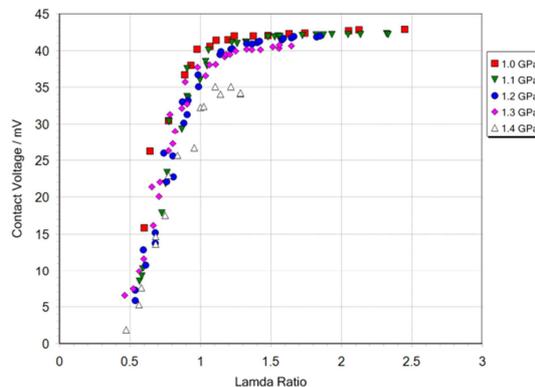


Figure 8: Variation of mean contact voltage with Lambda ratio

It can be clearly seen from Figure 8 that the lambda value is an effective parameter to take account of the various effects of load, speed and temperature on film thickness and, hence, on mean contact voltage levels. The data shows that, in the majority of conditions, there is metallic contact taking place. Only when  $\Lambda > 2$  does the mean contact voltage approach 43 mV and, even at these conditions, there are intermittent asperity contact events as evidenced by some of the data points being just below 43 mV. Between  $\Lambda \approx 1.2$  and  $\Lambda \approx 2$ , there is clearly some asperity contact taking place, since the mean contact voltage levels are below 43 mV, but these must be relatively

infrequent with only the most aggressive asperities able to penetrate the lubricant film. Below  $\Lambda \approx 1.2$ , the contact voltage drops approximately linearly with lambda ratio as the films become progressively thinner and more and more asperities make metallic contact. As the lambda value approaches 0.5, mean contact voltage levels become very low and are only a few millivolts, indicating that metallic contact is taking place almost continuously. The film thickness evaluated using [15] is a nominal film thickness for perfectly smooth surfaces operating at the same conditions so that the  $\Lambda$  value is a measure of the propensity of direct interaction of between asperities. When  $\Lambda$  becomes larger than unity asperity interaction levels can be expected to fall off significantly. However Figure 8 can be viewed as showing that this fall off is load dependent.

The variation of the mean friction coefficient with lambda ratio is shown in Figure 9. The friction coefficient was calculated using the measured friction force averaged over the final 60 seconds of each speed stage. At lower lambda ratios, the friction coefficient is relatively high due to increased levels of asperity contact. As the lambda ratio increases the friction coefficient continues to drop until values more typical of full film EHL contacts are achieved, due to asperity contact levels decreasing and thicker lubricant films being generated. It is interesting to note that, whilst the friction levels continue to drop as the lambda ratio increases above  $\Lambda \approx 1.5$ , the contact voltage levels at these points are at or near 43 mV, demonstrating the relative insensitivity of contact resistance measurements to film thickness once films are sufficiently thick that there are no (or very few) metallic contact events taking place.

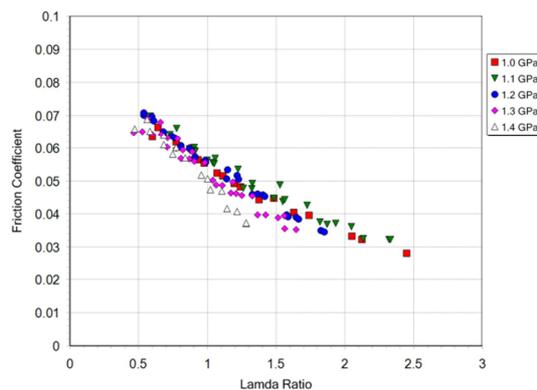


Figure 9: Variation of friction coefficient with Lambda ratio

These observations of the dependence of both friction and contact resistance on lambda ratio are consistent with the results of numerical rough surface mixed-EHL simulations carried out by Sharif *et al.* [16] who found that there was a marked reduction in the predicted count of surface contact events (asperity contacts) in simulated gear tooth contacts as the lambda ratio was increased from 0.1 to 2, coupled with a corresponding reduction of three orders of magnitude in predicted surface fatigue damage levels. Furthermore, Spikes and Guangteng [17] also concluded, based on optical interferometry measurements, that the mixed lubrication regime spanned a range of lambda ratios from 0.1 to around 2, which is consistent with the contact resistance results reported in this paper.

### 3.3 Detailed effects of load and temperature on contact voltage

A second set of experiments was carried out using previously well run in, stable, ground discs to investigate the effects of load on contact voltage further. Here, the disks were run at a constant fast shaft speed of 1500rpm, and the load was applied for a brief period of 25 seconds. High frequency contact voltage measurements were acquired every ninth rotation of the fast shaft so that the same portions of both fast and slow disc were in contact as described in Section 3.2. Figure 10(a) shows the detailed variation of contact voltage for an applied load of 1.0GPa whilst Figure 10(b) shows the variation of friction force, disc temperatures and mean contact voltage for the same experiment. It should be noted that the load is applied at 0 seconds, and removed at 25 seconds. Figure 10(b) shows additional short periods of data prior to 0 seconds and after 25 seconds.

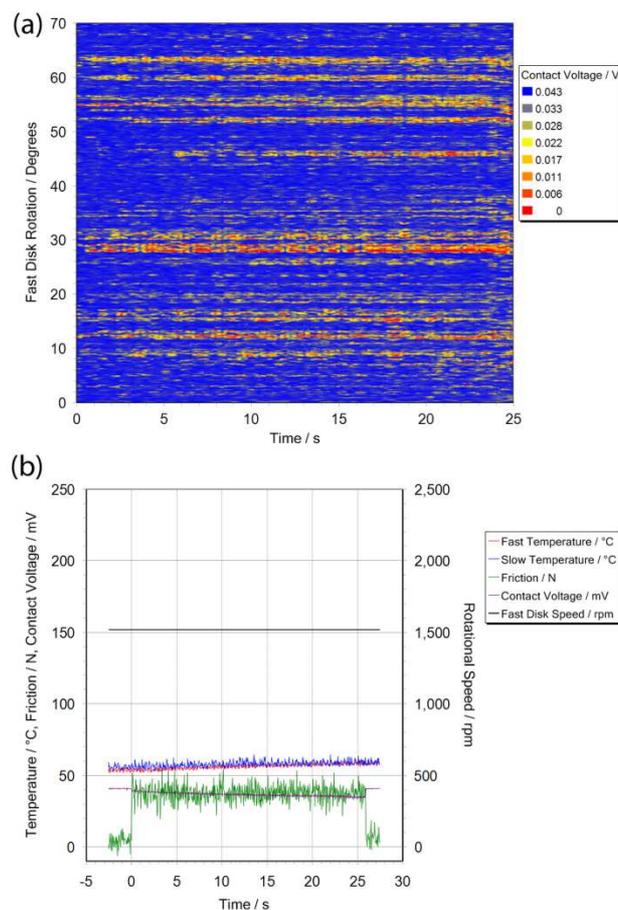


Figure 10: Variation of (a) detailed and (b) mean contact voltage with time, at a fast disc speed of 1500rpm and a load of 1.0GPa

Inspection of Figure 10(b) shows that the mean levels of contact voltage are high and decrease only slightly over the duration of the loading period, indicating very intermittent levels of metallic contact throughout. This is borne out by Figure 10(a), which shows the variation of contact voltage over seventy degrees of fast disc rotation, plotted as a function of time. It can be seen that throughout the test for the majority of the time, levels of metallic contact are very low, with contact voltages at high levels. Intermittently, the higher levels of metallic contact take place, where the lubricant film

is unable to separate particularly aggressive asperities, as indicated by the repeatable bands of low contact voltage shown in the figure. The transient variation in contact voltage over the disc rotation remains repeatable and at very similar levels throughout the 25 second period, since the kinematics of the contact are constant over the loading period, and the disc temperature rise is less than 5°C over the entire period. The mean contact voltage can be seen to fall gradually over the loading period, due to this slight temperature rise.

The experiment was repeated at a load of 1.4GPa, and the corresponding results can be seen in Figure 11.

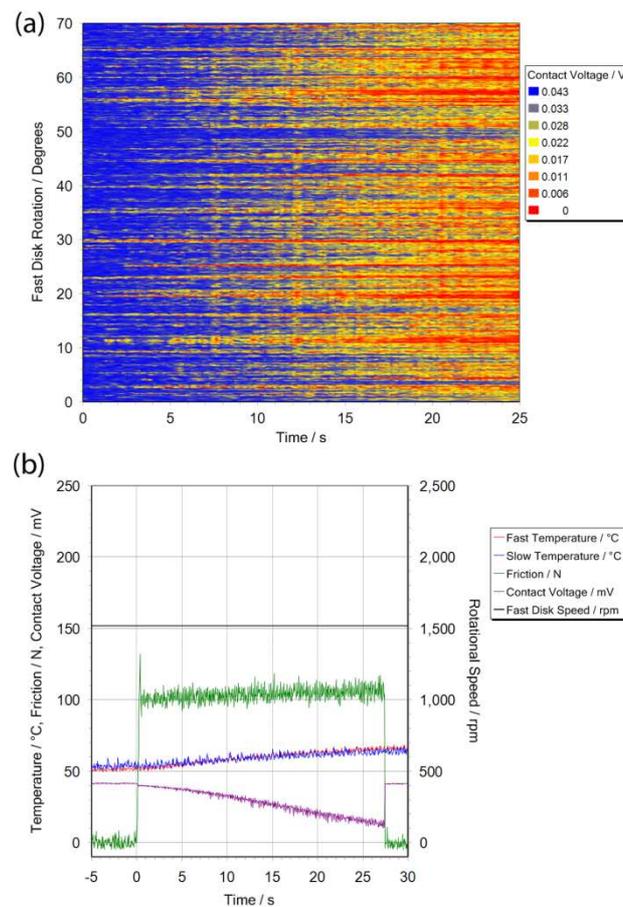


Figure 11: Variation of (a) detailed and (b) mean contact voltage with time, at a fast disc speed of 1500rpm and a load of 1.4GPa

At this higher load more heat is dissipated at the contact and the effects of temperature are more significant with both disks showing an increase in the measured temperatures of around 15°C over the 25 second period. This temperature increase can be seen to cause a significant variation of the contact voltage with time. The contact conditions can be seen to change from a situation where, for the majority of the 70° rotation there are only limited instances of metallic contact, to a condition where the instance of metallic contact is high with low contact resistance levels for most of the rotation. This change is caused by the reduction in film thickness due to the decrease in viscosity caused by the increase in temperature. A gradual increase in friction force can also be seen to

occur over the 25 second period, which is consistent with the reduction in film thickness and increase in metallic contact levels.

Finally, the experiment was repeated with the load increased to 1.7GPa, giving the results shown in Figure 12.

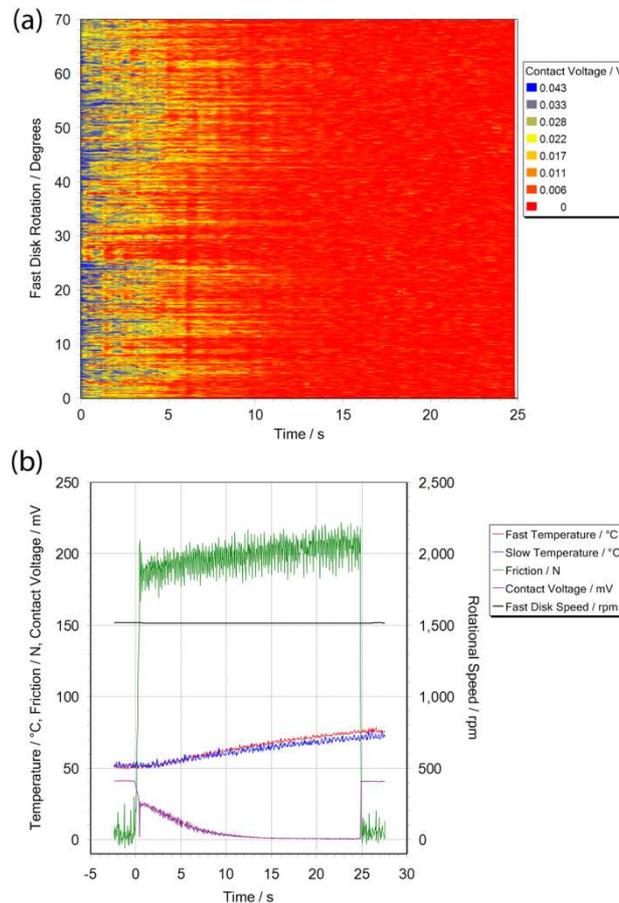


Figure 12: Variation of (a) detailed and (b) mean contact voltage with time, at a fast disc speed of 1500rpm and a load of 1.7GPa

In this experiment the significantly higher levels of friction lead to a temperature rise of around 25°C over the 25 second period. This leads to a relatively rapid decrease in contact voltage levels. The initial results show intermittent contact levels which changes over the first 10 seconds of running to an almost continuous metallic contact for all of the 70° section of disc rotation shown in Figure 12.

Following these tests, surface profiles were measured for both discs and compared to those taken at the start of the experiments after the running-in process was complete. For these comparisons the measured profiles were relocated by shifting their relative positions so that the detailed asperity shapes were aligned. The surfaces were found to retain the stable surface profiles having no significant changes in micro-geometry when compared to the start of the tests. It follows that the change in contact voltage during each 25 second loading period cannot be attributed to any form of surface modification, and is solely due to thermal changes within the contact leading to thinner

lubricant films and higher levels of mixed lubrication. It should be noted that the profile measurements were taken in situ using a portable surface profilometer instrument. In this way the alignment of the discs remained unaffected throughout the whole test sequence.

These experiments show that there is a significant effect of load on the contact voltage behaviour of these rough surface experiments. This is somewhat contradictory in terms of the usual assumption that elastohydrodynamic film thickness is relatively insensitive to load, e.g. [15], but may be clearly explained by consideration of the thermal contact conditions. A higher load leads to a higher level of frictional dissipation within the contact (as witnessed by the higher friction forces in Figures 10, 11 and 12 as the load is increased) which, due to the higher disk surface temperatures, leads to a reduction in lubricant viscosity at the inlet to the contact. This gives a reduced film-forming ability and hence higher levels of metallic contact.

#### **4. Conclusions**

A technique has been developed using electrical contact resistance to study both the average and detailed, transient variation of metallic contact levels in mixed lubrication conditions in rolling/sliding contact. It is shown that the electrical contact resistance measurements can provide detailed insight into contact conditions, and their dependence on operating parameters such as entrainment speed, load and temperature. The method has been shown to be robust and repeatable, using studies with both superfinished and axially ground discs. Repeatability of the transient contact resistance measurements when the surface roughness features are in the same relative kinematic positions shows that the contact resistance signal does indeed reflect the proximity of asperities or groups of asperities as they collide. Using axially ground discs, the variation of mean contact resistance with lambda value shows that even at relatively high lambda values there are still occurrences of metallic contact between aggressive asperity features. The variation of measured friction coefficient with lambda value shows good correlation with the higher levels of asperity interactions at low lambda values demonstrated by the contact resistance results. Finally, the effects of load have been studied by consideration of the detailed, high frequency variation in contact resistance. This has shown that the effect of load on metallic contact is significant, as a result of the influence of frictional heat dissipation within the contact which determines the disc surface temperatures and the effective lubricant viscosity in the film-forming entry region of the contact.

#### **5. Acknowledgements**

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