INFLUENCE OF SURFACE ROUGHNESS FEATURES ON MIXED FILM LUBRICATION

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SUMMARY
An optical technique (3D SLIM - Spacer Layer Imaging) has been developed to accurately map lubricant film thickness in thin film elastohydrodynamic contacts. This experimental technique has been used to study the influence of surface roughness features, asperity height, and slope on EHD film thickness. Single ridges transverse to the entrainment direction were used to represent asperities. It was found that surfaces with lower slopes generate thicker minimum films. Below a certain entrainment speed, the minimum film thickness declined at a rate dependent on asperity slope. At low speeds, surfaces with higher slopes entrapped a larger volume of lubricant ahead of the asperity and along the entrainment direction. For all speeds, increased asperity heights entrapped the most lubricant. Both asperity slope and height had a negligible effect on mean film thickness in the contact.

Keywords: Mixed Lubrication, Optical Interferometry, Surface Roughness, EHD Lubrication, Thin Film Lubrication.

1 INTRODUCTION
There is a progressive trend for machine elements to be operated at higher loads and higher temperatures than in the past, causing the lubricant film thickness to become progressively thinner. This means that bearings, cams, gears, splines and other engineering components operate for increased periods in the mixed lubrication regime where the lubricant film thickness separating the two surfaces is less than their combined roughnesses.

In thin film conditions, a higher proportion of the load is borne by asperity contact than by the lubricant. The very high pressures present at asperity contact make it important to know these proportions and thereby improve life predictions of machine elements.

The influence of surface roughness on lubricant film thickness is far more important in mixed lubrication than in full film lubrication. Surface roughness parameters such as asperity height, slope, and wavelength can affect lubricant entrainment and the consequent film thickness profile. Using model roughness features to represent asperities, optical interferometry experiments have been performed to study EHD lubricant film thickness in the 40 nm to 500 nm region [1-3]. The 3D SLIM (Spacer Layer Imaging) method has been employed in similar experiments for the 0 nm to 100 nm region [4]. From film thickness profiles, it is possible to calculate the pressure distribution in the contact [5].

This paper describes further development and optimisation of the 3D SLIM method to enable a detailed study of how model surface features affect ultra-thin lubricant film. Single transverse ridges, sputtered on the surface of a steel ball, have been used to represent asperities and the effects of slope and height on lubricant film have been explored.

2 EXPERIMENTAL SET-UP

2.1 3D SLIM Spacer Layer Imaging Method
A smooth steel ball is loaded against the flat side of a glass disk that is very thinly coated with chromium, on top of which is a silica spacer layer (Figure 1).

Figure 1: 3D Spacer Layer Imaging
White light is shone through the disk onto the point contact. Part of the light is reflected by the chromium layer while the rest travels through the spacer layer and any lubricant film present and is reflected by the surface of the steel ball. Upon recombination, these beams form an interference image of the contact that is captured by a CCD camera and analysed via a computer. Using a proper calibration, a film thickness map is produced.

2.2 3D SLIM Calibration
The RGB colour of the interference image measured for each pixel of the CCD camera detector is dependent on both the spacer layer and lubricant film thickness. The relationship between film thickness and RGB colour is directly calibrated against ultra-thin film interferometry [6]. Although the CCD camera detects individual R, G, and B values at each pixel, these were normalised via computer software by converting them to \(\{3R/(R+G+B)^2\}, \{3G/(R+G+B)^2\}, \text{and } \{3B/(R+G+B)^2\}\) respectively. The normalising procedure was done to...
reduce error caused by any light source degradation over time.

Using a smooth ball, ultra-thin film interferometry is used to generate the “log(central film thickness) vs. log(entrainment speed)” equation for a chosen test lubricant. The ball is then loaded against a disk that is coated only with chromium and not spacer layer. With the same test parameters as before, this set-up is run over a range of entrainment speed. The speed is gradually stepped down to the minimum speed. At each speed step, the central film thickness is calculated from the film thickness-speed equation and the interference image captured by the CCD camera is analysed for the corresponding normalised RGB combination. Hence, a curve relating normalised RGB and separation is obtained (Figure 2).

![Figure 2: Calibration curve relating film thickness with normalised RGB](image1)

This calibration method, subjected to random errors, is believed to yield an accuracy of ±2 nm. Subsequent film thickness experiments using 3D SLIM were then conducted with a thin spacer layer disk.

2.3 Experimental Technique and Specimens

2.3.1 Experimental Technique

For all tests, the ball, disk and lubricant chamber were thoroughly cleaned with toluene followed by isopropanol. After calibration, the silica spacer layer is mapped circumferentially around the disk to determine its varying thickness. This is done by loading a dry smooth ball against the disk and recording the spacer layer thickness at each disk position. The distance between each point is about 1 mm and the disk mapping accuracy is about ±1 nm (Figure 3).

![Figure 3: Spacer layer thickness map of disk track](image2)

The smooth ball is then replaced with a sputtered ball. This ball is attached to a shaft where an absolute encoder tracks its position. The encoder has a resolution of 4096 points per revolution giving an equivalent ball location accuracy of 15 µm. The ball is submerged to three quarters of its height with lubricant to obtain fully flooded test conditions. Both the ball and disk are driven by individual motors in nominally pure-rolling. The ball encoder is used to trigger the CCD camera when the roughness feature is at the centre of the contact while another encoder attached to the disk shaft records the disk position. A correction is made for the spacer layer thickness during image analysis.

2.3.2 Test Parameters and Specimens

All tests were performed at 40.0 ± 0.5°C. The properties of this lubricant are (i) viscosity = 22.0 cP at 40°C, 3.6 cP at 100°C, (ii) refractive index = 1.471, (iii) effective pressure-viscosity coefficient = 19.8 GPa⁻¹ at 40°C.

The glass disk has an elastic modulus of 75 GPa and CLA roughness of 9 nm. The steel balls used are 19.05 mm in diameter, have an elastic modulus of 207 GPa, and CLA roughness of 9 nm. A load of 20 N (maximum Hertzian stress = 0.527 GPa) has been used to press the ball against the disk.

![Figure 4: Influence of contact pressure on spacer layer thickness (relative to 0.527 GPa)](image3)

The silica spacer layer thickness was reduced from the 400 nm, used previously, to 140 nm. This resulted in the reduction of the layer compression due to contact pressure (Figure 4).

Three ridges of different sizes have been used. Their uncompressed profiles were measured using a Talysurf machine at various locations along their lengths and averaged (Table 1). The film thickness profile under steady state, nominally pure rolling conditions were then studied.

<table>
<thead>
<tr>
<th>Ridge</th>
<th>Height (nm)</th>
<th>Width (µm)</th>
<th>Slope (£)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>163</td>
<td>55</td>
<td>0.437</td>
</tr>
<tr>
<td>B</td>
<td>342</td>
<td>37</td>
<td>1.002</td>
</tr>
<tr>
<td>C</td>
<td>145</td>
<td>20</td>
<td>1.359</td>
</tr>
</tbody>
</table>

*Table 1: Single transverse ridges employed*
3 RESULTS

3.1 Orientation of Data

Figure 5 shows a typical image captured with the ridge near the centre of the contact (note: the original colour image has been converted to greyscale). A rectangular area 15 μm wide and 280 μm along the rolling direction was analysed for all the images. All film thickness profiles showed similar features. A film thickness minimum appears at the peak of the ridge and a lubricant entrapment is formed in front of the ridge, where a large pressure perturbation is expected.

![Image of typical image and film thickness profile](image)

Figure 5: Typical image and film thickness profile of transverse ridge in the contact

Film thicknesses at four locations along the entrainment direction in the contact have been studied. They are: (i) Entrapped lubricant - Max, (ii) Minimum at ridge peak - Min, (iii) Region between the inlet and ridge - Inlet, (iv) Region between the outlet and ridge – Outlet.

3.2 Effects of Single Transverse Ridges

3.2.1 General Film Thickness Features

Figure 6 shows the change in film thickness with entrainment speed. The mean central film thickness for a smooth ball test is plotted for reference. There is no significant difference between this value and the film thickness in regions near the inlet and outlet, but away from the ridge. Thus, asperity geometry has a negligible effect on mean film thickness.

The difference between the mean film thickness and the maximum film thickness decreases with speed. A similar trend is shown for the difference between the mean film thickness and minimum film thickness. Thus, the film thickness profile becomes more uniform as the entrainment speed decreases.

![Graphs of film thickness vs. speed for different ridges](image)

(a) Ridge A (H = 163 nm, Slope = 0.437 degrees)
(b) Ridge B (H = 342 nm, Slope = 1.002 degrees)
(c) Ridge C (H = 145 nm, Slope = 1.359 degrees)

Figure 6: Change of film thickness with speed for each transverse ridge

3.2.2 Minimum Film Thickness

Figure 7 shows a comparison of minimum film thickness between Ridge A (S = 0.437 deg) and C (S = 1.359 deg). At an entrainment speed of 0.05 ms⁻¹, the minimum film thickness was greatest for Ridge A and least for Ridge C. However, at 0.025 ms⁻¹, all three ridges gave a minimum film thickness close to or below the threshold of reliable measurement (2 nm).

![Graphs of minimum film thickness vs. speed for different ridges](image)

Figure 7: Effects of slope on minimum film thickness for a given speed
As a consequence of this, the rate at which the minimum thickness of the film declines below 0.05 ms$^{-1}$ appears to be related to the geometry of the asperity, being most marked in the case of the ridge of lowest slope (Figure 6). However, the behaviour of the film below a thickness of 2 nm cannot be reliably determined.

### 3.2.3 Maximum Film Thickness

![Figure 8: Effects of asperity slope and height on maximum film thickness](image)

Comparing Ridge A (H = 163 nm) and C (H = 145 nm) in Figure 8, higher slopes cause a larger volume of lubricant to be entrapped in front of the asperity as the speed decreases. Ridge B (H = 342 nm) entrapped the most lubricant. The magnitude of entrainment is dependant upon the corresponding pressure perturbation. However, it may be wrong to relate asperity height to pressure perturbation in the contact, as the slopes for all three ridges are distinctly different.

### 4 CONCLUSION

Improvements made to the 3D SLIM technique have enabled the study of model surface roughness features at very low film thickness measurements (0 to 210 nm). The improvements are (i) normalising the RGB values, (ii) reducing the silica spacer layer to 140 nm, (iii) mapping the spacer layer thickness around the disk track, and (iv) increasing the location accuracy of the ball to 15 µm.

Mean film thickness in the contact was not affected by asperity geometry. Surfaces with lower slopes generated thicker minimum films. Below a certain entrainment speed, the rate at which the minimum film declines was related to the asperity slope. At lower speeds, surfaces with higher slopes entrapped a larger volume of lubricant ahead of the asperity along the entrainment direction. Taller asperities entrapped more lubricant.

This work represents an initial quantitative study of how surface roughness features, slope, and height influence thin film, mixed lubrication. A complete study involving multiple transverse ridges, multiple bumps, and isotropic rough balls is now in progress.

### 5 REFERENCES


