POWER SPECTRAL DENSITY ANALYSIS OF STEEL SURFACE TOPOGRAPHY CHANGE ON A BOUNDARY LUBRICATED RECIPROCATING SLIDING CONTACT

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Abstract

Study the change of the surface topography using spectral density analysis was done by performing experiments on ball-on-plate steel under boundary lubricated reciprocating sliding contact. Measurement of the surface topography was executed by an optical profilometer: Micromap 512. Matching and Stitching computer code method was employed in order to get more detailed information about the surfaces before and after the experiment. The profile evolutions of the surface for a certain number of running cycles were presented on the PSD (Power Spectral Density) and spatial frequency form. In the analysis, results show that the surface changes more in the running direction than in the traverse direction.

Key words: PSD (Power Spectral Density), surface topography, boundary lubrication, sliding contact.

INTRODUCTION

The surfaces are completely separated when the contact geometry and the operating conditions are such that the load is fully supported by a fluid film. This condition is generally referred to as the hydrodynamic lubrication. Theory for fluid film design is well developed based on Reynolds' equations and continuum mechanics [1]. When the load is high and/or the speed is low, the hydrodynamic or hydrostatic pressure may not be sufficient to fully support the load, and the surfaces come into contact. The contact occurs at the peaks and hills of the surfaces, and these are referred to as asperities. The amount and the extent of the asperity contact depend on many factors: surface roughness, fluid film pressure, normal load, hardness, and elasticity of the asperities, etc.

Dowson and Higginson [2] define the regime of the elastohydrodynamic lubrication (EHL) when many of the asperities undergo elastic deformation under the contacting conditions, and the normal load is supported by the asperities and the thin fluid film. The EHL theories are reasonably well developed and are capable of describing the surface temperatures, fluid film thickness, and the fluid film pressures supporting the load. The theory assumes continuum mechanics and does not take into account the effects of wear and the presence of a third body or wear debris. Chemical effect between the asperity and the lubricant is not taken into account.

Further increase in the contact pressure beyond the EHL conditions causes the contacting asperities to deform plastically and the number of contacts to increase as well as for the fluid film thickness todecrease. When the average fluid film thickness falls below the average relative surface roughness, surface contact becomes a major part of the load supporting system.

Mechanical interactions of these contacts produce wear, deformation, abrasion, adhesion, and fatigue under dry sliding conditions. Chemical reactions between the lubricant molecules and the asperity surface, due to frictional heating, often produce a boundary chemical film which can be either beneficial or detrimental in terms of wear. The combination of the load sharing by the asperities and the occurrence of chemical reactions constitutes the lubrication regime commonly referred to as the boundary lubrication (BL) regime.

The lubrication regimes determine the effectiveness of fluid film formation, and hence, surface separation. The Stribeck curve was first recognised by Stribeck [3] in 1902 to study the regimes of journal bearing lubrication. The work was continued by Hersey [4] in 1915 by observing the variation of sliding friction using the number $\eta N/p$, where η is the lubricant viscosity, N the angular velocity and p the average contact pressure. The Stribeck curve divides lubrication into three regimes: thick film, thin film and boundary lubrication.

Interactions between the two surfaces take place in the form of asperities colliding with each other under boundary lubrication conditions. These collisions produce a wide range of consequences at the asperity level, from elastic deformation to plastic deformation to fracture. These collisions produce friction, heat, and sometimes wear. Chemical reactions between lubricant molecules and surfaces usually accompany such collisions producing organic and inorganic surface films. It has long been thought that surface films protect against wear. Closer examination of Hsu [5] suggests that some films are protective (antiwear), some films are benign, and some films are detrimental (prowear). A theory for a comprehensive view on boundary lubrication is currently lacking; however, models on lubricant chemistry and contact mechanics do exist [6-9]. Recently, molecular dynamics models have been developed to describe atomic interactions under simplified boundary lubricated conditions [10].

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The detailed physical and chemical processes occurring in the contact zone are still not well understood.

In this paper, a study to determine the microscopically change in the asperity-asperity contact level of surface was done in a boundary lubricated ball-on-plate reciprocating sliding experiment. Experiments were done for various number of cycles or sliding distances. To get a more detail and complete information of the surface topography, power spectral density analysis was done.

EXPERIMENTAL APPARATUS

S-Tribometer

Figure 1 shows the detail of the movement (wear track) and surface measurement direction of friction and wear tests carried out on the S-tribometer. The apparatus executes a sinusiodal reciprocating motion of a hemispherical specimen on the stationary counterface with amplitude of 46 mm. The hemispherical specimen is fixed in a holder, held in a loading arm, connected to the slider/support. The pivot of this loading arm lies in the plane of the sliding contact. The maximum velocity is $2\pi Af$, where A is the amplitude and f the frequency of the moving supports. The specimen is loaded through a short spindle by a pressurized air bellow fixed on top of the support. The support moves in a plane parallel to the counterface through a system of four roll blocks guiding two cylindrical bars fixed to the support. The counterface is held in an aluminium holder which is fixed to the heat exchanger. The heat exchanger is connected to a thermostatically controlled oil bath and is supported by two steel blade springs fixed to the frame of the tribometer. These springs only allow movement parallel to the direction of sliding. This movement is restricted by a piezoelectric force transducer fixed between the heat exchanger and the frame of the tribometer. A modification of the tribometer was made in order to unload the contact at and near the ends of travel by using a lift system. Omitting the lift system contact between pin and plate at the ends of travel exists.

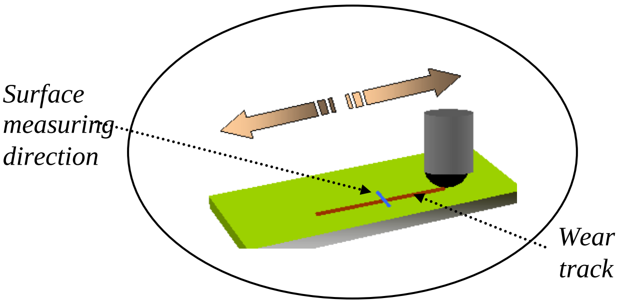


Figure 1. Wear track and surface measurement direction.

Micromap

There are many methods to determine and/or calculate surface roughness parameters (R_a, R_q, S_k, K_u, and R_t) such as mechanical stylus, optical, scanning probe microscopy, fluid, electrical, and electron microscopy. The optical method is a non-contact means of accurately measuring surface profiles-heights in 3 dimensions. The output is very similar to a standard geographical contour map where any given surface and individual bands of (false) colour represent area of equal height. Unfortunately at this level the styli of profilometers can behave like ploughshares and may destroy many of the features we would like to look at. The optical profilometry Micromap 512 was used to measure the surface topography parameters in these experiments. The Micromap 512 has the the following characteristics:

- High resolution of approximately 1 nm
- Size of the measured area 110x85 μm up to 4.42x3.45 mm
- 304x228 pixels, at very smooth surfaces 640x478 pixels (phase mode)

Figure 2 shows a schematic of an optical interference microscope. The instrument has several interchangeable magnifications objectives. Each objective contains an interferometer, consisting of a reference mirror and beams splitter, which produces interference fringes when light reflects off the reference mirror recombines with light reflected off the sample. In vertical scanning interferometry when short coherence white light is used, these interferences fringes are present only over a very shallow depth on the surface. The surface is profiled vertically so that each point on the surface produces an interference signal and then locating the exact vertical position where each signal reaches its maximum amplitude. To obtain the location of the peak, and hence the surface height information, this irradiance signal is detected using a CCD array. The instrument starts the measurement sequence by focusing above the top of the surface being profiled and quickly scanning downward. The signal is sampled at fixed intervals, such as every 50-100 nm, as the sample path is varied. The motion can be accomplished using a piezoelectric transducer (PZT). Frames of interference data imaged by a video camera are captured and processed by high-speed digital signal-processing hardware. As the system scans downward, an interference signal for each point on the surface is formed. Each point is processed in parallel and a three-dimensional map is obtained.

EXPERIMENTAL PROCEDURES

Testing conditions

Three hardened steel AISI 52100 plates and three SKF Standard Balls with the diameter of 20 mm were used as samples. Each pair of Ball and Plate was run under conditions as indicated in Table 1.

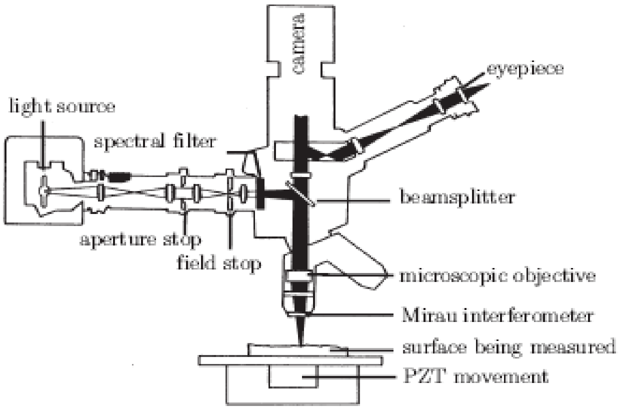


Figure 2. Schematic representation of a three-dimensional optical profiler

Table 1
Experimental conditions

Parameters	Value(s)
Sliding velocity (m/s)	0.01
Applied load (N)	100
Ambient temperature (^{o}C)	25
Initial roughness value R_a of the ball (nm)	8.5
Initial roughness value R_a of the plate (nm)	40
Number of cycles	1, 3 and 5

Shell Tellus R5 was used as lubricant in this experiment which has the property of viscosity η = 5.43 mPas at $T \approx 25^o$C. In order to run in the boundary lubrication regime, the parameter of Schipper [3] was used for determining the sliding velocity as shown in Fig. 2. Since the lubricant viscosity η, Ball roughness R_{ab}, and Plate roughness R_{ap}, are known the boundary lubrication sliding velocity V is easily determined where the combined surface roughness $R_{at} = (R_{ap}^2+R_{ab}^2)^{0.5}$.

Matching and Stitching

In most tribological experiments statistical parameters are used to get information about the surface changes during running-in. Unfortunately, this method is not sensitive to determine small local surface changes. In other words, the parameters do not change significantly while it clearly can be observed that the surfaces have changed due to wear.

To identify the micro-geometry change in surface topography, a new method was developed by de Rooij & Schipper [11] using interferometry microscope. Basically the method can be described as finding the maximum correlation and subsequently subtracting two 3D surface measurements before and after an experiment. In practise it is not possible to get a detailed image of a complete transverse section of a wear track with a small sampling interval in one surface roughness image measurement. One way to achieve this is to stitch a number of small but detailed images together (stitching process). It is necessary to take several measurements, each one having a certain overlap with the previous one. For every set of two neighbouring images, the mutual translation and rotation have to be determined, based on the area of overlap (matching process). Once all images are matched, the translation and rotation data are combined and one large image is formed. Finally, the stitched images before and after an experiment can be matched and subtracted from each other to get the very detailed view of the micro-geometry changes or micro-wear. The matching and stitching computer program has been improved by Sloetjes *et al.* [12-13] and was applied to this experiment.

Surface Roughness Measurements

The Micromap 512 interferometer was employed to measure the surface topography using the available highest magnification, 40X, in order to get more details in surface topography data. The 40X magnification has the property of 110 X 85 μm area with 304 X 228 data points. To predict how many surface images should be measured as input for the stitching process, the Hertzian contact area was calculated. Since the minimum track width is 374 μm, by using 40X magnification and a two-third overlapping area, 11 Ball surface images in the running direction and 19 Plate surface images perpendicular to the running direction were measured. These images will be used for the Matching and Stitching code for further surface analysis.

RESULTS AND DISCUSSIONS

A random surface can be represented by a multitude of different wavelengths. To identify the wavelengths of profile roughness a power spectral density (PSD) can be used. PSD decomposes the surface profile into its spatial Fourier component wavelength. It is given analytically by:

$$PSD(f) = \lim_{L\to\infty}\left(\frac{1}{L}\right)\left|\int_0^L y(x)e^{-2i\pi fx}dx\right|^2 \qquad (1)$$

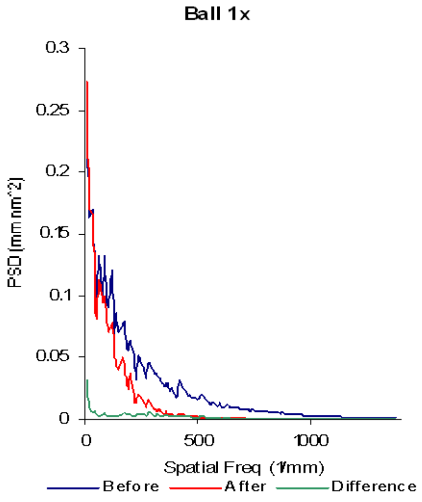
and is estimated in digitised form by:

$$PSD(f) = \frac{1}{N\Delta}\left|\sum_{j=1}^{N} y(j)e^{-2i\pi fj/N\Delta}\right|^2 \qquad (2)$$

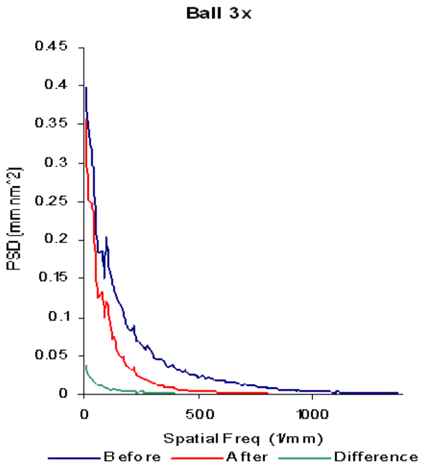
In Equation (1) and (2), Δ is the lateral point spacing (sampling interval) of the digitized data points, the total length of the profile, L, is equal to $N\Delta$, and the set of spatial frequencies, f, in the digitized PSD is given by k/L, where k is an integer that ranges from 1 to $N/2$.

Calculation of the digital Fourier transform in Equation (2) can be greatly speeded by using Fast Fourier Transform (FFT) algorithms.

The selected images which were used to analyse the roughness parameters were also used for the PSD analysis. Figure 3 and 4 show the change in the surface spectrum for the Ball and the Plate for the tests with the different number of cycle. These figures show a random surface with the PSD has a fairly decaying, although somewhat randomised distribution, with little evidence of periodic components. The PSD scales for the Plate were made logarithmic because of the very small change in the amplitude of the surfaces. It is hard to see the difference in the normal coordinate scale. The difference of the spectrum becomes larger as the number of cycles increases. The differences in spectra between before and after an experiment for the Ball are larger than the Plate as a consequence of wear. For the Plate, the spectrum between before and after experiment almost have the same shape, there is a small difference. Both the Ball and the Plate show that the difference spectrum in the x-axis (running direction) is larger than that in the traverse direction which agrees with the roughness analysis.



(a)



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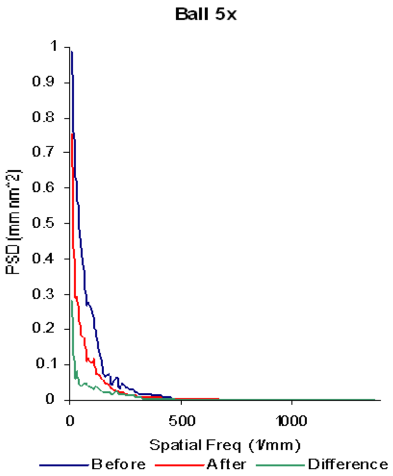

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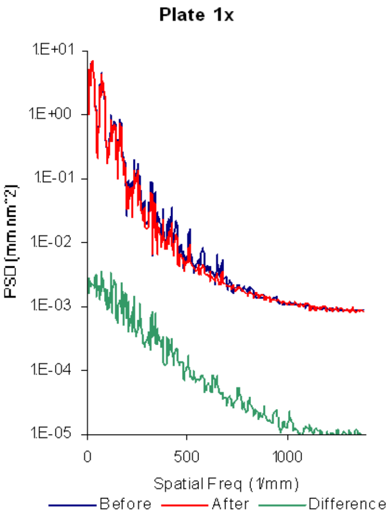
Figure 3. The change in the x-average profile Ball surface spectral density for the tests with different cycles.



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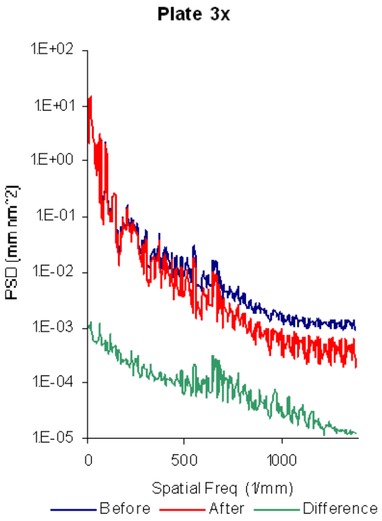

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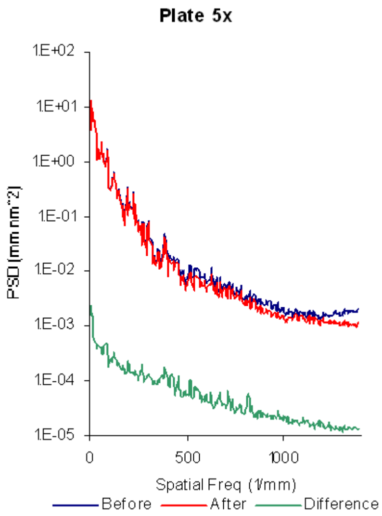

(c)

Figure 4. The change in x-average profile Plate surface spectral density for the tests with different cycles.

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CONCLUSIONS

As wear occurs, surface topography also changes. Depending on the nature and extent of chemical reactions, conformity of surfaces can either develop or disappear. This changes the real area of contact and, hence, the asperity stress distribution. Boundary lubrication usually occurs under high-load and low-speed conditions. Under these conditions, the lubricant viscosity is relatively unimportant and the physical and chemical interaction of the lubricant with the solid bodies controls friction and wear.

To get detail information of the surface tpography change in the experiments on ball-on-plate steel under boundary lubricated reciprocating sliding contact the Matching and Stitching method is applicable. The accurate measured information data can be used for further analysis such as the power spectral density. Results show that the surface changes more in the running direction than in the traverse direction. This was also confirmed by the surface roughness analysis.

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