Surface Roughness Effects under High Sliding EHL Conditions

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This paper is focused on the roughness induced effects in EHL contact under high sliding conditions when thermal effects can be expected. High sliding conditions include both the case when both surfaces are moving in the same direction and that when they move in the opposite directions. The presented results show that increasing magnitude of sliding connected with high in-contact temperatures has almost no effect on roughness deformation until the dimple phenomenon occur. The observations of film variations evolution, caused by roughness pass (complementary effect), can give information about flow processes in an EHL contact under dimple phenomenon conditions. Essentially different behavior was observed in a classic EHL contact and in a contact when dimple phenomenon has occurred.

Keywords: EHL, surface roughness, deformation, film thickness, thermal effects, dimple, complementary effect

1. Introduction

There is continuous effort to minimize energy consumption and power losses of highly loaded machine components as rolling bearing, gears, etc. This trend is accompanied with decreasing lubricant film thickness in tribological systems that is one of the important features of machine design. As a result, the surface micro-geometry plays an important role in the contact performance. That is why the understanding of the roughness behavior is very important.

Roughness features cause local fluctuations in film thickness and pressure that can lead to excessive wear and contact fatigue. Therefore, the effects of surface roughness and topography on lubrication film thickness and pressure have been a subject of a number of numerical and experimental studies [1,2]. However, real roughness is composed of various wavelengths and amplitudes with more or less random distribution that represents the key limitations for both experiments and numerical studies. Therefore, harmonic features of various wavelength and amplitudes were considered to explain the behavior of real roughness.

The systematic study of a low-amplitude surface roughness in elastohydrodynamic (EHL) contact has led to general model called amplitude attenuation theory [3-19]. It says that a general roughness deformation can be completely described by a single curve. It was concluded that short wavelengths are only slightly

deformed whereas long wavelength roughness features flatten almost completely. This approach can be used to propose simple engineering tools to obtain an estimate of the deformed profile of real roughness in EHL contacts.

Under pure rolling the conditions in contact inlet controls the magnitude of amplitude attenuation. However, the situation in rolling-sliding contact is more complex. In rolling-sliding contacts, two components model is necessary to explain the film variations. It is a roughness deformation and a complementary effect induced in contact inlet, the first moves at rough surface speed and the second is driven by mean entrainment speed. Recently, it was shown that the amplitude of the complementary effect is related to conditions in contact inlet contrary to the roughness deformation which is influenced by conditions inside the contact. The current amplitude attenuation model for rolling-sliding contacts is based on Ree-Eyring shear thinning theory and film thickness inside contact has strong influence.

Experimental studies dealing with surface roughness have shown that lubricant film can change significantly once the roughness features pass through the contact [e. g. 20-30]. Obviously, the rolling sliding conditions represent more complex case comparing pure rolling conditions. Depending on the size, depth, orientation and operational conditions the roughness features can cause both lubricant film increase and its collapse. That is why, the ability to predict the roughness features behavior is key factor in the optimization of machine design process.

Recent experimental studies provided results that enabled not only to validate amplitude attenuation theory but also showed its possible further development [31-33].

The aim of this study is to show how high sliding conditions, where thermal effects can take place, affect aspects of the roughness deformation and the complementary effect.

2. Materials and methods

The ball-on-disc optical tribometer was used for experimental study of roughness behavior (Fig. 1). It consists of a microscope and an optical test rig, where an elastohydrodynamic film is formed between a 25.4 mm steel ball and a flat glass disc. The disc has 150 mm in diameter and its thickness is 12.7 mm. The roughness features are produced on the ball. The lower surface of the disc is coated by thin chromium layer to obtain high quality of chromatic interferograms having wide dynamic range to enable detail evaluation of lubricant film changes. Interferograms are recorded by hi-speed camera to be able observe a progress of roughness feature pass through the contact. Thin film colorimetric interferometry was used for the film thickness evaluation. This technique is based on colorimetric analysis of chromatic interferograms using CIELAB color matching algorithm and calibration. This configuration enables film thickness measurement in the range from 1 to 800 nm and color matching algorithm has an accuracy of ± 1 nm [34].

Experiments were done with mineral bright stock oil of 1.0 Pa·s viscosity and 23.0 GPa⁻¹ pressure-viscosity coefficient the both at 23.5°C. The entrainment speed was adjusted to achieve roughly the same smooth central

Fig. 1 Experimental apparatus

Fig. 2 Measured initial profile of the ridge pattern

film thickness of 250 nm. It corresponds to mean speed of 30 mm/s for low sliding and 60 mm/s for high sliding conditions. The maximum Hertzian pressure was 0.65 GPa (the contact diameter about 420 μ m) and slide to roll ratio varied from 50% to 700%. The value of slide-to-roll ratio (SRR) represents ratio of sliding speed to rolling speed defined by $SRR = 2(u_d - u_b) / (u_d + u_b)$, where u_d and u_b are speeds of disc and ball, respectively. Positive value means that disc is faster than ball.

Multiple longitudinal ridges produced by deposition and etching technique on bearing steel ball were used in experiments. Their height is 255 nm, width is 60 μ m and wavelength 120 μ m. The profile measured on an optical profilometer is shown in Fig. 2.

3. Results and discussion

Experiments with longitudinal ridges were carried out under conditions of approximately same central film thickness and increasing slide-to-roll ratio from 50% to 700%. The cases over 200% of SRR represents opposite sliding. Under rolling/sliding conditions one can distinguish two effects of roughness features within the contact. These are roughness deformation and complementary effect. Once the roughness enters the contact it is deformed due to the high contact pressure. This deformation remains during the roughness passage through the contact. Simultaneously, as the roughness features enters the contact it influences lubricant flow in the inlet and thereby causes lubricant film changes. Under rolling/sliding conditions these changes travel through the contact at different speed than roughness features. That is why we can observe so called complementary effect. If the rough surface is faster than the smooth one, this complementary effect can be found behind the roughness feature and vice versa. These two effects will be discussed below to describe the behavior of roughness features on the lubricant film under high sliding conditions.

3.1. Roughness deformation

Measured interferograms in the moment of roughness pass are shown in Fig. 3. Two distinctive cases of behavior can be observed.

The first case includes deformed roughness features, shown in Fig. 3(a), under conditions with classic film thickness distribution. In this case, both surfaces are

Fig. 3 Interferograms showing two distinctive cases of behavior: (a) 150% slide-to-roll ratio (SRR); (b) 700% SRR

Fig. 4 Profile of transverse section from case of non-dimple conditions (Fig. 3(a))

moving in the same direction and the inlet is on the left side. Experiments were also carried out under various SRR conditions. The comparison of section profiles for the range of SRR from 50 to 500% is presented in Fig. 4. For better comparison only relative film thickness data were plotted. The deformed roughness profile is almost the same in this range. Very moderate trend of decreasing deformation can be observed for increasing sliding. Heat dissipated inside a contact is proportional to shear stress in a liquid and a sliding speed. Therefore, the increase of sliding by one order of magnitude should lead to increase of dissipated heat by the same power, if the shear stress remains. By considering this fact the temperature field should increase inside a contact significantly with changing SRR from 50% to 500%. This increase of temperature is related with approximately exponential decrease of lubricant viscosity. Surprisingly this expected decrease of lubricant viscosity has minor consequences on roughness features deformation observed during the pass through a high pressure contact zone.

The further increasing of sliding led to dimple phenomenon creation and deformation starts to change through the contact zone. The situation is shown in Fig. 3(b) where the roughness is present under dimple phenomenon with SRR equal to 700%. In this case both surfaces are moving in the opposite directions. In Fig. 3(b), several positions of evaluated profiles are highlighted on the interferogram. Corresponding profiles are depicted in Fig. 5. It can be seen as the local film thickness inside dimple is rising (from profile 5a to 5e) the roughness deformation is decreasing. It can be suggested that this effect is not caused by thermal effects but by flow in diverging layer of highly viscous lubricant. As the roughness meet the dimple peak positions its deformation starts to increase as the dimple film thickness is falling. It was shown in previous paper by validating theoretical model that the primary influence on roughness deformation under rolling-sliding has a central film thickness [35]. Nevertheless, the data presented here are not sufficient to exclude possible thermal effect in this case.

Fig. 5 Profiles of several transverse sections of dimple conditions and positions from a to e for SRR 700% (Fig. 3(b))

3.2. Complementary effect

Time-evolution of film thickness variations is presented on chromatic interferograms for SRR 300% and SRR 600% in Fig. 6. The film thickness variations are complementary effects caused by roughness pass through contact inlet.

It is clearly visible that the complementary effect persists inside contact much longer for the case of SRR 600%. It is the case when the dimple phenomenon was formed. It should be noted that time necessary to lubricant pass the contact at mean speed under conditions of both SRRs is approximately 8 ms. For SRR 300% this time (8 ms) roughly corresponds with time in which complementary effect diminish and contact switches to steady state. However for SRR 600%, it takes nine times longer to the complementary effect go away. It is evident that by transition from classic EHL contact (e. g. SRR 300%) to dimple phenomenon (SRR 600%) the conditions inside highly loaded zone change significantly. One can suggest that, for the dimpled contact, there has to be some portion of lubricant with very low speed. The amount of lubricant in this state can be estimated by evaluation differences between steady-state profile and profiles showing the height of film thickness variations during transient phases. This comparison is shown in Fig. 7. The time moment of 72 ms represents steady-state. The Fig. 7(a) reflects the situation after the longitudinal roughness passage. The differences between disrupted film variations and steady-state profile are plus/minus 100 nm according the position of profile. Figure 7(b) shows the moment after 8 ms where the major part of the profiles is unchanged. Modifications are occurring on the left side, it is the main inlet of the contact and direction of disc movement. Figure 7(c) depicts the progress of film thickness variations after another 10 ms. The film variations on right half of the contact is remaining almost unaffected while the left part is change. Thus, the progress of modifications coming from the main inlet continues. Because, the film variations decay starts in places close to the contact border and this decay is less intense in dimple peak area. It means that in the area of the dimple peak, there is a portion of lubricant that

Fig. 6 Series of interferograms showing progress of film evolution after roughness passage under a) 300% SRR. b) 700% SRR

Fig. 7 Comparison of transient film thickness profiles for three time moments with steady state profile in entrainment direction

probably almost stays on place. To conclude this section, the observation of temporal effects induced by roughness can provide clear indication of phenomenon which takes place inside highly loaded contacts.

4. Conclusions

This study deals with roughness induced effects in EHL contact under high sliding conditions when thermal effects can be expected. The presented results show that

increasing magnitude of sliding connected with increasing in-contact temperatures has almost no effect on roughness deformation. The deformation of roughness features changes after the dimple phenomena occurs. Moreover, the passage of roughness features produced film thickness disturbances, known as complementary effect, that move through a contact independently. This study presents analyses of the complementary effect time-evolution. Essentially different behavior was observed in a classic EHL contact (SRR 300%) and in a contact when dimple phenomenon has occurred (SRR 600%). Under conditions of dimple phenomenon a transient film thickness decaying took approximately nine times longer to reach steady-state film profile. This observation can advise information about flow processes in an EHL contact under dimple phenomenon. It was discussed that it can be explained by presence of lubricant with very low speed. In this case the flow profile could markedly diverge from classic isothermal Couette speed profile.

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