THE EXPERIMENTAL STUDY OF TRANSITION BETWEEN FULLY FLOODED AND STARVED REGIME IN EHL CONTACT

Petr Svoboda, David Košťál, Michal Popelka, Ivan Křupka*

This paper deals with an experimental study of lubricant film in an experimental device (tribometer). Lubricating film is formed between a glass disc and steel ball on which modification for friction surfaces have been made. The experiment is aimed at both fully flooded EHL lubrication regime as well as the starved. This document also deals with a comparison of micro dents passage through a contact at different degrees of slip.

Keywords: *EHD lubrication, micro dents, starvation, fully flooded*

1. Introduction

The thickness of the lubricant film in contact with non-conformal friction surfaces can be affected by a number of operational factors. The four basic factors that affect lubrication are: the amount of oil, contact surface area, oil viscosity and speed. All these factors may have effect whether the contact surface is in the starved or fully flooded regime.

Regarding the fully-flooded lubrication regime, it is obvious that increasing rolling speed increases lubricant film thickness. The increase in thickness is caused by the movement of friction surfaces during which the lubricant is carried to the contact. The film thickness is mainly affected by speed but also the dynamic viscosity of the lubricant η_0 and pressure-viscosity coefficient α.

On the other hand, lack is characterized by decreasing thickness of the film, while the speed is increasing. This decrease is caused by an insufficient amount of lubricant at the contact inlet. A small amount of lubricant may be pushed out of the contact's track after rolling.This means that there is no chance for it to flow back into the contact track. Another cause may be high viscosity of the lubricant used. Therefore, starvation can usually be found in high-speed bearings or in bearings lubricated with grease.

Wedeven [1] carried out the first experimental studies of the starved contact. In his work, he concluded that starvation in EHD contact is dependent on the location of the inlet meniscus. He also described that the central film thickness in the starved regime is the function of distance between the inlet meniscus and the Hertzian contact area. Wedeven observed in his experiments that the initial starvation is showed by reduced pressure in Hertzian contact area and the lubricant film thickness decreases to zero level as the inlet

* Ing. P. Svoboda, Ph.D., Ing. D. Košťál, Ing. M. Popelka, prof. Ing. I. Křupka, Ph.D., Institute of Machine and Industrial Design, Faculty of Mechanical Engineering, Brno University of Technology, Technická 2896/2, 616 69 Brno, Czech Republic

meniscus approaches the Hertzian area. The position of the inlet meniscus on film thickness was then also studied by Wolveridge [2] who used the semi-analytical solution method.

Starvation becomes progressively more severe as the viscosity and rolling speed increases. The surface tension of the lubricant can cause reflow to the orbital track, which prevents it from starvation. This reflow occurs only in the case where the layer of grease on the edge of the track is large enough to withstand the forces that cause the grease drain (gravity and centrifugal forces). Chiu [3] analysis showed that the degree of starvation depends mainly on the thickness of lubricant layer on the edge of the track. He also found that the lubricant film thickness depends on the amount of lubricant in a rolling system, as well as the centrifugal and gravitational force in a rotating system.

The first who mathematically described the inlet meniscus position dependence on the film thickness in the starved EHD regime were Hamrock, Dowson [4] and Ranger [5]. Experimental observation of EHD contact was also studied by Kingsbury [6] who dealt with the 'parched' EHD lubrication. The parched EHD lubrication regime is positioned between starved and mixed regimes. Bearings in the parched regime are characterized by the lowest torque and the best-defined axis of rotation of all lubrication regimes.

Starvation occurs largely in bearings lubricated with plastic lubricants. This issue was first addressed by Astrom [7]. Another approach to studying starved lubrication was represented by Elrod [8] and Chevalier [9]. Their work links the decrease in film thickness to the amount of lubricant on the surface of the orbital track. This parameter has the advantage of being easily measurable in practice.

Another person who studied the issue of starvation was Jacod [10] with his team. Having their observations, they concluded that replenishment mechanisms do not play an important task as dealing with thin layers of lubricants. These mechanisms make only a slight modification of the film thickness. This prediction was also supported by experimental observations.

Damiens in his publication [11] described the creation of a lubricating film in starved EHD regime as the function of lubricant volume, contact conditions and contact ellipticity. The ratio of M/L (dimensionless parameters of load and material) appears to be the decisive parameter predicting the flow of lubricant in the contact to the sides. Dimensionless parameter of starvation γ derived out by Chevalier was used to characterise starvation under various lubrication conditions in the piezo-elastic regime. Experimental and numerical results showed that the dimensionless parameter of γ (resistance to flow of the lubricant to the sides) depends on the parameter of M/L and it is also the function of film thickness. Recent publications have presented an example of Wijnant elaboration [12] which concerned the study of dynamic and starved EHL contact. Together with Elrod and Yin [13], he achieved a numerical solution for the starved thermal EHL contact (assuming Newtonian fluid as the lubricant).

The issue of starved EHD contact was observed by both Popovici [14] and Van Zoelen [15]. Popovici focused his experiments with the starved contact on the impact of rolling speed on the lubricant film thickness. Van Zoelen in his study dealt with the influence of the EHL contact pressure on the lubricant film thickness as on the disc orbit.

Modification of surfaces in starved contacts was studied by Lugt [16] who dealt with the mathematical description of the micro dents passage through the contact during lubricant-starved and fully flooded conditions. Lugt stated that the micro dents negatively affect the film thickness while being purely rolled. He also said that the micro dents created by entering a foreign body include the area around the micro dents which shows high concentration of tension, which may lead to surface cracking.

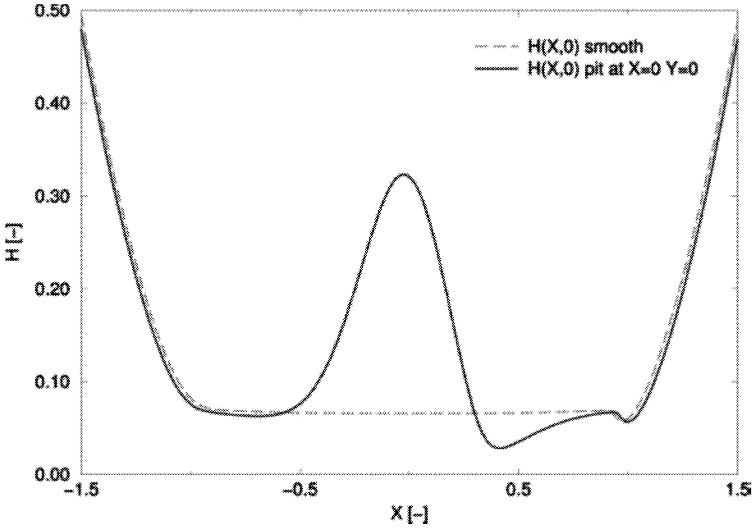

Fig.1: Film thicknes for a fully flooded contact – pit position at $X = 0$; $Y = 0$ [16]

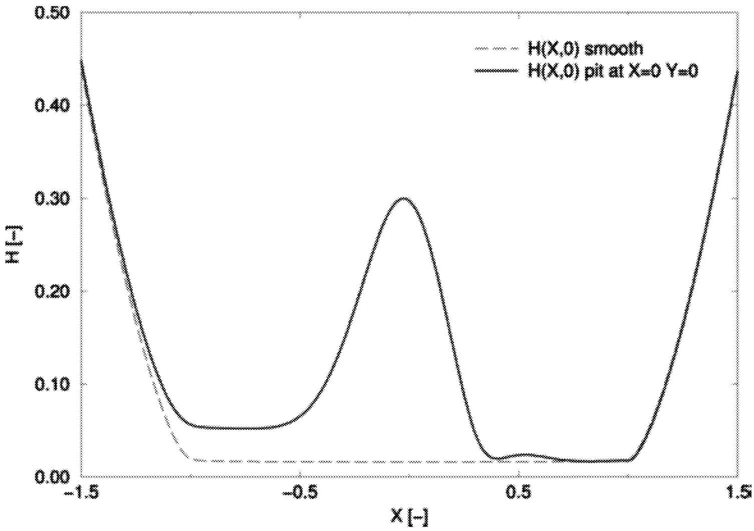

Fig.2: Film thicknes for a starved contact – pit position at $X = 0$; $Y = 0$; $H_{\mathrm{oil}} = 0.02$ [16]

In fully flooded conditions, as stated by Lugt, the film thickness is identical to the thickness in layers without the micro dents. The decrease occurs before the micro dents only (Fig. 1).

Behind the micro dents in the starved regime, the film thickness is up to 3 times higher than that one before the micro dents where the thickness does not differ much from the surfaces without the micro dents (Fig. 2).

Above-cited studies significantly contributed to the understanding of the phenomenon that happen in lubricated contacts under starved operational conditions. However, the experimental investigation of this phenomena and behavior of lubricating film under the conditions where the lubricating film breaks and the rubbing surfaces touch remains still unexplained.

This case of starved lubricated contacts represents one of the transient conditions that bring the risk of the surface damage. The experimental observation of the effects of surface dents artificially produced on the ball surface will help to understand better the behavior of real and textured surface topography and also the numerical model [16] can be verified. It can be suggested from the obtain results that properly designed topography of the rubbing surfaces can help to reduce the asperities interactions under starved operational conditions.

2. Experimental apparatus

To simulate real conditions that arise in tribological systems the tribometer which is shown in Fig. 3 is used. This apparatus is used for experimental observation of lubricating films. This tribometer uses colorimetric interferometry to study the thickness of the lubricating films. With this tribometer, it is possible to simulate conditions that occur in bearings, for example. Thin lubricating film is formed between the glass disc and steel ball with perpendicular rotation axes. The load is applied to the contact through a glass disc which is connected with a weight by using a double-reversible lever. The top side of the disc is covered with an anti-reflective layer; the lower side is covered by chromium layer. Both the friction surfaces are driven by servomotors. Thus, it is possible to set independent speeds for both the ball and the disc. The speeds are controlled by a programmable frequency converter. This is mostly used to simulate real conditions of the ball simply rolling on the disc, reversing or different degrees of slip.

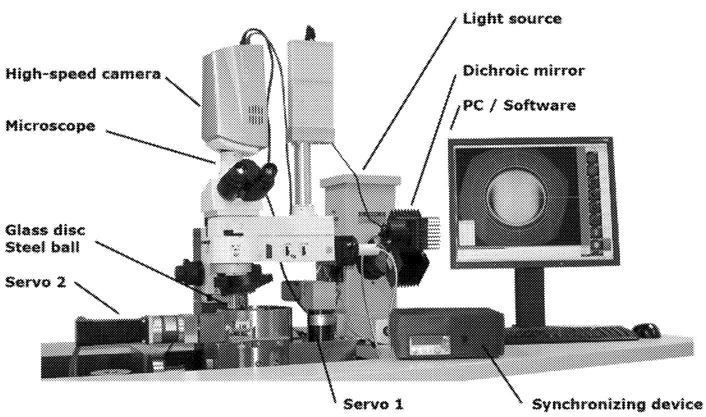

Fig.3: Experimental apparatus [17]

At the start of the experiment, the steel ball is in the tribometer with the required amount of lubricant applied to the ball or, if needed, the ball is placed in an oil supply container. Then, the glass disc is installed. During the experiment, chromatic interferograms are recorded when the ball passes the selected place on the sample surface with the lubricated contact. Using a microscope imaging system it is possible to observe the contact visually. There is also a high-speed camera positioned on this microscope, which allows making a record while monitoring the EHD contact. Another essential component necessary for recording the images is a white, xenon light source with output of up to 1000 W which, in combination with the above mentioned high-speed camera, allows capturing up to 7530 pictures per second at a resolution of 1280×1024 pixels. The interferograms were then evaluated in the software by using thin colorimetric interferometry.

3. Surface texturing

Surface texturing is done by creating the micro dents on the surface of the test object. In this study the micro dents were made using a Rockwell indentor. This device uses a microscope on which, instead of a classic lens, there is an indenting device fitted with a strain-gauge sensor. As the indenting object a diamond cone is used, commonly it is used in measuring of hardness according to Rockwell method. The cone has the top angle of 120° and tip radius of 0.2 mm. The micro dents are formed on the steel ball of AISI 52100 with the diameter of 25.4 mm and roughness of Ra 0.01 μm. There were six different micro dents with gradual increase in indenting force carried out. The indenting forces and depth values of the micro dents are shown in Tab. 1.

Force [N]	Depth [nm]
3	160
5	350
7.5	650
10	910
12.5	1200
15	1490

Tab.1: Depth of the micro dents

Designation of oil	LSBS
Dynamic viscosity η	0.69 Pa s (at 20 °C)
Index of refraction (diffraction)	1.492

Tab.2: Properties of oil

4. Results and discussion

4.1. Measurement of film thickness on the surface of the ball with a surface modification

As lubricant was used LSBS mineral base oil. The properties are given in Tab. 2.

In the first part of this article, observation was focused on the influence of the surface texture modification on the lubricant film thickness in EHD starved and fully flooded conditions in pure rolling. Pure rolling occurs when the two surfaces move at the same speed, and therefore the lubricant layer also moves at the same speed. Passage of the micro dents along the contact is recorded by a high-speed camera. The record consists of individual pictures from which are evaluate the influence of the micro dents on thickness of the lubricating film in the contact area. Passage of the micro dents through the contact in starved conditions is shown in Fig. 4. Fig. 5 shows passage of the micro dents through the contact in fully flooded conditions.

The speed of the two friction surfaces and lubricants was $u = 0.05763\,\mathrm{m\,s^{-1}}$. The average lubricant film thickness in EHD starved conditions in the area that was not affected by the micro dents was 200 nm in pure rolling and 160 nm at slip. The lubricant film thickness in fully flooded conditions in the area that was not affected by the micro dents was 450 nm in pure rolling and 400 nm at slip. The next part of this article was focused on the influence of surfaces with a targeted modification to the lubricant film thickness at slip (0.5 and 1) in both starved and fully flooded EHD contacts. If the frictional surfaces roll on each other at

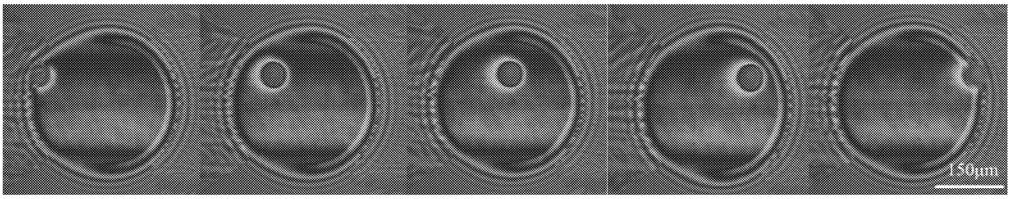

Fig.4: Passage of the micro dents through the starved contact of EHD during pure rolling

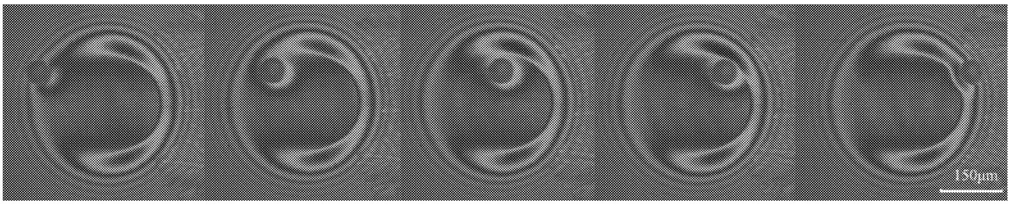

Fig.5: Passage of the micro dents through the fully flooded EHD contact during pure rolling

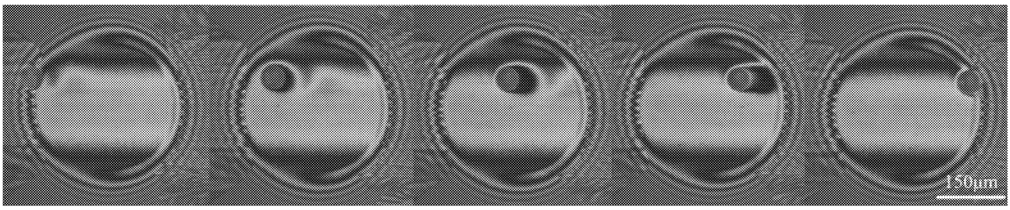

Fig.6: Passage of the micro dents through the starved contact of EHD during slip of 0.5

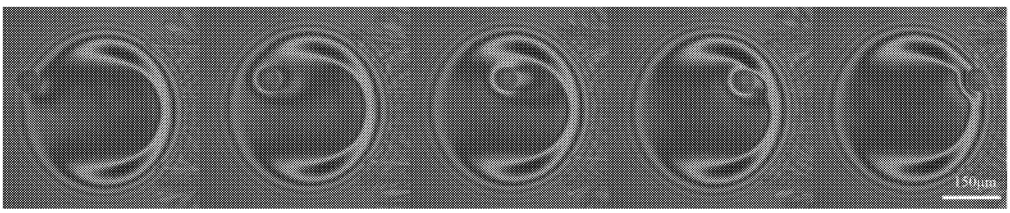

Fig.7: Passage of the micro dents through the fully flooded EHD contact during slip of 0.5

the different speeds, it is the case of slip. The slip may be defined with parameter of slip (1).

$$\Sigma = \frac{2\,(u_\mathrm{D} - u_\mathrm{B})}{u_\mathrm{D} + u_\mathrm{B}} \; . \tag{1}$$

Where u_D is the speed of the friction surface of the glass disc at the point of contact and u_B is the speed of friction surface of the ball. This relation implies that if the slip parameter is positive, the glass disc moves faster than the ball. If the slip parameter is negative, the glass disc moves slower than the ball. Interaction during slip is caused by a sharp increase in lubricant viscosity captured in the micro dents. This action closes the lubricant in the micro dents which then works as a lubricant reservoir [18]. Effects of different speeds of elastically deformed non-conformal surfaces cause highly viscous lubricant film extruding from the micro dents. This highly viscous lubricating film can overpass the micro dents or lag behind it, depending on the slip parameter. If the slip parameter is positive, the lubricant in the micro dents affects the area of contact before the micro dents and vice versa [18]. Passage of the micro dents through the contact in starved conditions is shown in Fig. 6. Fig. 7 shows passage of the micro dents through the contact in fully flooded conditions.

The positive slip of 0.5 and 1 was experimentally investigated. The speed of the friction surface in ball on slip 0.5 was $u_\mathrm{B} = 0.043\,\mathrm{m\,s^{-1}}$ and speed of the surface of the glass disc was $u_\mathrm{D} = 0.072\,\mathrm{m\,s^{-1}}$. These speeds were chosen so that the central speed (speed of the lubricant) was the same as for pure rolling, i.e. $u = 0.057\,\mathrm{m\,s^{-1}}$. In the case of slip 1, the

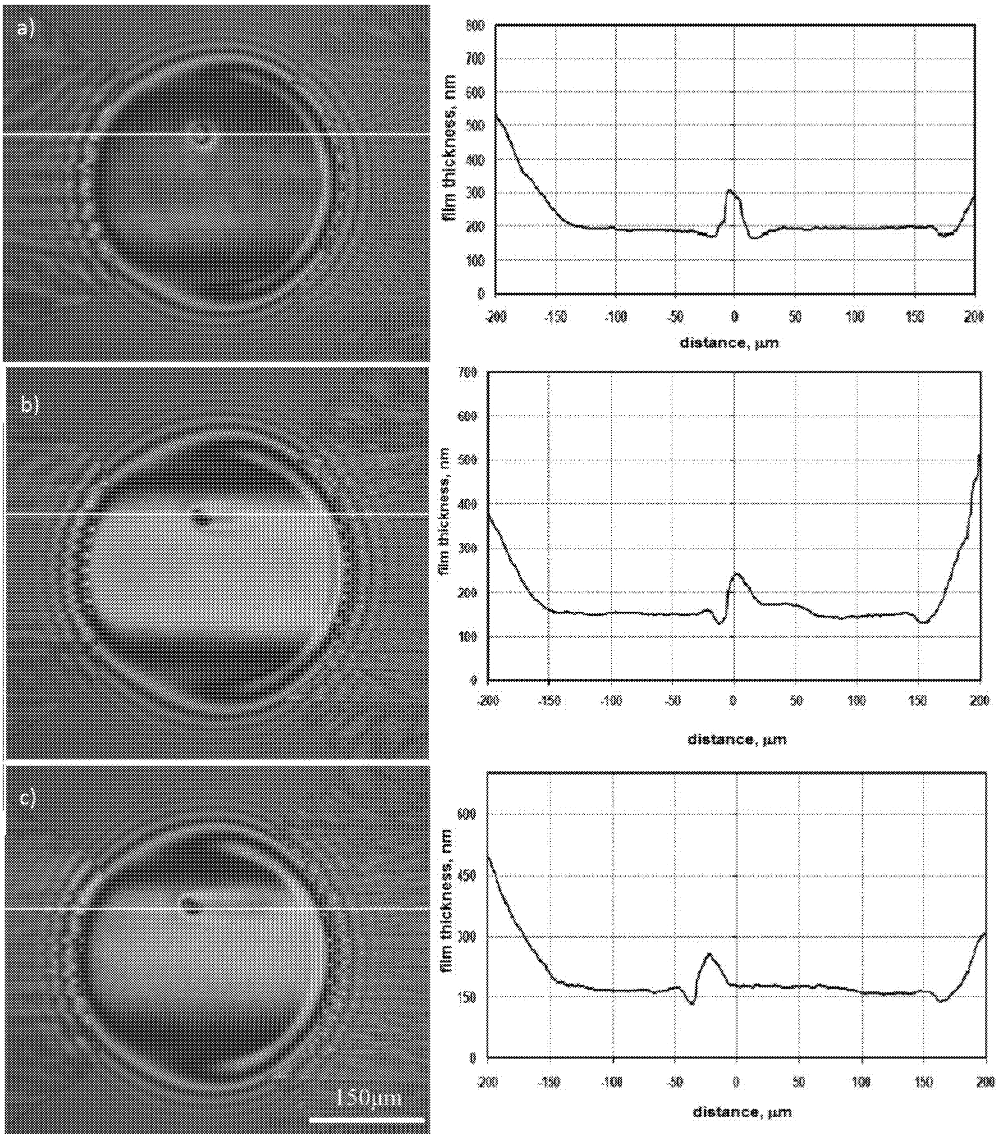

Fig.8: Chromatic interferograms and film thickness profiles for the slip parameter of 0; 0.5; 1 and also EHD starved conditions (indenture depth 160 nm)

speed of friction surface of the ball was $u_{\mathrm{B}} = 0.028\,\mathrm{m\,s^{-1}}$, the speed of the friction surface of the glass disc was $u_{\mathrm{D}} = 0.086\,\mathrm{m\,s^{-1}}$ in the way so that the same speed of lubricants in $u = 0.057\,\mathrm{m\,s^{-1}}$ is kept on.

4.2. The film thickness in starving EHD conditions (shallow dents)

In Fig. 8, there is a comparison of starved contact in slip parameter 0; 0.5 and 1. In all cases, a decrease in film thickness can be observed in the close of micro dents by a value of 40 nm. The central film thickness therefore reaches the level of 110 nm. This decrease occurs immediately after entry of the micro dents into contact area. Then it remains almost unchanged along the length of the contact. Figure 8a (slip 0) shows the decrease in the film

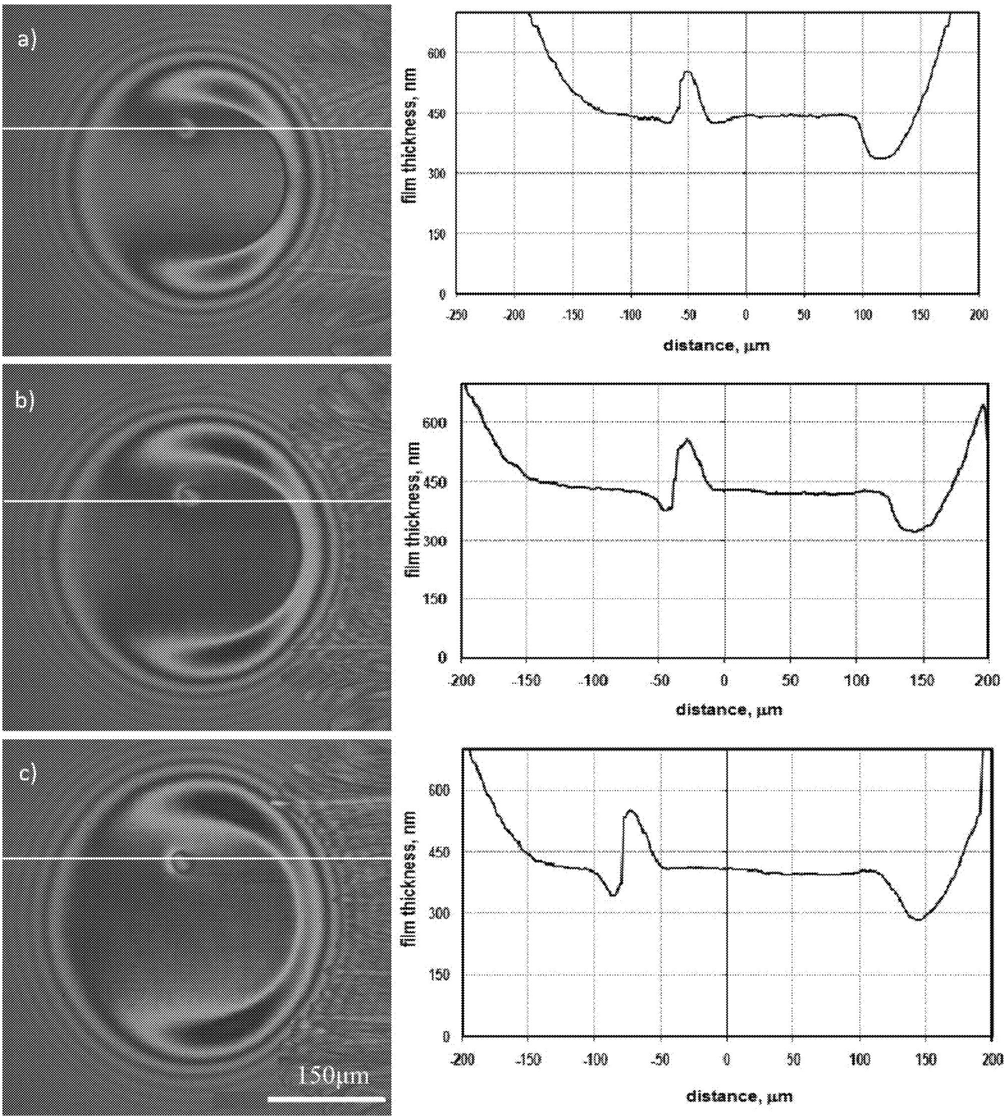

Fig.9: Chromatic interferograms and film thickness profiles for the slip parameter of 0; 0.5; 1 and also fully flooded EHD conditions (indenture depth 160 nm)

thickness around the entire micro dents. While Figure 8b and Figure 8c (slip 0.5; 1) show the decrease only behind the micro dents and on the sides. Furthermore, there is observation of the area before the contact having increased thickness of the film in this case. This is caused by gradual release of lubricants from the micro dents and it occurs only during slip of friction surfaces, as described above. Width of this area increases during the passage of the micro dents through the contact while there is the increase in the difference of path travelled by the lubricating film and the surface of ball. The film thickness before the micro dents increases by the value of 30 nm and reaches the level of up to 180 nm.

Film thickness profile in the slip parameter of 0 (Fig. 8a) compared to the numerical model of Lugt [16], in starved conditions in Fig. 2, it is seen that there is decrease in the film thickness before the micro dents unlike the numerical model. The difference in film thickness behind the micro dent was also observed. Regarding the numerical model [16], where was described the increase of the thickness, slight decrease was observed during the experiment.

4.3. The film thickness in fully flooded EHD conditions (shallow dents)

Fig. 9 shows the passage of the micro dents through the contact at slip level of 0; 0.5; 1 during fully flooded EHD conditions. There was observed during the micro dents passage decreasing of the film thickness around the micro dents by the value of up to 40 nm. Regarding the slip parameter 0 (Fig. 9a), this decrease is observed around the entire micro dent, while the slip parameter of 0.5 and 1 (Fig. 9a, b) shows the decrease behind the micro dent and on the sides.

When comparing film thickness profile in the slip parameter of 0 (Fig. 9a) with Lugt's numerical model [16] (Fig. 1) in fully flooded conditions, there is identical decrease of film thickness before the micro dent. The only difference was observed in the place behind the micro dents. There was again decrease in the film during the experimental measurement. While the film thickness in the numerical model does not differ from the film thickness during the contact passing without the micro dent.

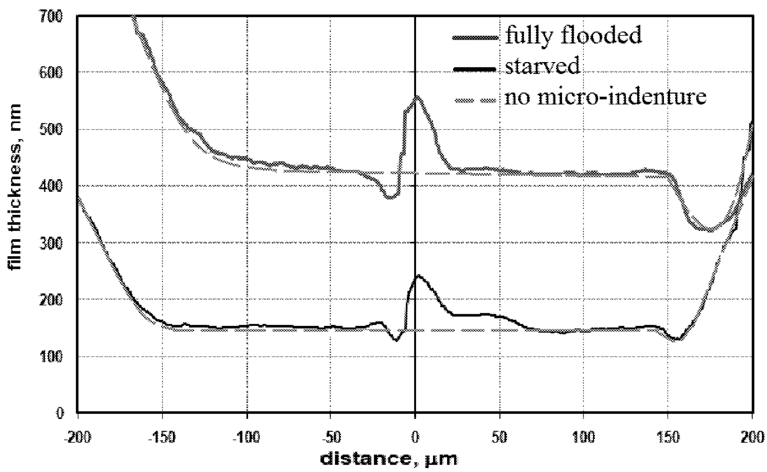

Fig.10: Comparison of film thickness in starving and fully flooded EHL conditions at sliding of 0.5

Since this is the case of the contact in fully flooded EHD conditions, the central film thickness is significantly higher (compared with the contact in starved EHD conditions), which is seen when comparing the results in Fig. 10. The area with the increase in film thickness, in the fully flooded regime, which arises in the place before the micro dent at the slip level of 0.5, is not as significant as in starved regime. The increase in film thickness before the micro dent during fully flooded regime increased only by 10 nm. The increase in central thickness of the contact under these conditions is minimal. Furthermore, when comparing these two curves in Fig. 10, it can be seen in the place behind the micro dent that the film thickness decrease is almost identical on both the curves. When comparing the two curves it can be also seen different thickness decrease at the end of the contact area, which is caused by the decrease of second pressure maximum in starved regime.

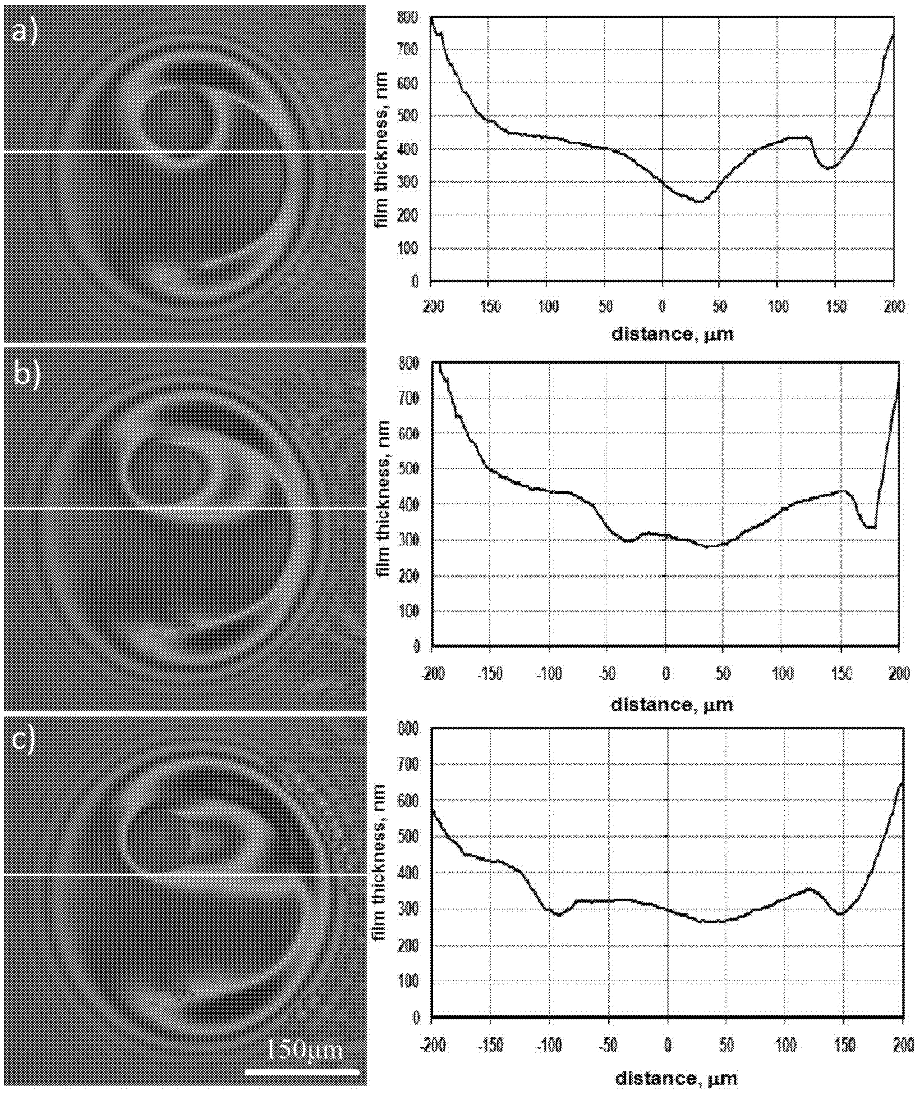

Fig.11: Chromatic interferograms and film thickness profiles for the slip parameter of 0; 0.5; 1 and also fully flooded EHD conditions (indenture depth 1490 nm)

4.4. The film thickness of lubricating film with deep dents passing

Fig. 11 shows interferograms and film thickness profile for slip parameters of 0; 0.5 and 1 for fully flooded EHD conditions. Because in the software there is limitation to evaluate the profile of film thickness in the middle of the micro dents. It is assessed only the profile on the edge of this micro dent (position of the evaluated film thickness profile is marked in the interferograms with white line).

Fig. 11 shows relatively large decrease in film thickness by the value of 200 nm when the deeper micro dents passes through the contact. Fig. 11a (slip 0) shows focusing of the thickness decrease around the micro dents; while Fig. 11b, c (slip 0.5 and 1) shows that this decrease is behind the micro dents and on the sides. However, the area of decrease can be

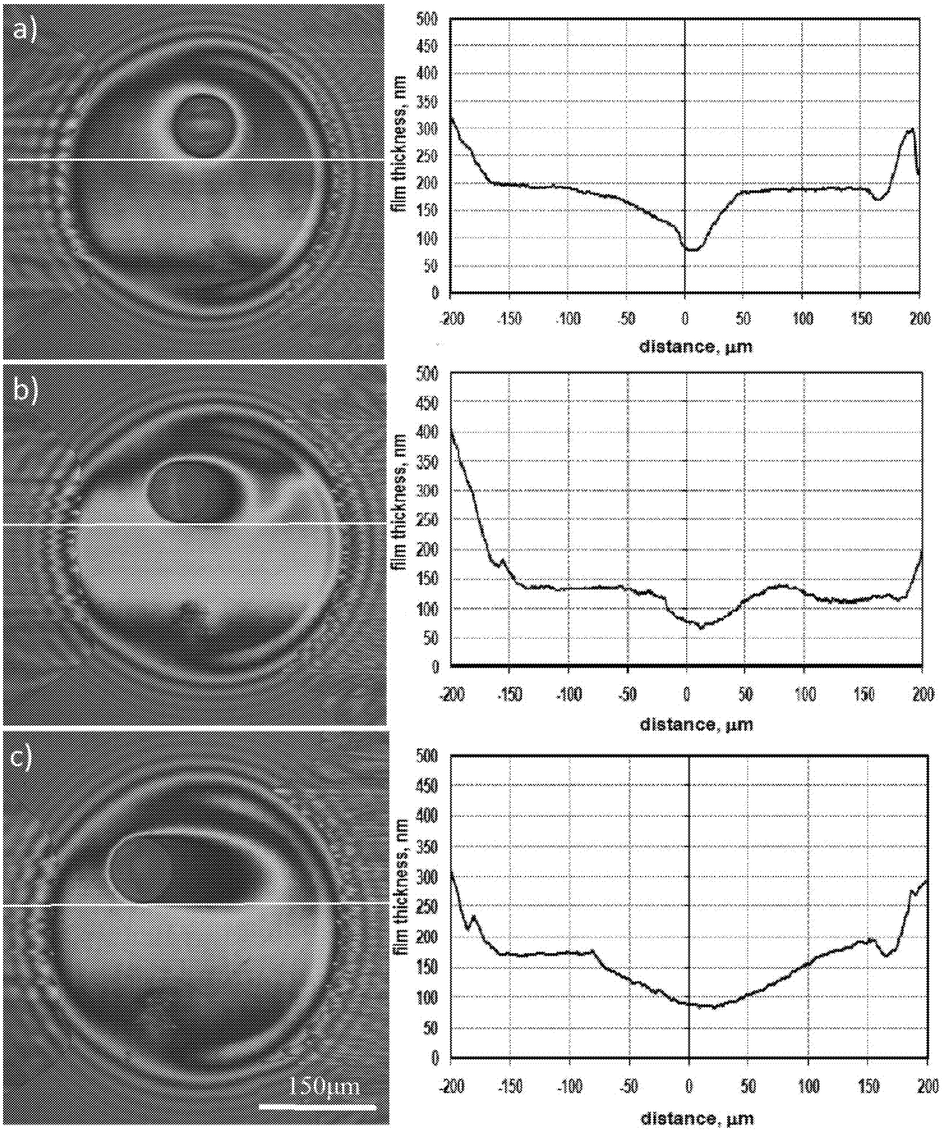

Fig.12: Chromatic interferograms and film thickness profiles for the slip parameter of 0; 0.5; 1 and also EHD starved conditions (indenture depth 1490 nm)

seen far before the micro dent too. Before micro dents – (as it was also with the shallow micro dents at slip of 0.5 and 1) the lubricant is gradually released and there is an area with an increase in film thickness appearing. This area is much larger than that of the shallow micro dents. This is caused by the larger diameter of the micro dents.

While deeper micro dents pass through the starved contact, as shown in the chromatic interferograms in Fig. 12, the micro dent cause rapid decrease in film thickness and there is even the case of failure of lubricating film. It was also found that in the case of slip at 0.5 and 1 (Fig. 12b, c) there is no or only slight release of lubricants from the micro dent, unlike previous cases.

5. Conclusions

In this article the authors described the transition between fully flooded and starved regime in EHL contacts with surface texturing. Some important experimental results and inferences are as follows:

– Modification of friction surfaces affects the lubricant film thickness, especially for starved EHL contact areas during the case of slip. It was found that the passage of a shallow micro dents through the contact in the case of slip positively affects the thickness of the film. There is increase in the thickness of the lubricating film during passing of this micro dents through the contact compared with contact with a smooth surface. These micro dents, which have a depth of only 160 nm, can effectively increase the service life of machine parts. Shallow micro dents in completely flooded regime can also increase the thickness of the film, but the central thickness is significantly larger, while the percentage increase is very small.

– It has been shown that a significantly larger affected area could be seen during of deep micro dents in the contact. However, this area did not show an increase in thickness, but rather a decrease. In certain cases, lubrication film failure was observed.

– Behind the micro dents in the starved EHL regime and slip parameter $\Sigma = 0$, the film thickness behavior is different compared to the numerical study published by Lugt [16]. There is decrease in the film thickness before the micro dents unlike in the numerical model. Regarding the numerical model, where was described the increase of the thickness, slight decrease was observed during the experiment.

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