FILM THICKNESS MAPPING IN LUBRICATED CONTACTS USING FLUORESCENCE

DAVID NECAS, PETR SPERKA, MARTIN VRBKA
IVAN KRUPKA, MARTIN HARTL
Brno University of Technology, Faculty of Mechanical Engineering
Institute of Machine and Industrial Design, Brno, Czech Republic

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e-mail: necas@fme.vutbr.cz

The present paper presents experimental method for film thickness mapping inside the contact of two bodies. Despite extensive experimental research in the area of contacts of rigid bodies, little is known about the film formation when at least one of the bodies is compliant. This is due to limitations disabling the usage of conventional methods. In present study, mercury lamp induced fluorescence is developed and applied. Evaluation process is verified by comparing theoretical predictions and experimental data for piezoviscous-elastic contact of ceramic ball and glass disc. Consequently, phenolic sample is used as a representative of compliant material. The contact was lubricated by mineral oil and the experiments were carried out under pure rolling conditions. Film thicknesses in a range from 50 nm to 1.2 um were measured for compliant contact. The measured data are little bit lower compared to theory, indicating that thermal effects may influence the lubricant film.

KEYWORDS
isoviscous, elastohydrodynamic, film thickness, fluorescence, compliant

1. INTRODUCTION

Tribological performance of machine elements play an important role nowadays, since it is well known that the friction influences power loss and therefore determines the efficiency of machine components [Reddyhoff 2010]. In an effort to better understand the lubrication processes, evaluation of lubricant film thickness is desirable. In many applications, elastohydrodynamic lubrication (EHL) occurs. EHL is typical for contact of rigid non-conformal bodies like gears, rolling bearings, or cams. Under EHL conditions, contact pressure causes substantial elastic deformation of surfaces and, in addition, leads to an increase of lubricant viscosity [Esfahanian 1991]. The operating lubrication regime of such contacts is known as piezoviscous-elastic (PE). In this case, optical interferometry method [Hartl 2001], as well as the electrical methods based on the change of electrical quantity [Spikes 1999], seem to be an established experimental approaches for film thickness measurement. An optical interference is a physical phenomenon occurring by composing the two light beams which are reflected from nearby interfaces. Due to the principle of the method, analysed bodies have to be reflective. Electrical methods converts the change in electrical quantity into a change of film thickness, therefore it is necessary to ensure sufficient electrical conductivity of the tested materials.

Much more challenging task is to investigate the film thickness when at least one of the contact bodies is compliant. The compliant means that modulus of elasticity of the body is in a range of units of GPa at maximum. Related to lubrication, isoviscous-elastic (IE) lubrication (i-EHL) regime usually occurs. In that case, the surfaces are deformed elastically, however the contact pressure is too low to increase the viscosity of lubricant [Esfahanian 1991]. Examples of compliant contacts can be found in both, technical and biological systems. From the technical point of view, typical applications are windscreen wipers, rubber o-seals, or tyres. In relation to biological systems, synovial joints, contact lenses or tongue-palate contact during food processing can be mentioned [Myant 2010b, Fowell 2014].

In meaning of theoretical predictions, two equations are generally used for film thickness estimation. Hamrock-Dowson derived the formula for film thickness determination as a function of dimensionless speed and load parameter [Hamrock 1978]. Later, the equation based on the dimensionless Moes load and lubricant parameter (M, L) was pronounced by Nijenbanning et al. [Nijenbanning 1994]. In the present study, the Hamrock-Dowson equation was used for comparison with the obtained experimental data.

For experimental investigation of compliant contacts, several methods were previously applied, such as optical interferometry [Roberts 1968, Roberts 1977a, Roberts 1977b], ultrasonic reflection method [Gasni 2011], Raman spectroscopy [Bongaerts 2008], or magnetic resistance method [Poll 1992]. However, each of the above mentioned approaches exhibits some limitations due to the characteristics of i-EHL contacts [Myant 2010a]:

- Film thickness varies in a very wide range – from several nanometers to the hundreds of micrometers.
- Larger contact areas in comparison with PE contacts.
- High roughness of surfaces, limited possibilities of polishing.
- Poor electrical conductivity and insufficient reflectivity of surfaces.
- Complicated coating by the reflective layers. These layers are prone to wear and may influence the surface properties of base material.

According to above mentioned information, usage of common experimental methods is very limited. From the literature [Spikes 1999], it can be assumed that optical method based on fluorescence microscopy seems to be a suitable approach for the investigation of film thickness in compliant contacts. The main difference against the optical interferometry is as follows. While the interferometry provides the direct distance between two surfaces based on the reflected light beams, fluorescence gives the information about the amount of lubricant which is presented inside the contact [Reddyhoff 2010]. The amount of lubricant is expressed by the intensity of lubricating film. It was previously proved that the dependence between the intensity of film and its thickness is linear [Azushima 2006].

First application of fluorescence method in tribology was pronounced in 1970th [Smart 1974, Ford 1978]. In the pilot study [Smart 1974], the authors employed fluorescence induced by a mercury lamp to measure the thickness of oil film on steel rotating cylinder. In the consequent study, the differences in excitation were analysed in a detail [Ford 1978]. A blue laser was used as the source of excitation. It was concluded that using the laser instead of the mercury lamp can bring several advantages such as higher efficiency of fluorescence, better stability of illumination, or less demanding design of the experimental apparatus. On the contrary, laser produces more inhomogeneities, such as speckles, so the calibration process is more complicated. A problem of losing the fluorescence emission was also discussed, as it can significantly influence the measured data.

Sugimura et al. [Sugimura 2000] investigated the lubricant film thickness by fluorescence technique in conventional ball-on-disc apparatus, originally introduced by Gohar and Cameron [Gohar 1963]. The authors could detect films down to 30 nm. A significant problem with calibration connected with the interference phenomena when the contact of steel ball and glass disc was illuminated was mentioned. In this case, the steel ball was substituted by glass lens during calibration. However, it was later pointed out [Myant 2010c] that different reflectivity between the calibration and test specimen can lead to inaccuracies in results.

The usage of fluorescent method for film thickness mapping in compliant contacts was provided by Myant et al. [Myant 2010c]. Laser induced fluorescence was employed to evaluate the film thickness between polydimethylsiloxane (PDMS) pin sliding against the glass disc. The effects of fully flooded conditions, as well as the starved lubricating conditions were investigated. Calibration process was described in a detail, as it significantly influences measured data. In this case, the calibration curve was obtained by using the same configuration as was used during the test. It was indicated that it is necessary to consider real optical properties of the contact bodies during calibration. In the paper, the authors were able to measure film thickness in a range from 200 nm to 25 um. In comparison with the theoretical predictions, the measured values were usually lower than predicted.

From the above mentioned references it is apparent that the investigation of compliant contacts is still a challenging task in the area of tribology. The aim of this study is to introduce an experimental approach enabling film thickness measurement in lubricated contacts independently on the reflectivity and conductivity of investigated materials. For this purpose, an optical method based on fluorescence microscopy in combination with ball-on-disc apparatus was employed.

2. MATERIALS AND METHODS

The experimental apparatus, employed in the present study, consists of conventional ball-on-disc tribometer [Gohar 1963] and optical imaging system, as can be seen in Fig. 1. Both components, the ball and the disc can be driven independently, so various kinematic conditions can be applied. Optical imaging system includes mercury lamp, episcopic microscope, scientific complementary metal oxide semiconductor (sCMOS) digital camera and PC.

For the film thickness measurement, optical method based on fluorescence microscopy was used. A fluorescence phenomenon was described as a consequence of three following steps [Haugland 1996]:

- Excitation: A photon is supplied by an external light source (lamp, laser) and is absorbed by the fluorophore, creating an excited electronic single state.
- Excited-state lifetime: Lasts usually 1 – 10 ns. During that time, the molecule can undergo some relaxation (energy dissipation) and is left in a state from which it can emit fluorescence.
- Fluorescence emission: A photon of energy is emitted, while the fluorophore returns to its ground state. Due to energy dissipation during the previous phase, the photon has lower energy and therefore the longer wavelength than the excited photon. The difference in wavelengths is known as Stokes shift, which is absolutely fundamental phenomenon since it allows separation of the measured emission from excitation.

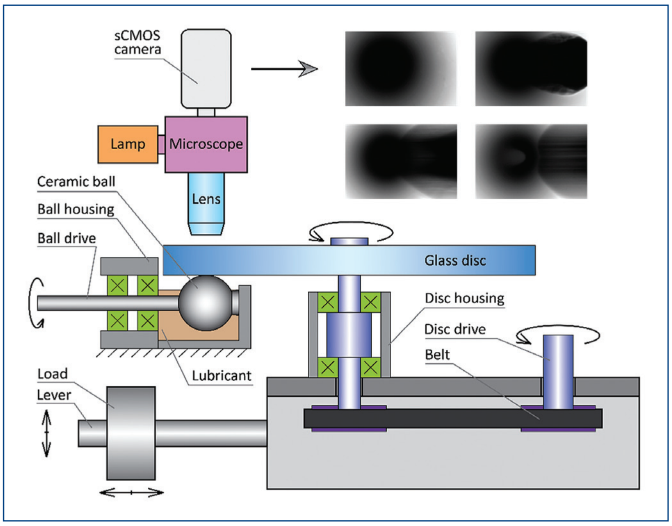

Figure 1. Scheme of the experimental apparatus.

The evaluation of lubricant film is fundamentally affected by the calibration process. The calibration curve is obtained from the knowledge of Hertz theory and the image of lightly loaded static contact. Moreover, to avoid light scattering, background image of lubricant is taken. The calibration curve is then matched with images taken by sCMOS camera, so the film thickness in arbitrary point can be determined.

To validate the measurement method, film thickness of PE contact, created by ceramic ball and glass disc was evaluated and compared with theoretical predictions. Hamrock and Dowson [Hamrock 1977] defined the following formula for dimensionless film thickness estimation in elliptical contact:

$$H_c = 2.69 \cdot U^{0.67} \cdot G^{0.53} \cdot W^{-0.067}(1 - 0.61 \cdot e^{-0.73 \cdot k}) \quad (1)$$

where H_c is defined by h_c/R'. h_c is central film thickness. For point contact, the ellipticity parameter k is reduced to unity. The dimensionless parameters *U, W, G* are:

$$\text{dimensionless speed parameter, } U = \frac{\eta_0 \cdot u}{E' \cdot R'} \quad (2)$$

$$\text{dimensionless load parameter, } W = \frac{F}{E' \cdot R'^2} \quad (3)$$

$$\text{dimensionless material parameter, } G = \alpha \cdot E' \quad (4)$$

where u is the rolling speed, η_0 is the dynamic viscosity of lubricant, *F* is the applied load, α is the pressure-viscous coefficient, R' is the reduced radius of curvature given by $1/R' = 1/r_x + 1/r_y$ and E' is the reduced elastic modulus defined as $2/E' = (1 - \mu_1^2)/E_1 + (1 - \mu_2^2)/E_2$, where r_y, r_y denote the radii in the rolling direction, E_1, E_2, μ_1, μ_2 are elastic modulus and Poisson´s ratios of the contacting bodies.

As a representative of compliant bodies, phenolic ball of the elastic modulus equal to 4 GPa was used. For i-EHL contacts, the formula for dimensionless central film thickness is as follows [Hamrock 1978]:

$$H_{c,compliant} = 7.32 \cdot U^{0.64} \cdot W^{-0.22}(1 - 0.72 \cdot e^{-0.28 \cdot k}) \quad (5)$$

Mineral oil of dynamic viscosity η = 0.6444 Pa·s was applied as a test lubricant since it emits fluorescence naturally when illuminated in UV. Sufficient amount of lubricant was used, therefore the lubricant film could be fully developed. The test conditions were as follows. In case of PE contact (ceramic-on-glass), the applied load was equal to 12 N, resulting in the maximum contact pressure of 401.7 MPa. Because of the repeatability, the experiment was conducted two times. The tests with ceramic ball were realized to validate the evaluation algorithm. After that, the measurements were carried out with the phenolic ball of low elastic modulus. Three different loads were applied, 12 N, 26 N, and 41 N, respectively; leading to Hertzian contact pressures equal to 66.5, 83.8, and 100.2 MPa. Independently on applied materials, the experiments were performed under pure rolling conditions for the rolling speeds in a range from 10 to 500 mm/s. Therefore, the dependence between film thickness and rolling speed was obtained. All the test conditions are summarized in Tab. 1.

	PE contact	IE (compliant) contact
Load [N]	12	12; 26; 41
Maximum contact pressure [MPa]	401.7	66.5; 83.8; 100.2
Slide-to-roll ratio [1]	0	0
Speed range [mm/s]	10 – 500	10 – 500

Table 1: Test conditions applied during the experiments.

3. RESULTS AND DISCUSSION

3.1 Method validation

In case of the PE contact, film thickness varied from 100 nm for 10 mm/s, up to 1.5 um for 500 mm/s. Images taken by sCMOS camera for ceramic-on-glass contact pair under various rolling speeds are displayed in Fig. 2. With increasing the rolling speed, typical horseshoe-shaped constriction is formed. The values of film thickness plotted against rolling speed and compared with theoretical predictions provided by

Hamrock and Dowson [Hamrock 1977] are shown in Fig. 3. As can be seen in this figure, the film thickness gradually increased over the whole range of applied speeds. As there is an excellent agreement between expected and measured data, the relevance of the evaluation process was clearly proved. The profiles of lubricant film along the rolling direction for selected speeds are drawn in Fig. 3.

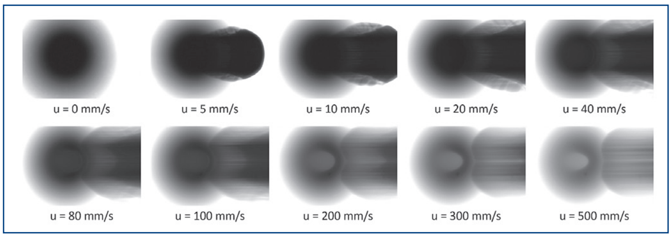

Figure 2. Film thickness maps of the lubricated PE contact. Inlet is on the left of each image.

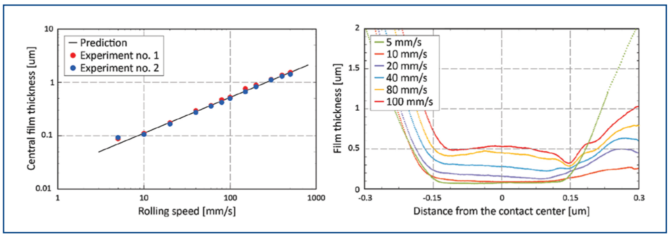

Figure 3. Left: The dependence between film thickness and rolling speed. Right: Film profiles for selected rolling speeds (inlet is on the left).

3.2 Compliant contact

For compliant contact, different loading and kinematic conditions were applied, as was mentioned above. Images of the contact loaded by force equal to 12 N are shown in Fig. 4. Generally, there was no significant effect of load on lubricant film. However, against expectations, increasing load led to an increase of lubricant film. The same phenomena was observed by Fowell et al. [Fowell 2014], where a slight increase of film thickness in contact between PDMS hemisphere and glass disc was detected while the load raised from 11 mN to 23.5 mN. The effect of load on lubricant film will be investigated in a more detail in further study. One of the point is the behaviour of phenolic sample under high pressure conditions. The surface topography can also play an important role. As is shown in Fig. 5, for all the applied loads, the measured film thicknesses were lower than predicted. As was pointed out by Myant et al. [Myant 2010c], in case of low viscosity fluids, there was a very good correlation with theory. On the contrary, when glycerol was used as a lubricant, the authors detected lower films than predicted. This fact is attributed to thermal effects and hygroscopic nature of applied fluid. Although the measurements in the present paper were realized under controlled ambient temperature (22 °C), the results can be also influenced by local thermal effects occurring inside the contact of two bodies. Viscosity of applied mineral oil was analysed in a detail, finding that increasing the temperature for just 3 °C leads to decrease of viscosity from 0.6444 Pa·s to 0.5122 Pa·s. As the viscosity drops, the lubricant film becomes lower. Experimental results are in very good agreement for the load equal to 41 N. Profiles of film thickness in the rolling direction for this load are plotted in the right part of Fig. 5. Previously, the authors were not able to observe such a significant constriction at the contact outlet in case of compliant contacts [Fowell 2014, Myant 2010c]. However it should be noted that in these references, very soft samples, with the modulus of elasticity in a range of units of MPa, were investigated. Another effect associated with relatively higher elastic modulus of the phenolic ball is the slope of the film in the rolling direction. Indications that central plateau region, which is associated with EHL, is absent in case of compliant contacts was confirmed by [Myant 2010a]. The slope of converging edge is supposed to increase with increasing speed [Fowell 2014, Myant 2010a, Myant 2010c]. Although there is an increase of slope with increasing rolling speed (see Fig. 5), the change is not such a rapid than previously observed [Fowell 2014, Myant 2010c]. This indicates that the higher elastic modulus of the compliant body leads to flattening of the central contact zone.

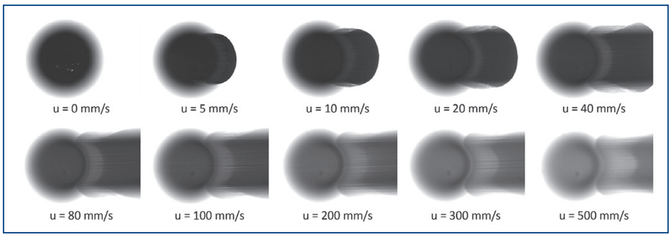

Figure 4. Film thickness maps of the lubricated compliant contact for load equal to 12 N. Inlet is on the left of each image.

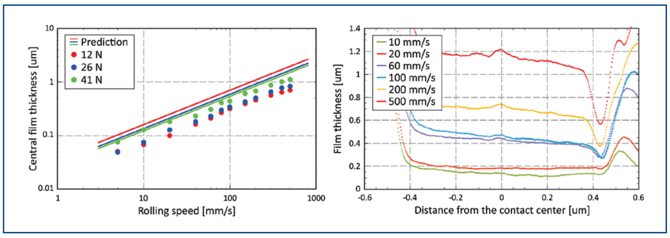

Figure 5. Left: The dependence between film thickness and rolling speed for different loading conditions. Right: Film profiles for selected rolling speeds for load equal to 41 N (inlet is on the left).

4. CONCLUSION

In the present paper, the experimental approach based on the fluorescent microscopy was introduced. The method was validated by conducting the central film thickness measurement for ceramic-on-glass contact, while the data were compared with the theoretical prediction made by Hamrock and Dowson [Hamrock 1977]. As there was a very good agreement with prediction, the relevance of the measured data was clearly proved. The main benefit of the above described technique is that the compliant bodies can be investigated. The phenolic ball was used as a representative of compliant material. Quite good correlation with prediction [Hamrock 1978] was found, however, the values were a little bit lower compared to expectations. This fact is attributed especially to thermal effects, as was previously pointed out by [Myant 2010c]. It can be concluded that the applied experimental approach is suitable for studying the compliant contacts. In the following paper, the effect of material properties, as well as the effect of loading and kinematic conditions, will be investigated.

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CONTACTS

Ing. David Necas
Ing. Petr Sperka, Ph.D.
doc. Ing. Martin Vrbka, Ph.D.
prof. Ing. Ivan Krupka, Ph.D.
prof. Ing. Martin Hartl, Ph.D.
Brno University of Technology, Faculty of Mechanical Engineering
Institute of Machine and Industrial Design
Technicka 2896/2, 616 69 Brno, Czech Republic
tel.: +420 541 143 227, e-mail: necas@fme.vutbr.cz
tel.: +420 541 143 238, e-mail: sperka@fme.vutbr.cz
tel.: +420 541 143 237, e-mail: vrbka.m@fme.vutbr.cz
tel.: +420 541 142 723, e-mail: krupka@fme.vutbr.cz
tel.: +420 541 142 769, e-mail: hartl@fme.vutbr.cz