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LUBRICATION OF ROLLING – SLIDING POLYMER CONTACTS

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Abstract: *The submitted article deals with polymer or hybrid contacts that are an alternative to a steel-steel contact in applications where one or both components have a low Young modulus. With respect to engineering applications such as cams or gears, a rolling-sliding ratio (SRR) between the contact surfaces is presented and the influence on film thickness is analyzed. Lubricated polymer contacts work mainly in the iso-viscous regime of the elastohydrodynamic lubrication (EHL) where a dependence of lubricant viscosity on the contact pressure is weak. The measurements were conducted on a ball-on-disc tribometer using the optical interferometry method to evaluate the distribution of film thickness. The experimentally obtained data are compared with the predictions for the soft EHL contacts and discussed. The experiments can contribute to the knowledge of the soft lubricated contacts and improvement of the design of gears made of polymer materials.*

Keywords: Polymer contact, film thickness, optical interferometry, ball-on-disc tribometer, rolling-sliding ratio.

1. Introduction

In recent years, polymer materials have been expanded in engineering applications where materials such as PA 66, POM or PEEK are increasingly used to produce gears. In practice, polymer spur and worm gears are commonly used; however, in contrast to steel equivalents, these gears dispose of the following advantages: they are less expensive, lower in mass, and relatively resistant to wear. On the other hand, the disadvantages of polymers compared to steel are low mechanical properties, especially the Young modulus $E < 5\,GPa$, which is pronouncedly dependent on the temperature. Another disadvantage is a worse surface topography with respect to higher surface roughness (RMS).

Polymer gears can work as lubricated (Dearn et al., 2013) or unlubricated (Harrass et al., 2010). In the case of lubricated contacts, the task of the lubricant is to dissipate heat resulting from contact pressure and shear stress between surfaces when the lubricant flows through the contact. At the same time, it maintains a stable lubrication film thickness to ensure a full film separation of contact surfaces.

Individual lubrication regimes are characterized by the Stribeck curve based on the lubrication parameter Λ, which depends on RMS. For polymers, it is necessary to ensure conditions where the surfaces are fully separated by film thickness of lubricant (Dearn et al., 2013). This is represented by the regime of elastohydrodynamic lubrication (EHL). The contact area between both surfaces is elastically deformed due to the hydrodynamic pressure exerted by the layer of the lubrication film on the surface of the material (Myant et al., 2010). In EHL, the minimum film thickness h_{min} is several times higher than the average height of surface asperities (RMS).

Elastohydrodynamic lubrication is characterized by a lubrication map which defines several regimes of EHL. One of them is called the iso-viscous regime or soft EHL. It occurs between non-conformal surfaces when the contact pressure p_m is sufficient to induce the elastic deformation of contact, but the low contact pressure does not induce a considerable change in the lubricant dynamic viscosity η (Myant

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et al., 2010 and Johnson, 1970). This is different from the piezo-viscous regime (hard EHL) where this change is significant.

In real applications, such as bearings, cams or gears, the film thickness is influenced by various factors, e.g. properties of lubricant, kinematic conditions, load, temperature, topography of contact surfaces, which can change the lubricant distribution in the contact. When the teeth are in contact, from the point of view of kinematical conditions, the rolling with slide occurs where SRR changes as a result of the movement of the pitch point along the pressure line. In the case of increasing sliding speed, the magnitude of shear stresses increases in the lubricant, thus reducing the film thickness (Hooke et al., 1972 and Marx et al., 2016).

Recent numerical and experimental studies (Marx et al., 2016 and Myant et al., 2010) have focused on the lubricated contact of steel and polymer materials located in the transition area between the iso-viscous and piezo-viscous regimes of EHL. The transition area is based on the results obtained by Greenwood (1972) and Hooke (1977) as the working space of mineral oil-lubricated polymers. Although the film thickness in dependence on the kinematic conditions is predicted in the studies of Hooke (1995) and Hamrock et al. (1978), there is a lack of experimental results (Myant et al., 2010 and Marx et al., 2016). In the case of experimental studies, the fluorescence (Myant et al., 2010) and optical interferometry methods (Hartl et al., 2001 and Marx et al., 2016) are often used to evaluate the film thickness distribution.

This article describes development of the minimal film thickness in soft EHL contact using the optical interferometry method under conditions of non-zero rolling-sliding ratios. The obtained experimental data are compared with the soft EHL predictions and the differences of the minimal film thickness are discussed.

2. Materials and Methods

Measurements of the film thickness were carried out on a ball-on-disc tribometer. The soft circular contact is ensured between a transparent PMMA disc with a semitransparent chrome layer and a 25.4 mm diameter polished steel ball. This material combination allows to simulate the soft contact and simultaneously to use the optical interferometry method. Before the experiments, the ball and the disc were properly cleaned by isopropyl-alcohol, then the ball was polished using the polishing paste; this resulted in smoothing of surface asperities and thus in a decrease of surface roughness to obtain quality interference images. The topography of the surface was measured on the optical profilometer to obtain the values of R_q. The properties of both materials are given in Tab. 1.

Tab. 1:Properties of used materials

Material	Specification	Root mean square roughness, R_q	Young modulus, E	Poisson 's ratio, ν
PMMA	Polymethyl-methacrylate	0.100 µm	3.3 GPa	0.39
Steel	100Cr6	0.005 µm	210 GPa	0.30

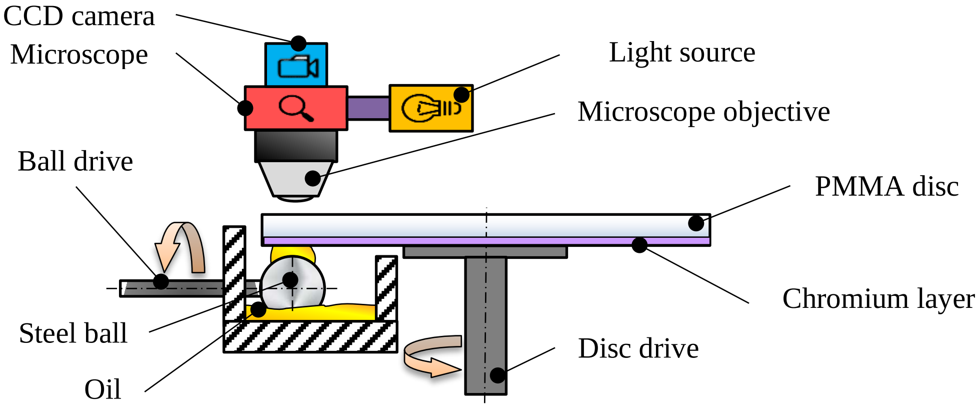

Fig. 1: Experimental apparatus.

The lubrication of the contact is ensured by the FVA3 mineral base oil, corresponding to the viscous index ISO VG 100. The lubricant properties are stated by Liu et al. (2018). All measurements were conducted at the oil temperature of $T_{oil} = 30 \pm 0.5$ ℃ which corresponds to the value of the lubricant dynamic viscosity $\eta_{30} = 0.1446\ Pa\ s$.

The film thickness was measured under conditions of the entrainment speed $U = 0.04 - 0.6\ m/s$ and load $W = 35\ N$. This load corresponds to the Hertzian contact pressure $p_m = 85\ MPa$ and the radius of the Hertzian contact $a = 0.443\ mm$. In terms of kinematics, experiments for two different rolling-sliding ratios $SRR = 0.25$ and $SRR = 0.5$ were performed.

The film thickness was measured and evaluated by the optical (colorimetric) interferometry method. The contact side of the polymer transparent PMMA disc was coated with semi-transparent chromium layer which enables a reflection of the wavelengths of light on the surface. The first part of the wave is reflected by the chromium layer onto the disc surface while the second part passes through the chromium layer over the lubricant and is reflected back by the polished steel ball. Both parts of wave interfere with each other, and the phase shift between the individual waves contains information about the thickness and the shape of the lubrication film at each location. The result is the acquisition of color interferograms which provide data via colors about film thickness distribution due to calibration between monochromatic and chromatic static contacts. A more detailed description of the experimental method can be found in publication Hartl et al. (2001). The scheme of experimental apparatus comprising the ball-on-disc tribometer is shown in Fig. 1.

3. Results and discussion

The outcome of the experiments is the determination of the distribution of the minimal and central thickness of the lubrication film depending on the kinematic conditions. For the purpose of this research, only the minimal film thickness was evaluated. Comparing the static contact sizes corresponds well with the experimental data and the Hertz theory by difference $\Delta < 5\ \mu m$. Fig. 2 represents experimentally obtained results that demonstrate the development of a minimal film thickness depending on the entrainment speed for different SRRs. In all measurements, the minimal thickness does not exceed $500\ nm$.

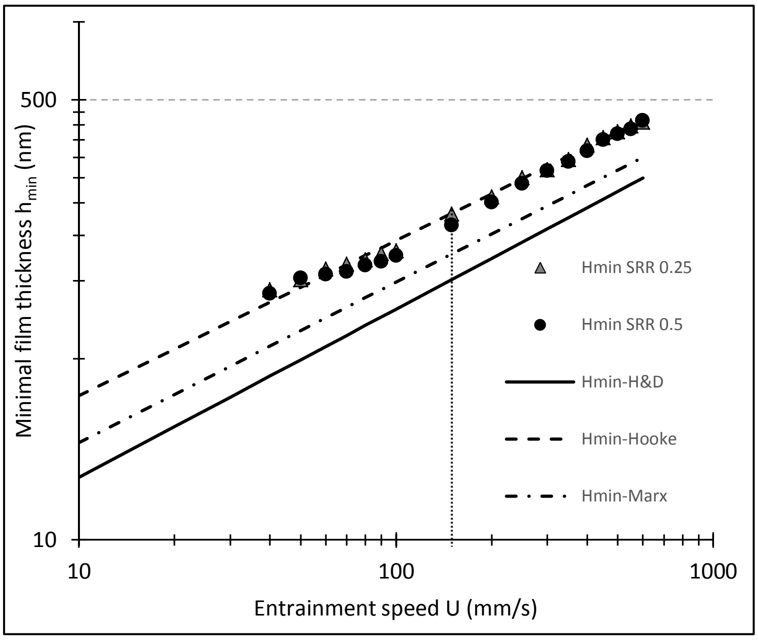

Fig. 2: Comparison of minimal film thickness with predictions. SRR = 0.25; SRR = 0.5; T = 30 °C; W = 35 N

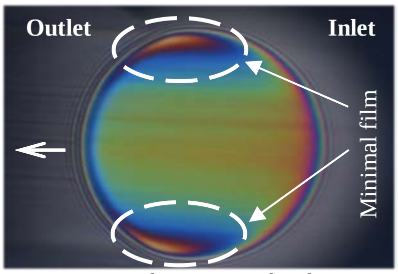

Fig. 3: Interferogram of soft EHL contact. U = 150 mm/s; W = 35 N; SRR = 0.25

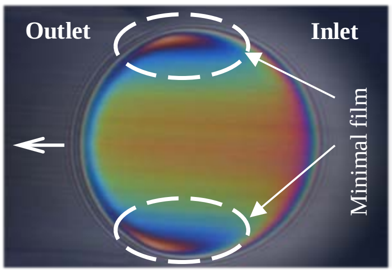

Fig. 4: Interferogram of soft EHL contact. U = 150 mm/s; W = 35 N; SRR = 0.5

Experimental results in Fig. 2 are compared with the predictions of the minimal film thickness for the soft EHL contact, which have already been presented by published models (Hamrock et al., 1978 and Hooke, 1995 and Marx et al., 2016). From Fig. 2, a good agreement of experimental data with the prediction published by Hooke (1995) is evident. This is especially true at higher speeds for both SRRs with $U > 200\ mm/s$. According to Fig. 2, the film thickness for $SRR = 0.25$ is slightly higher than in the case of $SRR = 0.5$. The difference is about 5 % on average. This can be explained by a smaller proportion of the sliding speed, which also causes a decrease of the friction in the contact. Friction is associated with increased temperature at the soft contact inlet, which negatively affects the viscosity of the lubricant and thus also the film thickness.

The main difference in the minimal thickness (dotted line in Fig. 2) was observed for $U = 150\ mm/s$ when it exceeded 10 %. This difference is also evident for the central thickness, as shown in Fig. 3 and Fig. 4. A lighter central area (Fig. 3) with respect to optical interferometry corresponds with the conditions under which the film thickness is higher. Figs. 3 and 4 also show narrowing of the horseshoe shape, especially on the side lobes where the minimal thickness is evident with increasing SRR; this is highlighted by dashed ellipses. The soft EHL predictions made by Hamrock et al. (1978) and Marx et al. (2016) are somewhat different from the experimental results.

4. Conclusions

This experimental study describes measurement of minimal film thickness in polymer contacts using the optical interferometry method. Thanks to the chromium layer on the surface of the PMMA disc, it was possible to obtain quality interference images that determine the film thickness distribution of soft contact under the conditions of non-zero SRR. The measured film thickness is compared to the predictions for soft EHL contact where the best match proves the prediction published by Hooke (1995). The minimal film thickness shows an insignificant dependence on the listed SRR in all range of the entrainment speed. However, in the case of higher rolling-sliding ratios, the minimal film thickness slightly decreased. These results can help to understand the formation of lubrication film in polymer contacts such as hybrid gears. The obtained experimental data for the minimal film thickness should be extended in the future to include the influence of higher rolling-sliding ratios that would give a further perspective to the issue of lubricating polymer contacts.

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