20th International Conference
ENGINEERING MECHANICS 2014
Svratka, Czech Republic, 12 – 15 May 2014

RECENT ADVANCES AND PROBLEMS IN LUBRICATED HERTZIAN CONTACTS

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Abstract: *This review paper provides an introduction to the issue of lubricated Hertzian contacts and related elastohydrodynamic regime of lubrication. It deals with recent advances in such contacts in more detail. Emphasis is placed on the effects of surface topography involving real roughness and artificial features. These problems are discussed on the basis of experiments carried out at Institute of Machine and Industrial Design, Faculty of Mechanical Engineering, Brno University of Technology.*

Keywords: Elastohydrodynamic Lubrication, Optical Interferometry, Roughness.

1. Introduction

Improved understanding of contact mechanics of critical components is required in the design process of modern high efficiency mechanical systems. When such contacts have to transfer high load under relative movement, lubrication is necessary to ensure low energy consumption and long durability. Many machine elements (gears; rolling element bearings; cam/follower systems etc.) have contacting surfaces that do not conform to each other and thus concentrated contact occurs. The contact area is very small and the resulting pressure is very high.

From the point of view of machine design it is essential to know the values of stresses acting in such contacts. With assumption of dry elastostatic contact, these stresses can be calculated from analytical formulae, based on theory developed by Hertz in 1881. For a general point contact (with different principal relative radii of curvature in orthogonal planes) this theory predicts an elliptical contact area and a semi-ellipsoid contact pressure distribution. When a movement of the surfaces occurs, rolling and sliding is presented in the contact. In general, rolling results in increase in contact area and modification of contact stress distribution. However, the most critical influence on subsurface stress is due to sliding.

Lubrication is an effective way how to reduce friction and subsurface shear stress, separate surfaces and remove wear in rolling/sliding contacts. This case of lubricated Hertzian contacts is called elastohydrodynamic lubrication (EHL). EHL is a mode of fluid-film lubrication in which hydrodynamic action is significantly enhanced by surface elastic deformation. The lubricant is exposed to high pressures (up to 3 GPa) and shear rates (up to 10^8 s^{-1}) whereas lubricant film thickness is in submicron scale. Under these conditions, change of lubricant viscosity with pressure plays an important role. The lubricant behaviour fundamentally affects pressure distribution and lubricant film shape.

The EHL film thickness and shape has been the main area of interest since 1960s when milestone isothermal EHL theory was proposed (Dowson et al., 1962) and confirmed experimentally not long after that (Gohar and Cameron, 1963). Classical EHL theory predicts typical horse-shoe shaped film thickness profile and exit pressure spike, as shown in Fig. 1. Up to the present, considerable effort has been devoted to describe various phenomena which occur in EHL. In this effort an experiment play an important role because it allows confirming new theories, or on other hand, it may shed new light on this problem.

One of the most powerful experimental approaches in EHL is ball-on-disc tribometer coupled with optical interferometry method, which allow to determine film thickness distribution in contact between steel ball and transparent (mainly glass) disc (Spikes, 1999; Hartl et al., 2001). Typical EHL interferogram is shown in Fig. 1.

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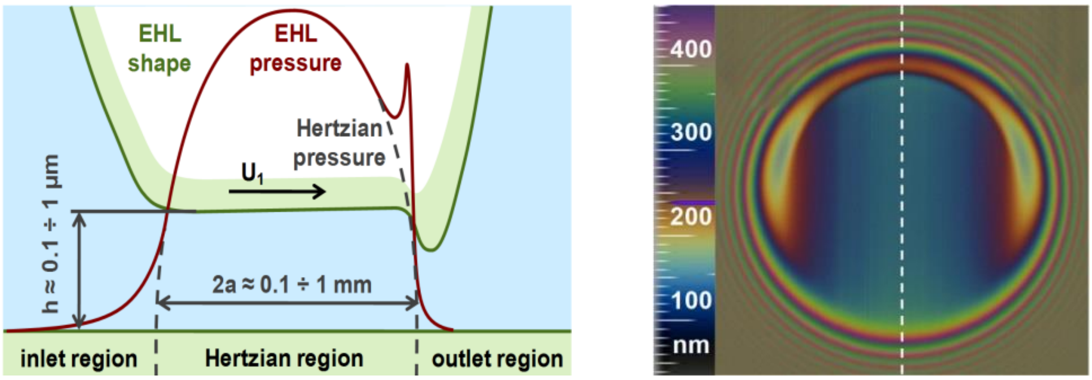

Fig. 1: EHL film thickness and pressure profile in rolling direction and EHL interferogram.

2. Surface Topography

2.1. Real roughness

In engineering practice no surface is ideally smooth. As the ratio of mean film thickness to surface roughness height is decreasing the roughness starts to substantially affect contact pressure distribution. When the film is broken down it results in further increase in the pressure as well as friction and wear caused by the direct surface interaction. Coherent effective lubricant film can be hardly formed under these operational conditions, so that, the knowledge of surface roughness influence on fluid film is essential. The initial studies of the roughness influence on the film thickness used a stochastic approach. Primarily the effects of roughness orientations on global film thickness variations were studied. During the last decades more interest has been focused on deterministic studies that can reflect local changes. One of the most important result have been development of an amplitude attenuation theory which provides analytical expressions that estimate how the amplitude of a given harmonic surface feature changes inside EHD contact. The behaviour can be completely described by a single curve known as an amplitude attenuation (reduction) curve, defined as the deformed to initial amplitude ratio. This theory says that roughness components with small wavelengths are deformed inside the contact much more than these with high wavelengths (Lubrecht and Venner, 1999). Recently, this theory was validated based on FFT analyses of real roughness measurements (Sperka et al., 2010; Sperka et al., 2012a). The scheme of this validation is shown in Fig. 2.

2.2. Artificial features

For a better understanding of the behavior of roughness in EHL contact, experimental works have been mostly oriented on the artificially produced asperities like ridges (negative) and bumps (positive). Someone can assume that passing of positive roughness features thru the contact should have strong impact on film thickness, while the effect of negative roughness features should be much less significant because this feature cannot interact with opposite surface. However, recent experiments show that the reality is the exact opposite, as shown in Fig. 3. Even a very high bump is nearly totally pushed into the surface thanks to high local pressure and a piezoviscosity of lubricant. However when equivalent surface ridge passes thru the contact, lubricant leaks from the surface feature due to low pressure and breakdown

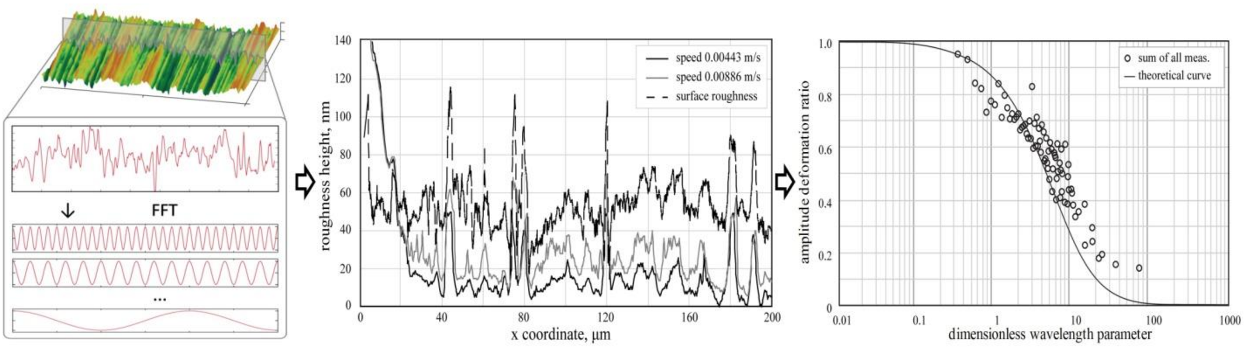

Fig. 2: Scheme of analysis of real roughness deformation (Sperka et al., 2010).

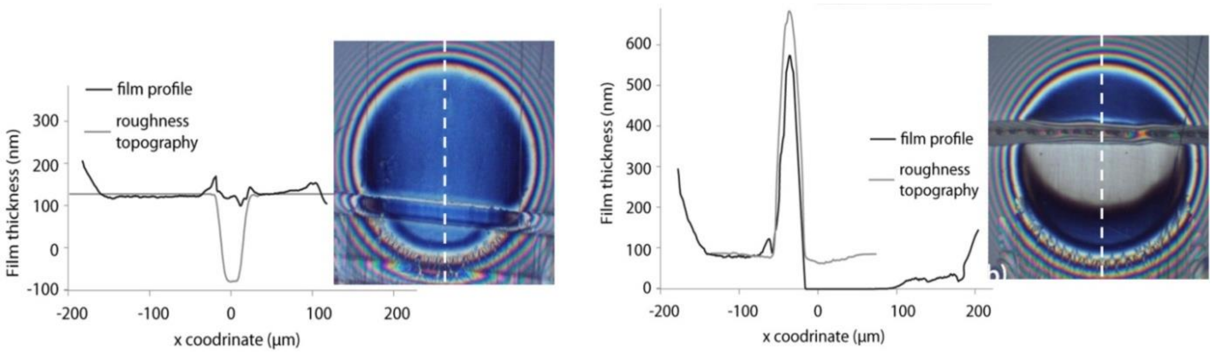

Fig. 3: Surface bump and ridge passing thru the EHL contact and its effect on film thickness.

of lubricant layer occurs (Kaneta et al., 1992; Sperka et al., 2012b). These results show that roughness effects on film thickness and roughness deformation cannot be neglected in prediction of lubrication regime. Other kind of surface topography consists in the artificial microtextured surfaces. Design of mechanical seals or piston rings involve lubricated contacts formed between conformal surfaces having artificially produced microfeatures of controlled size, shape, and density on sliding surfaces. In such a case of conformal sliding contact, microfeatures can be considered as lubricant reservoirs and can trap debris particles to diminish friction and wear.

Fig. 4 shows experimental results with an array of microdents prepared by mechanical indentation. They suggested that the microtexturing might help to improve the efficiency of lubrication films within highly loaded contacts once shallow microdents are used (Krupka et al., 2010). This effect may be beneficial mainly under transient conditions, especially when speed and load changes rapidly, as is the case of cam/tappet contact (Krupka et al., 2011). However, the presence of microdents within highly loaded contacts results not only in significant changes in lubricant film thickness but also in pressure distribution. Highly localized pressure peaks in the vicinity of microfeatures increase subsurface stresses. So, the effect of surface texturing on rolling contact fatigue was studied (Vrbka et al., 2010). It has been found that the application of surface texturing is not necessarily accompanied with the reduction of RCF life.

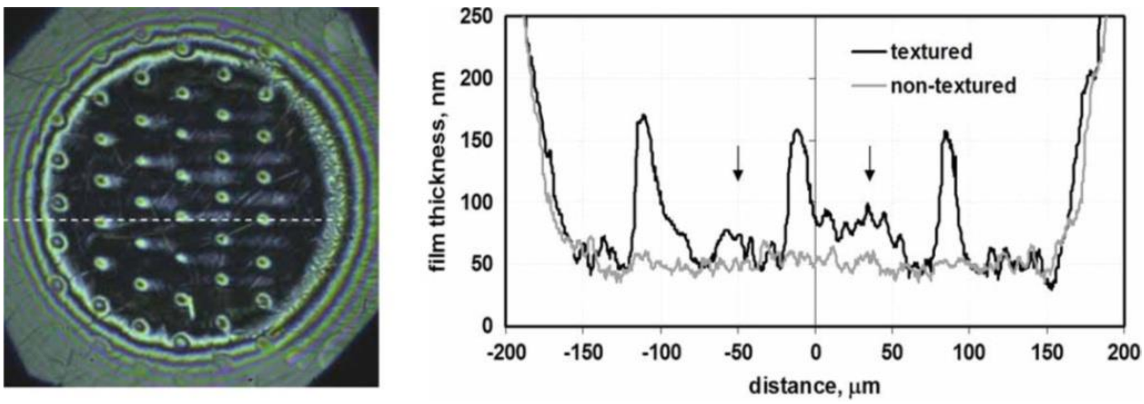

Fig. 4: Effect of surface texturing using microdents on film thickness (Krupka et al., 2010).

3. Specific In-Contact Film Shape

In smooth contacts classical EHL theory predicts flat plateau in central (in-contact) zone of EHL contact. However during last years some experimental and numerical studies showed that various film shape features may be formed in the in-contact zone, mainly under rolling-sliding conditions. Very common phenomenon is a dimple phenomenon (Kaneta et al., 1996). This effect is characterised by local increase in film thickness in the central part of the contact and occurs under the specific sliding conditions, as shown in Fig. 5. Several types of models have been proposed to explain the dimple phenomena. The most accepted is model of temperature–viscosity wedge action consisting in unequal temperature and thus viscosity distribution across the film thickness. Moreover, recently it has been found that among others also an angle between sliding and rolling velocity has a strong influence on in-contact film shape (Omasta et al., 2013). This phenomenon is due to the different heat flow through the contact.

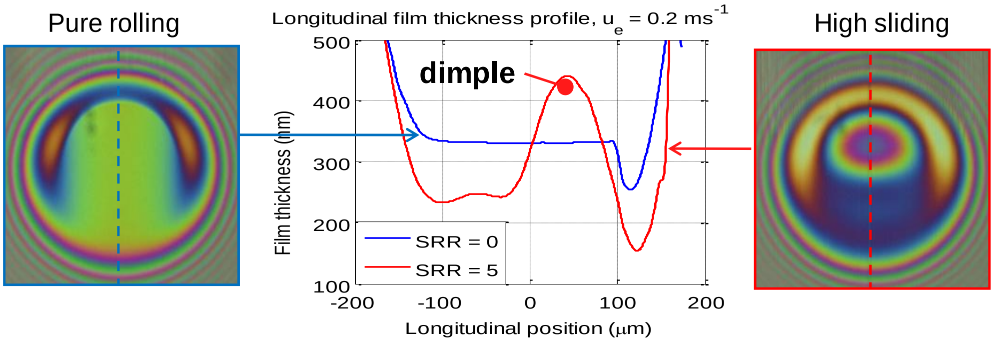

Fig. 5: Interferogram and film thickness profile for pure rolling and high sliding conditions.

4. Conclusions

Lubricated Hertzian contacts and hence EHL regime is of great importance in many mechanical components. An understanding of processes that take place in the contacts is crucial to make things work better. Recent findings obtained using optical interferometry brings new challenges and allow extending the present EHL theory.

Acknowledgement

This work is an output of research and scientific activities of NETME Centre, regional R&D centre built with the financial support from the Operational Programme Research and Development for Innovations within the project NETME Centre (New Technologies for Mechanical Engineering), Reg. No. CZ.1.05/2.1.00/01.0002 and, in the follow-up sustainability stage, supported through NETME CENTRE PLUS (LO1202) by financial means from the Ministry of Education, Youth and Sports under the „National Sustainability Programme I“.

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