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The effect of surface roughness on friction and film thickness in transition from EHL to mixed lubrication

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ABSTRACT

The purpose of this study is to reveal the connection between the film thickness and the friction for a uniform surface texture on transition from full film to mixed lubrication in non-conformal contacts. The current study tries to clarify the processes leading to the friction increase during the transition that is usually seen in the Stribeck curve. The transition to mixed lubrication and the friction increase are usually associated with a direct contact between surface irregularities. However, the experimental results showed that friction increases much earlier before the first contact was detected. It was revealed that a standard mixed friction modeling based on the area in a direct contact has significant limitations. Numerous possible explanations for this phenomenon are discussed.

1. Introduction

During the last few decades there has been a progressive trend to operate machines in higher loads, temperatures or other demanding conditions, in general causing the lubrication film thickness to become significantly thinner [1]. Another trend has been to use lubricants with lower viscosity to decrease the fluid film friction, which also contributes to the film thickness decrease. These conditions cause machine elements such as cams, rolling bearings or gears to operate under very hard conditions and very often on the border of transition between the full film and boundary lubrication [2]. In this case, a lubrication process is no longer only a function of kinematic conditions but it can be significantly influenced by surface roughness of rubbing surfaces or chemical processes between the lubricant and surfaces.

In the past several years, a lot of research has been done to understand lubrication and friction mechanisms in the highly-loaded lubricated contacts between two rubbing surfaces, especially in the case of transition from full film lubrication to mixed lubrication [3–5]. In full EHL, when two rubbing surfaces are completely separated by a thick film, the behavior of film thickness is controlled by elastohydrodynamic factors such as rolling speed, viscosity of lubricant, and load. In this case, the film thickness can be predicted by the Hamrock and Dawson formula [6]. However, in the case of boundary lubrication regime, which was firstly proposed by Hardy [7], when two surfaces are really close to each other, lubrication properties are no longer a function of elastohydrodynamic factors such as rolling speed but they depend on the chemical interaction between the lubricant and rubbing surfaces [8]. During the last several years, a significant progress in the fields of EHL and mixed lubrication has been made. However, lubrication and friction processes during the transition between these two regimes still remain not fully understood.

One of the attempts of how to explain the gap between the full film and boundary lubrication in the case of film thickness was the model of thin film lubrication (TFL), firstly published in 1994 [9]. Thin film lubrication was indicated as a regime where both physical and chemical processes influence the lubrication process. The above model was subsequently improved and verified experimentally by Krupka et al. [10,11], Liu [12] and Zhang [13]. Thin film lubrication occurs when the size of the gap between two rubbing surfaces is in the range of several nanometers. In this case, a TFL model shows that the film thickness still depends on the rolling speed, but the trend deviates from the classical EHL theory. In TFL, the molecular behavior of lubricant is dominant [8]. The behavior of lubricant in TFL is influenced by many factors such as rolling speed, contact pressure, molecular polarity, or slide-to-roll ratio.

Another approach assumes a gradual increase of a direct interaction between surface roughness, also known as a mixed lubrication theory. Mixed lubrication occurs when the separation between the rubbing surfaces decreases and the film thickness becomes thinner than the surface roughness height. The rubbing surfaces are no longer perfectly separated by coherent lubricant film, and the contact between the opposite surface irregularities may occur [14]. This process has a

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significant impact on friction and film thickness. The concept assumes that the friction force in mixed lubrication regime can be defined as a sum of the friction force due to fluid friction in lubricant itself FEHL and the friction force due to the direct contact between surface roughness FDC [15].

$$F_{mix} = F_{EHL} + F_{DC} \tag{1}$$

These forces can be defined in many ways. The friction during the transition from the full film lubrication to mixed lubrication is commonly described the Stribeck curve where individual regimes are separated by the lubrication parameter Λ. This parameter is defined as a ratio of film thickness and composite root mean square roughness, Λ = h/ΣRq. The lubrication parameter Λ ≈ 3 [14,16] is used as a transition point from the full film to mixed lubrication. However, some studies suggest that this transition could occur for much lower Λ values, below 1 [17]. One of the friction prediction formulas for mixed lubrication has been made based on this parameter for comparison of numerical and experimental data [18,19]. However, the lubrication parameter is limited because it does not include deformation of surface roughness as well as the surface roughness effect on film thickness [17]. For this reason, the other studies use different parameters to define the proportion between the fluid friction and friction due to a direct contact [18,20–23]. One of these ways is based on the ratio of the area in a direct contact ADC and the area which is still separated by coherent lubrication film AEHL. This can be written as [24]:

$$\mu_c = A_{EHL}\mu_{EHL} + A_{DC}\mu_{BL} \tag{2}$$

$$A_{EHL} + A_{DC} = 1 \tag{3}$$

Eq. (2) can be used for friction prediction in mixed lubrication regime. In the case of full film lubrication, the part of this equation defining a direct contact friction is equal to 0, and A_{EHL} is equal to 1. The friction coefficient in EHL (μ_{EHL}) can be predicted using the Newton's relation for shear stress in liquids. If the direct contact occurs, friction becomes higher than fluid film friction due to the contribution of direct contact friction. This phenomenon can be clearly seen in Fig. 1.

A lot of numerical works use this concept for their predictions based on asperity load sharing [25–28]. The experimental works also use this concept for evaluation of friction or estimation of the percentage of surface roughness in a direct contact [24]. This prediction approach was also verified by comparing the numerical data with the experimental results [20]. However, a significant deviation from the numerical results was observed.

Nevertheless, all presented theories have their own limitations. The most significant limitation is that each of these theories focuses on the same issue from a film or friction perspective separately. In the case of TFL studies, the field of interest lies mainly in the central film thickness. Studies focused on mixed lubrication are primarily oriented on friction. However, in mixed lubrication, a decrease in film thickness leads to a direct contact between the opposite surfaces, which could cause an increase in friction. In this case, the interconnection between friction and film thickness can provide more information on the processes that occur in a very thin films. It can help to better understand the transition from EHL to mixed lubrication in highly loaded contacts.

The aim of the current study is to extend knowledge on the processes during the transition from the full film to mixed lubrication. The current study tries to clarify processes which lead to the friction increase during this transition. This phenomenon is studied for four uniform surfaces with a different root mean square (RMS) value. The obtained results of friction are compared with a theoretical prediction.

2. Experimental methods and material

Measurements were conducted using a ball-on-disc tribometer. In this tribometer, a circular EHL contact is formed by loading an optically smooth (R_q = 0.5 nm) flat transparent disc made of optical glass against a 25.4 mm diameter ball made of AISI 52100 steel. This apparatus uses the optical interferometry technique, thereby it enables precise film measurements up to the nanometers. The theoretical film thickness resolution is 0.2 nm. The interference technique is based on two light beams passing through a glass disc. The first beam is reflected by a semitransparent chromium layer on the bottom side of the disc. The other beam passes through a chromium layer and also through the lubricant; after that this beam is reflected back from the polished surface of the ball. These two beams interfere. The interferogram and film thickness were connected by calibration using monochromatic and chromatic static contacts. A more detailed description of this experimental rig and evaluation technique can be found elsewhere [29] and [30]. The disc and the ball are driven separately by servo motors to obtain different kinematic conditions, defined by slide-to-roll ratios and mean speeds. The load is generated by a lever mechanism. The lubricant is fed to the contact area by dipping the ball in the lubricant reservoir. The temperature is measured by a thermocouple which is placed as close as possible to the inlet region. During the experiments the temperature was kept at 24 ± 0.5 °C.

Four balls with different uniform surfaces defined by the root mean square roughness R_q, skewness R_{sk} and kurtosis R_{ku} were used for experiments. Information on each specimen is shown in Table 1. In the case of R_q, there is also the information on standard deviation. A manufacturing process was repeatedly controlled by a 3D optical profilometer. For statistical precision, 10-point measurement throughout the circumference of every single ball was made. These measurements showed, that created surfaces are close to the Gaussian distribution because the transition to the mixed lubrication, in general, depends on the surface roughness distribution. Balls B1 and B2 were created by polishing technique with different diamond pastes. Balls B3 and B4 were created by scratch technique. During the scratching process, the diamond paste was applied on the ball surface. The scratches were

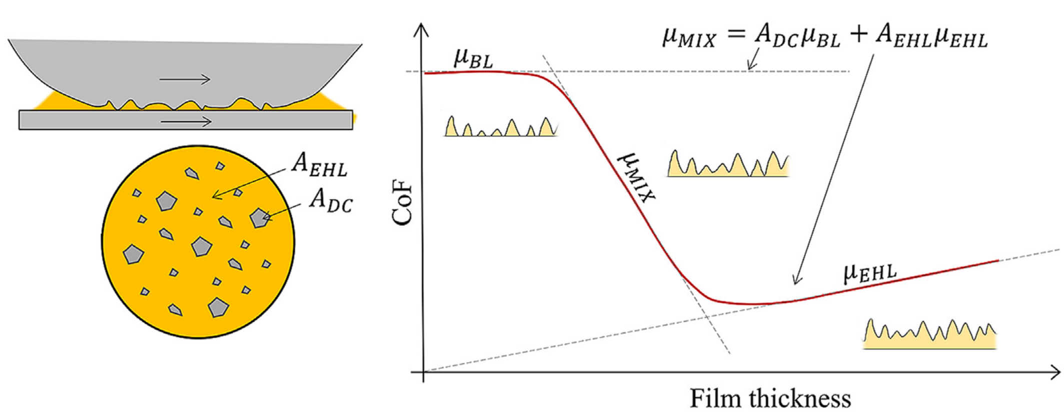

Fig. 1. A graphical representation of friction in mixed lubrication.