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The effect of surface grooves on film breakdowns in point contacts

P. Sperka *, I. Krupka, M. Hartl

Faculty of Mechanical Engineering, Brno University of Technology, Technicka 2896/2, 616 69 Brno, Czech Republic

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A B S T R A C T

Surface roughness plays an important role in transition from full to mixed elastohydrodynamic regime. One kind of features appearing on a real rough surface are grooves longer than contact diameter. It has already been reported that these grooves cause a local film reduction or a complete collapse. In this study, a ball-on-disc optical tribometer was used to quantitatively study the effect of grooves on film thickness in a point contact. It was observed that the main dependence on speed, the so-called lift-off curve, generally follows the logarithm function. The effects of build-up material, load, slide/roll ratio and groove geometry are presented. These results were fitted to the analytical description, which enables the estimation of groove effects on point contact lubrication.

1. Introduction

Formation of elastohydrodynamic lubrication (EHL) film between the smooth surfaces has been extensively studied. Nevertheless, surfaces of real mechanical parts have surface roughness. This can be related to the increased friction and enhanced damaging processes, e.g. wear, fatigue, etc. Formation of wear on practical surfaces is a symptom of transition from the full EHL regime to the mixed lubrication regime where the contacts between surface features occur. The main aim of experimental studies is to describe and explain the mechanisms which lead to transition from the EHL regime to the mixed lubrication regime.

Generally, features on rough surfaces could be divided into peaks and valleys. Together, they form a surface topography with a certain height distribution of surface area known as a bearing area curve. This curve is usually interpreted in tribological studies so that the peaks are being worn out at first, while the part of the topography that corresponds to valleys persists on the surface. There is a skewness roughness parameter *Rsk* related to the shape of the bearing area curve. If this parameter is negative, the topography contains more valleys than peeks and vice versa. Some researchers have studied the relation between the skewness parameter of rough surface and tribological properties [1–3]. Nevertheless, this kind of study represents an indirect observation where various effects like material, lubrication effects of complex roughness features, chemistry of tribolayers, etc. could have an unknown contribution to the final result. A more essential approach is to focus on the modeling of mixed lubrication (e.g. [4,5]) or the modeling of contact problem (e.g. [6]).

Three basic types of surface roughness features, i.e. ridges, dents and grooves, were investigated in experimental studies of roughness effects on lubrication. It was described that dents cause only a local reduction of film thickness when passing the contact inlet; afterwards, a film thickness increase can be observed once they enter the high pressure zone [7,8]. Additional pressure rippling caused by ridges and bumps lead to their large deformation in an EHL contact that could effectively protect the surfaces against a direct contact [9–11]. The grooves longer than the contact area are connected with a side leakage which causes a local reduction in film thickness or a complete collapse [12]. Therefore the grooves can be regarded as the most dangerous type of roughness features for distribution of lubricant film thickness in a point contact.

Pioneering experimental work on the effects of grooves in EHL contact by using optical interferometry has been done by Wedeven and Cusano [13,14]. In their papers, deformation of surfaces caused by micro-EHL pressure was studied for perpendicular and parallel orientation of groove under pure rolling and pure sliding conditions. Another extensive study was led by Kaneta [12,15]. The effects of surface grooves were studied under various slide/roll ratios (*SRR*) and mean speeds. It was shown that the side leakage is controlled by the groove width and depth. A groove on a real rough surface was studied by Hartl [16]. It can be stated that this groove causes the same effects as an artificial groove. Ali [17] studied shallow grooves with length less than a diameter of Hertzian contact. It was revealed that this type of groove works as a powerful oil reservoir. Under these conditions, the grooves do not cause a significant decrease in film thickness or a complete film collapse. More complete review on mixed lubricant and roughness effects in EHL contact can be found in [18,19].

* Corresponding author.
E-mail address: sperka@fme.vutbr.cz (P. Sperka).

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There exists a fundamental difference in groove effects on lubrication of conformal contacts [20–22] and non-conformal contacts [15]. In conformal contacts or the contacts between nominally flat surfaces, where pressure and lubricant viscosity are low, surface grooves could have a positive effect. However, this study concentrates on non-conformal contacts of elastohydrodynamic lubrication where a high lubricant viscosity, provided by lubricant piezo-viscous effect, is important to build a film layer and separate surfaces.

As far as the authors know there is no publication that quantitatively reports on the effects of transversely oriented surface grooves on film thickness in a point contact. The aim of this paper is to quantitatively describe the effects of operating conditions and the groove geometry on film thickness distribution.

2. Experimental apparatus and materials

Measurements were conducted using a ball-on-disc optical tribometer. In this apparatus, an EHL point contact was formed between a steel ball and a glass disc. The lower surface of BK7 glass disc is sputtered with a semi-reflecting chromium layer. The steel ball AISI 52100 with a groove has a diameter of 25.4 mm. The elastic modulus of the steel ball is 210 GPa and that of the glass disc is 81 GPa. The reduced elastic modulus is equal to 123.8 GPa. Three mineral base oils from group I were used, namely R560/88, SN650, R825/95 having dynamic viscosities of 1.15, 0.356, 0.06 Pa s at 25 °C, respectively. All experiments presented in this paper were carried out at room temperature of 24.5 ± 0.5 °C. Lubricant film thickness was evaluated by the colorimetric interferometry technique [23]. In the optical design, a configuration without silica spacer layer on the bottom side of disc was used [24].

Grooves were produced by means of indentation rig which uses an electromagnetic solenoid to create the impact between the indenter tip and the ball surface. This device uses a stepper motor to create a linear motion and the indentation process is fully automated as it is described in [17]. In this paper, three types of indenter tips were used. Two of them were Rockwell indenters with a tip angle of 120° and a slightly different radius of tip within the range of 0.2 ± 0.01 mm. The other indenter was the Knoop indenter with a tip of tetrahedral diamond pyramid and tip angles of 172.5 and 130° in two perpendicular planes. It was decided to primarily test the groove geometry without build-up material which is created during production due to plastic deformation. Therefore, a post-production treatment was needed to remove the build-up material after indentation. This material was removed by polishing with diamond paste. The polishing process did not significantly change the width of the groove but it significantly reduced its depth. Practically, a total depth of one groove before polishing was 930 nm (see the groove R5 in Table 1) and the groove depth after polishing was 630 nm (see the groove R6 in Table 1). Altogether, 13 different grooves were studied. Twelve of them were polished to remove build-up material and one was left unpolished (R5). Data of grooves are listed in Table 1. The grooves K were produced using the Knoop indenter while the grooves R, RS used Rockwell indenters. A commercial optical profilometer was used to determine the grooves geometry. Grooves were characterized by depth D, width W and height of build-up material H_B. These geometry parameters were schematically shown in Table 1. Representative profiles of unpolished groove (R5), polished groove (RS3) and the grove created by Knoop indenter (K3) are shown in Fig. 1. Because grooves had rounded edges, the width of the groove was determined as a distance between imaginary intersections of the straight parts of groove arms with smooth surface geometry.

3. Results and discussion

Fig. 2 shows interferograms observed at various time periods of the passage of groove K1 through the EHL point contact under conditions of mean speed of 0.02 m s^{-1}, Hertzian pressure 0.54 GPa, SN650 oil, slide/roll ratio $SRR=1$ (Fig. 2a–e) and $SRR=-1$ (Fig. 2f–j). Slide/roll ratio is defined as $2(u_d\text{-}u_b)/(u_d+u_b)$, where u_d and u_b are speeds of disc and ball respectively. In this figure, the contact inlet is on the left side. As it has already been described by Kaneta [12,15] when the leading edge of the groove enters the contact region (Fig. 2a and f), there is a rapid pressure drop inside the groove. Due to this pressure drop, the viscosity of lubricant is not sufficient to allow a flow continuation in entrainment direction. Lubricant is trapped by the groove, with the length greater than the diameter of Hertzian contact and lubricant is drained to the sides of the groove. The side leakage causes a local reduction or a complete collapse of film thickness downstream of entrainment motion. This local reduction in film thickness moves at mean speed across the entire contact region (Fig. 2b–d and g–i). It means that when the speed of surface with the groove (ball) is faster than the speed of lubricant ($SRR<0$), this local reduction takes place behind the groove (upstream from the groove). On the contrary, when the speed of surface with the groove (ball) is slower than the speed of lubricant ($SRR>0$), the local reduction of film thickness is takes place in front of the groove (downstream from the groove). A full EHL film is formed when the groove passes through the contact area (Fig. 2e and j).

Table 1
Parameters of grooves.

Groove indication	D (nm)	W (μm)	H_B (nm)
K1	830	8	0
K2	1140	10	0
K3	1790	12	0
R1	810	50	0
R2	280	40	0
R3	620	52	0
R4	1370	63	0
R5	930	54	270
R6	630	53	0
RS1	80	31	0
RS2	240	42	0
RS3	540	49	0
RS4	940	56	0