Tribology International 114 (2017) 373–388

Contents lists available at ScienceDirect

Tribology International

journal homepage: www.elsevier.com/locate/triboint

Grease film variation in reciprocating sliding motion

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ARTICLE INFO

Keywords:
Grease lubrication
Reciprocating motion
Grease starvation
Sliding

ABSTRACT

In this study, optical interferometry experiments were carried out to investigate the grease film distribution over long working periods in sliding reciprocating motion. In the experiments, the ball was stationary while the glass disk was sliding in a triangular wave or a rectangular wave. Due to the existence of the thickener fiber, in the first several working periods, the variations of the film shape in the first and second stokes are different. With the increase of the period, the starvation effect gradually emerges, together with the occurrence of the grease replenishment. Thus the variations of the grease film in both strokes are similar. For the same sliding speed $v_{\max}$, the replenishment is more drastic for a rectangular wave and the minimum film thickness is a little thicker.

1. Introduction

Reciprocating motions widely exist in engineering and is an important branch of transient elastohydrodynamic lubrication (EHL). It can be found in contacts such as gear teeth, cam and its follower, rolling element bearings etc. Due to the reversal of motion, the outlet cavitation zone in one stroke becomes the inlet starvation zone in the beginning of the next stroke, making the problem more complex. In 1972, Petrousevitch et al. [1] explored the oil shape and film thickness in reciprocation motion theoretically and experimentally. Hooke et al. [2] derived the dimensionless film thickness formula for reciprocating motion numerically. Their results were validated by Sugimura et al. [3] experimentally using an ultra-thin film optical interferometric technique. Wang et al. [4] simulated the line contact reciprocating motion and revealed the mechanism of the oil film formation and its characteristics. Later Wang et al. [5] compared experimental and theoretical results under short stroke reciprocating motions in point contacts and obtained good agreement. They found that the influence of reverse oil starvation increased with the increase of the working frequency. Izumi et al. [6] pointed out the film thickness in reciprocating motion was thinner than that in unidirectional motion because of the oil starvation caused by the reversal of the surfaces. Li et al. [7,8] conducted an experimental investigation to explore the grease film behaviour of point contact lubrication during micro-oscillation in the case of pure rolling or pure sliding and spotted a critical entraining speed in their experiments. They found that when the entraining velocity was lower than the critical value, the thickener fiber played a vital role in the grease film formation while the film thickness was far higher than the theoretical predicted value. With the increase of the entraining velocity, the thickener fiber was pushed out of the contact so that the variation of the film thickness coincided with the theoretically predicted values. Sudeep et al. [9] studied the effect of surface texture on the traction force in reciprocating motion and found around 30% off of the traction force.

Grease lubrication has been studied by many researchers. Cann and Lubrecht [10] found that the loading-unloading process would contribute to lubricant replenishment. For better understanding of replenishment, some researchers found that lateral vibration [11], temperature [12], centrifugal force [13,14] and surface tension [15] would also promote grease reflowing back to the contact. Ali et al. [16] introduced an innovative mechanism by channeling the lubricant towards the centerline of the over rolled track to reduce or overcome the negative effects of starved lubrication in concentrated contacts. Huang et al. [17] showed that slide/roll ratio contributed to replenishing the contact by transferring more grease to the vicinity of the contact to form a larger lubricant reservoir. Recently, they [18] found that the higher oil bleeding ratio of grease, the larger re-formed lubricant reservoir would be. Cyriac et al. [19] and Misty et al. [20] studied the effect of a mixture of water in grease on the lubrication performance. Cyriac et al. [21] experimentally explored the influence of the thickener particle size and concentration on the grease EHL film thickness and found that the film thickness increases with the increase in the particle size and concentration at medium speed. Zhang [22] explored the lubrication characteristics of lithium grease mixed with glycerinum in point contacts on a ball-on-disk test rig by optical interferometric technique. She found that at very low speed, due to the existence of thickener fiber, the grease

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http://dx.doi.org/10.1016/j.triboint.2017.04.049
Received 15 January 2017; Received in revised form 7 April 2017; Accepted 27 April 2017

film thickness was thicker than that using the base oil as lubricant. However, at higher speed, the grease film thickness was at the same level as the base oil film thickness. Laurentis et al. [23] experimentally measured the friction coefficients and film thickness of a series of commercial bearing greases and their bled oils. They reported that for lithium greases, a quite thick film was formed at low speed, which was much higher than that of their corresponding base oil film. There existed a "critical entraining velocity", above which the film thickness became nearly the same as that of the base oil. Gonçalves et al. [24] revealed the similar behaviour on a ball-on-disc test rig with optical interferometry using polymer greases.

The aim of the present study is to explore the basic behaviour of the grease lubrication film over long working periods. In the experiments, the steel ball is stationary while the glass disk is sliding in reciprocating motion in the form of a triangular wave or a rectangular wave.

2. Experimental methods

Experiments were conducted using a ball-on-disk apparatus, and the technique of relative optical interference intensity was used to study the film thickness and motion of the grease lubrication under reciprocating motion. The contacting pairs were composed of a 25.4 mm diameter steel ball and a glass disk with a diameter of 150 mm and a thickness of 15 mm. One side of the glass disk was coated with a Cr-layer approximately 20 nm thick to facilitate partial reflection. All the tests were conducted under a controlled laboratory environment with a constant room temperature of 23 °C.The properties of the steel and glass were reported in Table 1.

Either the glass disk or the steel ball has its driving system. Each includes a Mitsubishi AC servo motor, a high precision speed reducer and coupling etc.. The servo motor is programmable with a nominal power output of 400 W. A red point light source with a wavelength of 630 nm was used in the experiments. Images were collected with an image capture card (OK-LV20A) and a black-white camera (OK-AM1130) produced by Beijing JoinHope Image Technology Ltd. The OK camera employs LVDS(low voltage differential signaling) digital output technique.

In this study, optical interferometry experiments were carried out when the ball is stationary while the glass disk was moving in the form of a triangular wave or a rectangular wave, as shown in Fig. 1. With T the working period, for triangular wave, A=0.25; while for rectangular wave, A=0.5, the stroke length L reads

$$L = Av_{\max}T \tag{1}$$

The lithium grease of Centoplex 3 was used as the lubricant in the tests. Centoplex 3 is multi-purpose grease based on oxidation-resistant mineral oil and lithium soap. Due to the good resistance to work under normal temperatures and loads, this grease can be used for long-term lubrication, and its properties are listed in Table 2. Before all the tests, the disk, the ball and all the relevant parts of the apparatus were thoroughly cleaned with alcohol and acetone.

3. Results and discussions

The experiments were performed under sliding condition where the glass disk was rotating and the ball was stationary. By the limitation of the charge coupled device (CCD) used in the experiments, the working period is set as 1 s. The steel ball was loaded against the underside of the glass disk with a force of F=30 N.

Table 1
Properties of ball and disk materials.

Properties	Steel (ball)	Glass (disk)
Young's modulus (GPa)	210	81
Poisson's ratio	0.3	0.208
Density (kg/m^3)	7850	2510
Thermal conductivity (W/m K)	46	1.11
Specific heat (J/kg K)	470	840

One working period of reciprocating motion consists of two strokes. Based on an isothermal assumption, the Reynolds equation is written as

$$\frac{\partial}{\partial x}\left(\frac{\rho h^3}{\eta}\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{\rho h^3}{\eta}\frac{\partial p}{\partial y}\right)=12u_e\frac{\partial(\rho h)}{\partial x}+12\frac{\partial(\rho h)}{\partial t} \tag{2}$$

In oil lubricated reciprocating motion [4,5], the variation of oil film is controlled by wedge term ($12u_e\frac{\partial(\rho h)}{\partial x}$) and squeeze term ($12\frac{\partial(\rho h)}{\partial t}$). Around the stroke end, the squeeze term is dominant so that an entrapped oil film is formed with the inlet film thickness thinner than that at the outlet. Thereafter, with the increase of the entraining velocity, the wedge effect is enhanced so that the entrapped oil film is transported by the entraining velocity to the outlet, and a wedge shaped oil film is formed. Then with the further increase of the entraining velocity, the film thickness is lifted gradually, the wedge-shaped oil film is moved out of the contact, and the maximum central film thickness occurs a little later than at the stroke center. When the entraining velocity is reduced, the film thickness decreases with the decrease of the wedge effect. The squeeze effect becomes dominant again and at last an entrapped oil film is formed at the stroke end. The variation of the film thickness in the two strokes is completely same, except their different directions. The outlet cavitation zone formed in one stroke works as the inlet starvation zone in the next stroke after the moving direction is reversed. Under lower entraining velocity, the influence of oil starvation is trivial while the influence increases with the increase in working frequency [4,5]. When the starvation effect is significant, the existence time of the starvation in the two stroke should be the same if the vibration of the test rig, the measurement errors etc. are removed.

3.1. Triangular wave

Fig. 2 gives the optical interferograms and mid-section film profiles along the entraining direction in the first period for $v_{\max}$=20 mm/s , L=5 mm. In Figs. 2(a)-(e) for the first stroke, the inlet is at the left side while in Figs. 2(g)-(l) for the second stroke, the outlet is at the right side. The same applies to Figs. 3, 4, 7, 8. At startup time instant, the steel ball is loaded against the glass disk and the grease with thickener fiber lumps in the contact, shown as in Fig. 2(a). Due to the thickener fiber, the contact grease film thickness is thick and unevenly distributed. With the increase of the entraining velocity, the glass disk leaves the first location at the stroke end, some of the thickener is pushed out of the contact during the process so that the film thickness is reduced very much, as shown in Fig. 2(b). In Fig. 2(c) there is very little thickener fiber left in the contact so that the film thickness becomes much lower. In Fig. 2(d), the entraining velocity gets its maximum and the film thickness is obviously increased. Due to the decrease of the entraining velocity, it is seen that the film thickness drops at the inlet part, as shown in Fig. 2(e). In Fig. 2(f), at the stroke end, a wedge-shaped film thickness is formed, different from the common entrapped film shape at stroke end of oil lubricated reciprocating motion [4,5]. In the beginning of the reverse stroke, like what is shown in Fig. 2(g), the outlet cavitation zone in Fig. 2(f) becomes an inlet starvation region, which does not influence the film thickness because of the low entraining speed. The very low entraining velocity results in a reduced inlet film thickness and thus a small entrapment appears in Fig. 2(g). Once the wedge-shaped oil film formed at the stroke end leaves the contact, the film thickness takes on a new wedge-shape, as shown in Fig. 2(h). The film thickness is increased in the stroke center (Fig. 2(i)) and then decreased (Fig. 2(j)). Around the end of this period, the glass disk resumes to the previous location where some of the thickened fiber remains, the thick irregular film thickness is formed in Figs. 2(k) and 2(l). Moreover, the amount of the thickener fiber in Fig. 2(l) is less than