Tribology International 91 (2015) 6–13

Contents lists available at ScienceDirect

Tribology International

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

The film forming behavior at high speeds under oil – air lubrication

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ARTICLE INFO

Article history:
Received 11 February 2015
Received in revised form
1 June 2015
Accepted 2 June 2015
Available online 19 June 2015

Keywords:
High speeds
Elastohydrodynamic lubrication
Oil – air lubrication
Starvation

ABSTRACT

The film forming behavior has been investigated under oil – air lubrication, compared with that under oil – jet lubrication in present work. Images of microscopic oil reservoir and interference were obtained up to 30 m/s. A parameter η describing the oil supply effects is 30 times higher and the film thickness reduces in starved regime much slower under oil – air lubrication compared with that under oil – jet lubrication. The contribution of micron-order oil droplets on film forming is discussed. More micron-order oil droplets can spread onto the disc while less of them are driven away by centrifugal effects. As a result, the oil supply efficiency of oil – air lubrication is improved. The high pressure compressed air can blow off the oil and intensify the film oscillation.

1. Introduction

The lubrication film thickness distribution in a point contact could be measured experimentally by optical interferometry introduced by Gohar and Cameron [1,2] in the 1960s. Following this, different interferometry-based film thickness measurement techniques were developed [3–5]. These interferometry-based techniques made it easier to measure film thickness directly with high resolution up to a few nanometers under different conditions. For fully flooded lubrication, the film thicknesses under high speed [6,7], high pressure [8–10] and high slide-roll-ratio [11,12] were measured and showed deviations compared with those predicted by Hamorock and Dowson equations [13]. Many new phenomena of lubrication films showed close relation to the speed, i.e. thin film lubrication phenomenon [4,14,15] and superlubricity phenomenon [16–19]. For starved lubrication, the characteristics and the judge of starvation degree were on the focus. The mechanism in point contact was investigated by Wedeven et al. [20] and Chiu [21] using a ball-on-disc test rig, indicating that the starvation was determined by the fluid replenishment ability into the track. Later, the inlet film was adopted to define the degree of starvation by Chevalier et al. [22] and Damiens et al. [23] in numerical models of starved elastohydrodynamic lubrication and Svoboda et al. [24] in ball-on-disc experiments. Criteria were proposed by Liu and Wen [25] to determine lubrication conditions between fully flooded, starved and parched lubrication. The influence of operational parameters conditions, including speed, viscosity, load and lubricant volume, on the onset of starvation in EHL contacts were performed experimentally [7,26] later.

However, roller bearings in high-speed spindles and aircraft engines are likely to run at much higher speeds. Numerical studies by van Zoelen et al. [27,28] and experiments by Liang et al. [7,29] suggested that centrifugal effects might drive the lubricant to flow vertically and the film thickness distribution was asymmetric under starved lubrication.

Most of above works were under immersed or half immersed lubrication, which was proper for low speed conditions, but not for high-speed rolling ball-bearings in aircraft engine, high-speed spindles and other machine tools due to the high oil loss by splashing. Therefore, the oil – air lubrication, oil – mist lubrication and oil – jet lubrication were developed for improving the oil supply efficiency.

Under the oil – air lubrication and oil–mist lubrication, the oil is broken down into micro-droplets and then makes their way precisely into the friction point continually by high pressure compressed air flow. The difference is that under oil – air lubrication, the oil droplets are not atomized. Therefore, the oil – air lubrication system has the advantages of high lubricating efficiency and environmental benefits [30,31]. Under oil – jet lubrication, the oil is jetted into the bearings. It needs to deliver much more oil into the bearings compared with the other two ways. As a result, the oil – jet lubrication obtains lower bearing temperature and higher power losses [32].

The researches on oil – air lubrication mainly focus on its thermal effects. Ramesh et al. [33] found that convection was the major component of heat transfer in this method. Materials, rotating speed, preload, oil supply rate and other factors [34–36] were optimized to reach the lowest temperature rise. Few efforts were made on the film thickness measurement under oil – air

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http://dx.doi.org/10.1016/j.triboint.2015.06.010
0301-679X/

Nomenclature

h	lubricant film thickness (m)	u_1, u_2	surface velocities of disc and ball (m/s)
t_0	operating temperature (K)	E'	reduced modulus (Pa)
η_0	ambient viscosity (Pa s)	p_H	maximum Herzian pressure (Pa)
u	lubricant entrainment speed, $u=(u_1+u_2)/2$	b	theoretical Hertz contact radius (m)
		Re	Reynolds number, $\rho ud/\eta_0$
		d	diameter of oil droplets, m

lubrication system. It was proved that thin film maintained in bearing up to 20,000 rpm using the capacity method under oil–air lubrication by Ramesh et al. [33] and under oil–jet lubrication by Gorse et al. [37]. However, the film distribution and the film forming characteristic are still invisible perhaps due to the difficulties in validating experimental measurements.

In this article, the film forming behavior was investigated under the oil–air lubrication and compared with that under the oil–jet lubrication. Film thicknesses and temperature rises near the inlet zone were recorded on a ball-on-disc test rig for speeds up to 30 m/s using relative optical interference intensity (ROII) technology and compared with theories. The roles of high pressure compressed air and micron-order oil droplets on film forming behavior were discussed under oil–air lubrication.

2. Experimental

2.1. Ball on disc test rig

A homemade high-speed ball-on-disc test rig is used in the tests. The properties and functions are introduced in Ref. [7] . The material properties of the balls and discs were measured and are quoted in Table 1. Three 1-mm-diameter thermo couples (Omega, US) are located in the oil bath, near the inlet zone and near the outlet region of the contact on the disc separately, to record the temperature variations. The thermo couples are located close to the contact at macro level (about 5 mm away from the contact), however, it is still far away from the contact at micro level. What the thermo couples can detect is the temperature rise of the disc surface. If the thermo couples get closer to the contact, the temperature rise will increase. Therefore, during all tests, the positions of the thermo couples are fixed so that temperature rise of different tests can be compared.

Interference images are taken by use of a high speed camera. Film thicknesses are determined by the relative optical interference intensity (ROII) technique [4,38] and are given by the following expression [39]:

$$h=\frac{\lambda}{4\pi k}\left[\left(n+\left|\sin\frac{n\pi}{2}\right|\right)\cdot\pi+\arccos(\bar{I})\cdot\ \cos n\pi-\arccos(\bar{I_0})\right] \quad (1)$$

where λ represents wave length of the incident light, k is reflective index of lubricant, n is interference order, I is light intensity, I_{max}, I_{min} is maximum or minimum interference light intensity, $\bar{I}$ is relative interference light intensity ($\bar{I}=(2I-I_{max}-I_{min})/(I_{max}-I_{min})$) and $\bar{I}_0$ is relative light intensity when the lubricant film thickness is zero.

Table 1
Operating conditions for measurements.

Material properties			Operating conditions	
	Ball	Disc	Load (N)	15
Material	Steel	Glass with Cr coating	E' (GPa)	117
Radius(mm)	11.1125	45	p_H (GPa)	0.43
Roughness(nm)	5	3	b (μm)	128
			t_0 (°C)	25

2.2. Lubrication systems

The oil supply system is an autonomous system (Fig. 1). In the tests, both the oil–air lubrication system and the oil–jet lubrication system are used and can be replaced.

The basic structures of used oil–air lubrication device (SKF Vogel, Germany) are shown in Fig. 2. It consists of an oil reservoir, an oil pump and mixing valves. The oil pump delivers the oil intermittently into the mixing valves, where the oil and the compressed air are mixed and distributed to oil–air supply pipes. Finally, oil–air stream is ejected by means of the nozzle and shoots onto the disc. The oil flow rate, oil supply position and air pressure can be controlled.

The oil–jet lubrication is used as comparison. It contains an oil reservoir, a peristaltic pump and pipes. The oil is delivered from the oil reservoir via a pipe by the pump and then jets onto the disc through a nozzle near the inlet zone. The splashing oil is collected and flows back to the oil reservoir to form a supply circulation.

2.3. Test conditions

In the present work, all tests are carried out at pure rolling. The operating conditions are shown in Table 1. One kind of polyalphaolefin oil (PAO8) is used in the tests. The viscosity and density of PAO8 is about 86.55 mPa s and 833 kg/m^3 at 25 °C, as measured by a viscometer (Anton Paar, Austria) and the surface tension is 29.4 mN/m as measured by a surface tension-meter (Dataphysics DCAT21, Germany). Three lubrication conditions are used as shown in Table 2 and 3. The changes of film thickness and temperature rise as a function of entrainment speed are studied at various speeds from 3 m/s to 30 m/s.

3. Results and discussions

3.1. The effects of high pressure compressed air on film forming

The oil is supplied firstly near the inlet zone under oil–air lubrication, shown in Fig. 3. (Labelled as *Lub I* in Table 2). The oil supply of 0.11 ml/s and the high pressure compressed air of 3 bar and 6 bar are utilized. Fig. 4 shows the minimum film thickness as

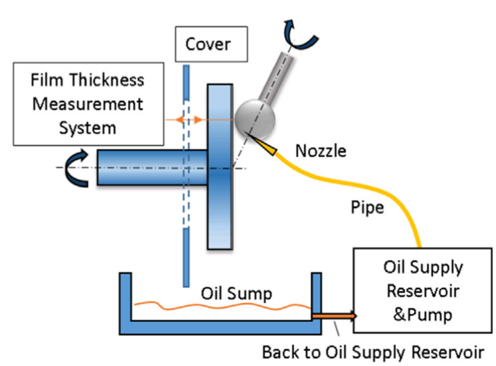

Fig. 1. Diagram of oil supply system.