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Contact ratio of rough surfaces with multiple asperities in mixed lubrication at high pressures

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ABSTRACT

Relative optical intensity interference was used to measure the lubrication film thickness when four kinds of polyalphaolefin (PAO) were used as lubricants confined between a smooth sapphire disc surface and a rough steel ball surface. Maximum Hertz contact pressure up to 3 GPa was applied in the central part of the contact region in mixed lubrication. It was found that the contact ratio (the ratio of real contact region to the whole nominal contact region) is related to the film thickness, the applied pressure, the surface roughness and the rolling speed, and so on. Contact ratio evidently reduces as lubrication film thickness or rolling speed increases. Quantitative relationship between the contact ratio and the influence factors was summarized based on the nonlinear fitting of experimental measurements. A formula was put forward to calculate the contact ratio at high pressure conditions according to the current experimental results.

1. Introduction

With the trend that more and more machine components work under heavy load, the lubricating film separating the contacting surfaces becomes progressively thinner. When the contact pressure exceeds certain value the thickness of the oil-based lubricant film sometimes gets down to several nanometers or even less [1–3]. When the film thickness is thinner than the height of surface roughness, lubrication state may turn from hydrodynamic or elastohydrodynamic lubrication to mixed lubrication. Mixed lubrication, as the name implies, is a lubrication state that the lubricating film is not able to completely separate the rubbing surface and different lubrication regimes, such that boundary lubrication, elastohydrodynamic lubrication and even direct solid to solid contact, coexist at the same time. In mixed lubrication the applied load is partly borne by asperity contact and partly by fluid film pressure. In such conditions, the pressure distribution and the lubrication film are greatly influenced by surface asperities.

In engineering practice, various mechanical components lubricated by grease or oil with counterformal contacts, such as rolling element bearings, cams and gears, usually operate in mixed lubrication, especially under high contact pressures. The thickness of lubricating film is sometimes in the same order of magnitude as the surface roughness. With thin lubrication film, direct solid to solid contact may break down the lubricating film and ultimately cause surface failure. Surface pitting, scuffing and sliding wear are the typical failures due to direct asperities contacts.

Many researchers have done remarkable work to reveal the features of the contact region between rough surfaces. It was reported by Meng et al. [4], for example, that microstructure dimples on parallel surfaces could reduce the friction coefficient when the ratio of film thickness to roughness was small. Using a home-made scanning force and friction microscope (SFFM), Muller et al. [5] studied frictional force between the tip of a scanning force microscope and a step on a graphite surface. The results indicated that two different contributions to the lateral force could be identified and their origin could be attributed to topographic and electronic effects.

With the rapid development of study in thin film lubrication down to nano scale, more researchers focused their attention on the study of mixed lubrication. On the other hand the introduction of high precision measuring systems, atomic force microscope for example, largely prompted the study of frictional force between surfaces with asperities in microscale [6,7]. Blencoe and Williams [8] studied the friction of sliding surfaces carrying boundary films. Ford [9] revealed how the roughness impacted the friction coefficient for multi-asperity contact between surfaces. Luo and Liu [10] using relative optical interference intensity (ROII) method, investigated the relation between film thickness and its influence factors. The influence of surface roughness or asperities on industry products has also been studied [11–13].

In simulation field, Tian and Bhushan [14] developed a numerical method to account for the micro-meniscus effect of an ultra-thin liquid film on the static friction of rough surface contact. Hu and Zhu [15], Zhu and Hu [16] and Wang et al. [17] published a series

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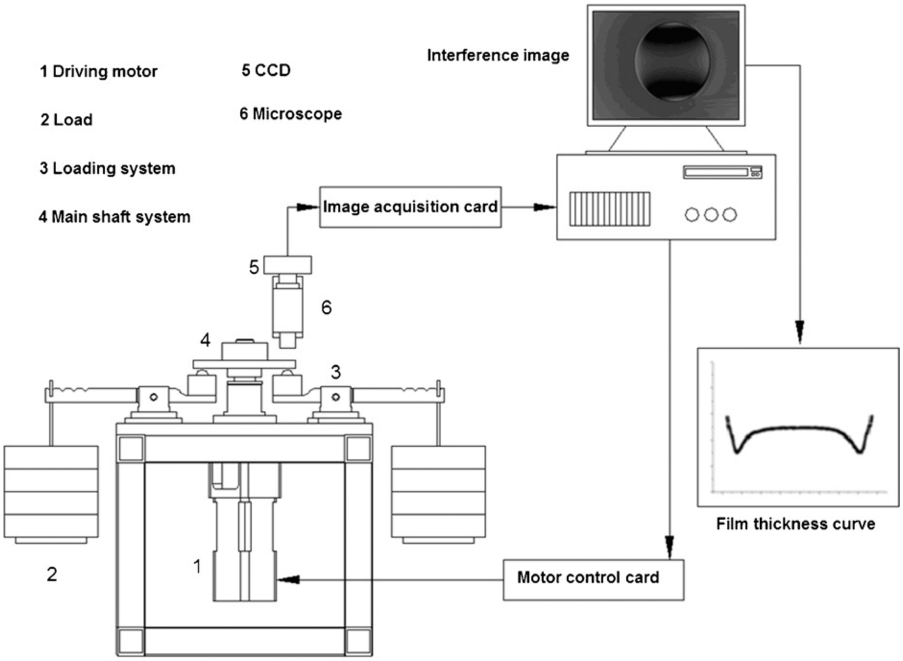

Fig. 1. Schematic representation of film measuring system.

of papers to find the numerical solution to mixed lubrication at various conditions.

Even though many studies have been done to reveal the details of mixed lubrication, some unsolved problems still concern the researchers [18,19]. Investigations into properties of mixed lubrication are hard to be carried out for two main obstacles. First, the complex nature of mixed lubrication makes it difficult for researchers to study. The fact that in mixed lubrication several lubrication states coexist makes it hard to judge the lubrication state of specific part in the contact region and to determine how the lubrication state varies with changing external conditions. Second, in mixed lubrication the film thickness usually gets down to the same level as the combined surface roughness which is about dozens of nanometers or even only several nanometers. Thus, experimental apparatus being able to measure the film thickness with rather high resolution is necessary to provide validate results. At the present time the ball-on-disc test rig in conjunction with the optical method is the main experimental apparatus to determine the film thickness with high resolution (about 1 nm). There are numerous variants [20–22] of this approach developed by research groups all over the world. Further, most of the previous study focused on the low and medium pressure conditions (less than 1 GPa) but in real applications very high contact pressures (up to 2–3 GPa) was found in roller or ball bearings, gears and cams, and so on [23]. Therefore, it is necessary to study the performance of lubricating film and the contact ratio of rough surfaces in mixed lubrication under high contact pressures.

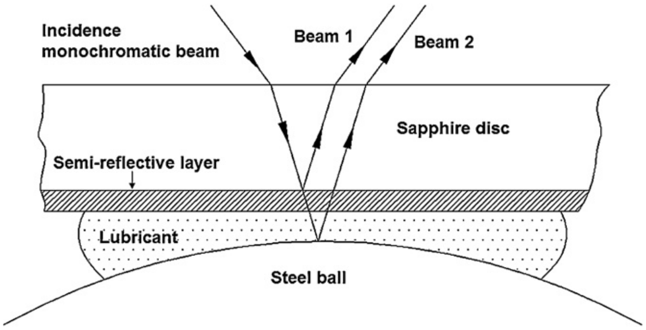

Fig. 2. Principle sketch of optical interference intensity.

In the current study, the film thicknesses of several lubricants were measured employing relative optical interference intensity method at high contact pressure conditions (up to 1–3 GPa). Then the contact ratio in mixed lubrication was estimated and relationship between the contact ratio and its influence factors was investigated.

2. Experimental conditions

2.1. Test instrument

The film thicknesses of lubricants were real timely measured employing the technique of relative optical interference intensity. In order to obtain clear images and accurate data, a test rig with high resolution was used in the current experiments. The schematic representation of the film measuring system is shown in Fig. 1. When the load is applied, a contact is formed between the surface of the sapphire disc coated with a semireflective layer of chromium and the surface of a GCr15 steel ball with diameter of 12.7 mm. When the monochromatic light whose wavelength is about 600 nm is shone into the contact region, part of the light is reflected from the chromium layer while some passes through the lubricant film and is reflected from the steel ball. And then the two beams reflected separately recombine and interfere. The monochromic interference fringe is then captured by a CCD which translates the optical signal into the electrical signal after the beams pass through a microscope. The electrical signal is processed by the image acquisition card and the image of the contact is then presented in the screen of computer. Finally, information of film thickness is obtained through process of these images.

2.2. Principle of relative optical interference intensity

The principle of relative optical interference intensity method is shown in Fig. 2 and briefly described below. The vertical resolution of this measurement method is 0.5 nm and the horizontal