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Film thickness in a ball-on-disc contact lubricated with greases, bleed oils and base oils

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ABSTRACT

Three different lubricating greases and their bleed and base oils were compared in terms of film thickness in a ball-on-disc test rig through optical interferometry. The theoretical values calculated according to Hamrock's equation are in close agreement with the base oil film thickness measurements, which validates the selected experimental methodology.

The grease and bleed oil film thickness under fully flooded lubrication conditions presented quite similar behaviour and levels. Therefore, the grease film thickness under full film conditions might be predicted using their bleed oil properties, namely the viscosity and pressure-viscosity coefficient. The base and bleed oil lubricant parameter *LP* are proportional to the measured film thickness.

A relationship between grease and the corresponding bleed oil film thickness was evidenced.

1. Introduction

Grease is by far the most common type of lubricant in rolling bearings. However, the lubrication mechanisms needed to predict grease behaviour in many different applications are not yet fully understood. A very interesting overview on grease lubrication in rolling bearings was published by Lugt in 2009 [1].

Several experimental investigations have been carried out to study grease film formation in concentrated contacts, such as those found in rolling bearings. Booser and Wilcock [2] postulated that rolling bearings are lubricated by the base oil released by the grease during operation. Wikström and Höglund [3] performed full rolling bearing tests using both grease and base oil, which showed similar bearing friction torque, and claimed that these tests confirm the theory of Booser and Wilcock. In a recent study, Cousseau [4] performed full rolling bearings tests, lubricated with different greases and their corresponding base oils, and measured the rolling bearing friction torque for wide ranges of the operating conditions, showing that grease and base oil generate significantly different friction torque values. These results contradict the findings presented by Wikström and Höglund [3], but they are in close agreement with the latest SKF rolling bearing friction torque model [5], which was validated by an extensive experimental program.

Other experimental studies with lubricating greases may be found in [6–10]. All these research works suggest the same grease film formation mechanism: initially grease builds-up a higher film thickness than its base oil, but it decreases with time and reaches a starved condition. Until now, no general theory or numerical model has been proposed to predict this film thickness generation mechanism.

In order to understand the differences between grease and base oil lubrication, Cann et al. [10,11] performed film thickness and rheological measurements, SEM photographs and FTIR spectroscopy analysis for several greases, under fully flooded conditions. The main conclusions from this study, nowadays accepted by many researchers, were:

- Thickener layers are present on the contact surface after test;
- Greases with the same formulation give higher film thickness for higher base oil viscosities;
- Greases with the same formulation give higher film thickness for higher thickener concentration;
- The film thickness difference between grease and its base oil depends on base oil viscosity, thickener type and concentration;
- The thickener of high shear stability greases is more able to survive inside the contact, making a significant contribution to EHD film thickness.

Based on these results, Cann [10,11] proposed a model for grease film formation, assuming that the surfaces are covered by a

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thin film of thickener, generating a film composed of base oil thickened with thickener material.

Another grease lubrication model is often used, the sponge model. This mechanism assumes that the grease 'bleeds' oil, which replenishes the film in the raceway and lubricates the contact zone [12,2]. The model considers that base and bleed oils have the same characteristics.

The most recent studies indicate that the grease lubrication mechanism is dominated by oil thickened with broken/sheared thickener. Most likely it is similar to the product obtained through the static bleed oil test IP 121 (see Section 2.3), which has rheological properties significantly different from those of the base oil [13]. To the authors' knowledge, few scientific studies have been published concerning the bleed oil properties and their influence on the tribological behaviour of the EHD contact, namely [14,15].

In this work the film thickness generated by the grease and by its bleed and base oils were measured and compared, in order to understand the role of the bleed oil in grease lubrication. The film thickness was measured on a ball-on-disc apparatus, under fully flooded conditions, for three different greases. The film thickness measurements were used to calculate the pressure coefficient values of the base and bleed oils.

2. Method and material

2.1. Experimental apparatus

The tests were performed in a WAM (Wedeven Associates machine) ball-on-disc test apparatus, model 11A. A full description of the capabilities of this machine is presented by Björling et al. [16]. An optical device was mounted in the WAM 11A machine in order to measure the film thickness. A picture of the WAM machine is presented in Fig. 1.

The optical interferometry measurements of lubricant film thickness have already been described by several authors. Details of this technique have been reported elsewhere [17–19] and only a brief description will be given here.

The lubricated contact is formed by the reflective steel ball and the flat surface of the glass disc. The load is applied by moving the disc downwards towards the ball. The disc is mounted on a shaft driven by an electric motor. The steel ball is also controlled by an electrical motor, allowing to run the tests under rolling/sliding conditions. The glass disc is coated with a chromium semi-reflecting coating, on top of which a spacer layer of transparent silica is deposited ($CrSiO_3$).

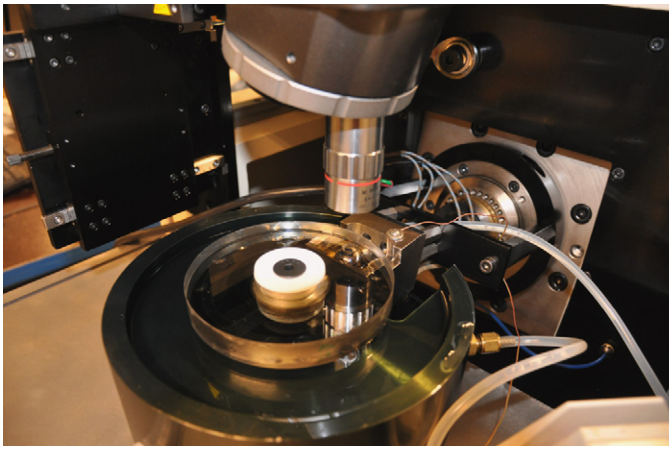

Fig. 1. View of the WAM 11A ball-on-disc test apparatus.

White light is shone through the glass disc into the contact. Part of it is reflected back by the chromium layer, while the rest passes through the silica layer and any oil film present, before being reflected back by the steel ball. Since the light has travelled different distances, upon recombination the two beams interfere optically at values of wavelength dependent on the path difference and thus the film thickness can be measured. The coloured interference image is detected by a CCD camera attached to a frame grabber, so that images could be taken from the contact region.

The method to translate the optical phase difference map into film thickness is described by several authors, see for example [19–21]. The method used here is the Lab-method described by Hartl et al. [21]. This technique is applicable also when spacer layers are used. The spacer layer imaging method allows the mapping of the film thickness with a resolution of 1 nm in the range 1 nm to 800 nm. The technique is useful for grease film thickness measurements, since the starved conditions are quickly reached and the film thickness values are in general lower than 80 nm under these conditions. With white light and without spacer layer discs it is very difficult to measure film thickness lower than 80 nm.

2.2. Test specimens

The standard ball specimen has a diameter of 13/16 in. (20.637 mm) and it is made from AISI 52100 bearing steel. The roughness of the balls was measured with a Wyko NT1100 optical profiling system from Veeco. Measurements were done using 10 × magnification and 0.5 × field of view (FOV).

The discs were made from glass which supports a maximum Hertz pressure of approximately 0.6 GPa. The silica spacer layer has a refractive index of 1.4785 according to the manufacturer.

The ball and disc properties are presented in Table 1.

2.3. Lubricants

Three lubricating greases with different formulations and their base and bleed oils were tested. The greases were named according to their chemical formulation (i.e., thickener + base oil): LiM1 thickened with lithium and mineral base oil; LiCaE thickened with lithium and calcium and ester base oil; PPAO thickened with polypropylene, co-thickened with an elastomer and polyalphaolefin base oil. The main properties of the lubricating greases are shown in Table 2.

Ester based grease LiCaE passed the test for biodegradability (OECD 301F and SS155470 class B) and eco-toxicity (OECD 202); see Table 2.

The refractive index of the lubricants were measured using an Abbot refractometer at ambient temperature and the other lubricant characteristics were provided by the grease manufacturers.

The bleed oils of the greases were obtained according to the modified IP 121 standard test method. The IP 121 is a standard static bleed oil test, consisting of a stainless steel separation cup with a 240 mesh woven wire cloth made as a cone. Oil separation is determined by placing the grease sample on the wire mesh cone

Table 1
Ball and disc data.

	Ball	Disc
Elastic modulus—E (Gpa)	210	64
Poison coefficient—ν(/)	0.29	0.2
Radius—R (mm)	10.3185	50
Surface roughness—Ra (nm)	50	≈ 5
Space layer thickness—(nm)	–	≈ 160
Space layer refractive index—(/)	–	≈ 1.4785