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Antiwear tribofilm growth in rolling bearings under boundary lubrication conditions

Andreas Stratmann[a,*], Georg Jacobs[a], Chia-Jui Hsu[b], Carsten Gachot[c], Gero Burghardt[a]

[a] Institute for Machine Elements and Machine Design, RWTH Aachen, Germany
[b] Chair of Functional Materials, Department of Material Science and Engineering, Saarland University, Germany
[c] Institute for Engineering Design and Logistics Engineering, TU Vienna, Austria

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ABSTRACT

Zinc dialkyldithiophosphates (ZDDP) are applied as a lubricant additive for wear protection in rolling bearing applications. Chemical interactions between the additive and the bearing material lead to the formation of a tribofilm on the bearing surfaces in contact. In the present study, tribofilm growth is evaluated with cylindrical roller thrust bearings operated in the boundary lubrication regime. The influence of lubrication conditions and the slide roll ratio on tribofilm formation is studied in a bearing test rig. It is found that higher slide roll ratios hinder the tribofilm from growing at the beginning of a test and accelerate tribofilm growth after an initial film is formed.

1. Introduction

Failures of rolling bearings, operated in the mixed or boundary lubrication regime, can occur due to abrasive and adhesive wear [1,2]. Typically, these operating conditions are avoided, but cannot be prevented in some applications with high loads and low speeds (e.g. wind turbines). Therefore, lubricants with suitable Antiwear (AW) and Extreme Pressure (EP) additives are used in these applications and reduce wear due to modifications at the surface of the rolling bearings [1,3,4]. Chemical and physical interactions between the lubricant and the bearing surface, enhanced by high stresses, lead to modifications of the surface near material and the deposition of additive components on the surface of the rolling bearing. The surface near area is called tribological boundary layer and described in an early stage by Schmaltz [5]. Several studies analysed the formed layer in rolling bearings [6–11]. The part of the layer with deposited additive elements is referred to as tribofilm [12].

In this study, the growth of tribofilms is investigated for the commonly used anti-wear additive zinc dialkyldithiophosphate (ZDDP). The influences of additive structure and contact conditions on tribofilm growth are determined in a rolling bearing test rig with cylindrical roller thrust bearings. The rolling contact of this bearing type is a line contact with changing sliding ratios over contact width. Consequently, the influence of different slide to roll ratios can be considered in the evaluation of one tests. The understanding of the contributing factors for the formation of tribofilms can promote the development of antiwear predictions for rolling bearings.

1.1. Tribological boundary layer

Boundary layers in rolling bearings are a system of individual layers divided into the inner and the outer boundary layer [6]. The inner boundary layer characterises a fine crystalline area which results from the surface finishing process at the end of machining or from the high stresses under severe operating conditions [11]. This part is also known as tribomutation layer [1] and has a thickness of 0.4–5 µm depending on the acting mechanical stresses. Due to the fine crystalline characteristics, the mechanical properties can differ from those of the base material [8,9].

The outer boundary layer or tribofilm is generally thinner than the inner boundary layer. After machining, an oxide layer of a few nanometres develops on top of the metal surface by oxidation processes at air environment [1]. Chemical reactions between the lubricant additives and the base material result in an additional layer, the so-called reaction layer. This layer is often described as a glass-like structure consisting of different reaction products of the chemical reactions between lubricant and material elements [13,14].

On top of these layers, lubricant components can adsorb. As they are mostly weakly bonded, these components are presumably removed during sample preparation for micro analytical analyses and thereby not detectable. But they are described to play a role in the separation of the contacting bodies in the mixed or boundary lubrication regime

* Corresponding author.
E-mail address: stratmann@ime.rwth-aachen.de (A. Stratmann).

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[15,16]. A strict separation of the layers is not always possible as the layers can mix during the friction process [17]. The layer reduces abrasive and adhesive wear effectively and therefore, it is also called antiwear tribofilm [12,18,19].

1.2. Tribofilm formation with zinc dialkyldithiophosphate (ZDDP)

One additive with AW- and EP-characteristics which is often applied, is zinc dialkyldithiophosphate (ZDDP). It has been used for several decades and also shows properties of an antioxidant and corrosion inhibitor [4]. ZDDP is a metal organic compound and has a good solubility in mineral oils [20]. The alkyl group of ZDDP can vary in length and structure, influencing the thermal and hydrolytic stability and thus the AW/EP performance [1]. The structure of the alkyl groups can be either primary, secondary or aromatic [21]. The thermal and hydrolytic stability rises with increasing chain length while the reactivity is reduced [1].

Various mechanisms have been proposed for the formation of the ZDDP induced tribofilms. They are based on thermal [22], oxidative [23] or catalytic [24] processes. The growth can be induced thermally or tribologically. At temperatures above 100–150 °C, ZDDP forms a layer on metal surfaces even without rubbing [25–27]. These “thermal films” have a similar composition as the tribologically induced “tribofilms”, but their antiwear properties are less pronounced [28]. Under tribological stresses, the layer generates faster and at lower temperatures [27,29]. The composition and structure of ZDDP induced tribofilms is analysed in a large number of studies. To summarise these studies, the main components deposited on the surface are sulfides, (poly-)phosphates and in some cases oxides [7,26,30–33].

The growth of tribofilms in EHL contacts was investigated in several studies [27,29,34,35]. As a continuous process, two different stages for the formation were derived from tests [34]. In the beginning, the tribofilm grows progressively, but slowly on the whole contact area. In the next step, the tribofilm grows fast in single patterns which continuously spread and finally cover the whole surface. AFM experiments with single asperity contact were conducted to analyse the influence of contact pressure and temperature on tribofilm formation process [34]. The two stage process was confirmed in that study for high contact pressures. Higher temperatures can promote the tribofilm growth as well as higher pressures [29,36]. Increasing the additive concentration leads to higher formation rates [29]. A maximum formation rate was found in another study for an intermediate concentration [37]. Beyond that concentration, the growth rate decreases. The lubrication conditions also influence the formation process. A pronounced solid body contact accelerates the growth and leads to thicker tribofilms [27].

2. Materials and methods

2.1. Rolling bearing type and test rig

In this study, the tests were performed with cylindrical roller thrust bearings of type 81212. The dimensions are given in Table 1. The material of the washers and rollers is AISI 52100 with an average roughness of R_a=0.04–0.06 µm and a hardness of 59–64 HRC. The cage of PA66 with 15 rollers instead of the usually used brass cage was

Table 1
Dimensions of cylindrical roller thrust bearing 81212.

Washer			Roller	
Inner diameter	Outer diameter	Middle wear track diameter	Diameter	Width
60 mm	95 mm	78 mm	11 mm	11 mm

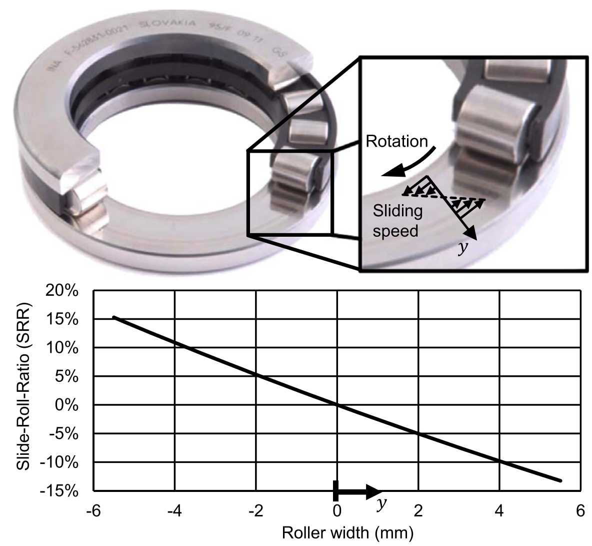

Fig. 1. Cylindrical roller thrust bearing of type 81212 and SRR values over width for the roller (inner diameter of washer: SRR > 0).

chosen to avoid chemical interactions with the lubricant or the steel components. This type of bearing is often used for testing an oil's wear protection capability due to the high Slide-Roll-Ratio (SRR). The SRR for the roller is defined as:

$$SRR = \frac{U_{slide}}{U_{roll}} = 2\frac{U_R - U_W}{U_R + U_W} = \frac{-2y}{(D_m + y)} \tag{1}$$

U_R and U_W are the roller and washer speeds in contact, y is the distance from the middle of the wear track. The SRR is only depending on the geometry of the bearing and not on the rotational speed. The dependency between roller width and SRR is shown in Fig. 1.

The SRR changes continuously over the roller width. This has a direct impact on the frictional energy input into the surface and, as long as energy is needed [20], on the tribofilm formation. The frictional energy can be calculated according to [38].

$$E_{friction}(x, y) = \int_0^{t_{contact}} \mu_c p_c(x, y, t)|U_{slide}(y)|dt \tag{2}$$

Assuming an ideal pressure distribution of a solid body contact thus neglecting the roughness and the influence of lubricant film formation, the frictional energy is independent from the rotational speed. The contact time and the roller's and washer's speeds are reciprocal. The energy per contact is given in Fig. 2. The frictional energy rises to the sides of the roller and is also positive for negative SRRs. The maximum energy input arises at an SRR of about ± 8%.

A rolling bearing test rig, based on the test rig concept of DIN 51819, was used for the tests with two rolling bearings operating at the same conditions. The axial load, temperature and rotational speed can be set independently and different conditions can be tested automati-

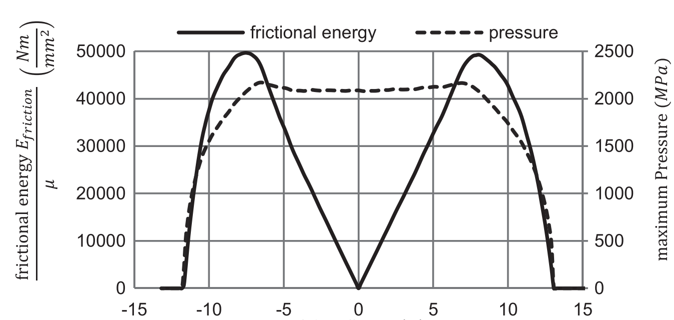

Fig. 2. Frictional energy input per friction coefficient into the roller's surface for a load of 80 kN.

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