Wear 320 (2014) 51–61

Contents lists available at ScienceDirect

Wear

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

Correlation between solid–solid contact ratios and lubrication regimes measured by a refined electrical resistivity circuit

Andreas Rosenkranz [a,*], Björn Martin [b], Simon Bettscheider [a], Carsten Gachot [a], Herbert Kliem [b], Frank Mücklich [a]

[a] Institute of Functional Materials, Saarland University, Department of Materials Science and Engineering, Campus, 66123 Saarbruecken, Germany
[b] Institute of Electrical Engineering Physics, Saarland University, Department of Physics and Mechatronics Engineering, Campus, 66123 Saarbruecken, Germany

A R T I C L E I N F O

Article history:
Received 2 June 2014
Received in revised form
28 August 2014
Accepted 31 August 2014
Available online 8 September 2014

Keywords:
Lubrication
Lubrication regimes
Electrical resistivity circuit
Solid–solid contact ratio
Wear

A B S T R A C T

The tribological performance of machine elements is mainly influenced by the contact conditions, the material pairing and the dominating lubrication regime.

The aim of this study is to introduce a precise solid–solid contact ratio which is based on a refined electrical resistivity circuit referring to Furey's concept from the early 1960s. This ratio can be directly derived from voltage–time-curves recorded by said electrical circuit. Due to the integral analysis of the input and output signal, all data points and not only the extreme values of voltage or resistance are considered, thus circumventing the definition of specific threshold values. The combination of this parameter with the high temporal (acquisition rate 1 MHz, time resolution ~1 μs) and spatial resolution (better than 0.5 nm) of the refined test rig allows for the in-situ monitoring of real contact conditions.

First, calibration tests of the test rig under dry and static conditions for closed and open contacts at low sliding velocities were done in order to ensure correct data acquisition. Thereafter, ball-on-disk sliding experiments under lubricated conditions, using a poly-(alpha)-olefin PAO 40 oil, combined with electrical measurements were performed for a mirror-polished substrate (AISI 304) and two bearing steel balls (AISI 52100) both having significantly different surface roughnesses ($R_{q,ball1} \sim 0.21$ μm vs. $R_{q,ball2} \sim 0.02$ μm). The PAO 40 oil was characterised with regard to electrical conductivity and permittivity. During the lubricated sliding tests, the sliding velocity was varied between 3.9 and 58.9 mm/s to achieve boundary, mixed and hydrodynamic lubrication. The resulting Stribeck curve and the subsequent analysis of the wear coefficient correlate well with the electric output signals and the solid–solid contact ratio. The combination of substrate and ball 1 (rougher) with higher combined surface roughness demonstrates the transition from boundary to mixed lubrication and from mixed to hydrodynamic lubrication at higher sliding velocities.

1. Introduction

Friction and related phenomena such as wear and lubrication play an important role in daily applications (for example passenger cars) [1–3]. To reduce friction and wear, several methods and techniques exist which can be applied to specific loaded components. The use of coatings with low shear strength or a defined change of surface roughness by surface texturing can lead to significant improvements in the tribological behaviour [4–7]. However, the separation of the contacting surfaces by an oil film seems to be the easiest and most effective way to reduce friction and wear. The effectiveness is mainly determined by the ratio of the oil film thickness to the combined surface roughness which is given by the λ parameter. This parameter can be used to distinguish between the typical lubrication regimes according to the Stribeck-curve [14]. In order to determine λ, the surface roughness of both contacting partners must be precisely measured. This can be done, for example, by white light interferometry (WLI) or atomic force microscopy (AFM).

Moreover, interferometric techniques are powerful tools for the precise determination of film thicknesses as well as the whole contact area being interesting for the analysis of mixed lubrication contacts [8–10]. However the main drawback of these techniques is based on the fact that at least one of the contacting surfaces must be transparent [10].

Besides the optical interferometry, electrical methods such as voltage discharge, resistive and capacitive techniques can be used for the investigation of film formation, the measurement of the

---

[*] Corresponding author. Tel.: +49 681 302 70546; fax: +49 681 302 70502.
E-mail address: a.rosenkranz@mx.uni-saarland.de (A. Rosenkranz).

http://dx.doi.org/10.1016/j.wear.2014.08.018
0043-1648/© 2014 Elsevier B.V. All rights reserved.

film thickness as well as the amount of asperity contact [8,9,11–18]. The main difficulties of the electrical methods are related to the dependency of the capacitance and resistance on the geometry of the contacting partners as well as the calibration [10]. Despite the abovementioned difficulties, the electrical methods are simple to apply even for real machine components [10]. In particular, electrical resistivity measurements provide valuable information regarding the metallic asperity contact, the governing lubrication regime and the monitoring of the sudden change between those regimes [8,9,11–14].

In the last 50 years, several studies have been performed in order to evaluate the amount of metallic contact under lubricated conditions depending on the sliding velocity, normal load, oil viscosity and other parameters. One of the first studies was performed by Lane and co-workers. They studied the mechanism of oil film formation between spur gear teeth by measuring the electrical resistance [15]. The measured changes in the resistance reflect differences in the resulting oil film thickness and can be therefore correlated with the governing lubrication regime. The calculation of the oil film thickness based upon the electrical resistance was not possible but quantitative statements with regard to lubrication regimes could be made [15]. Furey et al. developed a device for the study and the quantification of the metallic contact between sliding and lubricated surfaces. By means of this device, they were able to distinguish between hydrodynamic, mixed and boundary lubrication. Furthermore, it was possible to measure simultaneously the temporal evolution of the metallic contact and the friction force. A good correlation between the measured friction force and metallic contact could be achieved. The metallic contact and friction force were related to the time, load, speed, oil viscosity and surface roughness of both contacting surfaces. Concerning the oil viscosity, it could be concluded that oils with larger viscosity also have a larger load carrying capacity. Moreover, the surface roughness is an important measure concerning the transition from boundary to hydrodynamic lubrication. It could be stated that smoother surfaces lead to lower friction with less metallic contact. With regard to the wear volume, no direct correlation to the amount of metallic contact was given [16–18]. A further refinement of the mentioned Furey test rig was done by Tallian et al., who counted the number of low-resistance contacts under elastohydrodynamic conditions by a four-ball tester thus estimating the averaged lubricant thickness depending on speed and load [12]. Furthermore, Palacios also studied the temporal evolution of the number of contacts during the running-in process in a four-ball tester using the electrical resistivity method [14]. Nakatsuji and Mori investigated the tribological behaviour of micro-dents on steel surfaces in rolling-sliding contact conditions in order to study the underlying lubrication mechanism and pitting durability of these surface textures. An electrical circuit was built to study the oil film formation during the tribological experiments. They concluded that the micro-dents result in an enhanced run-in behaviour and that the surface textures effectively prevent metal–metal contact [19]. Kovalchenko et al. studied the possibility of modifying the tribological behaviour for point and line contacts and to precisely influence the lubrication regime by fabricating a well-defined surface texture. Experimental results of laser-textured surfaces demonstrate a shift, in the transition from mixed to hydrodynamic lubrication in the Stribeck curve, to higher loads and lower relative velocities. These results correlated well with the electrical contact resistance measurements [20–22].

The goal of the present research work is to build an advanced electrical resistivity circuit related to Furey's concept from the early 60's and the introduction of a solid–solid contact ratio which can be directly derived from the voltage–time-curves. The refinement of Furey's set-up is based upon a much higher data acquisition rate (1 MHz) leading to a spatial resolution of at least 0.5 nm (at highest sliding velocity) which is one order of magnitude below the roughness of used materials. This temporal and spatial resolution are finally necessary prerequisites for the monitoring of the actual contact conditions and therefore for a precise determination of the amount of solid–solid contact. A further advantage of the proposed method compared to Furey's approach is the integral analysis of the measured input and output signal. Usually specific threshold values for resistivity or voltage must be defined for the respective lubrication regimes which could lead to misunderstandings. According to Cameron et al. it is well known that hydrodynamic conditions can even be found for very low values of the electrical resistance [13]. The unambiguous assignment of the electrical resistance to a specific lubrication regime is therefore difficult. Our approach gets rid of the abovementioned specific threshold values for resistance or voltage by a standardisation of the integral output to the integral input signal. Furthermore, it is well accepted that the coefficient of friction does not necessarily provide a reliable value to distinguish between the different lubrication regimes [11]. In this research work, the main benefit is the coupling of the amount of solid–solid contact with the coefficient of friction thus resulting in a more precise determination of the lubrication regimes.

Prior to the tribological testing, the electrical conductivity of poly-(alpha)-olefin oil (PAO 40) was determined to $2.3 \times 10^{-13}\,(\Omega\,\mathrm{m})^{-1}$ showing good insulating properties which are important to avoid electrical breakdown. Thereafter, tribological and electrical measurements were performed for two different roughnesses of the ball counterbody (one order of magnitude) in a ball-on-disk set-up in order to study transitions in the lubrication state. Finally, the wear coefficient was calculated based on wear tracks measured by white light interferometry (WLI). The results of the electrical measurements correlate well with the results of the coefficient of friction (COF) and the wear coefficient.

2. Experimental procedure

In a first step, the electrical properties of the PAO 40 (properties see Table 1) shall be characterised. For that purpose, the oil is placed between two plane-parallel stainless steel plates at a distance d with a contact area A (Fig. 1a). Since oil is assumed to be a good insulator, a capacitance C is built between the steel

Table 1
Properties of the used PAO-oils as specified by the supplier.

Property	PAO 40
Kinematic viscosity at 100 °C/cSt	39.6
Viscosity index	147
Specific gravity	0.85

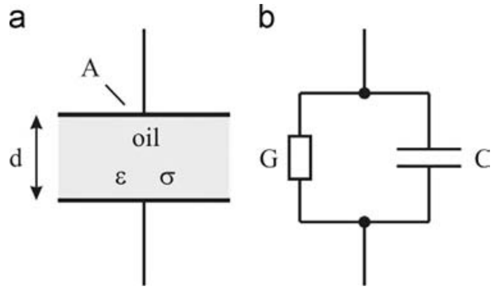

Fig. 1. (a) Oil film between two stainless steel plates. (b) Equivalent electrical circuit of the oil film between the electrodes.