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Zinc dialkyl dithiophosphate antiwear tribofilm and its effect on the topography evolution of surfaces: A numerical and experimental study

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ABSTRACT

A modelling framework has recently been developed which considers tribochemistry in deterministic contact mechanics simulations in boundary lubrication. One of the capabilities of the model is predicting the evolution of surface roughness with respect to the effect of tribochemistry. The surface roughness affects the behaviour of tribologically loaded contacts and is therefore of great importance for designers of machine elements in order to predict various surface damage modes (e.g. micropitting or scuffing) and to design more efficient tribosystems. The contact model considers plastic deformation of the surfaces and employs a modified localized version of Archard's wear equation at the asperity scale that accounts for the thickness of the tribofilm. The evolution of surface topography was calculated based on the model for a rolling/sliding contact and the predictions were validated against experimental results. The experiments were carried out using a Micropitting Rig (MPR) and the topography measurements were conducted using White Light Interferometry. Numerically, it is shown that growth of the ZDDP tribofilm on the contacting asperities affects the topography evolution of the surfaces. Scanning Electron Microscopy (SEM) and X-ray Photoelectron Spectroscopy (XPS) have been employed to confirm experimentally the presence of the tribofilm and its chemistry. The effects of the contact load and surface hardnesses on the evolution of surface topography have also been examined in the present work.

1. Introduction

Running-in is an important term used in the field of tribology. Due to the complexity and diversity of the phenomena occurring in this period various definitions of the term can be found in the literature [1]. As described by Blau [2], running-in is a combination of processes that occur prior to the steady-state when two surfaces are brought together under load and with relative motion, and this period is characterized by changes in friction, wear and physical and chemical properties of surfaces. During the running-in period, surface micro topography is subjected to various changes. In boundary and mixed lubrication conditions, the height of the asperities of rough surfaces normally decrease [3–6]. However, in the case of very smooth surfaces, an increase in the roughness value is observed [7,8]. During the process of change in the roughness of the surfaces, load carrying capacity is increased due to the gradual development of asperity-level conformity. The increase in the conformity of the surfaces is significant as peaks and valleys of the surfaces correspond to each other, and the overall performance of the system is improved [9–11].

Predicting changes in the topography of contacting bodies is important for designers to be able to predict the mechanical and chemical behaviour of surfaces in loaded tribological systems. The roughness of operating surfaces influences the efficiency of mechanical parts. In the design of machine elements and selection of materials, the film thickness parameter, known as the λ ratio, which is a representation of the severity of the contact, is important [12]. Its value is inversely proportional to the composite roughness of the two surfaces in contact. It is also widely reported that fatigue life of bearing components is dependent on their functional surfaces' characteristics, such as roughness. Optimization of the surface roughness can help in increasing the lifetime of bearings based on their applications [13,14]. Surface roughness can enhance stress concentrations that can lead to surface-initiated rolling contact fatigue [15]. Therefore, it is important to be able to predict the surface topography changes in a tribologically-loaded system.

The changes in topography can be either due to plastic deformation of the surface asperities or due to removal, loss or damage to the material, which is known as wear. Evaluating wear in

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boundary lubrication has been the subject of many studies. There are almost 300 equations for wear/friction in the literature which are for different conditions and material pairs but none of them can fully represent the physics of the problem and offer a universal prediction [16,17]. Some examples of these models are the Suh delamination theory of wear [18], the Rabinowicz model for abrasive wear [19] and the Archard wear equation [20,21]. Wear occurs by different interfacial mechanisms and all these mechanisms can contribute to changes in the topography. It has been widely reported that third body abrasive particles play an important role in changes in the topography of surfaces. There are several parameters that govern the wear behaviour in this situation such as wear debris particle size or shape, configuration of the contact and contact severity etc. [22–24]. It was reported by Godet [25] that a comprehensive mechanical view of wear should consider the third body abrasive particles and their effect on wear and topography changes. A study of abrasive wear under three-body conditions was carried out by Rabinowicz et al [26]. They proposed a simple mathematical model for third body abrasive wear rate and showed that the wear rate in this situation is about ten times less than two-body abrasive wear. It was reported by Williams et al. [27] that lubricant is used to drag the wear debris inside the interface and the abrasive wear action then depends on the particle size, its shape and the hardness of the materials. They reported that a critical ratio of particle size and film thickness can define the mode of surface damage. Despite the importance of a three-body abrasive wear mechanism there is no comprehensive mechanistic model to describe such a complicated mechanism. In the mild wear regime in lubricated contacts the effect of third body abrasive is often assumed to be insignificant.

Most of the work in the literature is based on using the well-known Archard wear equation to evaluate wear in both dry and lubricated contacts. Olofsson [28–30] used Archard's wear equation to evaluate wear in bearing applications and observed the same behaviour between model and experiments. Flodin [31] showed that Archard's wear equation is good enough to predict wear in spur helical gears application. Andersson et al. [32] tested and reviewed different wear models and reported that Archard's wear model can predict wear of lubricated and unlubricated contacts and is able to predict the surface topography both in macro and micro-scales. They tested their generalized Archard's wear model for random rough surface contact [33]. The Archard wear equation was widely used in numerical studies in order to predict the wear and topography at different scales [34–47].

Hegadekatte et al. [39] developed a multi-time-scale model for wear prediction. They used commercial codes to determine the contact pressure and deformations and then used Archard's wear equation to calculate wear. Andersson et al. [47] have employed the Archard wear equation to predict wear in a reciprocating ball-on-disc experiment. They used a wear model and implemented Fast Fourier Transforms (FFT) based contact mechanics simulations to calculate contact pressure and deformations. However, in all these implementations of Archard's wear equation in numerical models, which resulted in reasonably good agreement with experimental results, the effect of lubrication and lubricant properties was neglected. Recently, there have been some attempts to consider the lubrication effects in boundary lubrication modelling that could affect modifications to Archard's wear equation.

Bosman and Schipper [48] proposed a numerical model for mild wear prediction in boundary lubricated systems. They assumed that the main mechanisms that protect the boundary lubricated system are the chemically-reacted layers and when these layers are worn off, the system will restore the balance and the substrate will react with the oil to re-establish the tribofilm. They also proposed a transition from mild wear to more severe wear by making a complete wear map. In another recent work by Andersson et al. [49], contact mechanics of rough surfaces was used to develop a chemo-mechanical model for boundary lubrication. They used an Arrhenius-type thermodynamic equation to develop a mathematical model for formation of the tribofilm on the contacting asperities. They have also employed the mechanical properties of the antiwear tribofilm and used Archard's wear equation to predict wear of the surfaces. The coefficient of wear was assumed to be the same for the areas where the tribofilm is formed with the areas without the tribofilm.

Recent work by Morales Espejel et al. [50] used a mixed lubrication model to predict the surface roughness evolution of contacting bodies by using a local form of Archard's wear equation, and the model results show good agreement with experimental data. They used a spatially and time-dependent coefficient of wear that accounts for lubricated and unlubricated parts of the contact. The same modelling framework was used in other works of those authors to predict wear and micropitting [51].

A range of experimental work has investigated changes in surface roughness during tribological contacts. Karpinska [7] studied the evolution of surface roughness over time for both base oil and base oil with ZDDP. She also studied the wear of surfaces at different instants during running-in. It was suggested that a ZDDP tribofilm significantly affects the topographical changes of surfaces during running-in. Blau et al. [1] stated that friction and wear in running-in are time-dependent and related to the nature of energy dissipation in the contacts; they are governed by a combination of different mechanical and chemical processes. They showed that roughness evolution of contacting surfaces might have different patterns for both surfaces, depending on several parameters.

Despite the importance and the attempts in the literature to monitor and predict the roughness evolution of surfaces, there is no reported work that addresses the effect of tribochemistry. However, a modelling framework has recently been developed by the authors [52,53] that is capable of predicting changes in surface topography under boundary lubrication conditions, taking into account the simultaneous dynamics of an anti-wear tribofilm. The present paper therefore seeks to test and exploit this model to explore the effect of a ZDDP tribofilm on the evolution of surface topography. The topography evolution of both contacting surfaces is predicted, taking into account not only the effects of plastic deformation and mild wear but also the coupled development and influence of a ZDDP antiwear tribofilm.

Experimental results from a Micropitting Rig (identical to the one used in Ref [50]) are used to validate the model in terms of general prediction of topography changes and growth of the ZDDP tribofilm on the contacting asperities. The numerical model is described briefly in Section 2, while the experimental set-up that the numerical model is adapted to is explained in Section 3. The numerical results based on the model are then reported and discussed in Section 4, where special attention is given to the different parameters in the model that affect the surface topography evolution. The importance of the growth of ZDDP tribofilm in changing the topography of surfaces in the model is shown in that section. The experimental results from the MPR and surface roughness measurements are reported in Section 5, where the thickness of the tribofilm and the evolution of surface roughness are compared with the numerical results of Section 4. Using the validated model, the effects of two important physical parameters – the hardness and the load – are studied numerically in Sections 6 and 7.

2. Numerical model

The numerical model used in this work is the one reported by the authors in Ref [52]. The model is adaptable to tribosystems with different configurations which makes it possible to investigate different problems. The model consists of three important parts: