Wear 350-351 (2016) 74–81

Contents lists available at ScienceDirect

Wear

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

The measurement of wear using AFM and wear interpretation using a contact mechanics coupled wear model

J. Furustig [a,*], I. Dobryden [b,c], A. Almqvist [a], N. Almqvist [b], R. Larsson [a]

[a] Division of Machine Elements, Luleå University of Technology, 971 81 Luleå, Sweden
[b] Division of Material Science, Luleå University of Technology, 971 81 Luleå, Sweden
[c] Division of Surface and Corrosion Science, KTH Royal Institute of Technology, SE-100 44 Stockholm, Sweden

ARTICLE INFO

Article history:
Received 31 July 2015
Received in revised form
21 December 2015
Accepted 1 January 2016
Available online 22 January 2016

Keywords:
AFM
Wear
Topography
Numerical analysis

ABSTRACT

Detailed understanding of wear processes is required to improve the wear resistance and lifetime of machine components. Atomic force microscopy (AFM) is used to measure surface height profiles with high precision, before and after a wear experiment. The distribution and depth of wear on steel surfaces is then calculated using a relocation method. A numerical investigation of wear based on Archard's equation is conducted on the same measured surfaces. A good correlation was found between the model and experiment for wear larger than a hundred nm. The wear mechanisms considered in the numerical simulation was thus found to be the cause of the majority of the wear. On the scale of tens of nm the correlation was limited, but the measured wear was still analysed in detail.

1. Introduction

Wear is quantified by comparing measured quantities of a sample, such as volumetric material loss or mass loss, before and after a wear experiment [4]. It is well established that wear has a large impact on performance and lifetime of machines [19]. The financial losses due to wear is a significant part of an industrialised nations gross national product. This requires improved wear resistance, achievable through detailed understanding of wear processes. One good approach to increase the understanding of the wear process, is by means of numerical simulations. An advantage compared with experimental investigations is access to detailed information of the physical conditions in the contact during the wear process. The exact influence of contact conditions on wear, however, is still not well established. As the conditions can be calculated, a deciding factor for improved wear models are accurate wear measurements. The construction of reliable wear models requires exact measurements of wear with high accuracy and precise localization.

There are several commonly used techniques to measure surface topography, such as stylus profilometry, atomic force microscopy (AFM) and 3D surface measurement techniques based on optical methods [26,22]. Optical 3D surface measurement techniques such as vertical scanning (white-light) interferometry (VSI) can have a lateral resolution of 0.55 μm. Furthermore, optical techniques can introduce optical artefacts. In a recent publication by Spencer et al. [28] the difference between AFM and VSI, was investigated. The difference between measurements using AFM and VSI on an engineering surface was within 7%, in terms of a roughness parameter. In many cases, errors of this magnitude can be acceptable, while in other investigations, such as this work, more accurate measurements of the surfaces are desired. Traditional stylus profilometry, a contact method to measure line profiles of surfaces, has much lower resolution than AFM. AFM is considered herein as the most suitable technique with a highest possible lateral resolution of 0.2 nm and a vertical resolution up to 0.01 nm.

Relocation of the surface topography after the wear process is an important part of the wear analysis. Cabanettes and Rosen [6] recently measured contacting surfaces in a valve train test rig before and after the wear process and relocalised the wear on the surface. Many surface roughness parameters and their changes were investigated and a clear image of the wear distribution was provided. As the physical conditions vary and no contact mechanical analysis was conducted in [6], the study cannot be directly used to formulate wear equations. Similarly, Gåhlin and Jacobson [13] introduced relocalisation of topographies before and after the wear process on the nanoscale, using AFM. No contact mechanical analysis was included in their study.

* Corresponding author. Tel.: +46 70 7104144; fax: +46 920 49 1047.
E-mail addresses: joel.furustig@ltu.se (J. Furustig), illia.dobryden@ltu.se (I. Dobryden), andreas.almqvist@ltu.se (A. Almqvist), nils.almqvist@ltu.se (N. Almqvist), roland.larsson@ltu.se (R. Larsson).

http://dx.doi.org/10.1016/j.wear.2016.01.002
0043-1648/

Relocation methods give a detailed map of the wear distribution on a surface. Tribologically induced contact pressures and local temperatures, used to determine the wear in a continuum model [2], can be estimated by means of numerical simulations. Relations between the contact conditions and the wear are then needed. One commonly used relation is Archard's wear equation. In general, applying an equation such as Archard's leads to a non-linear initial value problem:

$$\frac{dV}{dt} = f(p, T, \ldots). \tag{1}$$

The wear rate $\frac{dV}{dt}$ depends on for example the pressure p and temperature T. The model system further considers wear occurring on top of a surface; sub-surface effects, *e.g.* crack formation, require a different approach.

The contact stress and temperature inside the interface between rough surfaces in relative motion, can be modelled and computed by means of numerical simulation methods. A minimum energy approach was used by Kalker [18] to formulate a relation between deformation and pressure. Similar relations between generated heat and temperature rise have been presented by Carslaw and Jaeger [7]. Fast Fourier transform (FFT) methods have been used to efficiently solve the system of equations for the temperature [11] and stresses [20] in rough surface contacts. Multi level multi integration (MLMI) has also been applied [5]. The MLMI method takes advantage of the fact that the local temperature rise or strain on a surface is mainly depending on the nearby friction heat or contact pressure. Both methods (FFT and MLMI) are similar in terms of numerical efficiency and have both been found to agree well with analytically solved special cases and with finite element method results.

Jamari [16] applied an elasto plastic model of the aforementioned type to model contact between rough measured surfaces. Jamari also measured the surface topography of the same surfaces after a wear process. The results from numerical simulation were compared with the results from experiments. Jamari found a reasonable agreement between measured wear depths and predicted plastic deformation. The matching and stitching method which was used in [16] to determine wear depths, is only suitable for non-conformal contacts, where there is a large area of unworn surface surrounding the worn area. A disadvantage with non-conformal contact is that the physical conditions, for instance contact pressure, vary due to both the roughness and the non-conformity of the test sample. Relocation and subtraction methods such as those used in [6,13,17], constitute a tool to measure wear depth locally and this can be used for improving and validating wear models. The wear depth reported in the aforementioned work [6], was measured in the order of micrometers, while in [16] and [13] sub micrometer wear depths were found. The wear depths measured by Gåhlin et al. [13] was determined with a precision in the order of 30 nm.

In this work, a relocation and subtraction method for measuring wear on the nanoscale using AFM is applied. In order to enable the study of the change in surface topography, the wear experiment is designed to produce small wear volumes on the summits of asperities. Furthermore, a goal with the experimental design is to achieve predictable conditions in the interface between the contacting bodies. Conditions that vary mainly due to wear rather than due to variations in the relative positioning of the contacting surfaces is strived for. The experiment design reaches this goal in terms of pressure but not in terms of temperature. Wear grooves with depths from a few tens to a few hundreds of nm are measured. The contact pressure between a surface exhibiting the topography measured with the AFM and a perfectly flat and smooth counter surface is calculated by means of numerical simulations. The numerical simulation utilises FFT. The contact pressure is then used to evaluate the wear depths applying Archard's equation. An iterative procedure where the geometry is updated and a new pressure distribution is repeatedly calculated is applied. The results from the measured wear depths from experiments are compared with the wear depths predicted by numerical simulation.

2. Method

A tribological wear test is designed to achieve controlled conditions in the interface between two disks in relative motion, on the topography scale. One flat, smoother, and one rough steel surface are used in a disk on disk test rig. Before and after the experiment the surfaces are measured with AFM. By using three indentation marks, a worn area on the rough surface is relocated after the wear test. The indentation marks were deep relative to the wear depth. The measurements of the rough surface before wear is used as input to a numerical wear simulation. The simulation calculates the gradual change of the surface topography due to wear, including iterative updates of the pressure distribution.

2.1. Experimental details

The wear experiment is conducted under dry conditions in a disk on disk (face to face) clutch test machine. The test rig is further described in [9]. Two steel disks with an outer diameter of 12 cm, as shown in [9], are used as test samples. The test rig is chosen due to the conformal contact between the disks.

The steel disks were both ground with abrasive paper. In order to achieve as close to steady state pressure as possible, one of the surfaces was further polished in order to achieve a significantly smoother surface finish compared with its counterpart. Gradually finer particles were used, with a final particles radius of 15.3 μm for the rougher surface and 1 μm for the flat surface. The average roughness (S_a) after polishing of the flat surface was 6.1 nm, measured over an area of 20 μm to 20 μm. The idea is that the same asperities on the rougher of the samples will be in contact with the smoother surface throughout the test. Due to wear on these asperities, the contact pressure will slowly change. The effect of temperature is limited through low sliding speeds and short run-times in the experiment.

The relocation of the same surface area on the rough steel disk after wearing, is of primary importance in order to study the topography changes due to wear. This is done by employing a Vickers hardness test to create indentation marks on the surface. A large square area on the steel surface is marked with 4 indents by 300 g load. Then a triangular area inside the large area is similarly marked using 3 small indents applying a load of 25 g. Three different areas were marked with this pattern. The depth of indents is approximately 1.24 μm. The 4 indents in a square formation are sizeable enough to relocate the reference points by visual inspection. The smaller indents are visible by microscope and can be found as they are located in a known position relative to the 4 deeper indents. The pattern of the indentations was used for relocating the surfaces after the wear process. The hardness was also recorded for the indentations with 300 g and 25 g. The micro indentation using loads of 300 g and 25 g, gave an average Vickers hardness of 311 and 301, respectively. The hardness translates into an ideal plastic contact pressure limit of 3 GPa, a value acquired by numerically reproducing the indentation marks. The flatter smoother counter surface had a Vickers hardness of 218. The indentations were made after the grinding procedure.

The test is run at 200 N but some fluctuations occurred. The force is kept between 100 and 260 N during the whole test, with an average load of 197 N. The test is run for 30 s, with a rotational