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A predictive modeling scheme for wear in tribometers

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ABSTRACT

Study of wear in complex micro-mechanical components is often accomplished experimentally using a pin-on-disc and twin-disc tribometer. The present paper proposes an approach that involves a computationally efficient incremental implementation of Archard's wear model on the global scale for modeling sliding and slipping wear in such experiments. It will be shown that this fast simplistic numerical tool can be used to identify the wear coefficient from pin-on-disc experimental data and also predict the wear depths within a limited range of parameter variation. Furthermore, it will also be used to study the effect of introducing friction coefficient into the wear model and also to model water lubricated experiments. A similar tool is presented to model wear due to a defined slip in a twin-disc tribometer. The resulting wear depths from this tool is verified using experimental data and two different finite element based numerical tools namely, the Wear-Processor, which is a FE post-processor, and a user-defined subroutine UMESHMOTION in the commercial FE package ABAQUS. It will be shown that the latter two tools have the potential for use in predicting wear and the effective life span of any general tribosystem using the identified wear coefficient from relevant tribometry data.

1. Introduction

Of the various reliability issues concerning micro-mechanical components, wear is the least predictable partially due to the imperfect knowledge of the appropriate wear rate for the selected material pair in the tribosystem which in turn greatly hinders our ability to predict the effective life span of these components. Often, experimental techniques like pin-on-disc, twin-disc, scratch test, AFM, etc., are used to characterize the tribological properties of various materials used for fabricating micro-machines in order to reduce the dependence on expensive in situ wear measurements on prototypes of micro-machines. These experiments attempt to mimic the contact conditions of the tribosystem under study in terms of contact pressure, sliding velocity, etc. The specimens have the same microstructure as the micro-machine itself and the loading chosen in the experiments are such that they mimic the micro-machine. For example, twin-disc rolling/sliding tribometer tries to mimic the rolling/sliding contact experienced by the teeth of two mating micro-gears. Such experiments allow for a qualitative study of the suitability of a particular material combination for a given application and therefore modeling of wear in such experiments is necessary in order to predict wear in micro-machines.

Over the past, modeling of wear has been a subject of extensive research [1] in order to derive predictive governing equations. The modeling of wear found in the literature [2–5] can broadly be classified into two main categories, namely, (i) mechanistic models, which are based on material failure mechanism, e.g., ratchetting theory for wear [6,7] and (ii) phenomenological models, which often involve quantities that have to be computed using principles of contact mechanics, e.g., Archard's wear model [8].

Archard's wear model is a simple phenomenological model, which assumes a linear relationship between the volume of material removed, V, for a given sliding distance, s, an applied normal load, F_N and the hardness (normal load over projected area) of the softer material, H. A proportionality constant, the wear coefficient, k, characterizes the wear resistance of the material

$$\frac{V}{s} = k\frac{F_N}{H}. \tag{1}$$

Wherever the conventional Archard's equation did not hold, researchers have modified the model to suit their specific cases.

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One such example is the modifications of Archard's equation to include wear of highly elastic/pseudo elastic materials in Ref. [9]. Sarkar has given an extention to the Archard's wear model that relates the friction coefficient and the volume of material removed [10]:

$$\frac{V}{s} = k\frac{F_N}{H}\sqrt{1+3\mu^2}. \quad (2)$$

Even though this model was originally introduced to study wear in the presence of asperity junction growth, it will be shown in this article that this model when applied on the global scale can favorably describe the trends observed in the experiments considering the uncertainties in the measurement.

Researchers have used both the above categories of wear models in computer simulation schemes, e.g., Ko et al. applied linear elastic fracture mechanics and finite element modeling to predict fatigue wear in steel [11] which basically is based on the idea of a mechanistic wear model (the delimination theory of wear) proposed by Suh [12,13]. The ratchetting theory for wear has been used in wear simulation schemes by Franklin et al. [14–16]. Christofides et al. and Yan et al. [17–19] made qualitative prediction of the wear of coated samples in a pin-on-disc tribometer which showed good qualitative agreement with experimental results. More recently modeling of wear taking into account of tribological layers have been carried out in Ref. [20] and a computational scheme based on discrete element method making use of this model was presented in Ref. [21].

On the other hand, a modification of Archard's phenomenological wear model where the hardness of the softer material was allowed to be a function of temperature was used by Molinari et al. [22] and they also used an elastic–plastic material model for the contacting bodies. Due to the computational expense, only a simple contact problem of a block sliding/oscillating over a disc was simulated. As a faster and efficient approach, post-processing of the finite element contact results with Archard's wear model to compute the progress of wear for a given time interval/sliding distance has started to gain popularity in the recent years as illustrated by the works in Refs. [23–30]. Hoffmann et al. and Sui et al. [31,32] have implemented a re-meshing scheme for geometry update in a similar setting. Hegadekatte et al., Kim et al., and Wu et al. [33–36] have included a three-dimensional finite element model and also a re-meshing scheme for simulating wear and have also shown that their results compare favorably with experimental data. The computational costs in such a finite element based approach is mainly from to the computation of the contact stresses, which requires the solution of a nonlinear boundary value problem often using commercial finite element packages.

In case of tribo-systems with simple geometries, especially tribometers, e.g., pin-on-disc, twin-disc, etc., the estimation of the contact area can be simple. In such cases, it may not be necessary to solve the contact problem using finite elements and instead wear can be modeled on the global scale like in the global incremental wear model (GIWM) to be presented in the following. The estimation of the contact area in the GIWM is accomplished by considering both the normal elastic displacement and wear, which is normal to the contacting surface. From the applied normal load and the estimated contact area, an average contact pressure across the contacting surface is calculated. The average contact pressure (global quantity) is then used in a suitable wear model to calculate the increment of wear depth for a pre-determined sliding distance increment. The wear depth is then integrated over the sliding distance to get the traditional wear depth over sliding distance curves. A detailed explanation on GIWM was presented in Ref. [34], where the GIWM was successfully applied to fit and predict predominantly disc wear in a pin-on-disc experiment.

2. Global incremental wear model for pin wear in a pin-on-disc tribometer

The experimental results presented in this work are for unidirectional sliding tests using a micro pin-on-disc tribometer with a spherical tipped pin and a disc of the same material. Two sets of experiments were carried out over a sliding distance of 500 m at room temperature, in ambient air and in water at various normal loads and a sliding speed of 400 mm/s. The dimensions of the ground disc specimens and the polished pin specimens as well as the properties of the specimens used in the experiments are listed in Table 1.

The loading used in the experiments like the pressure, sliding velocity, etc., were based on a system analysis of a micro-turbine and a micro-planetary gear train presented in chapter 1 of Ref. [37]. The normal force and the friction force were continuously measured with the help of strain gages during the tests. The sum of the wear depth on both the pin and the disc was also continuously measured capacitively within a resolution of $\pm 1\,\mu$m. In these experiments, it was observed that the wear on the disc was below 200 nm for Si_3N_4. For the WC–Co experiments, disc wear was not measurable. At the end of the experiment, the maximum wear depth of pin and disc was measured by white-light and contact profilometry, respectively. The discrepancy between in situ measured wear from the capacitive displacement sensor, which includes thermal drift, and the wear calculated from the flat circular contact area of the worn pin did not exceed $\pm$250 nm for the WC–Co pairing at the end of the experiment. The capacitively measured wear depth was corrected by matching the wear depth at the maximum sliding distance to the values obtained for pin wear from the flat circular contact area at the end of the experiment thus assuming a linear drift for the capacitive device. The wear depth data as a function of the sliding distance is shown in Fig. 1 for Si_3N_4.

The flow for the GIWM scheme is shown in Fig. 2, where p is the contact pressure, F_N is the applied normal load, a is the contact radius due to elastic displacement and wear, h is the total displacement at the pin tip, R_P is the curvature of the pin, h^e is the elastic displacement, h^w is the current wear depth, $k_D = k/H$ is the dimensional wear coefficient, Δs is the interval of the sliding distance, s_{max} is the maximum sliding distance, i is the current wear increment number and E_C is the elastic modulus of the equivalent surface calculated using the following equation (see p. 92 in Ref. [38]):

$$\frac{1}{E_C} = \frac{1-\nu_p^2}{E_p} + \frac{1-\nu_d^2}{E_d}, \quad (3)$$

where E_p and E_d are the Young's Modulus of the pin and disc, respectively, and the Poisson's ratios of the pin and the disc is represented by ν_p and ν_d, respectively.

Table 1
Various parameters for the specimens used in the experiments

	Disc		Pin	
	Si_3N_4	WC–Co	Si_3N_4	WC–Co
Surface roughness (μm)	0.11	0.019	0.07	0.020
Density (kg/m^3)	3.21	14.1	3.2	15.0
Vickers hardness	1650	1764	1600	1503
Fracture toughness (MPa m$^{1/2}$)	7	–	6	12
Diameter (mm)	8	8	1.588	1.588