Wear 303 (2013) 178–184

Contents lists available at SciVerse ScienceDirect

Wear

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

# Modelling of a thin soft layer on a self-lubricating ceramic composite

Mahdiar Valefi *, Matthijn de Rooij, Milad Mokhtari, Dirk J. Schipper

*University of Twente, Faculty of Engineering Technology, Surface Technology and Tribology, P.O. Box 217, 7500 AE Enschede, The Netherlands*

ARTICLE INFO

*Article history:*
Received 11 September 2012
Received in revised form
12 February 2013
Accepted 26 February 2013
Available online 17 March 2013

*Keywords:*
Wear
Modelling
Third body
Self-lubricating
Ceramic

ABSTRACT

Friction and wear of a self-lubricating ceramic composite under unlubricated sliding contact conditions is dependent on the formation and regeneration of a thin soft surface layer. Experimental observations have shown that a thin soft layer (third body) may be formed depending on the tribological tests conditions. This thin soft layer is a pre-requirement for the occurrence of low friction in the mild wear regime. This paper proposes a physically based model for the process of the formation and removal of the soft layer. The model is developed on the basis of mechanical stresses in the soft second phase and the elastic–plastic contact between a rough surface and a flat surface. Based on the model, the thickness of the soft surface layer on a ceramic substrate is predicted. The results show that the thickness of the soft layer is mainly determined by the mechanical properties of soft phase as well as the applied load.



## 1. Introduction

Self-lubricating composites are promising candidates for applications that sliding interfaces undergo in harsh conditions [1], possible applications include mechanical components experiencing high temperature conditions.

The tribological performance of the ceramic composite in contact is improved by the presence of a thin soft layer in the contact. The layer must be regenerated with time to maintain the self-lubricating ability at the interface of sliding components. Self-lubricating ceramic composites are widely used in for instance sliding bearings and cutting tool materials. According to Bowden and Tabor [2], it is well-recognized that the beneficial effect of self-lubricating composites depends on the thickness of the soft layer, the relative mechanical properties of the layer and subsurface as well as the contact pressure carried by the soft layer and substrate (first body). A few models have been introduced in literature to predict friction and wear of self-lubricating composites [3–5]. Alexeyev and Jahanmir used a slip-line field analysis to determine the process of deformation and flow of a soft phase towards the sliding interface for self-lubricating metal matrix composites [4]. Their results showed that properties of both matrix and soft second phase as well as shape and size of second phase control the soft layer formation. Bushe et al. [5] developed a model for extrusion of a soft phase on the surface of self-lubricating anti-friction aluminum alloy. In their work, the effect of the mechanical and geometric characteristics of the hard and soft phases of the aluminum alloy on the amount of the soft layer formed on the surface of the alloy in operation has been presented. Song et al. [6], developed a mechanical model to predict the thickness of a soft layer on a self-lubricating ceramic composite. They found that the thickness of the soft layer can be altered by the load and mechanical properties of the ceramic matrix and the soft second phase. In addition there are a few contact models that consider a soft film (solid lubricant) on a hard substrate and focusing on friction and wear [7–9]. However, there is no model for wear of self-lubricating composites in the current literature.

It has been observed by experiments that sliding wear of ceramics generates very fine wear particles, detached grains, deformed second phase and amorphous reaction products [10–12]. During prolonged sliding, some of these particles are ejected from the wear track and some debris remain in the wear track as shown in our earlier experimental work [11,13]. These remained debris can undergo deformation, fragmentation or chemical reaction in further sliding. The circulated debris in the contact constitute a “third body” in the sliding system and alter the contact pressure and consequently friction and wear. Valefi et al. [11,14], have recently found that a copper rich third body layer is formed during sliding tests of CuO–TZP composite against alumina and zirconia at and above 600 °C. The thickness of the third body layer is estimated by XPS analysis to be about 60 nm. Further, many experimental studies in self-lubricating composite suggested the presence of the soft layer at the sliding interface [11,15–16]. This soft layer can act as third body which reduces friction and wear [17].

Godet [18] introduced the concept of “third body” and its role on the tribological behaviour of sliding components. It is well known that the coefficient of friction is dependent on the

* Corresponding author. Tel.: +31 534894325; fax: +31 53489 4784.
*E-mail addresses:* m.valefi@utwente.nl, mavalefi@gmail.com (M. Valefi).

0043-1648/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.wear.2013.02.017

properties of the third body due to velocity accommodation in the third body. Fillot et al. [19], used the third body approach to model and predict wear of two bodies in contact. In their work, an analytical analysis is proposed that considers the particle detachment process and the particle ejection process separately. However they have considered a simple qualitative model that provide formation and the removal of the third body. In order to improve the understanding of the formation and restoration of the soft layer, it is necessary to use a model which is based on the physical phenomena responsible for supply and wear of the thin soft layer [20].

The aim of this work is to develop a model for the process involved in the formation and regeneration of the thin soft layer at the surface of a ceramic composite. The outcome of the model will be discussed in the context of experiments.

## 2. Modelling

### 2.1. Mass balance of the thin soft layer

Fig. 1 represents a schematic of a rough surface in contact with a flat and smooth surface with a soft layer (third body). As described by Fillot et al. [19], the third body is fed by a "source flow" ($Q_s$), which is either supply by particles or material squeezed out from one of the contacting bodies; whereas particles ejected from the interface as "wear flow" ($Q_w$). The mass balance of the third body can be written as follows:

$$\frac{dM_i}{dt} = Q_s - Q_w \tag{1}$$

Or in thickness (time or distance dependent) as follows:

$$h_{\,third\ body} = h_{source} - h_{wear} \tag{2}$$

Based on Fig. 1 and Eq. (2), it is important for a stable thickness of the third body to have a balance between the "source flow" and the "wear flow". The mass or thickness of this layer affects wear and if the third body layer approaches a stable thickness, the wear is more likely steady state and the composite material is protected from severe wear.

### 2.2. Supply to the thin soft layer

Based on this concept, it is needed to model the $Q_s$, so the mass flow towards the thin soft layer (third body) as well as the $Q_w$, being the mass flow due to wear of the thin soft layer. First, the mass flow $Q_s$ will be addressed. Several researchers reported that a soft second phase in the self-lubricating composite can be squeezed out by contact stresses and form an interfacial layer at the interface [4,15]. For instance, Deng et al. [21] studied the self-lubricating behaviour of a $Al_2O_3$–TiC–$CaF_2$ composite under dry contact conditions. Their results indicated that the $CaF_2$ soft phase can be deformed and squeezed out to the interface of a sliding pair and results in the continuous formation of a tribofilm responsible for low friction and wear. Since contact stresses are imposed on a surface in contact, and the second phase is significantly softer than the matrix in a self-lubricating composite at elevated temperatures, it is reasonable to consider that the second phase can be transported to the interface by squeezing out. A mechanical model for self-lubricating ceramic composite has been recently developed. Using this model, the amount of second phase squeezed out during the sliding process can be calculated [6]. In this model, a 3D representative volume element (RVE) of the disc at the contact interface is used to analyze the formation of the transfer layer as indicated in Fig. 2 and expressed in [6]. In the analysis it is assumed that the ball and the flat are smooth, in the sense that stress concentrations due to contact at asperity level will not significantly affect the subsurface stress field. The material properties of composite are calculated using the rule of mixtures. In order to calculate the average stresses beneath a sliding point contact in the ceramic composite, the explicit equations by Hamilton [22] were used. Furthermore it is assumed that the ceramic matrix deforms elastically and the second phase undergoes plastic deformation. For simplicity, an isotropic elastic–ideally plastic second phase is considered in this model. The model of Hashin [23] for a spherical second phase in an infinite elastic matrix was used. For more details the reader is referred to [6]. The following equation has been used to calculate the thickness of squeezed out soft material layer ($h_{source}$) during sliding process [6]:

$$h_{source} = \alpha_{supply} \frac{1}{2b} \sum_{j=1}^{s+1} \int_0^h \int_{-b}^{b} -\psi_i \varepsilon_{sq} dydz \tag{3}$$

with

$$\varepsilon_{sq} = \begin{cases} -\varepsilon_{kk}^i(1-\theta) & \text{when} \quad \varepsilon_{kk}^i < 0 \quad \text{and} \quad \sigma_i^M = \sigma_i^y \\ 0 & \text{otherwise} \end{cases} \tag{4}$$

in which $\varepsilon_{sq}$ is the squeezed volume fraction of the fully dense second phase material, $b$ and $h$ are width and height of the RVE, $\sigma_i^M$ is the equivalent von Mises stress in the second phase, $\Psi$ is the volume concentration of the second phase and $\theta$ is the porosity of the inclusion. Therefore, flow in the inclusion will only occur in the case of hydrostatic compressive strain in the inclusion and yield of inclusion. $\alpha_{supply}$ is a constant related to the source flow. If all plastically deformed material is transported to the surface, then $\alpha_{supply}=1$. In reality, the second phase is deformed

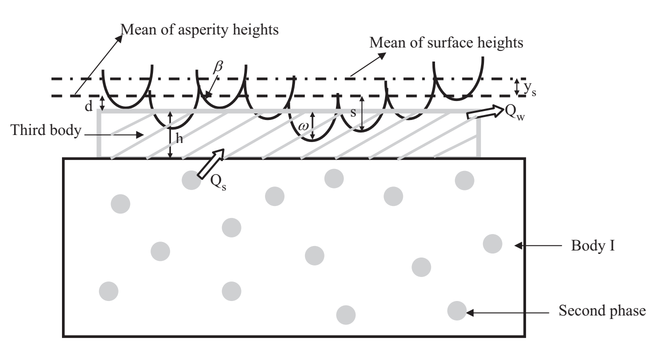


**Fig. 1.** Contact between a rough surface with a flat smooth surface covered with a thin soft layer (third body) generated from the self-lubricating composite.

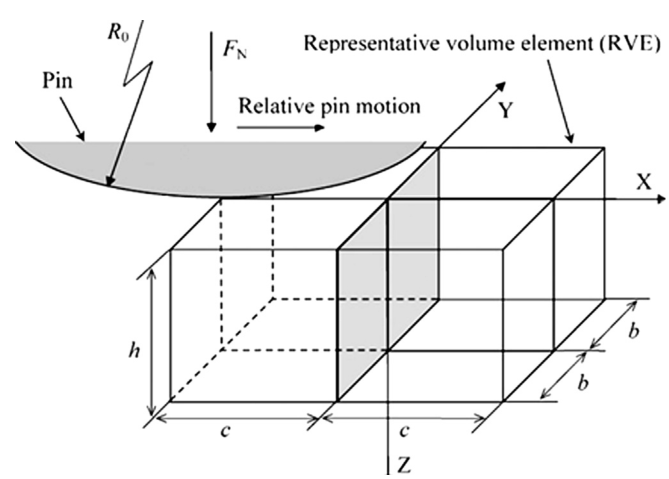


**Fig. 2.** Representative volume element (RVE) model for analyzing the formation of a soft layer, ball on flat configuration [6].