Wear 304 (2013) 173–182

Contents lists available at SciVerse ScienceDirect

Wear

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

A volumetric fractional coverage model to predict frictional behavior for *in situ* transfer film lubrication

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ARTICLE INFO

Article history:
Received 20 August 2012
Received in revised form
17 April 2013
Accepted 24 April 2013
Available online 21 May 2013

Keywords:
Powder lubrication
Volumetric fractional coverage model
Transfer film lubrication
Fractional coverage
Self-replenishing
Tribology

ABSTRACT

Solid lubricant films transferred from pellets, which are made by compacting MoS_2 powder lubricant into cylinders, can be deposited on surfaces to lubricate sliding contacts *in situ*. In order to understand the tribological behavior of solid lubricant transfer films, experiments have been conducted where a pellet is sheared against a disk surface while a downstream slider pad rides atop the disk. Similar to the slider bearing configuration, the loaded slider rides on the top of a lubricant film, but since the transferred film is essentially solid powder, the pad typically works to deplete the film unless a favorable transfer film resides on the disk. In order to describe this film transfer and depletion lubrication process, various experimentally validated height-based asperity fractional coverage modeling descriptions have been proposed in the past. In this work, a new three-dimensional (3D) volumetric fractional coverage (VFC) modeling approach is introduced in concert with more robust methods for calculating the wear coefficients at both pellet/disk and slider/disk interfaces. The goal is to increase the fidelity of the previous fractional coverage model in predicting the friction coefficients at the pellet/disk and slider/disk interfaces as functions of the fraction of lubricant covering the disk asperities. Results are shown for the predicted friction coefficient, wear trends, and time constants, and these results are validated against slider-on-disk with pellet tribometer experiments.

1. Introduction

The ongoing depletion of the limited petroleum oil supply has increased the need for alternative forms of lubrication. In addition, petroleum based lubricants provide insufficient load carrying capacity at extreme temperatures, thus, solid lubricants are often employed to protect these sliding contacts in the absence of oil [1–3]. In addition to the conventional coatings seen in commercial applications, solid lubricants in the form of powders are also being explored as transfer film lubricants. For example, lamellar powders can be compacted into cylindrical pellets, which are then sheared or “worn” against a spinning tungsten carbide (WC) disk. The pellets lubricate by forming a thin transfer film on the disk surface. A slider, which is located downstream from the pellet on the disk, is set up to deplete the lubricant film from the disk. It represents the load-bearing element in a sliding contact. The friction coefficient between the slider and the disk is measured by a load cell. Numerous studies have shown that lamellar powders in a sliding contact can reduce wear in tribological systems by providing load carrying capacity, while decreasing friction below levels found in boundary lubrication [4–6]. In this study, we assume that the thin-film lubrication is happening within the spatial domain encompassing the asperity peaks and valleys and can be expressed through the concept of fractional coverage.

It should be noted that fractional coverage has been used to describe the viability of many different lubrication configurations and has been defined as a ratio of the surface covered by lubricant to that which is not, based on either height or area coverage. In terms of experiment, fractional coverage has been used primarily as a means to track lubricant life when starvation is a problem. In one particular case, area fractional coverage was used to help identify the maximum film thickness for hydrodynamic lubrication of textured steel surfaces [7]. In terms of modeling, fractional coverage has been used to simulate the adsorption and removal of environmental gas contaminants in order to predict the evolution of friction coefficients for experiments on a super low friction diamond-like carbon coating [8]. In addition, an area fractional coverage model was developed to describe the tribological behaviors for vapor-phase lubrication of combined rolling and sliding contact surfaces [9,10]. Area fractional coverage has also been implemented to relate the friction coefficient and the surface adsorption of a two-component lubricant in boundary lubrication [11]. These works by Sawyer and collaborators typically assume the film thickness is

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http://dx.doi.org/10.1016/j.wear.2013.04.029

Nomenclature

$\dot{S}$	storage rate
$\dot{I}$	input rate
$\dot{O}$	output rate
Θ_i	percentage of total cycle time of which the volume of interest, or the patch, has lubricant input
Θ_o	percentage of total cycle time of which the patch has lubricant output
Θ_p	percentage of total cycle time of which the patch is underneath the pellet
Θ_s	percentage of total cycle time of which the patch is underneath the slider
T	time interval for one full cycle of a patch around the wear track
T_p	time interval of a patch–pellet interaction
T_s	time interval of a patch–slider interaction
D	wear track diameter
U	linear sliding velocity of the patch of interest
L_p	diameter of the pellet
L_s	length of the slider pad
$\dot{V}$	volume rate of the wear debris being generated
K	dimensional wear coefficient
F_n	normal load
F_p	normal force of the pellet
F_s	normal force of the slider
$F_{patch,p}$	equivalent normal force of the pellet
$F_{patch,s}$	equivalent normal force of the slider
A_{patch}	nominal area of the interest on the disk surface
A_p	nominal contact area of the pellet against the disk
A_s	nominal contact area of the slider against the disk
$\overline{V}$	volumetric fractional coverage of the third body film
$V(t)$	volume of the third body film at time t
V_{neg}	negative space that can be potentially filled up with the third body film
V_{max}	rectangular prism volume enclosing the asperities
V_{asp}	volume of asperities
K_p	wear coefficient of the pellet at pellet/disk interface
K_{ep}	wear coefficient of the lubricant film on the disk due to the interactions between pellet/disk
K_{es}	wear coefficient of the lubricant film on the disk due to the interactions between slider/disk
μ_p	friction coefficient at the pellet/disk interface
μ_s	friction coefficient at the slider/disk interface
μ_{lub}	lubricated friction coefficient when $\overline{V}$ is 1
μ_{unlub}	un-lubricated friction coefficient when $\overline{V}$ is 0

constant while the areal domain is fractional. Most recently, a height-based fractional coverage (HFC) model was developed by the authors [12] to predict the frictional behavior for molybdenum disulfide (MoS_2) powder transfer films based on the percentage of lubricant height covering each asperity. The new volumetric fractional coverage (VFC) model proposed in this work expands the range of capability of the HFC model in that it uses the true three-dimensional control volume that can be occupied by the lubricant, thus yielding a more precise accounting of the mass in the control volume.

In this study, molybdenum disulfide (MoS_2) powder is the solid lubricant. As described in previous works by the authors [12,13], a slider-on-disk with pellet tribometer was used to measure the tribological performance of the system. This setup was designed so that the lubrication process is passively self-replenishing, which means that when the disk was starved of lubricant, the pellet encounters an unlubricated disk which causes it to deposit lubricant *in situ* and as-needed. Thus, the self-replenishing nature of the tribosystem is passive and inherently a characteristic of the condition of the surface (Fig. 1).

The hypothesis of this study is that the frictional behavior can be more accurately predicted by assuming that the friction coefficients at the pellet/disk and slider/disk interfaces are functions of the fraction of lubricant occupying a three-dimensional (3D) control volume of the lubricated track. The experimental validation of the prior fractional coverage framework has also been refined in this work by the development of a higher fidelity method for calculating the wear coefficients at each interface. After introducing the proposed modeling theory for the VFC model, this paper will present case studies exploring the effectiveness of the VFC model by comparing its results to the previous HFC model and experiments. It will also present the new experimental method to obtain more robust wear coefficients for the slider-on-disk with pellet tribometer.

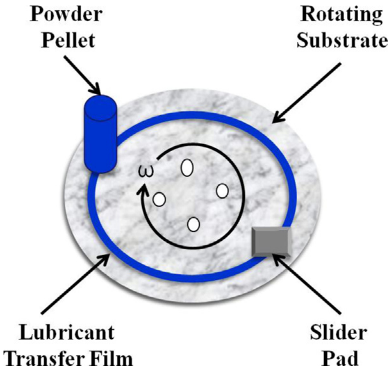

Fig. 1. Experimental setup.

1.1. Model development

Fig. 2 shows a simplified diagram of the slider-on-disk with pellet configuration, where the volume that can be filled up by the lubricant film will be treated as a finite control volume.

The control volume in this work is a sub-domain or patch of the asperities on the disk. The patch is formed to encompass all of the asperities on a prescribed region of the disk (see Section 1.2). The 50 μm × 50 μm patch of the disk topography, as measured by an atomic force microscope (AFM), is assumed to be representative of the entire disk. The pellet and the slider pad, which are in

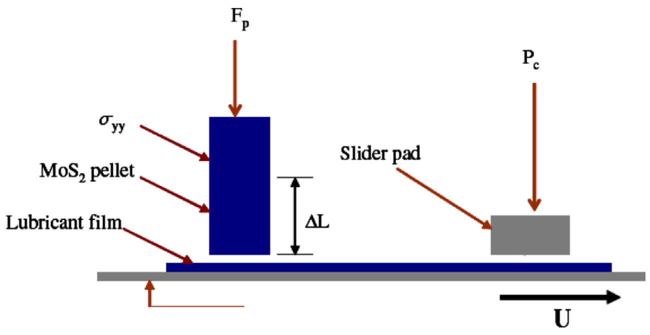

Fig. 2. Simplified diagram of the slider-on-disk with pellet setup.