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An investigation of the wear mechanism leading to self-replenishing transfer films

Patrick S.M. Dougherty, Randyka Pudjoprawoto, C. Fred Higgs III*

Particle Flow and Tribology Laboratory, Carnegie Mellon University, Pittsburgh, PA, USA

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ABSTRACT

Since the late 1980s, interest has risen in solid powder lubrication due to its proven ability to provide low friction and wear in interfaces unsuitable for traditional oils. This may be in the form of augmenting oil performance as an additive, or in the form of thin, solid transfer films since it was found that sliding materials sometimes inherently generate a film that can protect the contact interface during relative motion. In particular, *in situ* self- replenishing solid lubrication has shown the ability to maintain lubricious conditions through the continual deposition of thin powder transfer films to "dry" surface asperities from a sacrificial compact. An emerging class of self-lubricating compacts is being developed by compacting lamellar powder particles into different homogeneous and heterogeneous solid lubricant structures or "pellets." An *in situ* self-replenishing solid lubricant system may be created by placing these pellets into tribosystems in such a way that their transferred film is continuously applied to dry asperities in load-bearing interfaces. Therefore, special emphasis must be given to understanding the method of transfer film deposition and depletion, if the lubrication process is to be predicted, controlled, and optimized. The purpose of this investigation is to examine the wear mechanisms which govern transfer film deposition and depletion in an *in situ* self-replenishing system, such that a more accurate modeling approach may be undertaken in the future. Surface analysis of contact interfaces was performed using an optical interferometer, while friction and wear relationships were gleaned from experiments on a pellet-on-disk with slider pad tribometer. Through an analysis of numerous qualitative and quantitative parameters that describe surface topography, it was found that abrasive wear is the predominant wear mechanism governing the transfer film process. Consequently, an alternate wear description of the *in situ* self-replenishing transfer film lubrication process is proposed.

1. Introduction

While oil-based lubrication remains one of the most prolific areas of lubrication study, continued advancements in mechanical technologies continues to push interfacial temperatures for bearing related contacts beyond the capabilities of liquid lubrication. In fact, at temperatures above approximately 500 °C, oil based lubricants can actually dissociate and lose their ability to carry load or provide ample lubrication [1].

Lamellar powders or solid lubricants have become a promising alternative as thick film powder flows [2–4], transfer films [1,5] and also as multifunctional additives to existing oil based lubricants [6]. Despite extreme temperatures and pressures, these lamellar powders have shown environmentally friendly potential while also providing extremely low friction coefficients as low as 0.02 [7,8]. Furthermore, the emergence of thin transfer films applied through "pelletized" lamellar powders have proven beneficial for *in situ* solid lubrication [5] and special multifunctional applications such as sliding electrical contacts [10]. However, the mechanics involved in powder lubrication, while thought to express a mixture of both hydrodynamic and morphological effects, are still largely misunderstood [3,4,9,10,12].

This current work aims to elucidate the precise wear mechanisms which produce and remove the transfer film when a compacted powder pellet under load is slid against a hard tungsten carbide disk in the presence of a loaded slider pad. In the past, it was assumed that this was primarily governed by adhesive wear occurring at the pellet-on-disk and slider-on-disk interfaces. However, this paper conducts a detailed investigation of the tribosurfaces before and after wear testing, in which optical profilometry techniques are used to identify the most probable wear mechanisms. Furthermore this study also sheds light on the nature of the transfer film coverage. Since the friction coefficient is assumed to vary with the fraction of the asperity domain covered by solid lubricant [5,17], there have been questions regarding whether the transfer film coverage occurs at varying heights with uniform area, or at

* Corresponding author. Tel.: +1 41 2268 2486; fax: +1 41 2268 3348.
E-mail address: higgs@andrew.cmu.edu (C.F. Higgs III).

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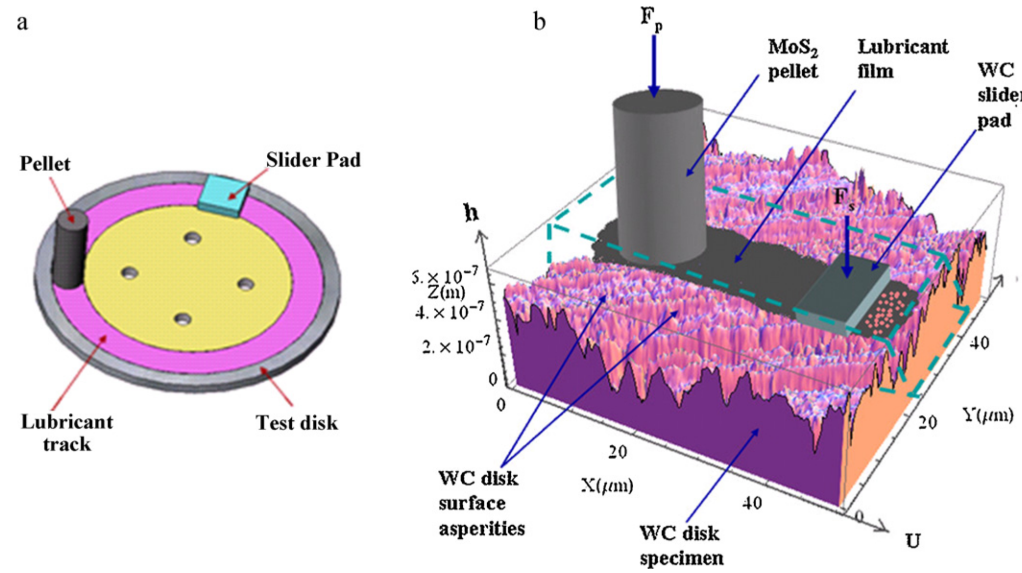

Fig. 1. Visualization of the self-replenishing tribosystem.

varying areas with uniform heights. Results from this investigation provide insight into these issues as well. The paper begins with an overview of the research problem with respect to observed lubricant deposition and depletion behaviors. It then progresses to the experiments conducted to investigate the wear mechanism leading to the pellet transfer films. Finally, the results are presented and then discussed in order to explain why abrasive wear is likely the dominant wear mode leading to the transfer films observed, and ultimately the friction coefficients measured.

2. Overview of the research problem

The annular configuration of the *in situ* self-replenishing system can be seen in Fig. 1a. During operation, a lubricious transfer film is deposited by a loaded powder pellet onto a rotating disk which carries the film into the sliding contact of a riding slider pad. Fig. 1b displays a schematic of the asperity regime, which helps to highlight the self-replenishing nature of the system by exaggerating the slider pad and pellet to be on the asperity size scale. The film itself is partially removed by the slider pad and disk asperity interaction, represented in Fig. 1b by the sparsely uncovered asperities. As the disk retraces its original path, these uncovered asperities interact with the pellet and a new transfer film is deposited. Thus it is inherently "self-replenishing" [1,5,17]. While there have been successes in modeling thick-film powder lubrication as fifth-order rheological models in a continuum framework [3,4,9,11,12], the mechanics of transfer film formation *in* situ prevents this type of approach for two reasons. First, these models neglect the mechanics of the lubricant in the asperity regime, where thin transfer films reside. Second, thick-film volume remains constant during operation whereas the volume in the interface of the thin transfer film increases and decreases as wear events are continuously occurring locally and globally within the film [1,5,17].

Despite modeling challenges, the transfer film form of solid lubrication has great potential in the field of Tribology due to the system's potential to be self-contained and activated without external controls [13–16]. In order to describe this type of tribosystem, models have been suggested which account for the transfer film mechanics through the use of competing rate equations derived from lubricant mass balances [5,10,13,17]. In the Control Volume Fractional Coverage [5] model developed by Higgs and Wornyoh, a governing equation was developed to relate coefficient of friction (COF) to the deposition and depletion rates of the powder transfer film. Contrary to the rheological models which focus on distributed shear stress throughout powder films, the CVFC expresses COF as a function of the lubricant film height present within the asperity domain with uniform area coverage [5,17]. In this type of model, a low friction coefficient is achieved by ensuring a large enough lubricant deposition rate, with respect to lubricant depletion rate, such that the lubricant coverage remains at a maximum during operation.

In fractional coverage models, the deposition and depletion rates of the transfer film are formulated based on Archard's adhesive wear law as shown below [5,17].

$$\dot{V} = \frac{K \times F \times U}{H} \qquad (1)$$

where $\dot{V}$ is the volumetric flow rate of worn material, K is an empirical wear coefficient representing the probability of wear, F is the normal force between the bodies in sliding contact, and H is the hardness of the body being worn. K values are found typically through pin-on-disk testing in conjunction with tabulated approximations for two materials in adhesive wear [5,17,18].

This has three important consequences. First, these coefficients are often situation specific to the conditions present during testing. Secondly, the use of tabulated values carries a large amount of inherent error due to approximation assumptions [5,17,18]. And finally, these K values represent the probability of a wear event occurring, meaning they are merely a fraction between 0 and 1 meant to account for the average wear over a given time. However, due to the aforementioned transfer film models' inherent reliance on competing wear rates to determine COF, this type of averaging fails to capture the highly transient nature of the self-replenishing system.

For example, Figs. 2 and 3 display the results for two different instances where erratic wear behavior *in situ* leads to a subsequent inability to predict the transfer film dynamics of the self-replenishing system. In these figures, the pellet wear, displayed as the change in pellet height over time captured through a linear differential voltage transducer (LVDT), is graphed below friction coefficient of the slider pad. One should note that pellet "wear" actually refers to the "deposition" of lubricant film on the rotating disk as shown in Fig. 1.