



Shear-induced particle size segregation in composite powder transfer films



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ABSTRACT

Transfer films have been engineered to act as solid lubricants between sliding surfaces in environments where fluids cannot exist or are not desired. Composite transfer films can be crafted to combine the low friction behavior of a powder lubricant, with another powder component that offers an alternative functionality, such as electrical conductivity or oxidation control. However, transient rises in friction often occur during sliding as shown by tribological testing of multi-component, powder lubricant transfer films both in this work and in the literature. In this work, the potential for an electrically-conductive composite film to maintain favorable tribological performance under shear is explored. The effects of the constituents' composition percentage and relative particle sizes are studied in thin, composite transfer films consisting of copper (Cu) and molybdenum disulfide (MoS_2). The transfer films are formed through a shearing process and tested on a pellet and slider pad-on-disk tribometer. An interesting dependence of friction performance on equating the constituents' particle sizes is observed, which may be explained by the phenomenon of shear-induced particle size segregation often witnessed in granular flows. The effect of particle size segregation on the coefficient of friction (μ) in composite powder films is discussed within a quasi-hydrodynamic framework. Conclusions are drawn in regards to how particle size segregation would lead to the observed frictional phenomena for both the results obtained in this study, as well as results from prior studies within the literature.

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1. Introduction

In tribology (the study of friction, lubrication, and wear), it is known that harsher operating conditions of new turbomachinery-based technologies have rendered many oil-based lubricants unfit for long term tribological performance [1]. This difficulty with oils manifests itself primarily as a tendency to dissociate at temperatures above 500 °C [1]. As a result, many solid powder lubricants such as graphite and molybdenum disulfide (MoS_2) were developed as high temperature alternatives with ultra-low coefficients of friction (μ), as low as 0.02 [1]. In both cases, the solid lubricants are thought to accommodate velocity by the interfacial shearing of lamellae which comprise their molecular arrangements.

After the establishment of these two powders as viable options for high-temperature lubrication, a plethora of other conditions soon followed which were well-suited for the employment of solid lubricants. These conditions include ultra-low temperature environments such as those found in superconductors [2], vacuum contacts found extensively in space applications [3,4], low-speed or reciprocating sliding contacts for start-up and shut-down [5], and finally, electrically conductive contacts such as those for the rail-gun or power generation industries [6–8]. In each of these situations, the nature of liquid lubricants

prohibits their implementation due to issues such as freezing, outgassing, loss of load carrying capacity low speeds, and lack of electrical conductivity.

While many solid lubricants have been shown to be suitable replacements for oils, they are not without their own environmental constraints. For example, graphite performs well in moist environments, while MoS_2 prefers arid interfaces. This key difference stems from the chemistry of the respective lamellae, where H_2O molecules will be absorbed. While beneficial to graphite in providing hydrogen planes on which to slide, the hydrogen molecules actually prevent the smooth sliding of sulfur planes through the tribo-oxidation of dangling bonds in MoS_2 films [9,10]. These types of differences have led to a restricted list of potential solid lubricant applications.

One novel method of applying these solid lubricants in situ (i.e., during sliding) is through film transfer. In transfer film lubrication, there exists the potential to lubricate contacts in situ through an inherently self-replenishing process, as long as the transfer film is continuously deposited. In order to accomplish this, a compacted powder pellet is often used to transfer a thin lubricant film onto a moving substrate wherever uncovered asperities exist [11]. In many ways this is similar to burnishing but without the need for smart systems or consistent human intervention. This type of transfer film lubrication system also has a large amount of flexibility in contacts requiring special functionality, because most solid lubricants can be employed in pellet form. For instance, the

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potential to lubricate electrical sliding contacts has already been explored with graphite powders, which are inherently conductive [7]. However, though lubricious graphite is known to possess moderate conductivity, its reliance on moist environments, as mentioned above, may make it a poor choice for conductive contacts. Other difficulties can also stem from the delivery system of pellet shearing. For example, tribo-oxidation can prohibit transfer film deposition, due to hardening of the pellet surface caused by excessive polishing and subsequent oxidation of the surface [9–11]. This can ruin a self-replenishing configuration because it leads to starvation of the interface from its lubricant source [11]. In other words, while many benefits do exist, there are specific drawbacks that prohibit the robust performance of a homogenous transfer film lubricant under broad conditions.

1.1. Multi-functional transfer films from powder composites

In an attempt to mitigate the need for case-specific solid lubricant selection, many researchers have sought to find combinations wrought from compounds that can perform different functions. This in turn has generated a desire to understand the complexities inherent in having a lubricating medium that is not only solid but also made of different “composite” elements. It should be noted that solid film mechanics have been studied in theory and experiment, and those which develop both naturally, through the sliding wear of the two materials [1,12–15], or purposefully by design [1–4,6,11,12,15–21], can provide lubricating qualities. In terms of *composite* solids, naturally occurring composite films have been shown, such as in the work of Heshmat et al., to develop through the creation of wear particles which are of differing size or elemental makeup [13,15]. These films are especially important because they lead to complex interfacial behavior which may not have been expected in the original design. While these films help to emphasize the need for further study of interfacial phenomena created through wear, this work will be more concerned with films which were designed and applied in composite form to serve a multifunctional purpose. For instance, by combining graphite and MoS₂ in sintered matrices, a “chameleon” effect was displayed where one type of powder would act depending on whether the contact was humid or dry [22]. In a previous work by the authors, composite films made of either copper (Cu) and MoS₂ for electrically conductive solid lubrication, or MoS₂ and Sb₂O₃ for oxidation resistant solid lubrication, were shown to perform better than homogeneous films [16]. Similarly, Sb₂O₃ additives have been used in other solid lubrication studies to improve performance [23,24], such as in the work of Sharf et al., where Sb₂O₃ and Au dopants were used in sputtered composite coatings to increase hardness, density, and oxidation resistance. Although representing an elegant possibility for alloying powders and their lubrication characteristics into a multi-functional lubricant, these approaches can still lead to inherent and yet unexplained problems. For instance, many composite film studies have reported transient issues with maintaining friction performance and uniform composition [6,25]. In those studies, the desired performance was found to deteriorate over time without a definitive explanation. In investigating this issue, it is hypothesized by the authors that particle size segregation, a well-understood phenomenon within the granular flow community, may play a role in the transient segregation or “un-mixing” of composite powder films. This “un-mixing” could then affect the capacity of the composite powder to exploit the advantages of both its constituents. The implications of this effect would extend not only to friction, but also to other functions such as oxidation resistance or conductivity which are heavily dependent on a well mixed, uniform composition in the film [23,26].

1.2. Particle segregation in granular flows

Granular flow resides under the broader dry particulate flow community, where it is similar to, but distinct from powder flow, as described by Worniyoh et al. [1]. Powder lubricants are comprised of soft

particles which flatten and coalesce into a film that is also known to adhere to the surfaces during sliding. However, granular flows are comprised of hard particles which retain their shape mostly and remain distinct particles which do not stick to surfaces, but rather slip on surfaces excessively. One interesting property of granular flow particles is that they are known to segregate when there are small variations in particle properties. Particle segregation involves the separation of individual particle species inside a bidisperse or polydisperse flow, which is designated as a flow with two or more species (constituents). Bi/polydispersity in a particle flow can be due to differences in any number of particle properties or characteristics such as the restitution and friction coefficient, size, shape, and material density. While particle flow segregation can be induced by variations in all of these characteristics, perhaps the most prevalent is particle size segregation. For example, Ottino and Khakar [27] provide a detailed review of studies examining both density and size segregation for a range of particle flow geometries and situations. Particle size segregation has been observed in a wide variety of natural processes and industrial applications as well. Natural processes, such as avalanches, were studied by Gray and Ancy [28] who demonstrated that in an avalanche flow, the larger particles segregate to the top, where the flow velocity is largest, and move towards the flow front. In terms of industrial applications, size segregation has been studied in hoppers [29,30] and silos [31,32], as well as mixers [33]. Each of these geometries is used extensively in the solid processing industries such as pharmaceuticals and food processing.

Particle size segregation is a phenomenon which is seen in granular shear flows, as the shearing force induces the separation of species comprised of different particle sizes. Size segregation in chute flow was studied computationally by Fan and Hill [34], while size segregation in an annular-type shearing geometry was experimentally studied by Khosropour et al. [35]. Shear-driven size segregation in a parallel-type shearing geometry has been studied extensively by Golick and Daniels [36] and May et al. [37,38]. In the work of Golick and Daniels [36], a bidisperse flow using glass particles with diameters of 4 mm and 6 mm was initially placed between two disks such that the smaller particles resided at the top, while the larger particles resided at the bottom. As the flow was sheared between parallel disks, the larger particles began to segregate to the top creating a mixed flow for a period of time. However, by the end of the experiment, the flow was fully-segregated, with the larger particles now residing at the top of the flow and the smaller particles at the bottom. This classic trend of larger particles segregating to the top occurs because the smaller particles tend to fall through the gaps between the large particles in a sieve-like fashion.

1.3. The potential of size segregation in composite powder transfer films

In the current work, it is proposed that the shear-induced size segregation behavior witnessed in particle flows can be used to explain the frictional performance of composite powder transfer films in sliding contacts. As such, it is the objective of this paper to propose particle size segregation as the driving agent for the poor tribological performance of select composite transfer films. In composite films where the powder is comprised of a solid lubricant component and a non-lubricant functional additive, drastic increases in friction have been observed that could be explained due to significant sections of the film become composed primarily of the non-lubricious constituent.

2. Experimental setup and procedure

Composite transfer films were produced by the shearing of powder compacts often called pellets. The original motivation, detailed in a previous work [16], was to create a multi-functional solid lubricant that could be applied during sliding as an electrically conductive transfer film. The creation of these composite lubricant pellets was carried out using copper (Cu) and MoS₂ powders. Two separate MoS₂ powders (obtained from Rose Mill Co.), with particle sizes of 6 μm and 1.5 μm, were

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