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Surface observations of a powder layer during the damage process under particulate lubrication

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ABSTRACT

Loose powder is used to lubricate the tribopair with the replenishing mechanism. This work analyzes the contact and the damage behavior of the powder layer during powder lubrication. The typical life cycle of a powder layer includes the full powder layer, partial detachment, serious detachment, and complete destruction, which can be concluded from the powder layer images. The carbon and copper content remaining on the surface are analyzed using scanning electron microscopy and energy dispersive X-ray spectroscopy. Layer blistering, partial detachment, delamination, and scuffing, which represent the different forms of damage and deterioration grades, are observed using an optical microscope. Layer blistering, partial detachment, and delamination are the damage forms that occur at earlier stages. Meanwhile, most of the speed difference is accommodated via shearing and sliding of the powder layer. Scuffing, which indicates direct contact and rubbing between the steel surface of the top sample and the copper surface of the bottom sample, is a serious form of damage and is often observed before the full destruction of the powder layer.

1. Introduction

Solid lubricants can be applied to a tribological interface in various forms, and used successfully in many engineering areas [1–4]. In most modern applications, thin films of solid lubricants are typically deposited on surfaces via advanced vacuum deposition processes to achieve strong bonding and obtain a dense microstructure and uniform thickness [5–8]. Moreover, solid lubricants can strongly bond with a surface using proper adhesives to provide a longer wear life [9–11], and can also be dispersed or impregnated into a composite structure [12–14]. However, the lifetime of most solid lubricants are still limited because of the finite lubricant film thickness. To increase their durability, a self-replenishing or resupply system is needed but is difficult to achieve [15].

Loose powders were also successfully used to lubricate sliding bearing surfaces. Certain powder lubricants have been blended in an aerosol carrier and sprayed directly onto the surfaces [16–19]. The results showed that powder lubricant films provide a lift and separate the bearing surfaces, resulting in a drastically reduced friction coefficient and wear of the tribomaterials. Furthermore, bearing side leakage carries away most of the heat generated by shearing [20]. Heshmat et al. [21] proposed a theoretical model for quasi-hydrodynamic lubrication using particulate matter, and several solutions were obtained. The in situ deposition of boric acid in dry powder form is investigated as a potential, environmentally benign, solid lubricant for sliding metal contacts [22]. In their study, boric acid powder is aerosolized and entrained in a low velocity jet of nitrogen gas, which is directed at a sliding contact in a rotating pin-on-disk tribometer. Friction coefficient below 0.1 can be consistently reached and maintained as long as the powder flow continues. Wear rate is reduced over two orders of magnitude.

Many factors, such as the powder properties, the experimental setup, and service conditions affect the characteristics of powder lubrication. Higgs and his colleagues [23–25] conducted a series of tests on a tribometer consisting of simultaneous pellet-on-disk and pad-on-disk sliding contacts, and proposed an asperity-based fractional coverage model for studying the process of lubricant film transfer. Their work showed that the MoS_2 pellet actually acted as a self-repairing, self-replenishing, and oil-free lubricant, and found that abrasive wear is the predominant wear mechanism governing the transfer film process. Their analysis model can predict both the friction coefficient at the pad/disk interface and the wear factor of the lubricated pellet/disk sliding contact. McKeague et al. [26,27] presented a theory for predicting the behavior of a powder-lubricated slider bearing that considers the slip of the flow velocity at the boundaries. The formulation includes the boundary roughness and granular temperature. Kimura et al. [28,29] investigated the effect of the components

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and composition of powder lubricants on their insulating and lubricating ability. Results showed that the insulating ability of powder lubricants is higher than that of conventional oil- or water-soluble lubricants and effectively prevents the formation of a scattered chill structure. Drozdov et al. [30,31] applied magnetic powder as a lubricant to the rubbing zone. Gears were placed in a magnetic field so that the lubricant and the magnet formed a single magnetic circuit. Using magnetic powder lubricants enabled the toothed reduction gears to operate satisfactorily under Hertzian contact loads of up to 1100 MPa. Reddy et al. [32,33] conducted a series of experiments to study the effect of a graphite lubricant on surface roughness, grinding force, and specific energy during the grinding of silicon carbide (SiC) materials. Results showed a considerable improvement in the performance of grinding SiC using graphite as a lubricant compared with dry grinding in terms of specific energy requirements, surface roughness, and damage. Wang et al. [34,35] carried out the ring-on-flat experiments that proved the powder properties significantly affect the tribological characteristics of powder lubrication and analyzed the effects of the sliding velocity and normal load.

The presence of powder in the rubbing interface is the precondition for powder lubrication. Previous experiments showed that powder could be introduced into the frictional clearance without any special treatment. In these studies, the powders were compacted, and the powder layer was formed under pressure from the tribopair. Several macroscopic phenomena related to the powder layer were reported, while the microscopic process are not well discussed. The process and mechanism of powder layer micro-damage is yet to be elucidated because little research has so far focused on this topic. However, the damage behavior of the compacted powder layer is important to the lubrication characteristics. The current study tries to reveal the state of the powder layer during powder lubrication. It, especially, focuses on the typical microscopic damage and its inherent mechanism, which helps to understand better the process of powder lubrication.

2. Experimental setup

The tribotester used in the experiments is equipped with a ring-on-flat contact rubbing pair (Fig. 1). The annular top sample, with a 24 mm outside diameter and 16 mm inside diameter, is made of carbon steel, with a hardness of HRC52 and a surface roughness *Ra* of 0.75 μm. To facilitate powder entrance into the frictional interface, four notches (3 mm) are made along the radial direction, and the contact face corner (1 mm) is rounded. The lower sample is manufactured via powder metallurgy, which consisted of several steps, namely, mixing the alloy powders (LBC3/$Cu_{10}Sn_{10}Pb$), spreading the mixture on a carbon steel belt (Thickness 1 mm), sintering (850 °C, 15 min, ammonia decomposition N_2+H_2), roller compaction (Diameter 260 mm, double roller, rolling reduction 20%), resintering (820 °C, 15 min, ammonia decomposition N_2+H_2), and roller re-compaction. The sheet is cut into 32 × 32 × 3 mm square pieces. The surface roughness *Ra* of the lower sample is 5 μm. The residual porosity of the copper alloy layer is approximately 5%. Before the top sample is brought in contact with the bottom sample, ten grams of loose graphite powder are covered on the bottom sample evenly. These loose powders are then compacted by the normal load, which is applied along the vertical axis of the upper specimen. During the experiments, the upper sample keeps rotated, whereas the lower sample is fixed. Some powder inside the interface may leaked out from the friction interface. Meanwhile, some of the powder remains outside of contact occasionally drawn in the interface along with the movement of the top sample. The average diameter of graphite powder particles is 30 μm. The duration time of every test is 10 min. The environment temperature is 25 °C, and the relative humidity is 75%. The sliding velocity, which is calculated based on the middle line of the annular face, is from 0.2 to 0.8 m/s and the normal load is from 2.94 to 17.64 MPa. The friction torque and normal load are obtained using two force sensors, and the friction coefficient is calculated via conversion based on the structural relationship. The sample temperature is measured in real time using a thermocouple placed at the center of the bottom sample. After the tests, the powder layers on the surface of the bottom sample are observed using a digital camera, an Olympus BH-20 optical microscope and a scanning electron microscope (SEM, JSM-6490LV). The surface elements are analyzed using an energy dispersive X-ray spectrometer (EDS, JSM-6490LV), which conducted the area measurement at the same area observed under SEM. The roughness of the friction surface is measured by a Talyor-Hobson-6.

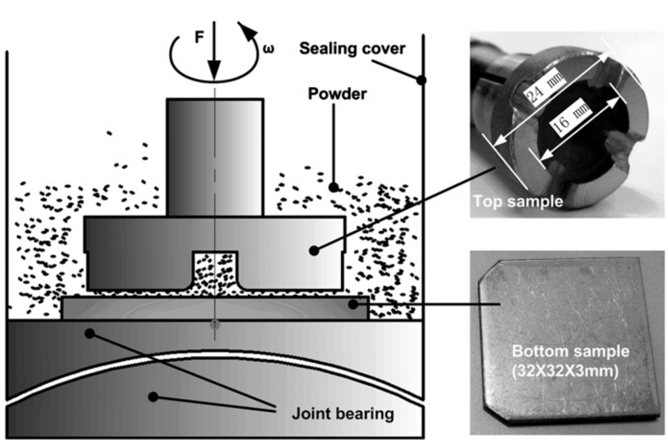

Fig. 1. Schematic diagram of the tribopair and images of the rubbing pairs.

3. Typical life cycle of the powder layer

3.1. Four distinct stages

Known from previous studies [34,35], the effects of the sliding velocity and normal load on the lubrication characteristics and powder layer formation are complicated and should be analyzed according to the running conditions of a real application. In Fig. 2, four regions have been divided to indicate the powder layer state and friction characteristics according to variations of service condition. It should be noted that no critical value indicated the transition of each powder layer state. Instead, the transition from one state to another was gradual and was related to real service conditions. Region I is working under high velocity and light load. The friction coefficient is 0.08–0.16 and the full powder layer

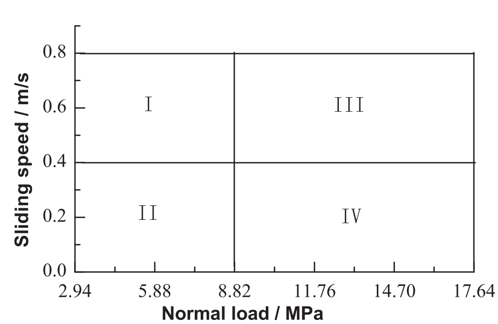

Fig. 2. State chart of powder lubrication corresponding to service conditions.