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The tribological performance of selected solid lubricant films in sand-dust environments

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ABSTRACT

Solid lubricant films have received considerable research attention in the last decades owing to their remarkable improved tribological characteristics. In this paper, the abrasive wear behaviour of five types of solid lubricant films (magnetron-sputtered diamond-like carbon, magnetron-sputtered molybdenum disulfide, bonded molybdenum disulfide, bonded polytetrafluoroethylene and bonded graphite) in sand-dust environment has been investigated using a reciprocating pin-on-disc test rig. The effects of applied load, amount of sand and particle size on the tribological performance of these films were systemically studied. Experimental results show that magnetron-sputtered films give excellent anti-friction and wear-resistance performances under sand-dust environments compared to bonded solid lubricant films. The significant differences of surface roughness, hardness, microstructure and intrinsic lubricating property directly lead to the different tribological performances and worn morphology. The formed composite transfer layer plays a vital role in reducing friction and wear due to its anti-friction and shielding action of the film surface from the hard metal asperities. Two main abrasive wear mechanisms (three-body rolling wear and two-body grooving wear) occur simultaneously in the tribological process under sand-dust environments. A transfer layer-hardening composite wear modeling was established to further explain the anti-wear mechanisms and friction-reducing capacity of these solid lubricant films under sand-dust environments.

1. Introduction

Historically, the important development in the formulation and use of solid lubricants is first due to the natural ability of various materials to exhibit rather low friction and low wear under specific conditions [1]. Solid lubricant coatings are primarily used to control friction and wear under severe application conditions (such as high vacuum, aerospace, high-speeds, high loads, sand-dust environment and very low or high temperatures), where conventional materials and lubricants cannot provide the desired levels of performance or durability [2]. Basic solid lubricants are generally classified in two categories, i.e. soft and hard lubricant films, depending on whether the hardness value is lower or higher than 10 GPa [3,4]. The hard solid lubricants exhibit higher wear resistance in addition to lower friction when compared with soft lubricants, which can provide low friction but not always high wear resistance.

Solid lubricant films have come a long way in recent years, and they are now capable of providing extremely low friction and wear coefficients under certain or highly controlled test conditions. Lamellar solids (MoS_2, WS_2), soft metals (Au, Ag, In), diamond and DLC films, lubricious oxides (PbO), and certain polymers (PTFE, PI) are well-known solid lubricants. Their uses are expected to further increase in coming years, mainly because the operating conditions of future tribosystems are becoming more and more demanding and liquid and grease-type lubricants are undesirable due to environmental concerns. However, the abrasive wear behaviour of these solid lubricant films in sand-dust environment has not received enough attention and extensive research.

The sand-dust environment can be a very important influencing factor for the application of solid lubricant films in tribosystems. Sand-dust environments account for about 21% of total land area of the world, and comprise the greater proportion in Australia, Saudi Arabia and the northwest of China. Wear by hard particles occurs in many different situations such as with earth-moving equipment, slurry pumps or pipelines, rock drilling, rock or ore crushers, pneumatic transport of powders, dies in power metallurgy, extruders, or chutes. More particularly in the moon probe project, the sand dust environment contains small, angular and irregularly shaped particles that have demonstrated high wear and abrasion on mechanical and sealing systems [5,6]. In abrasive wear, the material is displaced or detached from the solid surface by hard particles or hard parti-

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Table 1
Characteristics of selected solid lubricant films.

Film	Film material	Thickness/μm	Ra/μm	Hardness
MS H-DLC	Carbon, hydrogen and Ti	2.0 ± 0.2	50×10^{-3}	20 ± 2 (GPa)
MS MoS_2	MoS_2 and Ti	1.5 ± 0.2	30×10^{-3}	10 ± 2 (GPa)
Bonded MoS_2	MoS_2, polyimide, others (proprietary blend)	10 ± 2.0	1.2 ± 0.1	55 ± 5 ($Hv_{1\,N}$)
Bonded PTFE	PTFE, novolac-epoxy, others (proprietary blend)	15 ± 2.0	2.1 ± 0.2	20 ± 5 ($Hv_{1\,N}$)
Bonded graphite	Carbon, organic silicon, others (proprietary blend)	10 ± 2.0	1.0 ± 0.1	65 ± 5 ($Hv_{1\,N}$)

Table 2
Summary of MS MoS_2 films deposition conditions.

Item	Parameters
Base pressure (Pa)	10^{-3}
Ar gas flow rate (sccm)	120
MoS_2 target power (kW)	6
Ti target power (kW)	2
Substrate bias (V)	−50
Substrate temperature (°C)	~100
Coating time (min)	60

cles between or embedded in one or both of the two solid surfaces in relative motion, or by the presence of hard protuberances on the counterface sliding with the velocity relatively along the surface [7]. Therefore, one of the best alternatives to resolving the tribological problems of mechanical systems in sand-dust environments is to apply effective protective films with good wear-resistance and friction-reducing capacity on the moving parts.

The intention of this work was to elucidate the role of sand dust in determining the tribological performance of selected solid lubricant films. The friction and wear behaviour of these films were compared and the influence of applied load, amount of sand and particle size examined.

2. Selected solid lubricant films

Five film types, magnetron-sputtered hydrogenated-DLC (MS H-DLC), magnetron-sputtered MoS_2 (MS MoS_2), bonded MoS_2, bonded PTFE, bonded graphite, were produced on AISI 440C steel substrates. Characteristics of the five types of newly developed, dry, solid film lubricant are present in Table 1.

2.1. Magnetron-sputtered solid lubricant films

Molybdenum disulfide is a versatile and useful solid lubricant. The MS MoS_2 films were prepared by the unbalanced magnetron sputtering PVD. The worktable was fixed to the center of the deposition chamber, and three sputtering targets were fastened to the wall of deposition chamber. Among them, there are two unbalanced magnetic MoS_2 targets and one conventional Ti target. Prior to deposition, the substrates were first ultrasonically cleaned in acetone for about 20 min, and pickle liqour for 15 s to remove the oxide layer, and then ultrasonically cleaned in alcohol for 15 min. After drying with dried gas, the samples were put into the depositing chamber and cleaned using Ar^+ bombardment for 30 min at a pulsed substrate negative bias voltage of −1000 V, to remove some adhering impurities and native oxide layer on substrates. Subsequently, a Ti interlayer was deposited for 15 min under 120 sccm Ar gas flow rate and negative bias voltage of −500 V, and medium frequency (20 kHz) was kept at constant current of 2.0 A on the substrate. Finally the three targets were operated synchronously and MoS_2–Ti composite film deposited. The deposition conditions are shown in Table 2.

As for the magnetron sputtering H-DLC, the detailed description of deposition was presented in previous paper [8].

2.2. Bonded solid lubricant films

Bonded solid film lubricant is a kind of paint with solid lubricant dispersed in an organic or inorganic binder [9]. Bonded solid lubricant films were originally developed for aviation and aerospace applications as effective dry lubricants, and presently are widely used in many fields [10–13]. The specific process for applying bonded composite solid lubricant films (MoS_2, PTFE and Graphite) is as follows: initially, in order to improve bond strength between lubricants and substrates, the substrate surfaces of AISI 440C steel sheet were roughened by sandblasting to a surface roughness (Ra) of 2.00 ± 0.20 μm, and then ultrasonically cleaned with acetone for 10 min. After that MoS_2, PTFE and Graphite lubricant particles and solid filler were homogeneously dispersed in adhesive of a resin system, respectively, which contained binder (polyimide, novolac-epoxy and organic silicon resin), solvent, and modifying agent. Then the paint containing the lubricant particles and the resin system was sprayed onto the specimen surfaces by a spray gun with 0.2 MPa nitrogen gas and cured in a container with relative humidity of 40–50% and temperature of 20–25 °C. After solvent evaporation, a thin film was obtained on the substrate and then cured at 150 °C for 1 h, and 180 °C for 2 h, respectively.

3. Experimental details

The friction and wear properties of the selected solid lubricant films were examined under dry sliding with and without sand environments under ambient conditions (20–25 °C, 25–35% RH). Reciprocating pin-on-disk sliding friction experiments were conducted with 2 mm-diameter AISI 1045 steel pin in the sliding contact with the solid lubricant films. The steel pin slides against films at a frequency of 5 Hz and sliding distance of 5 mm for the whole test process. The applied load was selected to be 1, 3, 5 and 7 N for MS H-DLC, MS MoS_2, bonded MoS_2, and bonded graphite. For bonded PTFE, in order to reduce the measurement error (at lower applied load, such as 1 N, 3 N, 5 N, the bonded PTFE is so hard to abrade that the wear volume is very small), the applied load was selected to be 7, 9, 11 and 15 N. The sliding time and the friction coefficient were recorded automatically during the wear test. Before the abrasive wear tests, the counterpart pin were polished against the different grade of silicon abrasive paper (800, 1500, 2000 mesh) on the test rig for 1 h, cleaned in distilled water and acetone, and then blown dry by nitrogen. Four different range of particle sizes (in diameter) used in the wear tests are (i) smaller than 45 μm, (ii) 45–97 μm, (iii) 97–180 μm, and (iv) larger than 180 μm. The image of scattered sand particles on the surface of coating before the test are shown in Fig. 1. Three different amounts of sand particles were measured using a Sartorious CP225D electronic balance with a sensitivity of 0.01 mg. The specific amount of sand particles scattered on the specimen flat are: 23.8 ± 0.5 mg/cm^2 for the large amount of sand, 4.23 ± 0.3 mg/cm^2 for the small amount of sand and 1.75 ± 0.2 mg/cm^2 for the least amount of sand, respectively. The morphology of abrasive sand was shown in Fig. 1d.

The resultant solid lubricant films and their wear surfaces were characterized by JSM-5600LV scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDX), stereo microscope