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Role of surface roughness and lubricant film thickness in nanolubrication of sliding components in adaptive optics

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ABSTRACT

Integrated microprojectors are being developed to project a large image on any surface chosen by users. For a laser-based microprojector, a piezo-electric based adaptive optics unit is adopted in the green laser architecture. Nanolubrication of adaptive optics sliding components is needed to reduce wear and for smooth operation. Mobile lubricant film thickness needs to be optimized for a given interface with a certain surface roughness to minimize stiction/friction and maximize durability. In this paper, the role of roughness and film thickness on adhesion, friction, and wear of the interface is studied. The results and associated mechanisms are presented.

1. Introduction

The development of microprojectors represents the miniaturization of the commercial projector. The microprojectors being sold commercially to date come as lightweight devices (about 100–150 g) that can be attached to other hand-held devices (such as mobile phones) and can display images on any surface. One of these, laser-based microprojectors, uses two-dimensional pixel-by-pixel scanning with modulated laser beams as the light source (Microvision, Redmond, Washington) [19,34]. It uses a single scan mirror to create a pixel array. It requires red, green, and blue lasers to provide a high contrast, high brightness, high resolution, and focus-free image and low power consumption. A compact green laser with high power is not commercially available. In order to produce a compact green laser, a frequency doubling technique is used with a distributed Bragg reflector (DBR) laser diode, where a 1060 nm wavelength light is passed through a second harmonic generating crystal to produce a 530 nm green laser [1,2]. To correct for any lens misalignment, the green laser module uses an adaptive optics component with a drive mechanism to align the optics and maintain a constant power output with time and temperature [2,3]. The drive mechanism is commonly referred to as the smooth impact drive mechanism (SIDM) (Fig. 1). The device consists of two SIDM units for x-axis and y-axis movement. The main components of the drive mechanism are the piezo element, driving rod, moving body, and friction plate. The moving body is a U-shaped frame upon which the lens is attached. The driving rod sits in the frame with friction plates on two sides and clamped with a leaf spring. Carbon fiber reinforced polymer (CFRP) is the material used as the driving rod in the drive mechanism [16,17]. It is used as a component for a wide variety of engineering applications. For the moving body, Zn alloy commonly used in automotive applications is used as the die-cast part.

Wear is a significant concern for actuators such as the adaptive optics drive mechanism components described above, due to the high friction encountered during sliding [23,25,16,17]. The friction and wear behavior of materials is dependent on their mechanical properties, surface roughness, and the operating environment [7,8,10,11]. To improve the tribological performance of the sliding components, perfluoropolyether (PFPE) lubricants are applied to the surfaces. The ideal lubricant should be molecularly thick to protect the surface from wear, easily applied, able to chemically bond to the surface, and insensitive to the environment. PFPE lubricants are known to be most desirable [21,22,35,26,33,13,30,31]. They have low surface tension, high contact angle, and high adhesion to the substrate, allowing easy application and spreading onto the surface as well as providing hydrophobicity. Their chemical and thermal stability and low vapor pressure provide low degradation and low out-gassing. PFPEs have been extensively investigated, especially in the magnetic disk drive industry [4,14]. It has been shown that they reduce friction and wear, resulting in lower disk drive failure. A lubricant from Moresco (A20H), which has one hydroxyl group on one end and a PFPE backbone of a commonly used Z-DOL, is commonly used. At the opposite end of A20H, there is a cyclotriphosphazene group, giving A20H the characteristics of a phosphazene lubricant. A phosphazene lubricant renders the surface hydrophobic, minimizes stiction, and improves durability of a

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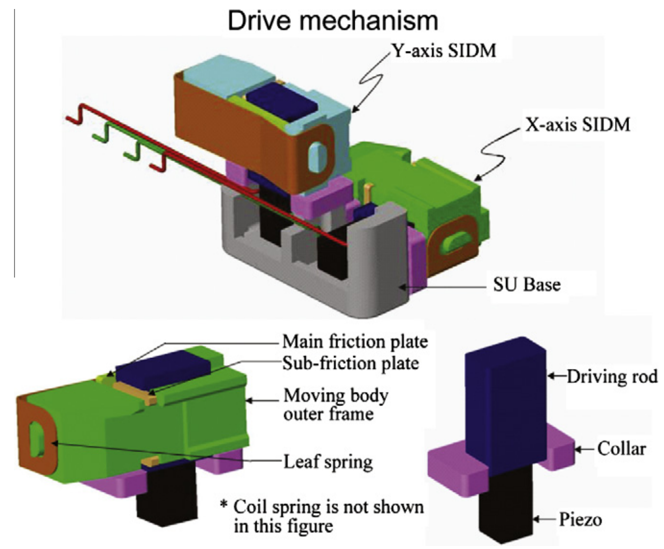

Fig. 1. Schematic showing detailed construction of the drive mechanism (SIDM assembly) [2,3,29].

sample, especially in high humidity environments [33,13,15, 30,31].

The lubricant film can form menisci, which may result in high adhesion and stiction. In disk drive research, it has been shown that there is a critical $h_{mobile}/\sigma_{composite}$ below which the device should be operated for optimum tribological performance [20,36,37,14,7]. Here, h_{mobile} is the total thickness of mobile liquid, and $\sigma_{composite}$ is the composite standard deviation of surface roughness to the two mating surfaces.

The objective of this research is to explore the role of surface roughness of CFRP and lubricant film thickness on adhesion, friction, and wear in order to obtain an optimum h/σ. Results and associated mechanisms follow.

2. Experimental

2.1. Materials and sample preparation

The CFRP rod, a carbon fiber reinforced polymer, is most often epoxy, but other polymers such as polyester, vinyl ester, and nylon are also used. In the fabrication of a CFRP rod, carbon fibers are aligned parallel to the long axis of the fiber and bound up by epoxy as a bundle. The dimension of a single fiber is about 2–5 μm in diameter and about 15 mm in length. It has a high strength-to-weight ratio due to its low density, and it has high strength. Moreover, it has a low coefficient of thermal expansion along the direction of the fiber. These are some of the reasons. The CFRP rod is chosen for an adaptive optics sliding component in micro-projectors. The binder ratio measured using thermogravimetric analysis (TGA) is about 30%. The glass transition temperature (Tg) of the CFRP rod measured using a differential scanning calorimeter (DSC) is about 180 °C [16,17].

The CFRP rods were polished mechanically to obtain lower roughness (σ) using a polishing wheel (EcoMet 3, Buehler, IL, US) at 50 rpm and a downward pressure of 2 N to obtain various roughnesses. Silicon carbide polishing pads (Buehler, IL, US) were used with grit sizes of p120, p1200, and p2400 and a nylon polishing cloth (40–7052) for 1 min, 5 min, 3 h and 3 h, respectively. The CFRP rods with 130 nm roughness were obtained by polishing using p120, p1200, and p2400 pads. For 55 nm roughness samples, all four polishing pads were used. During the polishing process, Al_2O_3 powder (0.3 μm, MicroPolish II, Buehler, IL, US) with water was applied between the samples and the polishing pad. Material removal initially takes place on top of the asperities on carbon fibers, resulting in a flat surface on CFRP rods.

For the nanolubrication studies, a lubricant with a hydroxyl group on one end and a cyclotriphosphazene group on the other end (Moresco A20H) was applied to a CFRP using a dip-coating technique. The method and the apparatus used have been described elsewhere [26,33]. Briefly, the dip-coater allows withdrawal of the samples from the lubricant reservoir at a constant velocity. The withdrawal speed ranged from 0.3 to 20 mm/s. The CFRP rod was submerged into a beaker containing a dilute solution of lubricant with a concentration of 0.4% lubricant in HFE 7100 (3 M, St. Paul, MN), which consists of isomers of methoxynonafluorobutane ($C_4F_9OCH_3$). After 10 min, the CFRP rod was withdrawn from the solution. The thickness of the lubricant on the CFRP rod was measured by a thickness mapping technique using AFM [16]. The film thickness of lubricant on CFRP rod was controlled by the withdrawal speed of the dip-coating. The film thickness increases with the withdrawal speed as there is less time available for lubricant to drain at higher withdrawal speeds.

Lubricant was deposited on both the unpolished samples (410 nm in RMS, roughness) and the polished (130 and 55 nm RMS) samples using a typical dip-coater [4,16,17]. The sample roughness and lubricant thickness used are shown in Table 1. The average film thicknesses of the lubricant as a function of the withdrawal speed of the dip-coater are shown in Fig. 2. It is observed that the lubricant film thickness decreases with decreasing surface roughness at the same withdrawal speed of the dip-coater. While withdrawing the CFRP rods from the lubricant reservoir, lubricant on smooth samples could drain easier than that from the rough surfaces. It is also shown that the lubricant thickness on epoxy is higher than that on carbon fibers. However, the thickness difference between epoxy and carbon fibers decreases with a decrease in sample roughness. This suggests that the uniformity of lubricant distribution on the CFRP rods is improved by decreasing the sample roughness. The length of error bars (standard deviation) becomes smaller with decreasing roughness of the CFRP rods. Bhushan et al. [16] reported that the lubricant on the CFRP rods is mobile and not chemically bonded.

2.2. Nanoscale surface height, adhesion, friction and lubricant thickness measurements

A commercial AFM (Nanoscope IIIa, Veeco, Santa Barbara, CA, USA) was used for this study [10,11]. Silicon nitride tips of nominal 50 nm radius attached to the end of a triangular cantilever beam (DNP, spring constant of 0.12 N/m) were used for surface height, adhesion, friction, and lubricant film thickness measurements. Adhesive force and lubricant film thickness on CFRP rod was calculated using the force distance curve technique [12,24,18,27,16]. The experiments were performed at room temperature (21 °C) and 45–55% relative humidity.

The force distance curves were collected at the same maximum cantilever deflection of 70 nm (relative trigger mode). In order to obtain a map of adhesive forces and lubricant film thickness, a 64 × 64 force distance curve array (total of 4096 measurement points) was collected over a scan area of 20 μm × 20 μm with a 3 Hz scan rate for a CFRP. For each force distance curve, there are

Table 1
Sample roughness (RMS) and lubricant thickness used in experiments.

Roughness (RMS, nm)	410	130	55
Approximate lubricant thickness (h, nm)	15, 30, 45, 65, 115	15, 30, 45, 60	5, 10, 30