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Influence of surface roughness and coating on the friction properties of nanometer-thick liquid lubricant films

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ABSTRACT

The friction properties of nanometer-thick lubricant films are crucial in the reliability and durability of miniaturized moving mechanical components in micro- and nanoelectromechanical systems and hard disk drives. In this work, gas cluster ion beam treatments were applied to prepare smoothed glass sliding pins and diamond-like carbon (DLC) coated sliding pins for pin-on-disk friction tests to study the effect of the surface roughness and the DLC coating on the friction properties of perfluoropolyether (PFPE) films. The effect of the texture of the solid surface on the friction properties was also investigated. The friction properties were not exclusively determined by the surface energies of the solids. The friction coefficients of the nanometer-thick PFPE films, confined between solid surfaces were sensitive to the surface roughness of the solids. The friction coefficient generally increased with an increasing surface roughness (the composite standard deviation of the surface roughnesses of the pair of solid surfaces). This tendency was reversed when there was a strong longitudinal roughness effect at the contact interface. Moreover, the DLC-coated sliding pins had lower friction coefficients than the glass sliding pins, indicating that the friction properties were noticeably affected by the hardness and Young's modulus of the contact materials. The mechanisms for the effects of the surface roughness, surface texture and contact materials on the friction properties are discussed.

1. Introduction

Friction on the micro/nanometer scale directly affects the performance and reliability of miniaturized moving mechanical components, such as in micro- and nanoelectromechanical systems (MEMS/NEMS) and hard disk drives (HDD) [1,2]. To improve the tribological performance of the sliding components, the surfaces are generally separated by an ultrathin liquid lubricant film. In HDD, 1–2 nm thick perfluoropolyether (PFPE) films are employed as a lubricant to reduce friction and wear [3,4]. As the HDD industry is striving to achieve ultrahigh recording densities, the flying height of a head over a disk (currently less than 4 nm) should be decreased [5,6]. However, doing this will increase the probability of head-disk conflicts and may even cause sustained contact between the head and the disk. Consequently, a better understanding on the friction of nanometer-thick liquid lubricant films confined between two solid surfaces is crucial. The friction is generally dependent on many factors, such as surface roughness, surface texturing, solid material and lubricant used. Based on the optimization of the interplay of the surface roughness and the lubricant film thickness, the friction coefficient and wear decreased with an increase in the ratio between the film thickness and the surface roughness [7,8]. In addition, the nanotextured surfaces, subject to elastic deformation, reduced the friction coefficient in the presence of liquid lubricants with a linear molecular structure, but not in the presence of branched lubricants [9]. However, the mechanism for how the surface roughness, surface texturing and mechanical properties of the contact materials affect the friction performance on the nanometer scale has not been fully elucidated.

Gas cluster ion beam (GCIB) processing is a powerful technique for smoothing surfaces at the atomic level, and it can also assist in the deposition of diamond-like carbon (DLC) with high hardness [10–12]. In this work, GCIB smoothing and GCIB assisted DLC coating were introduced to develop sliding pins with different surface roughnesses and different surface materials. The friction properties of the nanometer-thick PFPE films coated on textured

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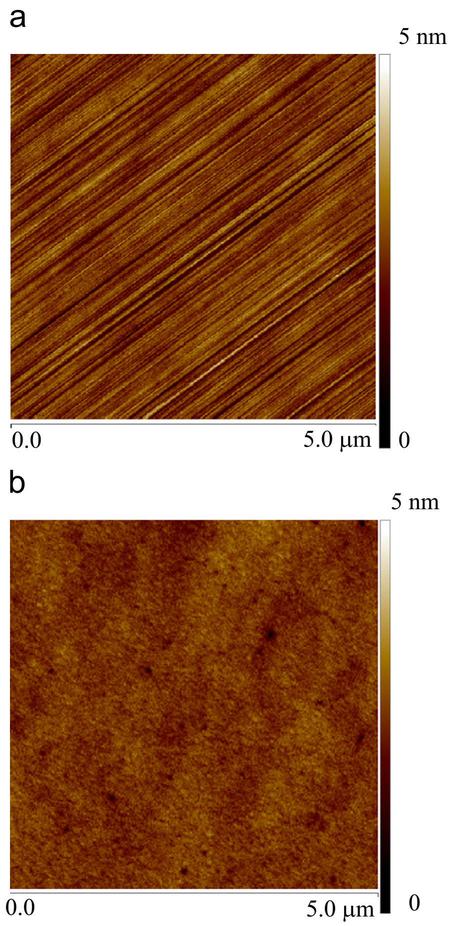

Fig. 1. Surface morphology of the textured disk (a) and the nontextured disk (b) measured in a 5.0 μm × 5.0 μm area.

and nontextured solid surfaces were studied using these sliding pins.

2. Experimental details

Textured and nontextured DLC films deposited on 2.5-inch-diameter magnetic disks were used as substrates to discuss the effects of surface texturing on the friction. In addition to the DLC films, the magnetic disks were comprised of a glass substrate and a magnetic layer. The DLC films were about 3.5 nm thick. Fig. 1 shows the surface morphology of the textured and nontextured disks, measured using the tapping mode of an atomic force microscope (AFM; Bruker AXS: Dimension Icon) with a 5.0 μm × 5.0 μm area. From Fig. 1(a), many peaks along the circumferential direction of the textured disk were confirmed, which was parallel to the sliding direction in the friction measurements. Thus, this is referred to as the longitudinal roughness. The arithmetic mean roughness (Ra) of the textured disk was 0.36 nm, the root-mean-square roughness (Rq) was 0.46 nm, the maximum peak height (Rp) was 1.99 nm, and the maximum roughness depth (Rmax) was 4.24 nm. For the surface roughness of the nontextured disk, Ra was 0.22 nm, Rq was 0.28 nm, Rp was 1.27 nm, and Rmax was 2.96 nm.

PFPE Zdol4000 was used to lubricate the substrates. Its chemical structure is $HO–CH_2–CF_2–O–(C_2F_4O)_p–(CF_2O)_q–CF_2–CH_2–OH$ with $p/q=1$, and its nominal molecular weight was 4000 g/mol. The lubricant was diluted in an HFE-7200 solvent to a concentration of 0.15 wt% and then applied to the disks using a standard dip-coating method. The lubricant films were adjusted to roughly the same thicknesses: 0.99 nm on the nontextured disks and 1.06 nm on the textured disks. The film thicknesses were measured with a scanning ellipsometer. Using an optical surface analyzer, it was confirmed that the films were distributed uniformly and displayed no evidence of de-wetting of the lubricant. All samples were stored for more than 48 h in a desiccator with 20% humidity to allow the lubricant films to relax prior to the friction measurements.

The sliding pins used were optical glass balls (material: LaSFN9) with a diameter of 2 mm. The pins were processed with a GCIB treatment. One set of pins (the sliding pins, Ar1 and Ar8) were treated with different argon-GCIB (Ar-GCIB) doses (Ar1: 1×10^{16} ions/cm^2 and Ar8: 8×10^{16} ions/cm^2). The other set of pins (the sliding pins, DLC_A and DLC_B) were first treated with Ar-GCIB (Ar dose: 1×10^{16} ions/cm^2). Analogous to the magnetic heads whose top surface was coated with DLC, the pins then had 300 nm thick DLC films deposited on them, with the assistance of Ar-GCIB irradiation. The DLC_B sliding pin was further treated with nitrogen-GCIB (N_2 dose: 1×10^{16} ions/cm^2). The accelerating voltage for the Ar and N_2 cluster ions was 10 kV, the current density was 1 μA/cm^2, and the gas pressure was 0.60 MPa. As a reference, an untreated sliding pin was also used. The surface roughness was measured with the tapping mode of an AFM over an area of 5.0 μm × 5.0 μm on sliding pins' apexes. The results for all of the sliding pins used in this work are summarized in Table 1. The sliding pins exhibited nearly isotropic surface roughnesses, which were confirmed with the AFM measurements.

The sliding pins were adhered to the end of cantilever suspensions and then mounted on a self-developed pin-on-disk tribometer, which features a highly sensitive system for measuring friction under light load conditions [7]. Friction force was determined from the horizontal displacement of a friction transducer consisting of two pairs of parallel leaves. The displacement was measured by a capacitance-type sensor with a resolution of 2.5 nm, giving rise to a resolution of 10 μN for friction force measurements. The sliding pin together with the friction transducer was driven up/down by a high-precision Z piezoelectric stage with a built-in displacement magnification mechanism. The load resolution was 3.5 μN, as determined by the displacement resolution of the Z stage and the spring constant of the suspension. To avoid the influence of solid–solid contact on the measured friction force, the external load should be small enough not to easily break the nanometer-thick lubricant films. Therefore, we used light external loads of 0.4–1.6 mN with an increment of 0.2 mN. We also must prevent vibration of the sliding pin and the friction transducer to ensure reliable and stable friction measurements. In this study, friction measurements were carried out at the 20-mm disk radius. The disk rotational speed was 30 rpm, corresponding to a sliding speed of 0.063 m/s. By monitoring the vertical vibration of the sliding pin and the horizontal vibration of the friction transducer with two laser Doppler vibrometers, we confirmed that stable contact sliding between the sliding pin and the samples was achieved during the friction measurements under the above conditions. At each external load, friction forces were measured for 15 cycles. To eliminate the variation during the running-in

Table 1
Surface roughnesses of the sliding pins.

No.	Ra (nm)	Rq (nm)	Rp (nm)	Rmax (nm)
Untreated	1.72	2.22	11.8	20.0
Ar1	0.86	1.10	4.10	8.36
Ar8	0.18	0.22	0.79	1.61
DLC_A	0.71	0.90	5.56	8.81
DLC_B	0.46	0.57	2.46	4.65