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Micro- and nanoscale surface texturing effects on surface friction

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ABSTRACT

The surface friction of smooth, microtextured, and nanotextured aluminum substrates against a half-ball shape of polydimethylsiloxane rubber was investigated under different surface humidity conditions. The work of adhesion estimated by the contact angle on nanotextured surfaces having a 250 nm scale dimple structure array was much higher than that on microtextured surfaces having a 3 μm scale dome structure array. Surface textures increased the work of adhesion, thus the surface friction of microtextured and nanotextured surfaces was increased compared to that of a smooth surface under dry conditions. On the other hand, the nanotextured surface considerably reduced the surface friction under wet surface conditions, while the surface friction of the microtextured surface was similar in both dry and wet surface conditions. In dry surface conditions, the measured surface frictions of microtextured and nanotextured aluminum substrates were 1.26 times and 2.69 times higher, respectively, than that of a smooth one. Under water lubricant conditions, the microtextured surface showed approximately 2 times higher surface friction than the smooth one, but the surface friction of the nanotextured surface was only 32% of the smooth surface.

1. Introduction

Surface textures are widely applied in mechanical joints for sealing and lubricating [1] and in biomedical chips for increasing surface area [2]. Surface textures promote the retention of lubricants, the trapping of wear particles, and the formation of lubricant films [3]. In addition, when work of adhesion is significantly high, micro/nanoscale surface textures can decrease surface friction by reducing the true contact area in not only for solid–solid contact [3–5], but also for solid–liquid contact [2]. In order to investigate surface texture effects on surface friction, microscale textures have mostly been made in steel [4–9] and polydimethylsiloxane (PDMS) [3,10]. The microtexturing process in steel has been carried out by laser-assisted machining [4,6,8], mechanical cutting [7], and shot blasting [7], while microtextured PDMS was prepared by the soft lithography process [3]. Microcavities [4,7,8] significantly reduced friction under oil lubricated sliding conditions in comparison with smooth steel surfaces. The range of diameters and depth of microcavities were 35–100 μm and 8–48 μm, respectively. On the other hand, ridge-groove patterns [7] and pillar patterns [6] led to a higher friction coefficient. The range of depths and spacing of patterns were 2–48 μm and 100–500 μm, respectively. However, in the case of pillar patterns, the friction coefficient was reduced, compared to that of the smooth surface, when the spacing between pillars was narrower than two times of the width of pillar [3].

In previously reported works related to surface texturing, steel was the main substrate investigated. In this work, high purity aluminum was considered as the substrate for surface texturing, because high purity aluminum is easily transformed into alumina by anodic oxidation without any morphology change [11]. In addition, alumina is a material of interest for mechanical tools and biomedical implant applications due to its high hardness, wear resistance, and chemical inertness [12,13]. Smooth, microtextured, and nanotextured aluminum substrates were prepared, and their surface frictions against a PDMS half-ball were measured under different surface humidity conditions.

2. Material and methods

2.1. Sample preparation

Three different samples, including smooth, microtextured, and nanotextured aluminum substrates, were prepared to investigate surface friction as shown in Fig. 1. For the preparation of the smooth aluminum substrate, high purity aluminum (99.999%) was deposited on a silicon wafer to ensure ultra-flatness. The high purity aluminum layer was deposited by sputtering to a thickness of 1 μm. Fig. 1(a) shows the surface of the thin film aluminum on the silicon

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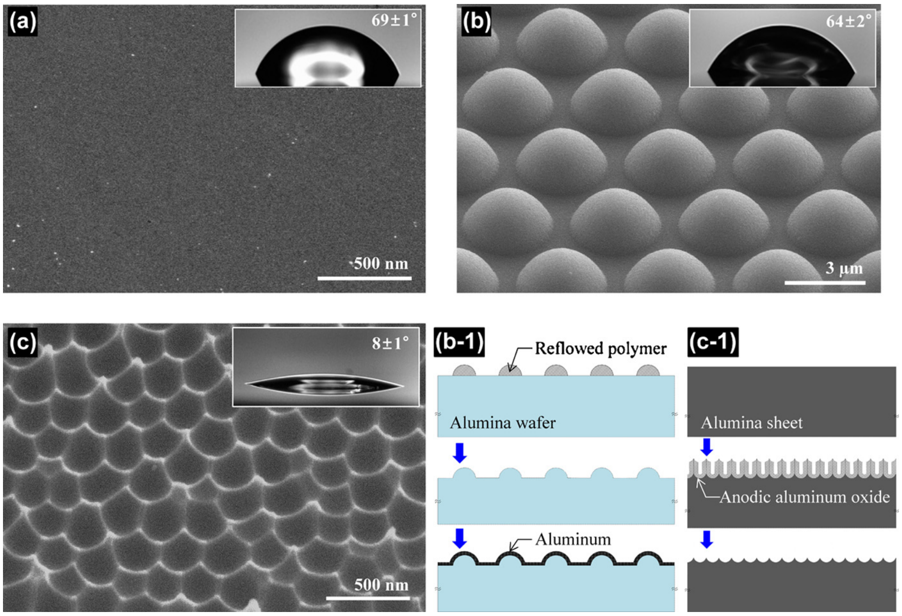

Fig. 1. Scanning electron microscope images of three different samples: (a) Smooth aluminum surface, (b) Microtextured aluminum surface with dome structure array, (c) Nanotextured aluminum surface with dimple structure array. Inset in each image shows the contact angle. (b-1) and (c-1) were schematic fabrication flow of microtextured and nanotextured aluminum surfaces, respectively.

wafer, and the surface roughness of the smooth aluminum layer was less than 1 nm.

In the microtextured substrate of Fig. 1(b), micro-dome structures were considered and arranged in a hexagonal array in order to minimize the contact area against the PDMS half-ball during surface friction measurements. The facet diameter, height, and spacing of the microstructures were 3 μm, 1.5 μm, and 1 μm, respectively. For the fabrication of the microtextured surface as shown in Fig. 1(b-1), micro-dome structures were formed on the alumina wafer using a polymer reflow technique, and then the alumina substrate was etched by a BCl_3-based inductively coupled plasma etching process. During the plasma etching process, polymer micro-dome structures on the alumina substrate were slightly etched, and then the revealed alumina underneath the polymer micro-dome structures was etched. Eventually, the polymer micro-dome structures were completely etched away, and the shape of the micro-dome structures was transferred to the surface of the alumina substrate. Finally, thin film aluminum was deposited on the microtextured alumina substrate in the same manner as the smooth aluminum substrate. The thickness of the deposited aluminum was 300 nm.

In the case of the nanotextured substrate, nanoscale dimple structures were formed on the high purity aluminum substrate using a simple and cost effective method of anodic aluminum oxidation as shown in Fig. 1(c-1). High purity aluminum (99.999%) was prepared by mechanical lapping and electrochemical polishing. Anodic aluminum oxidation was performed using 0.1 M oxalic acid as the electrolyte and with a voltage of 100 V. After the formed alumina layer was removed with 0.2 M chromic acid, nanoscale dimple structures were fabricated on the surface of the aluminum substrate as shown in Fig. 1(c). The diameter of the nanoscale dimples was about 250 ± 20 nm, and the dimples were formed in a hexagonal array. When high purity aluminum was exposed to air, an ultra-thin amorphous oxide layer was formed on its surface. At room temperature (298 K), the stable thicknesses of native oxide films on the {111}, {110}, and {100} crystallographic faces of aluminum are 0.25, 4.08, and 2.13 nm, respectively [14]. Approximately, the thickness of native oxide film on bulk aluminum substrate is less than 5 nm [15]. Therefore, there must be ultra-thin native aluminum oxide layers on the three different samples prepared.

The PDMS half-ball was fabricated by the casting process. A 10:1 mixture of the pre-polymer of PDMS (Sylgard® 184 silicone elastomer, Dow Corning Co.) and curing agent were used, and the curing temperature was 80 °C. A quartz half-ball lens, 5 mm in diameter (Edmund Optics Inc.), was used as a mold. The PDMS half-ball was prepared after performing the PDMS casting process twice.

For the contact of the elastic sphere and flat substrate, friction is related to the work of adhesion [16]. The work of adhesion W_{ad} can be expressed by the Young-Dupre equation [17]:

$$W_{ad} = \gamma_L (1 + \cos\theta) \tag{1}$$

where γ_L is the surface tension of the liquid on the solid surface, and θ is the contact angle. The work of adhesion decreases as the contact angle increases when the surface of the substrate is hydrophilic and the contact angle is less than 90°. From Eq. (1), we know that the tendency of the friction can be estimated by contact angle. The insets in Fig. 1 were the measured contact angle for each sample substrate. The contact angles of the smooth, microtextured, and nanotextured aluminum substrates were 69 ± 1°, 64 ± 2°, and 8 ± 1°, respectively. Consequently, higher surface friction can be expected in the order of nanotextured, microtextured, and smooth substrates.

2.2. Surface friction measurement setup

Surface friction force depends on the material properties of the two contact objects, the normal contact force, and the sliding speed. In this work, the materials of the prepared samples and contacting object were high purity aluminum and PDMS, respectively. In order to measure the contact force in the normal direction and the frictional force in the lateral direction, a dual-axis leaf flexure module was used. Fig. 2 shows the schematic diagram of the dual-axis leaf flexure module for the measurement of surface friction. Four leaf flexures were fixed on rigid members. If the stiffness of the flexure module of k_z and k_x is known, contact force R in the z-direction and friction force F_f in the x-direction are estimated by measuring the deflections of the dual-axis leaf flexures, δ_z and δ_x. Moreover, a precise load cell was mounted on a motorized stage to monitor the normal contact force.