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Study of the anisotropic frictional and deformation behavior of surfaces textured with silver nanorods

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A B S T R A C T

In this study, we investigated the anisotropic frictional and deformation behavior of a nanostructured thin film (NSTF) consisting of silver (Ag) nanorods tilted at an average angle of 65° to the surface normal and compared to that of a continuous thin film of Ag. The NSTF demonstrated significant frictional anisotropy with the coefficient of friction (COF) being ~45% higher against the tilt direction than that of along the tilt direction. Furthermore, the NSTF sample exhibited lower COF than the continuous thin film at low applied normal load and higher COF at higher normal loads. In addition, the deformation of the nanorods increased with increasing normal loads and is shown to be also dependent on the direction of the scratch.

1. Introduction

Friction is one of the most common and influential means by which two objects can mechanically interact. Everything from automobiles, to computers, to human joints encounters friction in various forms and strengths. Friction can be a useful force such as allowing the tires of a car to propel the vehicle forward and it can also be harmful to a process as in causing wear on human joints and electronic devices. Because of its importance in nearly every discipline, friction has been an important area of study since a long time. Literature shows a significant number of studies that have focused on ways to increase, decrease, or eliminate friction or ways to manipulate friction in a beneficial manner. One way to control the frictional behavior of a system is through surface topography modification [1,2]. Numerous studies in the literature clearly demonstrate that the use of nanotextured surfaces is one of the most reasonable and effective ways to manipulate and control friction forces [1–6].

Frictional anisotropy is another phenomenon which has earned considerable interest among researchers around the globe to better understand the underlying mechanisms. Several materials such as: single crystal diamond, mica, Cu, Ni, Pd and NaCl exhibit anisotropy in frictional properties and have been investigated for the same [7–12]. For example, single crystal diamond displayed anisotropic friction forces when slid in air against itself. The coefficient of friction was observed to be higher in the [100] direction than in the [110] direction [7]. This anisotropic frictional behavior was explained to come because of a preferred slip system during plastic deformation. Single crystal of muscovite mica showed frictional anisotropy with respect to the lattice misfit angle that was interpreted from the aspect of lattice commensurability [8]. Frictional anisotropy is also displayed by nature in some organisms such as geckos and snakes [13–18]. For example, skins on the snake's abdomen consist of nanostructured pattern which gives them the ability to move because of anisotropic frictional behavior [17,18]. Frictional anisotropy governs the attachment and detachment mechanism of gecko's feet on smooth vertical surfaces. This is the mechanism that gives geckos the remarkable ability to climb and run rapidly on ceilings and smooth vertical walls [13–15]. This unique ability in geckos comes from the hierarchical structure of setae present on gecko toe. A single seta has small rod-like structure and each gecko toe consists of thousands of this seta [15,16,19]. Considerable efforts have been made to understand the underlying mechanisms which are responsible for gecko's swift movement on ceilings and vertical walls. Researchers have also been making attempts to design new surfaces mimicking gecko's toe which can enable sticking while sliding on a surface [16,20–22]. Recent studies have demonstrated that nanostructured surfaces with tilted polypropylene microfiber arrays [20] and tilted polydimethylsiloxane (PDMS) half-cylinder micron-scale fibers [21,22] show directional adhesion similar to that of gecko's toe. This suggests that tilted

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micro-/nanostructures are a promising direction in developing gecko-inspired adhesive surfaces.

Glancing angle deposition (GLAD) is a technique that involves an obliquely incident flux of atoms/molecules in a typical vapor deposition system such as sputtering or thermal evaporation. It is a versatile nanofabrication method and can be used to create nanostructured arrays of various shapes (e.g. rods, springs, and zigzags) on a wide range of substrates. GLAD can produce nanostructured surfaces consisting of tilted nanorods with very pronounced structural anisotropy which forms the basis for many interesting physical properties [23–27]. Several recent studies have focused on investigating the tribological behavior of nanostructured thin films made up of different materials grown by GLAD technique [28–30]. In a recent study, Stempfle et al. showed that the tribological behavior of nano-textured thin films of chromium grown by GLAD method is strongly influenced by the growth mechanism and deposition parameters. They also suggested that nano-textured surfaces with tailored properties can be grown by controlling deposition parameters [28]. In another study, nanostructured parylene films grown using GLAD method were scratched and were shown to exhibit anisotropic frictional behavior, with a lower COF when scratched against the direction of nanorods tilt than along it [29]. Hirakata et al. performed a similar study focusing on the frictional anisotropy of tilted Ti nanorod arrays fabricated by GLAD [30]. This study, however, used a small indenting tip for the tests, which was of the same size as the nanorod tips. The results in the case of Ti nanorods showed a higher COF when scratched against the tilt direction than with the tilt, which was opposite to that observed in case of nanostructured parylene films. These studies highlight the importance of the size and material of the nanorods in determining the behavior of the surface.

In a recently published work, we have reported the frictional anisotropy and deformation behavior of nanostructured thin film (NSTF) consisting of tilted molybdenum (Mo) nanorods [31]. Current work investigates the frictional anisotropy and deformation behavior of NSTF made up of tilted silver (Ag) nanorods which is much softer compared to Mo. In this study, frictional behavior of two types of silver thin films on glass substrates has been compared; one is a surface textured with tilted nanorods, referred to as NSTF, while the other is simply a continuous thin film. The NSTF was tested for anisotropic frictional behavior, in order to determine its potential for application in small devices as a means of directional manipulation of frictional forces. The NSTF displayed highly anisotropic frictional behavior between against and along the tilt direction. Furthermore, deformation analysis of the samples showed a striking contrast between the deformations of the two surfaces.

2. Experimental details

The NSTF consisting of tilted Ag nanorods was created by using a custom made GLAD set-up. Ag particles placed in a tungsten boat were used as the thermal evaporation source material. Glass microscope slide substrates that were attached to a sample tilt manipulator were placed at a distance of about 30 cm away from the thermal evaporation source. Conventional thin film and tilted nanorod NSTF depositions of Ag were held at room temperature under 1.7×10^{-6} mbar base pressure by setting the deposition angle to 0° (normal incidence) and 85°, respectively (i.e. deposition angle with respect to the surface normal of the substrate). Thickness of the coatings and tilt angle of the GLAD nanorods were measured by the analysis of cross-sectional scanning electron microscopy (SEM, JEOL JSM 7000F) images. SEM was also used to investigate the morphological properties of thin film and NSTF samples before and after the scratch tests that are described below.

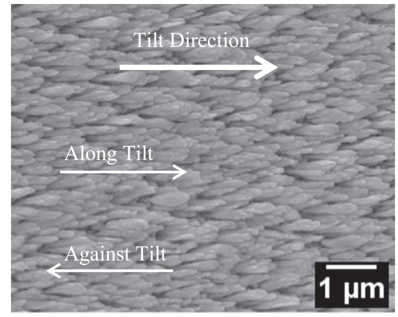

Fig. 1. Illustration showing different scratching directions on the NSTF, which is made of tilted Ag nanorods.

All the friction tests were carried out in atmospheric conditions using a TI 900 triboindenter system (Hysitron, Minneapolis, MN) with a 90° conical diamond tip having a 100 μm tip radius. The triboindenter has the ability to continuously sense both forces and displacements in lateral and normal directions during a test through the use of a 3-plate capacitive system connected to the probing tip. Accordingly, the coefficient of friction (COF) is then determined from the lateral and vertical forces during the scratch.

A small cross-hair was manually scribed onto a clean corner of the thin film to allow for the scratches to be easily identified later on. In addition, the scribe was oriented on the nano-textured thin film in such a way that one line was parallel to the tilt direction and the other was perpendicular to the tilt direction. To investigate the anisotropic frictional behavior, the scratch tests on the NSTF were performed against the direction of nanorods' tilt and along the tilt. Fig. 1 shows the two different scratching directions. The continuous thin film sample was tested in two different directions opposite to one another. The first set of the scratch tests was performed in an arbitrary direction as the continuous thin film is expected to be uniform in all directions and the COF is expected to be the same irrespective of the scratching direction. The second set of tests was performed in the opposite scratching direction in regards to the first set to confirm the thin film's lack of friction anisotropy. Normal loads ranging from 100 μN to 8000 μN were applied in order to study the variation in frictional anisotropy with load. All of the scratches were 8 μm in length as it was the maximum scratch length permitted by the equipment and was chosen to obtain the most data per scratch. Five scratches were performed at each applied normal load in each scratch direction. It should be noted that the data obtained for scratch tests performed at normal load of 8000 μN are not reported due to excess noise in the data. However, the scratches have been used to study the deformation behavior of nanorods.

After the scratch tests were completed, an environmental scanning electron microscope (ESEM, JEOL JSM-6335F) was used to characterize the deformation caused to the thin film surfaces during the scratch tests. Due to the nonconductive glass substrate, it was necessary to apply a light gold sputter to both samples to eliminate charging effects so that the individual nanorods could be observed. In addition, images were also obtained through the use of conductive tape without gold sputtering in order to determine what effect the sputter had on the surface topography.

3. Results and discussion

3.1. Surface topography

Fig. 2(a)–(c) shows the top down and cross-sectional views of the NSTF consisting of tilted nanorods and top down view of continuous thin film is shown in Fig. 2(d). The cross-sectional view in Fig. 2(c) shows that the nanorods are tilted at 25° to the surface. The