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Friction and frictional tracks on thick silica films prepared by vacuum deposition

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Friction and frictional tracks on 2 μm thick SiO_2 films evaporated on polymethylmethacrylate (PMMA) substrate were investigated. Diamond spherical sliders of radius 30 and 100 μm, respectively, were slid on these coatings under a load of 50 to 200 g at a sliding speed of 15 cm min^{-1}. The static and dynamic friction coefficients for SiO_2 films were found to be 0.1 and 0.06, respectively, depending on the load and radius of the slider. For lower load and small slider radius the tracks on SiO_2 film were groove-like, and whisker-like cracks regularly grew from the edges of the tracks. For higher loads and larger slider radius, semicircular cracks in the film were regularly found behind the slider, but in thicker film (6 μm thick), circular cracks occurred. The origin of these cracks is discussed in terms of a tension zone produced around the contact area between the slider and the substrate under frictional force.

1. Introduction

Vacuum-deposited silica films have been variously used for optical interference films and electrical insulating films, as well as hard protective films for plastics. Recently, silica has also been used as a hard coating material for plastic ophthalmic lenses to prevent scratches or flaws produced by friction of hard dust such as silica sand particles. Therefore, it is necessary to investigate the mechanical properties of deposited thick silica films. We have previously studied the microhardness of vacuum-evaporated thick silica films [1] and also the wear properties in relation to their microhardness [2]. However, in practical uses of hard coated plastics, friction and frictional tracks may occur on cleaning off dust particles adhered to the coating. In this study we investigated the frictional properties and tracks on thick silica films made by vacuum evaporation. It is expected that if soft plastics are coated by a hard silica film, the deformation process of the plastics under load would be changed, so that the frictional properties and tracks would be somewhat modified.

2. Experimental details

2.1. Sample preparation

Silica was evaporated in vacuum by electron beam evaporation. The substrate was polymethylmethacrylate (PMMA) plate several millimetres thick. For reference, commercial glass substrate was also used. The pressure during evaporation was in the range 4 to 8×10^{-5} torr. The silica film thickness for the coating was fixed normally to be 2 μm throughout the experiments.

2.2. Friction tester

The Bowden–Leben type friction tester was used in our experiments. We used sliders of well-polished diamond spheres with radii of 30 and 100 μm. The load was 50 to 200 g and frictional force was measured from the tangential force detected by a strain gauge attached to a horizontal arm supporting the slider. The sample was moved smoothly by a motor-driven oil cylinder at a constant speed of 15 cm min^{-1}. Friction tracks made during the sliding experiments were observed by optical microscopy.

3. Results and discussion

3.1. Friction coefficient

Fig. 1 shows the dynamic friction coefficient (μ_K) between diamond spherical sliders of 30 and 100 μm radius and PMMA as a function of sliding load (W). μ_K increases with increasing load for the slider of 100 μm radius but is constant ($\mu_K = 0.62$) for that of 30 μm radius. The results are different from those known for various plastics, in which μ_K decreases according to the relation $\mu_K \propto W^{-n}$ (n is a constant depending on the material) [3] for sliders of radius 3 mm to several centimetres.

Fig. 2 shows the results of static (μ_S) and dynamic friction coefficients for SiO_2 films about 2 μm thick evaporated on to a PMMA plate. Obviously, μ_S is always higher than μ_K, and μ_K increases for loads of 50 to 200 g, irrespective of the radius of the slider. For example, we obtained $\mu_S = 0.1$ and $\mu_K = 0.06$ for $W = 50$ g and for a 100 μm radius slider.

The effects of the underlying substrate (PMMA) for a slider of 100 μm radius are seen in Fig. 1. For lower loading the deformation under the slider may be smaller than in higher loading, which may result in μ_S and μ_K of the SiO_2 film itself, although reflecting the effect of the slider radius. This means that the effect of plastic deformation of PMMA may not be so dominant. However, for the 30 μm radius slider and at a higher load ($\sim$ 200 g), the stress concentration under the slider becomes so high that the frictional force may include a component for the plastic deformation of PMMA, which results in μ_S and μ_K values approaching that of PMMA itself (Fig. 1).

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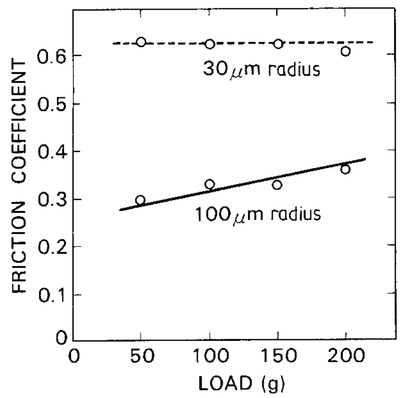


Figure 1 Relationship between dynamic friction coefficient (μ_K) and load for PMMA (slider radius; 30, 100 μm).

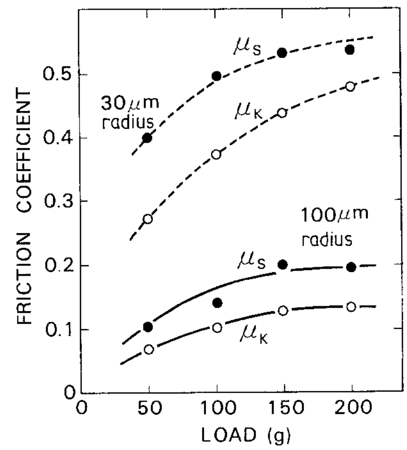


Figure 2 Static and dynamic friction coefficient for SiO_2 films on PMMA (slider radius; 30, 100 μm).

3.2. Effect of substrate materials on frictional tracks

Fig. 3 shows frictional tracks formed when the diamond slider of 30 μm radius slid on SiO_2 film/PMMA or SiO_2 film/glass under a load of 50 g, where the arrow shows the direction of sliding. A track on the PMMA substrate with no silica film (Fig. 3a) clearly shows a smooth furrow indicating plastic deformation of the substrate material.

A frictional track entirely different in aspect was obtained by depositing only a 2 μm thick SiO_2 film on PMMA, as shown in Fig. 3b. The width of the track was approximately 50 μm and on its inside densely distributed fine cracks were seen. Along both sides of the track whisker-like cracks growing forwards in the direction of sliding motion were also regularly seen; this is different from the case of TiN film/Crofer where cracks grew behind sliding direction [4]. The regular occurrence of cracks was considered to be caused by the stick–slip frictional motion between the slider and the substrate. The aspect of this track was a plastic deformation of the coated substrate, which means that the PMMA deformed first under the sliding load, such as in Fig. 3a, and then, accompanying this deformation, the SiO_2 film deformed. Detachment of the film may be prevented by the adhesion of the SiO_2 film to PMMA.

A frictional track on glass which is harder and more brittle than PMMA, is shown in Fig. 3c. Brittle surface fracture was indicated to be caused during sliding of the slider; the track width was not constant along the track. Inside the crack regular cracks crossing perpendicularly to the sliding direction are seen. The

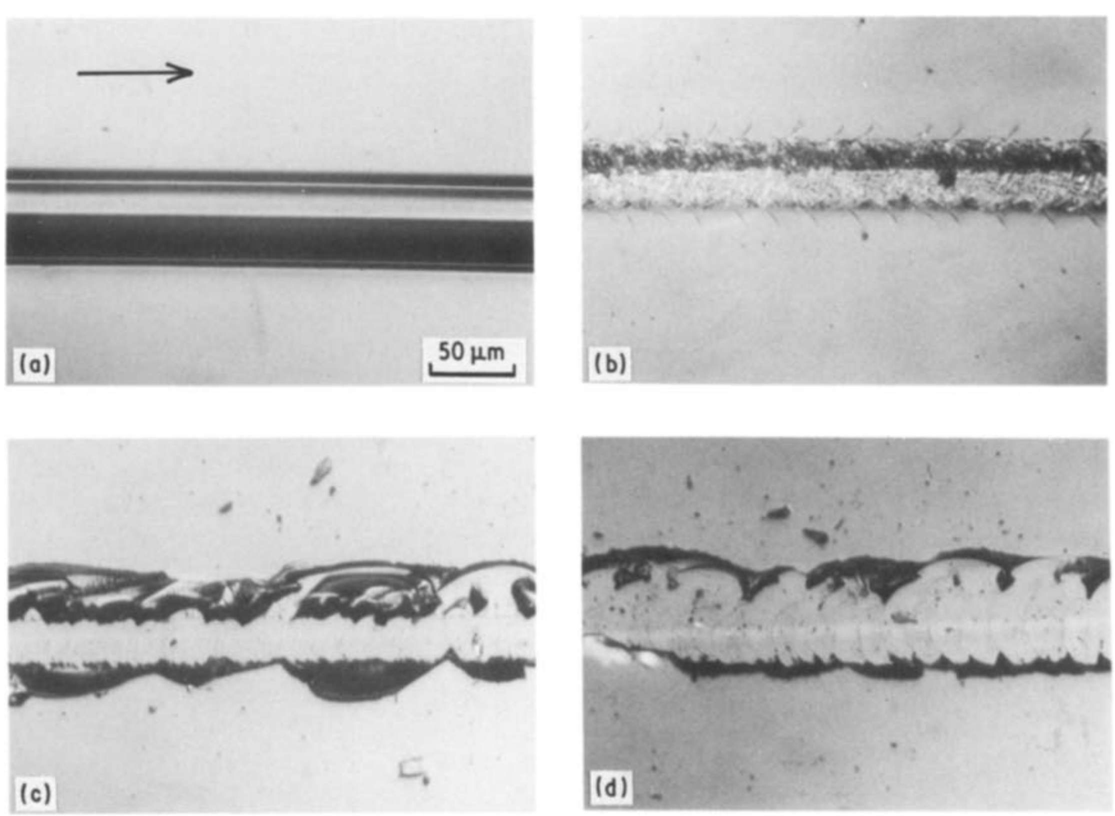


Figure 3 Frictional tracks on various substrates formed with a 30 μm radius slider under 50 g load. (The arrow shows direction of sliding and is the same for Figs 4 to 6.) (a) PMMA, (b) SiO_2 film/PMMA, (c) glass, (d) SiO_2 film/glass.

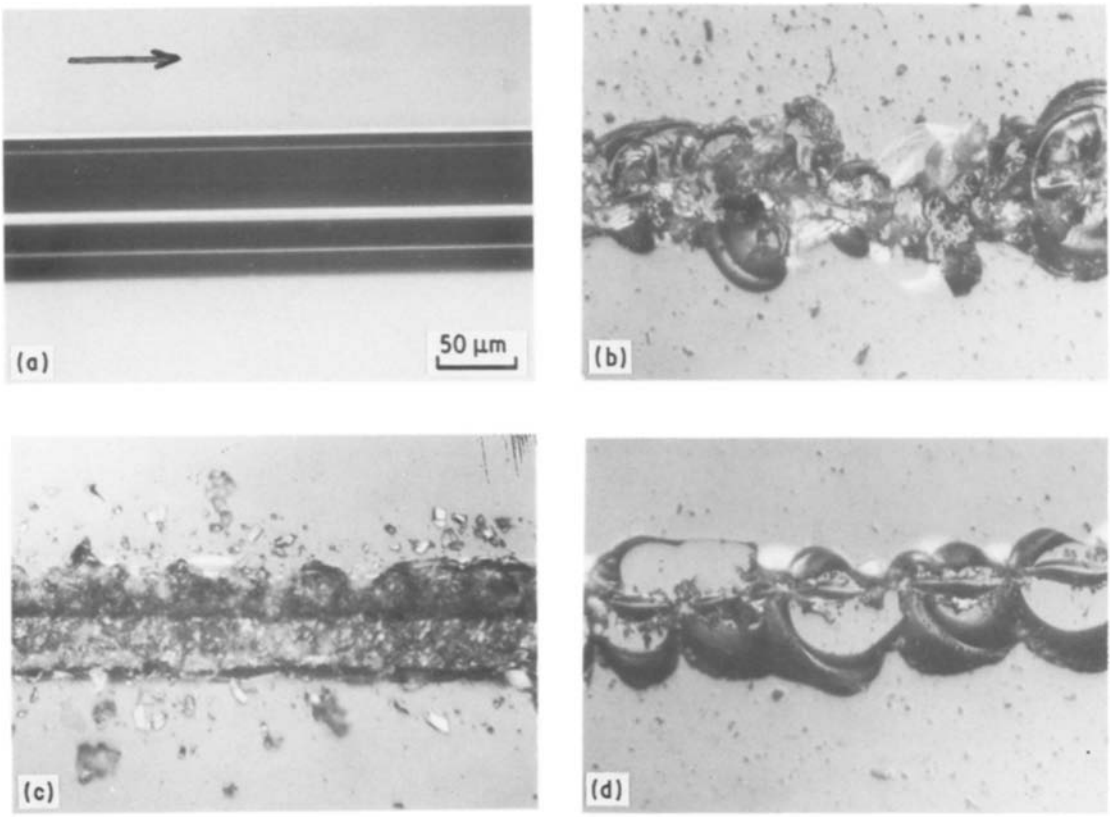


Figure 4 Frictional tracks on various substrates formed with a 30 μm radius slider under 100 g load. (a) PMMA, (b) glass, (c) SiO_2 film/PMMA, (d) SiO_2 film/glass.

same view is shown for SiO_2 film/glass in Fig. 3d, in which both SiO_2 film and the glass substrate fractured.

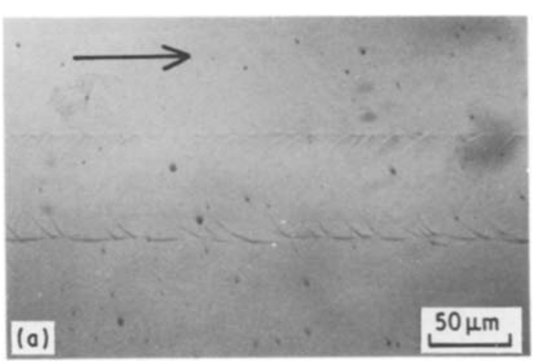
Fig. 4 shows tracks obtained for the same cases as in Fig. 3, except for a 100 g load. A smooth track for PMMA with no SiO_2 film (Fig. 4a) was caused by plastic deformation corresponding to Fig. 3a. On the other hand, intense conchoidal surface fractures were found for the glass substrate (Fig. 4b), this is the same aspect as seen for SiO_2 film/glass (Fig. 4d).

For (2 μm thick) SiO_2 film/PMMA (Fig. 4c), a frictional track like a groove, accompanied the plastic deformation of PMMA, but the SiO_2 film inside the track was detached from the substrate and scattered, in fine pieces outside the track.

Hamilton and Goodman [5] demonstrated that a maximum shear stress acts in the surface of circular sliding contacts between rigid bodies. Although the stress distribution may be more complicated for a film-deposited substrate, it is considered that brittle surface-fracture of an SiO_2 film and its detachment from the PMMA are due to this large shear stress in the film.

3.3. Effect of load on frictional tracks

Fig. 5 shows frictional tracks made with a slider of 100 μm radius as a function of sliding load. In Fig. 5a, for the slider under 100 g load, semi-circular cracks of



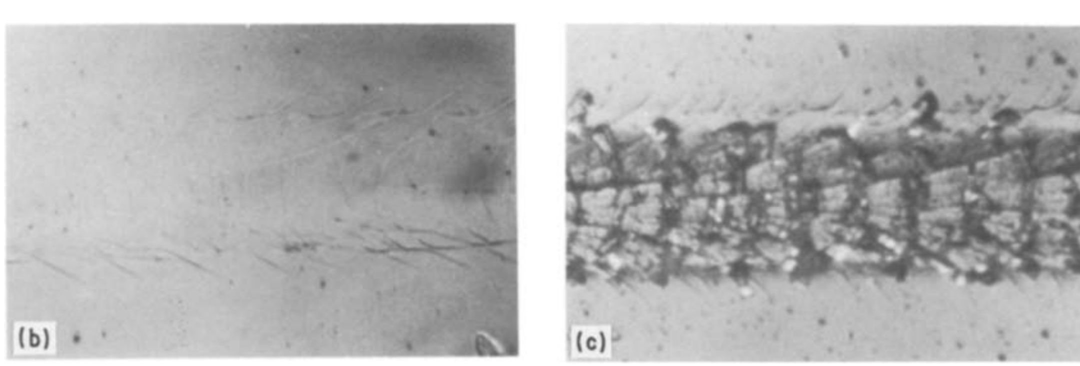


Figure 5 Frictional tracks on SiO_2 film/PMMA made using a radius slider. (a) 100 g, (b) 200 g, (c) 300 g.

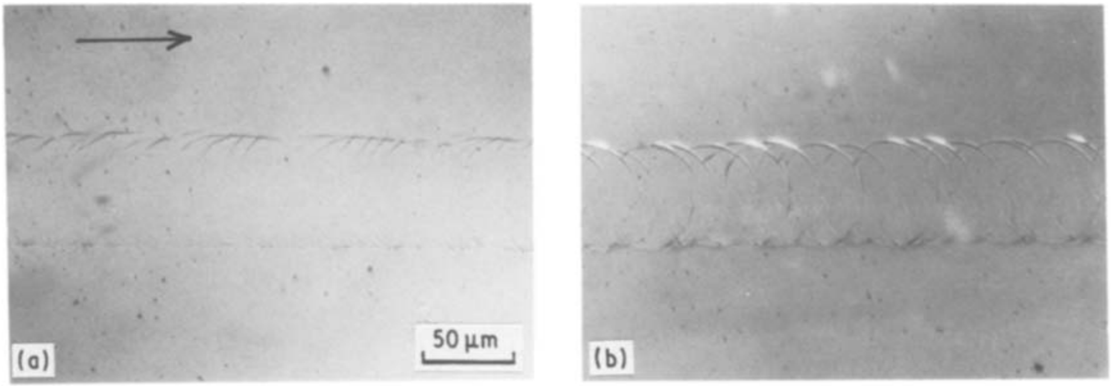


Figure 6 Frictional tracks on SiO_2 films of different thickness on PMMA made using a 100 μm radius slider under 100 g load. (a) 2 μm thick, (b) 6 μm thick.

the SiO_2 film regularly occurred inside the track and grew backwards along the direction of sliding. In addition, for a 200 g load (Fig. 5b), whisker-like cracks grew regularly forwards in the direction of sliding.

The view of a track for a 300 g load (Fig. 5c) is much more complicated: cracks seen in Fig. 5b were further developed and some parts of the SiO_2 film became detached from the PMMA.

3.4. Effect of film thickness on frictional tracks

Frictional tracks on 2 μm thick SiO_2 film/PMMA and 6 μm thick SiO_2 film/PMMA made by the slider of 100 μm radius under a load of 100 g are shown in Fig. 6. For the 2 μm thick film (Fig. 6a), semi-circular cracks were regularly produced inside the track and along the sliding direction, which were connected to each other along both track edges. In the 6 μm thick film (Fig. 6b), on the other hand, circular-cracks were regularly found inside the track, and extended forwards and backwards in the direction of sliding.

We considered the origin of these cracks to be as follows: in general, when two elastic rigid bodies are in contact under tractive and normal forces, the substrate is deformed so as to produce a surface tensile stress ahead of and behind the contact [6]. Accordingly, in the case of higher elastic modulus of the film than that of the substrate, cracking or plastic flow can occur. This situation is illustrated in Fig. 7. In the present case (SiO_2 film/PMMA) the elastic modulus of a thick SiO_2 film is higher than that of PMMA, because the microhardness of the SiO_2 film is nearly 620 kg mm^{-2} [1], which is evidently higher than that of PMMA, 32 $\pm$ 3 kg mm^{-2} [7]. This explains the occurrence of cracks in the film on sliding. For the 2 μm thick SiO_2 film, the plastic deformation of PMMA under the contact area is larger than that for the 6 μm thick film, so the deformation may be smaller in the tension zone just ahead of the slider; but in contrast, the zone behind the slider is under the tension zone caused by the sliding force, which may cause cracking in this zone. If the film is thicker, the surface of the substrate becomes harder and, because its plastic deformation is small, this may result in cracks produced behind the slider, growing towards the tension zone ahead of the slider.

In another point of view regarding the thinner rigid SiO_2 film, is that the elastic energy stored in the film itself when the slider starts to move is small, so the crack length relating to liberation of elastic energy becomes short; however, for the thicker film, highly stored elastic energy creates a long circular crack after the slider is moved.

The regular occurrence of cracks for these cases is attributable to the stick–slip phenomenon in the friction between the slider and the film.

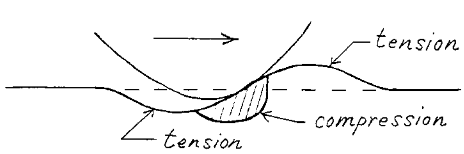


Figure 7 Compressive and tensile stresses caused by traction of the slider.

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