Friction of Elastomer-on-Glass System and Direct Observation of Its Frictional Interface

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Abstract. We performed a study on the static friction of PDMS elastomers with well-defined surface topography sliding over glass. An experimental setup for simultaneous measurements of friction force and direct observations of frictional interface has been developed. The static friction force was nearly proportional to normal load. The static friction force was independent of stick time. The simultaneous measurements revealed that the static friction force was proportional to the total area of contact. The coefficient was nearly independent of the surface topography of PDMS elastomers.

1. Introduction
Nominally flat solid surfaces are covered with microscopic asperities. When two solid bodies are brought into contact, contacts occur through the asperities forming multiple asperity contact. This multiple asperity contact is essential in understanding sliding friction [1, 2].

In spite of its importance, there are only a few reports on direct observations of sliding frictional interfaces [3-7]. Furthermore, experimental characterizations of the asperities are not straightforward due to the random nature of solid surfaces [8, 9]. Firstly, measured roughness and correlation length depend on measuring instruments and the sampling intervals [10]. This indicates that a wide range of length scales of asperities are superimposed. That is, there is no single length scale, such as curvature of asperities, assumed in Greenwood and Williamson’s theory [2]. Secondly, relevant asperity size in a particular problem depends on the sliding condition. For instance, small asperities play important roles under low normal load. On the other hand, larger ones do under high normal load.

In this report we used poly-(dimethylsiloxane) (PDMS) elastomers with well-defined surface topographies as sliding samples to avoid ambiguity in interpretation of asperities. In addition, an experimental setup for simultaneous measurement of friction force and direct observation of frictional interface has been developed. Using this setup, the static friction force of the PDMS elastomer sliders was characterized and the relationship between the static friction force and the total area of contact is discussed.
2. Materials and Method

2.1. Sample preparation
PDMS prepolymer was poured on machined moulds. The PDMS elastomers were peeled off from the moulds after the prepolymer solidified at room temperature. Figure 1 shows the obtained PDMS samples. Three types of surface topographies were used in this study: 5 x 5 identical conical asperities, 5 x 5 identical hemisphere asperities, and random surface with RMS roughness of around 50 μm. The lateral dimension of the PDMS elastomers was around 20 x 20 mm². The thickness of the elastomers was 3 - 5 mm. The PDMS elastomers were glued onto stainless steel plates of 25 x 25 x 1 mm³ through which normal load and shear force were applied.

Fig. 1. PDMS elastomer samples; (a) Random surface; (b) Conical asperities; (c) hemisphere asperities.

2.2. Experimental Setup
Figure 2 shows a schematic representation of the experimental set-up. Elastomer samples slid on a right angle prism of 300 mm in length. The sliders were driven by a coiled spring mounted to a translation stage. The spring constant ranged from 14 N/m to 1.3 x 10³ N/m. The translation stage moved at a velocity V ranging from 0.033 mm/s to 1.0 mm/s by an AC servo motor. Normal load was applied by adding calibrated masses atop. The shear force was measured with a load cell. The signal from the load cell was sampled at the rate of 100 Hz with Analog/Digital converter. The use of the right angle prism enabled direct observations of contacts at the frictional interface [3]. The frictional interface was illuminated by LED backlight at the incident angle of 45° which exceeds the critical angle of air/BK7 interface, so that the incident light was reflected at the air/BK7 interface. On the other hand, the incident light can transmit the PDMS/BK7 interface. Hence, when the reflection was observed by CCD camera, the contact area can be visualized as darker regions in a bright background. The image or movie was captured via an image capture board.
3. Results and Discussion

3.1. Direct observation of frictional interfaces
Figure 3 shows typical images of multiple asperity contact interfaces between the PDMS elastomers and the right angle prism. Contact areas can be seen as dark regions in a bright background. In case of PDMS sliders of random surface topography, growth of existing contacts, coalescence of contacts and appearance of new contacts were observed when normal load was increased as shown in the photographs. In case of PDMS sliders with hemispherical or conical asperities, regular lattice patterns of contact regions were observed as expected. In figure 3 (d), there is inhomogeneity in contact area among contacts, reflecting height variance among the asperities. There are also voids in contacts. These facts show low precision of machining of moulds. In future studies, moulds made with precision machining should be used.
3.2. Time evolution of shear force

Figure 4 shows a representative time evolution of the shear force when loading a PDMS elastomer slider with conical asperities from rest at the driving velocity $V = 0.33$ mm/s with normal load of 0.8 N. When starting to load from rest at a constant $V$, a linear rise was observed corresponding to the spring elongation during a stick phase. This stick phase was followed by a stick-slip sliding. The static friction was defined as the peaks of the shear force. No steady sliding was observed in the parameter range of our measurements ($V = 0.033$ to 1.0 mm/s; $k = 14$ to $1.3 \times 10^3$ N/m).
3.3. Normal load dependence of static friction
Figure 5 shows normal load dependence of the static friction forces of PDMS samples with the three types of surface topography. The static friction forces monotonically increased with normal load. The double logarithmic plot of Figure 5 showed that the static friction forces increased as a power of normal load. The exponents were 0.84 (a random surface topography PDMS sample), 0.78 (a PDMS sample with hemispherical asperities) and 0.83 (a PDMS sample with conical asperities). The discrepancy in the exponents from the Hertzian theory of contact may result from low precision machining of the moulds indicated in Figure 3 (d). The static friction coefficients were computed to be 4.0 (a random surface topography PDMS sample) and 1.4 (a PDMS sample with hemispherical asperities and one with conical asperities), assuming that linear relationship between normal load and the static friction forces. The static friction coefficients were larger than those of standard materials in tribology such as metals or rocks.
3.4. Stick time dependence of static friction

Figure 6 shows stick time dependence of the static friction force of a PDMS slider with conical asperities with normal load of 0.6 N. Stick time was varied by changing $V$ from 0.033 up to 1.0 mm/s. The static friction force was independent of stick time.

Fig. 5. Normal load dependence of static friction forces of a random surface topography PDMS sample (squares), a PDMS sample with hemispherical asperities (open circles), and a PDMS sample with conical asperities (triangles).

Fig. 6. Plot of the static friction force of a PDMS slider with conical asperities vs stick time.
3.5. Simultaneous measurements of static friction force and contact area

Figure 7 (a) shows normal load dependence of the static friction force and of the total area of contact of a PDMS slider with conical asperities. The static friction force and the total area of contact showed similar dependence on normal load. Figure 5 (b) shows the static friction forces of the three types of PDMS samples as a function of the total area of contact. The three plots showed linear relationship between the static friction forces and the total area of contact, consistent with the conventional multiple asperity contact model of sliding friction [1]. The proportional coefficient was 0.3 x 10^6 N/m^2 and almost independent of surface topography. During sliding, contacts around the leading front of the slider were larger than those around the tailing end, suggesting that more careful application of shear force is required.

![Figure 7](image-url)

Fig. 7. (a) Plot of the static friction force (squares) and the real contact area (open squares) of a PDMS slider with conical asperities vs normal load. (b) The real contact area dependence of the static friction forces of a PDMS slider with conical asperities (triangles), one with hemispherical asperities (open circles) and one with random surface topography.

4. Summary

To avoid the ambiguity in interpretation of asperities, samples with well-defined surface topography were used. An experimental setup for simultaneous measurement of friction force and direct observation of frictional interface has been developed. The static friction was nearly proportional to normal load. The static friction coefficient was 4.0 for PDMS elastomers with random surface topography and 1.4 for ones with conical or hemispherical asperities. The static friction force was independent of stick time. Although it was inferred that further improvements in our experimental setup should be made, the correspondence was shown between the static friction force and area of real contact, that is, the static friction force was proportional to the area of real contact. The coefficient was around 0.3 x 10^6 N/m^2 and almost independent of surface topography.

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