Mimicry of Biological Adhesion Through Fabrication of Fibrillar Surfaces

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Abstract:
The extraordinary climbing ability of geckos is because of the fine structure of their toe pads. It contains a layer of fine fibrils terminated by spatula-like features. This project aims to fabricate artificial mimics of these structures to make dry adhesives. We have made adhesive surfaces using the polymer poly(dimethylsiloxane) (PDMS). Our samples have thin pillars (fibrils) standing on the PDMS base and are topped by a thin continuous film of PDMS. Significantly enhanced adhesion and static friction on this sample has been reported. We further investigated the rate-dependence on adhesion and frictional properties of these samples and a significant further enhancement in adhesion and static friction is found with increasing rate. Also, it is found that the dynamic friction of our fibrillar samples is independent of spacing (geometry) and displacement rate and is close to that of the flat control sample. Our fabrication procedures include making a master mold by etching a Si wafer.

Sample Fabrication:
Samples with thin pillars/fibrils are made by molding PDMS (Sylgard 184, Dow Corning) in silicon molds. Silicon molds are made using standard photolithography and deep ion etch techniques. The depth of the holes is estimated by the duration of etch, and that decides the height of the pillars in the samples. After the holes of desired depth and with desired pattern are made on the Si wafer, a self assembled monolayer (SAM) of the molecule n-hexadecyltrichlorosilane is deposited on the wafer to reduce its surface energy. The polymer is poured in the Si mold and sandwiched between a glass slide (having SAM on it) and the mold. It is then cured in an oven at 80°C for 2 hours and then kept in dry ice for around 6 hours. In dry ice, the PDMS shrinks more than silicon, making it easier to remove it from the mold. The final step of affixing a thin terminal plate of PDMS on the pillars is accomplished by spin-coating a SAM-coated Si wafer with PDMS, and then placing the samples on this wafer with pillars in contact with liquid polymer. The assembly is then cured at 80°C for an hour in the oven. Glass coverslips are attached to the back of the samples while they are still on the wafer using oxygen plasma to activate adhesion between the two. Once the samples have the additional backing of a cover-slip, they are carefully pulled off the wafer. Figure 1 shows a typical sample.

Figure 1: Scanning electron micrograph of a synthetic fibrillar array with a terminal thin film. Fibrils are arranged in a square pattern. Their height is about 30 µm. The nearest neighbor distance between fibrils is about 65 µm. Each fibril is square in cross-section with sides nominally 10 µm wide. The terminal film is about 4 µm thick.
**Normal Indentation Experiments:**

The samples were subjected to cyclic normal indentation by a sphere at different rates of indenter displacement. Samples were indented with a glass sphere that had been treated with a self-assembled monolayer of hexadecyltrichlorosilane. The glass indenter was lowered on the samples (placed on an inverted microscope) and after it reached a particular depth in the sample, it was retracted until there was no contact. The motion of the indenter is controlled by a motorized linear stage (Newport ESP MFA-CC) using motion controller (Newport ESP300), and the indenter speed was constant during the test. The force on the indenter is measured by an in-line load cell (Transducer Techniques GSO-10). The displacement of the indenter is obtained by subtracting displacement due to system compliance from the displacement of the motorized stage. Also, the contact between the indenter and sample was monitored during the test by recording its image through the inverted microscope. Experiments were conducted on each sample with different indenter speeds ranging from 0.05 µm/s to 300 µm/s (Figure 2).

The shear force is measured by a load cell in line with the balance arm. Deformation of the contact region is recorded by means of an optical microscope. Typical experimental force and displacement data for a flat control and a fibrillar surface are shown in Figure 3. Two main characteristics of the shear response of our fibrillar samples compared to the unstructured sample are: 1) the strong enhancement of the static friction force; and 2) dynamic friction force remains almost unchanged with changes in geometry.

![Figure 2: Experimental force-displacement data for a (a) fibrillar sample (80 µm inter-fibrillar spacing) at different indenter rates and (b) unstructured control sample.](image)

**Shear Experiments:**

The shear experiments were conducted on a custom apparatus built on an inverted optical microscope on which the sample is placed. A spherical glass indenter with a 2 mm radius is placed on the fibrillar surface. The surface of the indenter is treated with a monolayer to reduce the shear force between the indenter and the PDMS sample. The fixed normal force, $P$, is applied by means of a mechanical balance. The actual value of normal force corresponding to this contact area is obtained by performing an independent indentation experiment as described above. The shear is applied by translating the glass slide at a constant rate of 30 µm/s.

![Figure 3: Typical shear force response of (a) fibrillar sample with $w = 35$ µm and (b) unstructured control sample as a function of shear displacement at five displacement rates.](image)

**Results:**

Both in fibrillar samples and unstructured control samples, significant enhancement in adhesion and static friction is found with increasing indenter rates (Figures 2 and 3). By studying the effect of rate on adhesion and static friction, we show that both adhesion and static friction enhancement are due to a crack trapping mechanism in our fibrillar samples. Moreover, this crack-trapping mechanism is found to be multiplicatively coupled with rate-dependent *intrinsic* interfacial adhesion energy. The shear experiments showed that dynamic friction of our fibrillar samples is independent of inter-fibrillar spacing (geometry) and displacement rate, and is close to that of unstructured control samples.

**References:**

