GECKO-INSPIRED DRY ADHESIVE FOR ROBOTIC APPLICATIONS

John Tamelier*, Sathya Chary, and Kimberly Turner
Department of Mechanical Engineering, University of California, Santa Barbara
Santa Barbara, CA, 93106

Jing Yu, Saurabh Das, and Jacob Israelachvili
Department of Chemical Engineering, University of California, Santa Barbara
Santa Barbara, CA, 93106

ABSTRACT

Materials with the capability to simultaneously support large shear (friction) and normal (adhesion) forces are essential to successful static robotic clinging applications (Zeng et al., 2009). In order to be mobile, these forces must be able to be dynamically controlled with rapid switching between sticky and non-sticky states. Much of the current development has been inspired by the gecko because it is the heaviest animal to be able to stick to a variety of surfaces in almost any orientation. Although a material which outperforms the animal in every aspect has yet to be developed, progress is being made through a variety of approaches and materials. Micron-scale, rectangular flaps composed of a polymer have been fabricated over centimeter sized areas with the intention to create a switchable, high friction, high adhesion, anisotropic material similar to that found on the gecko. The developed material is batch-fabricated using massively parallel microelectromechanical systems (MEMS) techniques and is designed to have different shear properties for the in-plane directions. The high compliance in one direction enables conformation to small asperities and achievement of large true areas of contact for high adhesion and friction forces. The anisotropy built into the design will allow for controllability based on shearing length and switchability based on shearing direction. These properties, when coupled with suitable articulation mechanisms, produce a mobile reversible adhesion system.

1. INTRODUCTION

The impressive climbing ability of the gecko can be attributed to the hierarchical foot pad structure. Each of the five digits on the four feet of the gecko is comprised of micrometer and nanometer sized features composed of β-keratin. The exact value of the Young’s modulus is unknown at the present time, but features found in two other types of geckos place the value around 1.5 GPa (Peattie et al., 2007). The β-keratin structures found on the bottom surface of each of the gecko’s toes are arranged in rows producing thin plate-like structures, lamellae. These lamellae contain rows of setae which are initially straight but curve at their ends. The setae are 4.2 µm cylindrical shafts, 110 µm in length (Maderson, 1964), and start at an angle of 45° with respect to the skin. Each seta then branches out to hundreds of spatulae which form the final structure of the gecko adhesive system. The spatulae are roughly triangular shaped with a length of 500 nm, a width of 200 nm, and a thickness of 10 nm (Ruibal and Ernst, 1965).

Because this hierarchical structure is able to conform to roughness asperities, the gecko is able to obtain intimate contact with the opposing surface. Close contact is essential for the short-range van der Waals forces, which have been shown to be primarily responsible for the gecko’s impressive climbing and clinging abilities (Autumn et al., 2002) along with capillary forces (Huber et al., 2005) in a secondary role. The van der Waals force is weak for a single small contact such as a spatula, but this force can be substantial when summed over all the available spatulae branching out from approximately 6 million setae.

Measurements on the gecko have shown that the area of the two front feet, 227 mm², is capable of supporting 20.1 N in the direction parallel to the surface (Irschick et al., 1996). With a density of 14,400 setae/mm² the average shear force per setae for a whole foot measurement would be approximately 6.2 μN. A separate test performed on a single setae showed the shear force could reach as high as 194 μN (Autumn et al., 2000). Small scale tests often give high force values, but these levels are often not attainable in larger scale testing because of the inability of all the spatulae to make sufficient contact with the other surface, even on ones that are smooth. This problem is amplified for the animal in its natural environment where surfaces, such as bark and rock, can contain varying degrees of roughness or can be dirty, degrading the adhesive surface. Materials developed must also have some factor of safety built in for the common situations where only a small percentage of the sites make adequate contact.

The first theories developed for the relation between friction force and applied load on dry, unlubricated surfaces showed a direct proportionality between friction and normal load, without any dependence on
contact area. This is commonly called Amontons’ law and can be related by:

\[ F = \mu L, \tag{1} \]

where \( F \) is the friction force, \( \mu \) is a constant of proportionality called the coefficient of friction, and \( L \) is the load, or normal force. For many situations this equation is perfectly acceptable. However, when the two surfaces adhere to each other, Amontons’ law cannot describe the measurable friction forces at zero and negative loads. In these situations, a critical shear stress is needed to initiate movement between the two surfaces. Because equation 1 does not agree with this observation, a term must be added to the original equation. The addition includes the critical shear stress, \( S_c \), and an area of contact, \( A \), which leaves:

\[ F = \mu L + S_c A. \tag{2} \]

Once the shear stress has been exceeded and the surfaces are moving, they will, in most cases, continue sliding past each other. It is possible for the surfaces to slide in small regular jerks relative to each other which is known as stick-slip. In equation 2 it can be seen that at low loads the adhesion portion of the friction force will be dominant, adhesion-controlled friction, whereas at high loads the load term will be more significant, load-controlled friction.

2. FABRICATION

The structures developed used microfabrication techniques to define a mold which was then filled with a polymer, polydimethylsiloxane (PDMS) (Sylgard 184, Dow Corning Corporation, Midland, MI). Microfabrication describes the process of creating small structures, generally with dimensions of micrometers or smaller. Many of its processes originally came from the early development of semiconductor and integrated circuit devices, but now there is a wide variety of products made using similar techniques. The processes used to define the structures created in this work have the capability to reduce the dimensions to the sub-micrometer range, something currently not available to all gecko synthetic adhesives. An additional advantage is the parallelism inherent to microfabrication. A single wafer can produce hundreds of copies of a single design, depending on the sample size. These copies are all subjected to the same microfabrication process, resulting in reduced creation time and high uniformity across the wafer. Once the mold is created, it can be used for multiple cycles, thereby reducing future processing time and cost associated with creating the structures.

2.1 Vertical Flaps

The flap microstructures were photolithographically defined with twice the density of the angled flaps and dimensions of 10 \( \mu m \) width and 4 \( \mu m \) thickness. The photoresist pattern was transferred using the deep reactive-ion etch (DRIE) process 15 \( \mu m \) into the exposed silicon to create a negative mold. The DRIE process was chosen because it allows for greater etching depths when compared to other conventional reactive-ion etching (RIE) processes. In future designs, the etching depth into the silicon can be altered if needed. To facilitate removal of the PDMS from the silicon mold, octadecyltrichlorosilane (OTS) was vapor-deposited on the silicon wafer immediately before molding. After pouring PDMS onto the silicon mold, the polymer was left to cure in an oven at 100\( ^\circ \)C for 10 minutes. The two materials were then separated, resulting in cm-scale PDMS samples and the original silicon piece in good enough condition to be reused for creating future copies of the mold.

\[ \text{Fig. 1. Vertical PDMS flaps created using a silicon molding process.} \]

2.2 Angled Flaps

Standard microfabrication techniques are two-dimensional with the third dimension defined by deposition or etching. Therefore, some modifications have been made to fabricate angled three-dimensional structures with anisotropic friction properties. An angled lithography process has been developed to fabricate a negative mold for angled flaps in polymethylglutarimide (PMGI). A glass wafer is used to avoid reflections from the substrate during the angled exposure step. In the first step, the glass wafer is coated with a thick layer of PMGI SF-15 - multiple coats may be used to increase thickness as desired - and soft baked. A coat of a thin imaging photoresist is then applied over this
to form a bilayer. The lateral flap dimensions as defined on the mask are transferred into the imaging resist layer upon exposure to i-line (365nm) UV light in a wafer stepper aligner. PMGI SF-15 is not photoactive in i-line UV, but is sensitive to deep UV wavelengths. After developing the top imaging resist layer, the wafer is then mounted at an angle in a deep UV exposure system. In this step, the pattern in the imaging resist acts as a mask for deep UV exposure of PMGI. The lower resist layer is then developed in a separate developer solution to fabricate angled slots with the lateral dimensions already defined in the top resist layer. After O₂ plasma and silane exposure, the angled slots are then used as a negative mold to fabricate three-dimensional anisotropic angled flaps with PDMS. The process is being currently improved to achieve structures with a higher aspect ratio. Flaps fabricated have a height of 10 µm, width of 10 µm, thickness of 3.5 µm, and an angle of 20 degrees.

3. TESTING

In order to quantify the adhesion and friction properties of the fabricated structures, a 3D displacement and force sensing probe attachment for the surface forces apparatus (SFA) 2000 has been developed. The new attachment (Kristiansen et al., 2008) generates both normal and lateral movement of surfaces, and measures the resulting normal and lateral forces independently. The attachment can perform both load/pull and load/drag/pull tests of the fabricated structures with a contact area around 0.1-1 mm². The actual contact area during experiments was dependent on the applied load. In the experiment, a thin PDMS sheet with fabricated PDMS micro-flaps was glued on a flat glass disk. Prior to use, the glass disk was soaked in chloroform (EMD Chemical Inc., Gibbstown, NJ) for 1 day and then rinsed thoroughly with ethanol followed by drying in dry-nitrogen gas. The disk was then mounted onto a double cantilever spring of a SFA box for testing. The normal load was measured by a strain gauge glued on the double cantilever spring with a known spring constant. Applying normal load causes the deformation of the double cantilever spring, which can be measured by the strain gauge as it transfers the deformation into electric signal for data analysis. A spherical glass disk with a radius of curvature of 2 cm was mounted to an upper friction device, which can generate lateral motion with a sliding distance of 500 µm and measure friction forces. During sliding, the friction device measures the friction force and the strain gauge measures the load on the PDMS flaps. The adhesion and friction tests were performed with the spherical glass disk compressing and sliding against the opposing PDMS micro-flaps.

3.1 Adhesion Testing

To measure the adhesion forces, the spherical glass disk was first pressed against the PDMS micro-flaps until a desired load was reached. The two surfaces were then separated from each other at an angle perpendicular to the bottom surface. Adhesion tests were performed one time for a given preload with loading and separation done at a constant speed of about 0.06 µm/s.

3.2 Friction Testing

To measure the friction forces, the spherical glass
disk was pressed against the PDMS microstructures at a speed of about 0.06 \( \mu \text{m/s} \) until a desired load was reached. The spherical disk then slid a distance of 200 \( \mu \text{m} \) at a speed of 20 \( \mu \text{m/s} \) forwards and backwards in directions perpendicular to either the long or short edges of the fabricated flaps. When the sliding concluded, the surfaces were separated from each other at an angle perpendicular to the bottom surface at a speed of about 0.06 \( \mu \text{m/s} \). Any adhesion force generated during separation is recorded as a frictional adhesion force. The friction test was repeated on the flap geometry eight times.

4. RESULTS

The vertical PDMS micro-flaps exhibited strong adhesion against the glass surface, as shown in Fig. 4. During testing, the vertical pillars are compressed axially until they either buckle or are slightly bent over due to the curvature of the sphere. A larger normal load gives rise to a larger elastic deformation of the PDMS flaps, resulting in a higher number of contacts and therefore greater adhesion.

![Fig. 4. Strong adhesion, increasing with applied preload, was evident during separation of the vertical micro-flaps and the spherical glass disk.](image)

The vertical micro-flaps exhibited anisotropic frictional behaviors while sliding along different directions of the micro-flaps as seen in Fig. 5. Sliding in the x-direction, perpendicular to the smaller face, shows only load-controlled friction, where the friction force is proportional to the normal loading force. Sliding towards the large edge of flaps, in the y-direction, gives rise to adhesion-controlled friction, where the friction force is proportional to contact area, at loads less than 15 mN. Above 15 mN loads, the friction mechanism then is dominated by load-controlled friction.

![Fig. 5. Sliding in different directions of the vertical micro-flaps gives rise to different frictional behaviors. Sliding in the x-direction shows only load-controlled friction. Sliding towards the large edge of flaps, y-direction, exhibits adhesion-controlled friction at low loads and load-controlled fiction at higher loads.](image)

Interestingly, sliding perpendicular to the smaller face, in the x-direction, also gave very regular stick-slip behavior as can be seen in Fig. 6. The width of the micro-flaps is about 2.5 times as big as the thickness and therefore gives a much higher stiffness along the smaller face of the flaps. Due to this higher stiffness in the x-direction, the flaps are hard to deform elastically, and this causes the stick-slip spikes during sliding. The high stiffness also prevents a large contact area between the spherical glass disk and the micro-flaps. Consequently, there does not exist strong adhesion between surfaces, which would explain the pure load-controlled behavior of the friction when sliding along the x-direction.

![Fig. 6. Stick-slip spikes were evident in the friction trace while sliding in the x-direction for the vertical](image)
flaps.

As seen in Fig. 7, there was no stick-slip behavior exhibited while sliding in the y-direction, shown in Fig. 1. The smaller ratio of flap height to width along the large face results in the vertical flaps being easier to bend and deform. Because individual contact addition or losses are not as easily discernible due to the decreased stiffness, no stick-slip friction spikes were observed during sliding. The higher elastic deformation does give rise to a larger contact area, especially at low loads, and thus causes the adhesion-controlled friction seen in Fig. 5.

The angled flaps exhibited a remarkably different trend for both adhesion and friction when compared to the vertical flaps. It was expected that the flaps would be bent elastically in the direction of their initial tilt and that higher preloads would result in higher adhesion values because of the additional contact area. However, the adhesion forces were roughly constant during adhesion testing. The adhesion force was very low and never exceeded 0.1 mN for the tested preloads between 0.8 and 6.5 mN.

The angled structures were only tested for friction in the y-direction as marked in Fig. 2. Although differences were expected in sliding with and against the tilt, the forces for a given preload were very similar in both directions. Higher friction forces were also expected for the angled structures, but testing, as can be seen in Fig. 8, revealed the opposite with forces around one order of magnitude less. The geometry of the flaps, as discussed in the following section, could be responsible for this decrease in ability to withstand friction forces.

Fig. 8. Friction force generated by the angled flaps when a glass disk was slid in the direction perpendicular to the large face of flaps.

After friction testing, there existed an adhesion force during separation between the glass puck and angled flaps which was not seen in the vertical flap testing. This force, caused by the additional contact area generated during sliding, represents a two to eight fold increase over the pure adhesion test result. Frictional adhesion is the mechanism employed by the gecko to rapidly stick and unstick with ease. The frictional adhesion values generated after the friction test are shown in Fig. 9.

Fig. 9. The frictional adhesion force created by the angled flaps when tested against a spherical glass disk.

5. DISCUSSION

In the vertical flap adhesion tests, the adhesion value was still increasing and had not yet reached a
maximum, suggesting that even higher loads could be supported. Values for the tilted structures were very low with none reaching higher than 0.1 mN. It is not surprising that at low loads the vertical structures exhibit higher adhesion. With double the flap density and a flat top, instead of curved as is the case in the angled structures, the vertical arrangement has more surface area to contact the glass puck. However, when the load is sufficiently increased, the angled flaps should be able to bend and bring the face of the flap, which can provide a larger contact area, into contact with the other surface. It is possible that the loads were not sufficiently high for the enough bending to occur for large contact areas. When comparing Fig. 1 and 2, differences in flap surface roughness are also clearly visible. Since angled flaps have curvature and varying surface roughness, these structures are not able to create the same areas of contact for high adhesion. It should be noted that for mobile robots, a non-sticky default state, as was seen with the angled flaps, is preferable. If the adhesive were to be sticky all the time, large amounts of energy would be wasted separating the two surfaces with each step of the robot. Work is in progress with exposure and development characterization of the photolithography process to remedy the surface and shape characteristics of the angled flaps.

Frictional tests in the y-direction between the vertical and angled flaps showed a large difference in the amount of force the structures resist, with the vertical flaps being able to withstand at least an order of magnitude more force. As can be seen by the SEM picture in Fig. 2, the angled flaps have a 2 µm wide and 1 µm tall base where the features have been defined during the photolithography step of the microfabrication. This small region can act similar to a hinge when bending the flaps a small amount, making it easier to bend them in either direction. In future fabrication processes, this region can be removed prior to molding in order to stiffen the structures. Although the angled flaps’ scaled shear pressure of 30 kPa falls short of the gecko’s value of 100 kPa, it is controllable. Depending on if the material is sheared some distance, adhesion forces can be present or absent. The scaled shear pressure for the vertical flaps is able to exceed the gecko’s value with a shear pressure of 300 kPa.

Time effects on adhesion and friction are currently being tested against the two flap geometries. Current data showing these effects is available only for the angled flaps and therefore has not been included in this work. Testing of the vertical flaps is scheduled for the near future and will allow for comparison.

CONCLUSIONS

Two microfabrication schemes have been presented for constructing thin rectangular flaps with a vertical and angled orientation. Centimeter sized areas have been produced with a high degree of repeatability across the mold. Using the SFA, both the adhesion and friction characteristics have been tested for low mN preload ranges. Adhesion values for angled flaps were below those of vertical flaps due to failure to achieve high contact area. Friction forces for the angled flaps were also lower than the vertical flap at all loads. The angled flaps exhibited frictional adhesion following low mN friction tests with values superior to those achieved during adhesion tests. The vertical flaps showed both load-controlled and adhesion-controlled friction depending on the orientation in addition to the stick-slip friction seen when sliding against the smaller face of the flap. Although the vertical geometry could not be controlled, a shear pressure higher than the gecko was achieved. Future work will extend the preload to higher values in order to discover the where friction and adhesion forces will plateau. It is also planned to test these structures, and others with different angles, over larger areas with a flat contacting surface to find the scalability of these structures. These results will be important for future integration onto robotic platforms.

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REFERENCES


