A HIERARCHICAL GECKO-INSPIRED SWITCHABLE ADHESIVE

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Abstract

The gecko, as well as other insects and lizards, have a very clever mechanism for reversibly adhering to just about any surface. An integrated multi-scale system enables geckos to run up, down and across vertical or inverted surfaces. Here we report the fabrication of a switchable on/off adhesive. Inspired by the gecko, a hierarchical system composed of aligned vertical polymeric nanorods coating ferromagnetic nickel platforms was fabricated. When subjected to a magnetic field, the nickel platforms undergo a reversible conformational change, reducing the available contact area, and reducing adhesion by 40 fold. Development of such adhesives will lead to a new paradigm in latching systems, and will enable microrobots to climb just about anything, allowing them to enter environments inhospitable to man.

Introduction

The mechanism of adhesion in the gecko dry adhesive has been of scientific interest since Aristotle observed a gecko running up and down a tree (1). Recently there has been an intensifying scientific investigation into the fundamental physics of the adhesive isolating van der Waals as the primary interaction (2, 3), with some contention that capillarity contributes to the adhesion (4, 5). Regardless of the fundamental interactions at the atomic scale, there is clearly a great deal of function contained in the hierarchical structure of the gecko's tarsus (6-9). The structure consists of 200 nm spatular termini at the ends of ~100 μm long, ~5 μm diameter setae, which extend from a compliant tarsal pad cushioned by blood sinuses (10-13). With each added level of surface compliance there is an increase in the contact area of system, correspondingly increasing adhesion (6). Even the toe of the gecko, which can wrap around surface features, serves to increase surface contact area. To better understand this concept, compare the comfort of sitting on a hard wooden bench to that of a cushioned recliner. The recliner is much more comfortable, because the weight of your body is displaced over a larger area. Now imagine they are both coated with an adhesive. Which will be more difficult to get out of? Thus a critical factor in the functionality of an adhesive is the ability of the surface to deform, to evenly displace load, and increase contact area.

There is, however, evidence that the hierarchical structure may serve another purpose – to reduce adhesion (2, 14, 15). Just as interesting as the gecko adhesion mechanism is the mechanism by which the gecko is able to release a surface. The specific geometries of the gecko's setae and spatulae allow the

gecko to control adhesion through macroscopic movements of its toes. By flexing muscles the toe of gecko peels away from the surface in an inward fashion. This in itself aids in the detachment of the foot, just as peeling a piece of tape off of a surface is easier than trying to pull it off all at once. But there is more to the story. It has been shown theoretically (16) and experimentally (3) that the magnitude of adhesion of the setae is greatly dependent on the angle of applied pull-off force. Thus when the gecko goes from a squeezing mechanism to a peeling mechanism, the adhesive force goes from a maximum to a minimum (16). This can also be seen at the nanoscale as the resolved force on the spatulae changes the interactions from a frictional regime to a peeling regime, greatly reducing the adhesion (6). So through clever geometrical design of a hierarchical structure the gecko is able to control the adhesion mechanics from the macro-scale to nano-scale through a macroscopic muscle movement.

Previously, a synthetic system enhancing adhesion through a hierarchical structure was fabricated and tested (17). Just as the gecko uses this system to both increase and decrease adhesion, here a hierarchical structure has been fabricated to turn on and off adhesion. However, where the gecko uses muscle to actuate a β -keratin structure, the synthetic system uses a magnetic field to actuate nickel cantilevers. The nickel beams, when placed in a magnetic field, reorient themselves so that the terminal pad of the structure, responsible for adhesion, rotates orthogonally to an adhering surface. This conformational change effectively turns off the adhesion of the structure.

Fabrication

Released 150-500 nm thick and 100 μm long nickel structures, coated with aligned vertical arrays of stiff polymeric nanorods ~200 nm in diameter and ~3 μm tall, were fabricated using a combination of compatible massively parallel fabrication techniques. The fabrication process began by coating blank 4 inch (100) silicon wafers with a 1.4 μm thick layer of image reversal photoresist, AZ 5214. The negative image of the desired platforms was then transferred into the resist across the entire wafer using a Karl Suss MA6 contact aligner. After developing, a 150 nm thick nickel layer was electron beam evaporated onto the entire wafer. The photoresist was then removed, via an ultrasonic acetone bath, lifting off the excess nickel. The wafer was then cleaned and dried and a 7 μm layer of photoresist was spun onto the wafer surface, Shipley SPR 220-7. The positive pattern of the platforms was then transferred into the resist, aligned with the nickel platforms below. The resist and nickel pattern was then transferred into

the exposed silicon alternating between a highly reactive mostly isotropic SF_6 etch and a C_4F_8 passivation deposition, the Bosch process, effectively etching vertically into the silicon. After etching approximately 30 μm into the silicon, a sustained SF_6 etch was performed to undercut the nickel/photoresist platforms. The released platforms were then placed in oxygen plasma with an applied bias between wafer and plasma, creating ~ 200 nm diameter nanorods, orthogonally on the surface, with an aspect ratio of ~ 15 , Fig. 1.

Fig. 1 – Electron micrographs of released structures. (A) Paddle surface coated with evenly spaced uncondensed aligned vertical polymer nanorods, scale bar 10 μm . **(B)** Freestanding nickel cantilevers and paddles coated with nanorods, scale bar 50 μm . **(C)** Lower magnification view of a portion of the array, scale bar 500 μm .

Adhesion Testing

The structures were characterized using a home built adhesion test apparatus, Fig. 2. The basic operating principle of the system is very similar to an atomic force microscope, except on a larger scale, where the deflection of a cantilever is monitored, using laser interferometry, to determine the forces applied to a probe tip. In this work, a custom 5 mm flat punch glass probe was manufactured. Proper registration of tip and stage was accomplished by the marriage of probe and cantilever (using high strength glue), with the cantilever secured in the apparatus, and the probe resting flush on the sample stage. Test samples were placed on the micropositioning stage and moved to near contact with the test probe. The probe was then lowered using a piezo electric actuator, and proper probe/sample alignment was observed through a horizontally oriented stereomicroscope. Actuation of the probe and data collection was performed using an automated National Instruments Lab View program. The program simultaneously moved the probe towards the surface and monitored the deflection of the cantilever. Through calibration of the cantilever, spring constant equal to 137.1 N/m, it was possible to determine the interaction forces between the flat punch probe and the test surface. Upon withdrawal from the surface, adhesion would produce a characteristic pull-off event, evident in the negative dip of the force curve, Fig. 4. The reversible adhesive was tested with and without a Neodymium Iron Boron rare earth metal magnet below the silicon chip.

Fig. 2 – Schematic of the adhesion test apparatus. A laser interferometer monitors the deflection of a glass cantilever spring as a piezo actuator moves a 5 mm glass flat punch into and away from the test surface. The interaction forces are calculated by relating the stiffness and deflection of the cantilever upon contact with the surface.

Results and Discussion

Fabrication of the multi-scale structures required the integration of two different processing modalities. The nickel platform microstructures were photolithographically defined and etched using standard microfabrication reactive ion etching. The vertically aligned polymeric nanostructures were created through a stochastic growth method. Both methods employ batch fabrication techniques and scalable for production quantities. So in addition to being the first actuated hierarchical biomimetic adhesive, this system does not present a technological dead end.

The bilayer of the photoresist coating the nickel beams induces a stress mismatch which causes the beams to bend up and out of the device plane, Fig. 1. The upwards bent cantilevers aid in adhesion through enhanced structural compliance, and move the active portion of the adhesive away from the surface. With the active portion of the adhesive isolated the properties of the adhesive could then be controlled by actuating the platforms. High-aspect-ratio ferromagnetic structures have been shown to rotate within a magnetic field to align their long axis with a magnetic field (18). When the structures were placed on top of a permanent magnet the platforms were observed to rotate about their long axis, Fig. 3. This rotation is attributed to the preferential alignment of the long axis of the width of the pad in the magnetic field. This rotation reduces the orthogonal contact area, as evident in the stereo-micrograph in figure 3.

Fig. 3 - Stereomicrographs of the adhesive: (A) in the ‘ON’ state, no applied magnetic field, with the adhesive paddles facing vertically; and (B) in the ‘OFF’ state, with an applied magnetic field rotating the paddles sideways, concealing the adhesive faces. Scale bars, 100 µm.

Adhesion testing of the structures, without an applied magnetic field, produced loading and unloading curves with a characteristic pull-off event, Fig. 4. The magnitude of the pull-off force was taken to be the adhesion, and was observed to vary with the maximum applied normal load (due to slight misalignments between the flat punch and the test surface) until a saturation adhesion strength of ~17 Pa was observed (obtained by dividing the adhesion force by the projected area of the pad surfaces), Fig. 4.

Fig. 4 - Adhesion results showing the on/off behavior of the structures without and with an applied magnetic field, respectively. The plots represent loading and unloading curves during testing, where in the ‘ON’ state distinctive pull-off events were observed (top) and in the ‘OFF’ state no pull-off events were observed (bottom). Strength values were obtained by dividing the interaction force by the contact area of the paddles. In the ‘ON’ state, the devices showed an initial increase in adhesion with preload force, characteristic of increased surface contact with applied load. In the off state there was no detectable adhesion.

Alignment issues, surface inconsistencies and unknown probe geometries have presented difficulties in quantification of non-pressure-sensitive-adhesives. One suggested metric is to simply divide the adhesion force by the maximum preload force, $\mu' = F_{\text{adhesion}}/F_{\text{normal}}$, thus distinguishing these systems from pressure sensitive adhesives (19). In the system described here the maximum μ' value was found to be ~ 1.5 , occurring at the minimum detectable level of adhesion (limited by the noise level of the instrumentation). This value offers a substantial increase from previous synthetic work; where Northen and Turner reported a $\mu' = 0.125$ (17), and Geim et al. a $\mu' = 0.06$ (20), but still falls short of the gecko with $\mu' = 8$ to 16 (19).

In contrast to the adhesion seen in a rest state, the application of magnetic field to the structures produced a catastrophic loss of adhesion, Fig. 4. For no tests performed was any adhesive event observed. This complete reduction in adhesion is attributed to the concealing of the nanorod coated platforms from the test probe. Under an applied magnetic field the platforms tend to rotate about the long axis of the cantilever. This rotation leaves the edge of the platforms facing in the normal direction and the sticky face to the side – turning a cheek to adhesion, if you will.

Additionally, an increase in surface stiffness was seen with an applied magnetic field. The twisting of the cantilevers increases the second moment of area of the structures, relative to the indenting tip, increasing the stiffness and consequently reducing the compliance of the system. Although not a primary factor in the reduction of adhesion, reduction of the compliance of the system serves to lock out one of the hierarchies of this multi-scale adhesive. Ultimately the sideways rotated paddles will contact the underlying substrate and statically inhibit contact between the adhesive and the test substrate, completely turning off the adhesive.

Conclusion

In this paper a novel approach has been presented for micro- and nano-fabricating a synthetic analogue to the gecko adhesive system. The hierarchical system is composed of aligned vertical nanorods coating flexible micron scale cantilever paddles. The paddles, composed of nickel, rotate when subjected to a magnetic field. This rotation conceals the nanostructures on the paddle surface and greatly reduces the available surface area for adhesion. Testing of the system showed reversible adhesion behavior switching from a μ' value ($F_{\text{adhesion}}/F_{\text{preload}}$) of ~ 1.5 (largest reported value for a biomimetic system to date (19)) to a value less than the noise level in the instrumentation. Thus an active hierarchical structure, inspired by the gecko, has been fabricated and demonstrated to display controlled and reversible adhesion.

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