KSTLE International Journal, Vol. 9, No. 1/2, December 2008, pp. 13-16

Artificial Adhesive Surfaces Mimicking Gecko Setae: Novel Approaches in Surface Engineering

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Abstract: Surface Engineering is a field closely related to Tribology. Surfaces are engineered to reduce adhesion, friction and wear between moving components in engineering applications. On the contrary, it is also necessary to have high adhesion between surfaces so as to hold/stick surfaces together. In this context, surface engineering plays an important role. In recent times, scientists are drawing inspiration from nature to create effective artificial adhesive surfaces. This article provides some examples of novel surface engineering approaches conducted by various research groups worldwide that have significantly contributed in the creation of bio-inspired artificial adhesive surfaces.

Keywords: *biomimetic, bio-inspired, adhesion, surface engineering*

1. Introduction

Adhesion and friction forces are surface forces that have significant importance in various engineering applications. In miniaturized devices such as Micro/Nano-Electro-Mechanical-Systems, reduction in surfaces forces is a necessity, whereas in synthetic adhesive tapes, increasing these forces is the prime objective [1]. Thus, the need to decrease/increase the surface forces solely depends on the nature of the application and its needs. In this article, we present some examples of bio-inspired research works conducted by various research groups that have succeeded in creating excellent artificial adhesives.

2. Experimental

Creation of surfaces with excellent adhesion properties involves fabrication of shape/size-engineered patterns on polymeric films/coatings that mimic the structure of Gecko setae. Some of the techniques and fabrication routes include electron-beam lithography and deep reactive ion etching. Tests to evaluate the adhesive property of the surfaces mainly include AFM (Atomic Force Microscopy) and micro/macro testers. For more details on the fabrication techniques and their property evaluation, reference to papers [1-10] is suggested.

3. Results and Discussion

In nature, it is seen that many insects, spiders, and lizards have the ability to attach themselves to surfaces without falling off, even when the surfaces are vertically inclined. The presence of micro/nanostructures, small hairs called "setae," on their attachment pads enables these creatures to attach and detach easily over any surface. Animals cannot increase the area of the attachment devices proportional to the body size owing to the different scaling behavior of mass and surface area. Therefore, an increase in their attachment abilities is realized by increasing the number of single contact points, i.e., by increasing their hair density (Fig. 1) [2]. Amongst these creatures, the gecko is the largest animal that has this kind of dry attachment system; therefore, it has been of main interest for scientific research. Figure 2 shows a SEM micrograph of gecko foot-hairs or setae [3]. Microscopy has shown that a gecko's foot has nearly 500,000 keratinous hairs or setae. Each 30-130 Mm long seta is only one-tenth the diameter of a human hair and contains hundreds of projections terminating in 0.2-0.5 Mm spatula-shaped structures [4]. Autumn et al. [4] for the first time conducted direct measurements of the single setal force by using a two-dimensional micro-electro-mechanical systems force sensor and a wire as a force gauge. Measurements revealed that the maximum adhesive force of a single seta averaged about 194±25 MN. The direct setal force measurements indicate that the adhesion in geckos is the result of intermolecular forces and that the adhesive force values support the hypothesis that individual seta operate by van der Waals forces. Interestingly, if all setae were simultaneously and maximally attached, a single foot of a gecko could produce an amazing adhesive force of 100 N [4].

Van der Waals bonds are secondary bonds and are weaker when compared to other physical bonds. However, for two planar surfaces, the van der Waals force between two surfaces is inversely proportional to the cube of the spacing between the two surfaces. As a result, when the spacing is on the order of atomic spacing (~0.3 nm), the van der Waals forces can in fact be very large. As the hairy attachment systems of Gecko setae are comprised of structures that terminate on the micro/

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nanoscale, a large real area of the attachment pads is able to come into close proximity with random rough surfaces that leads to large van der Waals forces [5]. In an investigation, Autumn, Sitti and their group [6], further confirmed the fact that the remarkable adhesive property of gecko setae is mainly due to a van der Waals mechanism. They fabricated synthetic spatulae from polymers (PDMS, polydimethylsiloxane and polyester resin) and conducted perpendicular pull-off force measurements using a flat AFM probe. Results showed that the adhesive force of the synthetic spatulae was similar to that of natural gecko setae, thereby suggesting that an array of small, simple structures can be an effective adhesive.

A prototype of re-attachable dry adhesive surface called 'Gecko tape' was fabricated by Geim et al. [7]. They used electron-beam lithography and dry etching in oxygen to fabricate arrays of flexible polyimide pillars (Fig. 3). The geometry of the pillars was optimized to ensure their collective adhesion. In the course of their research work, an important observation was made. Arrays of plastic tips when fabricated on solid substrate fail to make complete physical contact with the opposite surfaces, as only a small fraction of tips come into contact. Thus, to create a gecko adhesive, not only does one have to make the pillars sufficiently flexible but most importantly one has to place them on a soft, flexible substrate so that the individual tips can act in unison and attach to uneven surfaces all at the same time.

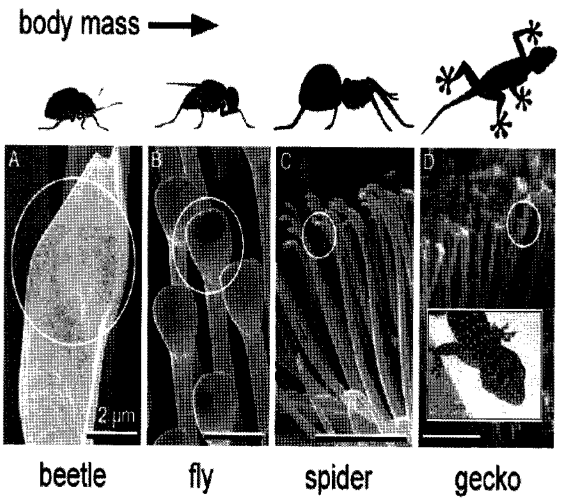

Fig. 1. Terminal elements found on the attachment pads of various insects and of a gecko [2]. The inset at the bottom on the right hand side shows a picture of a Tokay Gecko. As the size (mass) of the creature increases, the radius of the terminal attachment structures decreases while the density of the structures increases [2].

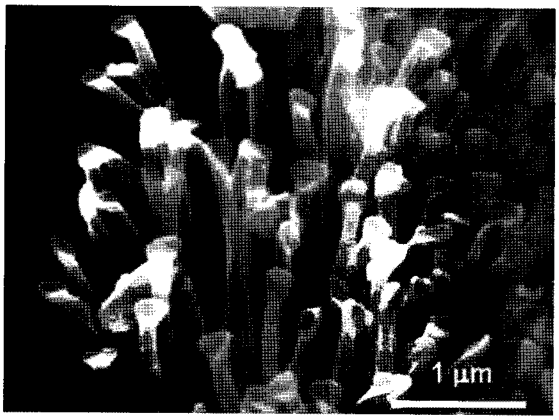

Fig. 2. SEM micrograph of gecko foot-hairs or setae (scale bar: 1 μm) [3].

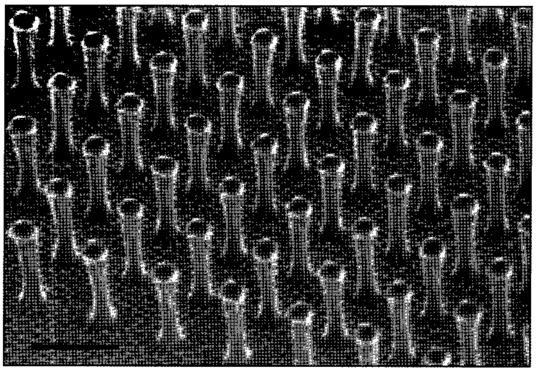

Fig. 3. Arrays of flexible polyimide pillars fabricated by Geim et al. (scale bar: 2 μm) [6].

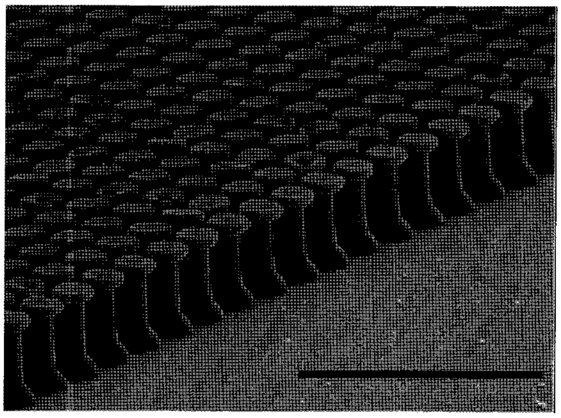

Fig. 4. Microfibers with flat spatulate tips fabricated by Kim and Sitti (scale bar: 30 μm) [8].

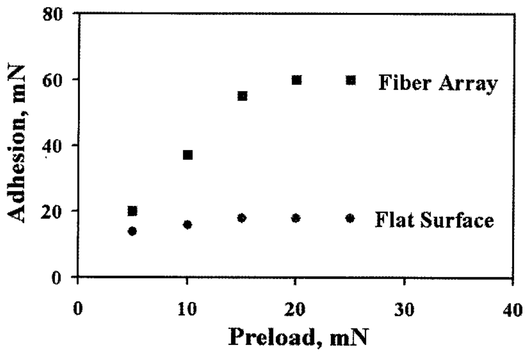

Fig. 5. Adhesive property of the microfiber array and that of the flat elastomer surface as observed by Kim and Sitti [8].

Kim and Sitti [8] fabricated an adhesive surface made of microfibers with flat spatulate tips by using deep reactive ion etching and the notching effect to mold a master template. Figure 4 shows an SEM image of the polyurethane elastomer microfiber array fabricated by them. Each fiber has a diameter of 4.5 μm, a tip diameter of 9 Mm, and a length of 20 μm. The surface with the microfiber array so fabricated was tested for its adhesive property in comparison with that of the flat elastomer surface. Tests revealed that the array of fibers had more than three times higher adhesion than the flat surface at a preload of 25 mN (Fig. 5).

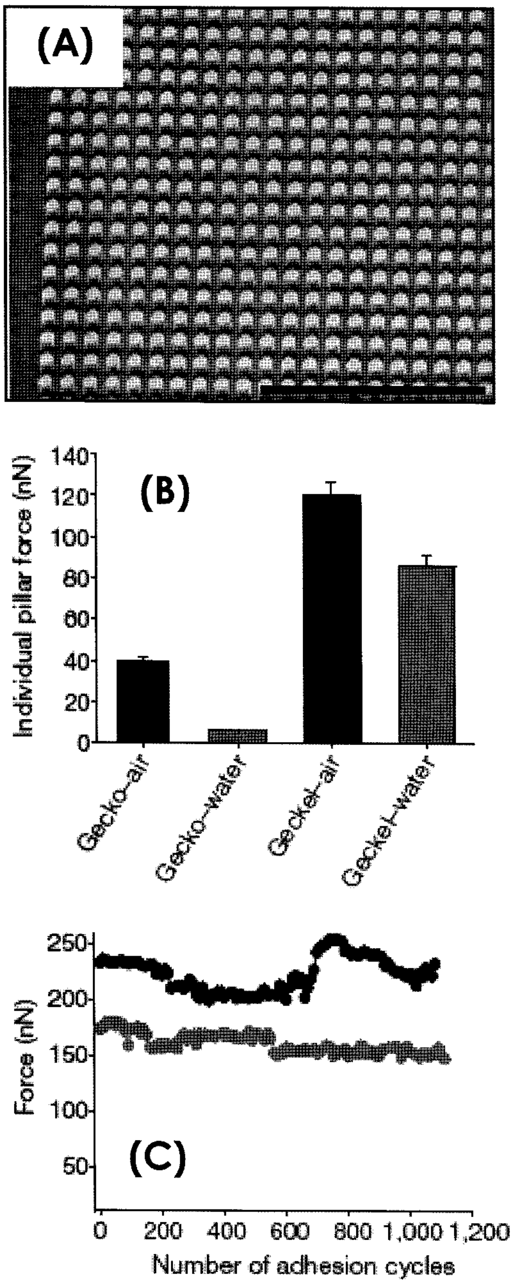

Fig. 6. (A) Geckel surface [9] (scale bar: 10 Mm). (B) Adhesion test results of individual pillar of geckel and gecko in air and under water. (C) Adhesion force of geckel as a function of adhesion cycles (black line: in air, grey line: in water).

Recently, scientists have produced a super-adhesive material called "Geckel" by studying geckos and mussels [9]. Using electron-beam lithography, they first created arrays of polymeric nano-pillars, as shown in Figure 6 (a). Later, they coated the nano-pillars with a polymer modeled on an amino acid that is one of the building blocks of the "glue" protein in mussels; the result was "Geckel" (gecko + mussel). Figure 6 (b) shows the adhesion test results of individual pillar of geckel in comparison with that of the gecko setae. It could be seen that the individual pillar force of geckel is higher than that of the gecko setae. Interestingly, geckel shows good adhesive property when compared to the gecko setae even under water too.

Figure 6 (c) shows the adhesion force of the geckel as a function of number of adhesion cycles, both in air and water. It can be observed that geckel can stick through 1000 contact/ release cycles and can remain highly adhesive even under water.

Figure 7 shows polymeric nanostructures fabricated by a simple capillarity driven molding technique, followed by elongation through controlled adhesion between the mold and the polymer interface [10]. These nanostructures resemble gecko foot hairs. The spherical tips of these nanostructures resemble gecko's spatulae and increase adhesion through an

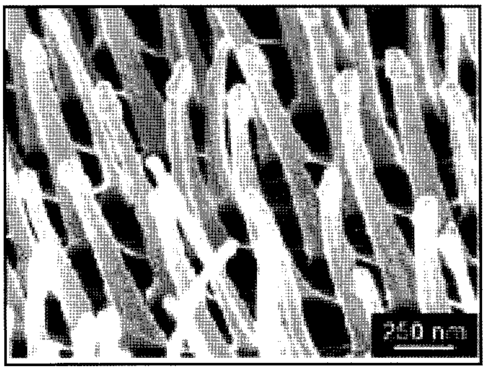

Fig. 7. Stretched polymeric (PMMA) nanostructures fabricated by capillarity-driven molding. The nanostructures were elongated by controlled adhesive force at the mold/polymer interface (scale bar: 250 nm) [10].

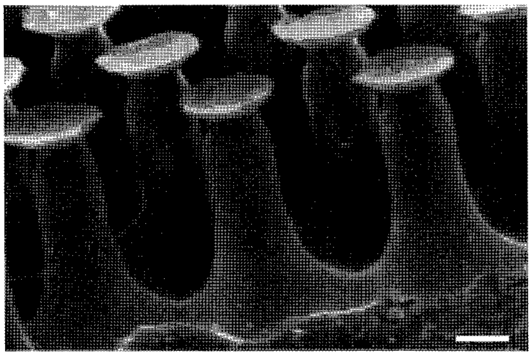

Fig. 8. Polyvinylsilixane sample consisting of microscale pillars fabricated by Bhushan and Sayer (scale bar: 30 Mm) [5].

increase in contact area.

Gecko setae has not only inspired researchers to fabricate synthetic adhesives but has also inspired tribologists to create high-friction surfaces. One such example is the polymeric surface fabricated by Bhushan et al. [5]. Figure 8 shows an SEM image of a polyvinylsilixane sample consisting of microscale pillars fabricated by them to replicate biological attachment systems. Friction tests at the macro-scale showed that the coefficient of kinetic friction of the structured sample was almost four times greater than that of the unstructured sample. Interestingly, they observed that the static and the kinetic friction of the structured sample remained almost the same while the unstructured sample experiences a significant decrease. Such a behavior of the structured sample was attributed to its ability to recreate contacts with the mating surface during sliding. On the other hand, the unstructured surface lacked that ability. It is well known that the coefficient of kinetic friction depends on the contact area; thus, the larger real area of contact in the case of the structured sample gives rise to a higher value of the friction coefficient [5].

4. Conclusions

In this article, some interesting examples of novel surface engineering approaches related to bio-inspired adhesive surfaces were presented. Polymer science is closely connected with the fabrication of these advanced surfaces. Although most of these adhesives have been produced and tested at the laboratory scale, more R&D is required for their commercialization. For commercialization, issues such as large scale production, repeatability of structure-properties and cost effectiveness are vital and therefore they need to be considered.

Acknowledgement

This research was supported by KIST Institutional Program and the Intelligent Microsystem Center (IMC; http://www.microsystem.re.kr), which carries out one of the 21st century's Frontier R&D Projects sponsored by the Korea Ministry Of Commerce, Industry and Energy.

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