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EDITORIAL

Reversible Dry Adhesives

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Adhesion is ubiquitous, from cell-matrix adhesion to tendon-bone attachment, from medical tapes to Post-It® notes. Many man-made adhesives aim at gluing separate surfaces together permanently, in which case adhesion strength and longevity are major concerns. The best example is probably cyanoacrylate superglues that can virtually bond anything, including bio-tissues. In contrast, reversible adhesives are designed to form a temporary bond and can be removed without damaging the adherend. Reversible adhesives are used in applications such as surface protection films, note papers, and for skin contact, including wound care dressings, athletic tape, and so on. Some reversible adhesives are designed to stick and unstick repeatedly but generally have low adhesion and hence cannot support much weight. Reversible adhesives capable of strong bonding would be really useful for climbing robots or robots moving in low-gravity environments.

In fact, various insects and lizards, notably gecko lizards, have developed an amazing ability to climb on walls and run on ceilings. Prof. Duncan J. Irschick and colleagues have measured the climbing ability of 14 pad-bearing lizard species and found the adhesion strength of gecko toe pads to be 100 kPa, which is about half of the adhesive strength of 3M Scotch® tape. Such findings have inspired a wealth of research studies on the physics of gecko adhesion. German anatomist Uwe Hiller discovered the bristle-like, hierarchical structure of the gecko's toe pads by electron microscopy as early as 1960. With the development of scanning electron microscopy (SEM), more details of the gecko's toe pads are revealed by Prof. Kellar Autumn and colleagues where the hierarchical structure is based on the *lamellae*, from which the individual adhesive pillars, referred as *setae*, protrude. Each seta is about 20 μm in diameter and 130 μm long with tinier and finer ends, referred as *spatula*, which are about 200 nm long and 20 nm in diameter. Using a microelectromechanical system (MEMS), Prof. Kellar Autumn and colleagues measured that each seta is able to produce an average force of 20 mN and an average stress of 100 kPa. They also confirmed that the gecko's adhesive abilities mainly rely on van der Waals (vdW) forces between the spatula and the target surface instead of chemical bonding because skin glands are not present on the feet of lizards. Since adhesion is enabled by physical interaction instead of chemical bonding, this type of adhesive is called dry adhesive. Although vdW forces only exist over extremely short range of interactions ($\sim$1 nm), the hierarchical architecture of the fibrillary structure (i.e., lamellae-setae-spatula) enables intimate contact with the target surface over large areas. As a result, strong adhesion force can be generated, and it enables the gecko to climb on a wide variety of surfaces of any orientation. Studies of the contact strengths of animals with hairy attachment pads have also revealed that adhesion strength increases as the fibril radius reduces. In addition to the remarkable attachment performance, the gecko system also exhibits a superior reversibility: when loaded in the reverse direction, the gecko's toe pads can easily peel off from the surface without leaving behind any residue. Moreover, the gecko's toe pads show a superior self-cleaning ability: the gecko can run through sandy environments and, after several steps on a clean surface, the adhesive structures return to cleanness.

Inspired by the gecko fibrillary system, tremendous efforts have gone into synthetic mimics with microscale surface features reminiscent of setae. For example, when micro-pillars are implemented on the feet or treads of climbing robots, a steady climbing performance can be achieved on vertically orientated surfaces. As another example, gecko-like fibrillary adhesives have been applied to life-science applications such as bandages and drug-delivery systems. Among many different methods used to fabricate fibrillary structures, the best known is photolithography, which refers to a collection of pattern-replication methods. It requires the fabrication of a micro-structured hard master, which serves as the negative replica of the pillared polymer. A liquid prepolymer (most commonly polydimethylsiloxane; i.e., PDMS) is cast and thermally cured on the hard mask. The PDMS replica can be considered as the final patterned surface or it can be used as a stamp for the subsequent replication process. In addition to photolithography, many other manufacturing techniques have been developed, including hot embossing, filling nanoporous membranes, electron-beam lithography to create super high-quality artificial adhesives.

To achieve high-strength artificial adhesives, many studies have been carried out to optimize the structural features of micro-pillars. It has been shown that adhesion strengths increase as the fibril radius reduces or as the aspect ratio increases. The enhanced adhesion afforded by smaller contact

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elements is attributed to the so called ''contact splitting'' effect proposed by Prof. Eduard Arzt and Prof. Robert McMeeking. The contact splitting theory lumps together many extrinsic/intrinsic contributions, including fibril deformation, adaptability to rough surfaces, size effects due to surface-to-volume ratio, uniformity of stress distribution, and defect-controlled adhesion. In addition to fiber radius, the fiber tip geometry, fiber tilting angle, and the level of hierarchy also play significant roles. Various fiber tip geometries, including flat, spherical, spatula, concave, mushroom-like, and rectangular shapes, have been developed. Among them, spatula and mushroom-like shapes have shown promising adhesion strength under relatively low preload, and have thus become the most popular pillar tip geometries. If reversible gecko-inspired adhesives are to be fabricated, tilted fibrillary structures are required to allow the micro-pillars to be peeled off easily. Since real gecko-like toe pads have a hierarchical structure, hierarchy of synthetic mimics is another area of interest. For example, Prof. Jinyou Shao and Prof. Yucheng Ding fabricated dual-level hierarchical mushroom-shaped micro-pillars with a tip radius of around 15 μm in the first level and 500 nm in the second level by conventional photolithography and molding. Other design parameters such as material properties of pillars and backing layers have also been studied theoretically and experimentally. After extensive studies, comprehensive manufacturing design maps for microfibril-based reversible dry adhesives are now readily available. According to a recent review by Prof. Hong Yee Low and Prof. Avinash Baji, the normal and shear strengths of most gecko-mimetic dry adhesives are capped by 200 kPa.

Instead of extruding pillars, reversible adhesives can also be achieved by concavity. In fact, macroscopic suction cups have been used ubiquitously as reversible adhesives in both nature and man-made materials. In nature, cephalopods such as the octopus can manipulate items and reversibly anchor to rocks for prolonged time through negative pressure generated by suction cups distributed over their tentacles. Commercially, suction cup hooks and electrocardiogram (ECG) electrodes are widely available. Recently, several startups try to sell so called antigravity cell-phone cases enabled by polymers with micropores.

To achieve a greater quantitative understanding, micro- or nano-surface dimples on polymer sheets have been engineered and various adhesion strengths have been achieved. For example, in 2014, Prof. Yi-Chang Chung created an array of nano-suckers on UV resin and measured shear adhesion strength on silicon wafer to be as high as 750 kPa, which is much stronger than most gecko-mimetic dry adhesives. In a 2015 paper, Prof. Dae-Hyeong Kim created octopus mimetic micro-suction cups on the surface of PDMS and found the shear adhesion strength to be 16 kPa, which is higher compared with PDMS with flat or pillared surfaces according to their measurements. I developed analytical solutions to the negative pressure generated in the micro-suction cups and tried to elucidate the effect of suction-cup geometry on the generation of negative pressure. In another 2015 paper, Prof. Marleen Kamperman fabricated close-packed nano-dimples on PDMS using colloidal lithography and found that the pull-off force is enhanced compared with flat PDMS control and that the geometry of the dimple governs the pull-off force. Prof. Marleen Kamperman also noticed that the pull-off force depends on the preload, which is a distinctive feature from microfibril-enabled dry adhesives. It means that the adhesion is pressure sensitive. When the polymer is gently placed on the target surface, the adhesion is almost negligible, and detachment would be very easy. When the polymer is firmly compressed against the target surface, the adhesion can be much improved for hanging or climbing purposes. This property is useful for adhesives that are constantly making contact with other surfaces, but should only be activated when needed. A good example would be the antigravity cell-phone cases, which should remain non-sticky and easy to pick up when simply placing cell phones on a table, whereas they should be sticky enough to hold the cell phone vertically when pressed against a wall or window. For retrieval, the adhesive can be readily released when pulled from an edge without damaging the adherend. Such adhesives can be reused many times and are also easy to clean.

Another dry adhesion strategy named electroadhesion has also been pursued for surface climbing robots. Since electroadhesion comes from the electrostatic effect of astriction between two surfaces subjected to an electrical field, the clamping pressure is relatively small (ranging from 5 to 15 kPa).

In summary, reversible dry adhesion is a field undergoing rapid development. The investigation of diverse mechanisms for dry adhesion and the manufacture of cost-effective reversible adhesives will continue to benefit robotics as well as many other fields.