ACS APPLIED MATERIALS & INTERFACES

Research Article

www.acsami.org

Controllable Interfacial Adhesion Applied to Transfer Light and Fragile Objects by Using Gecko Inspired Mushroom-Shaped Pillar Surface

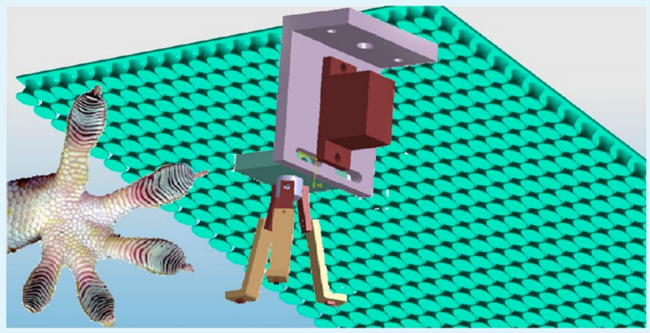
Ming Zhou,[†,‡] Yu Tian,*,[†] Dan Sameoto,[§] Xiangjun Zhang,[†] Yonggang Meng,[†] and Shizhu Wen[†]

[†]State Key Laboratory of Tribology, Tsinghua University, Beijing 100084, China

[‡]Institute of Mechanical Manufacturing Technology, China Academy of Engineering Physics, Mianyang 62190, China

[§]Department of Mechanical Engineering, University of Alberta, Edmonton, Alberta, T6G 2G8, Canada

ABSTRACT: Gecko-inspired surfaces are smart dry adhesive surfaces that have attracted much attention because of their wide range of potential applications. However, strong frictional force, rather than adhesive force, is frequently targeted in most of research in this area. In this study, the interfacial adhesive and frictional properties of a gecko-inspired mushroom-shaped polyurethane pillar array surface have been systematically characterized to design and control the interfacial adhesion of the surface by considering the nanoscale interfacial adhesion, the microscale structural compliance and deformation, and the macro-scale actuation. Matching the movement of the leg springs and the interfacial adhesive characteristics between the pillar array surfaces and substrates, a three-legged clamp prototype has been designed and fabricated to successfully pick up and release light and fragile objects with a smooth upper surface, such as a silicon wafer. These results provide a new insight into not only the theoretical understanding of the integrating adhesion mechanisms, but also the practical applications of utilizing and controlling the adhesive and frictional forces of gecko-inspired surfaces.



KEYWORDS: *adhesion, peel, interface, gecko inspired, clamp, pillar surface*

1. INTRODUCTION

Fibrillar structured surfaces have a wide range of potential applications.[1,2] Recently, artificial fiber array surfaces inspired by the gecko, which shows remarkable climbing abilities,[3−7] have attracted significant attention from scientists and engineers all over the world because of their wide range of applications, such as wall-climbing robots, clamp systems for antiterrorism, reconnaissance, and aerospace applications.[8,9] Basically, it is widely accepted that the strong adhesion of the gecko setae comes from van der Waals forces between the setae and the substrate,[10] and the capillary force may enhance the adhesive force.[11,12] Additionally, the hierarchical structures of the setal array have good adaptability to the roughness of surfaces.[13,14] Furthermore, the gecko is able to control the attachment and detachment process by opening and shutting its toes, which alters the peel angle of the spatula pads, the terminal structure of the gecko setae.[5]

On the basis of this understanding of the mechanism of gecko adhesion, design principles have been proposed,[8,15−18] and many types of gecko-inspired fiber array surfaces have been fabricated.[19−30] In the first stage, simple cylindrical fiber array surfaces were fabricated using the mold replication method.[8,19] The maximum adhesion strength reached was 30 kPa.[8] With the application of other photolithography steps, fiber array surfaces with different fiber end shapes were fabricated, such as mushroom-shaped fibers, asymmetric pads, and concave structures,[20−22] which exhibited much higher adhesion strength. For example, Kim et al. fabricated a form of polyurethane fiber array surface, spatulate at the terminal ends, with adhesion strength of 220 kPa.[23] The theoretical analysis showed that the perfectly smooth surfaces showed the best adhesion property than other shaped fibers.[24] Further, Varenberg and Gorb proposed that the narrow necks of the fibers could promote reliable adhesion.[25] Therefore, it is accepted that mushroom shaped fibers with high aspect ratio improved robustness and stability on smooth surfaces and are suited for the application of transferring light objects.[26] Recently, a thin film-terminated fibrillar design was used to enhance adhesion and compliance.[27−29] Besides, by coating a layer of mussel protein, one-level pillar array surfaces showed strong adhesion force under water.[30] Further, hierarchical structures were incorporated into the fiber arrays, which showed excellent ability to adapt to surface roughness.[31−36]

Inspired by the anisotropic shape and mechanical properties of the gecko setal arrays, tilted pillar array surfaces have also been invented,[9,36−39] which have exhibited a directional

Received: July 15, 2013
Accepted: September 16, 2013
Published: September 16, 2013

adhesion friction. Jeong et al. reported a form of angled PUA nanofiber array surface exhibiting strong shear force along the angled direction and less than one-tenth of that shear force against the angled direction, which could be used to control the attachment and detachment between the gecko-inspired surface and the substrate.[36] Similar works were reported by other researchers.[9,37−39] More recently, Bae et al. proposed a method to switch the adhesion by peeling the bridged micro pillars.[29] However, most of these works used the lateral frictional force of the gecko-inspired surfaces, which is much higher than the adhesion force and easier to control.

Previous studies have revealed that the interfacial adhesion of the terminal structure of gecko setae strongly relied to the deformation of the hierarchical structures and the soft lamellar skin, which provided good adaptability and compliance for making intimate contacts on rough surfaces and help to maintain the system in a wide range of adhesive state.[40] Besides, the macro-scale rolling actuation controlled the attachment and detachment process.[5] In this study, we propose a form of smart three-legged clamp prototype based on the gecko-inspired polyurethane vertical pillar array surface. The adhesion and frictional properties of a mushroom-shaped gecko-inspired surface molded using soft lithography techniques were systematically characterized to provide the design principles of the attachment and detachment control of the surface. On the basis of these principles, a three-legged clamp was designed, fabricated, and successfully used to transfer light and fragile objects with smooth upper surface, such as a silicon wafer as a typical case.

2. EXPERIMENTS

The gecko-inspired surfaces were prepared by the lithography method,[41] as shown in Figure.1: (1) First, the SU-8 photoresist was spin-coated and then baked on the polymethylmethacrylate (PMMA) substrate, as shown in Figure 1a. (2) Second, the SU-8 was exposed, baked and then developed to create the features, as shown in Figure 1b and c. (3) Then the SU-8 layer developed on the PMMA substrate was exposed under 254 nm uncollimated light, as shown in Figure 1d. (4) The PMMA was developed in the propylene glycol monomethylether acetate (PGMEA), as shown in Figure 1e. The mushroom-shaped fiber array mold was thus obtained. (5) Silicone rubber (TC-5030, BJB Enterprises) was poured on the SU-8/PMMA structure and then degassed and cured, as shown in Figure 1f. (6) The cured silicone rubber structure was slowly peeled off from the SU-8/PMMA mold, as shown in Figure 1g. (7) Finally, polyurethane(ST-1060, BJB Enterprises) was used to replicate the negative mold of the silicone rubber to obtain the final dry adhesives, similar to steps 5 and 6, as shown in Figure 1h and i. The SEM images of this pillar array surface are shown in Figure 2.

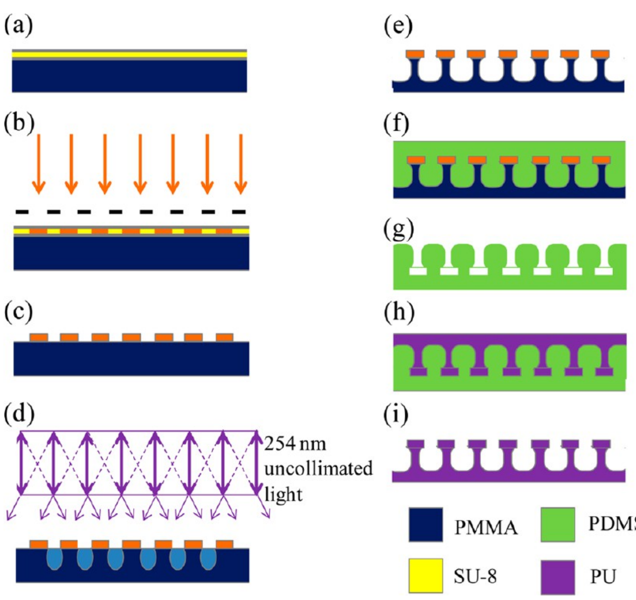


Figure 1. Fabrication process of the gecko-inspired mushroom-shaped polyurethane fiber array surface.

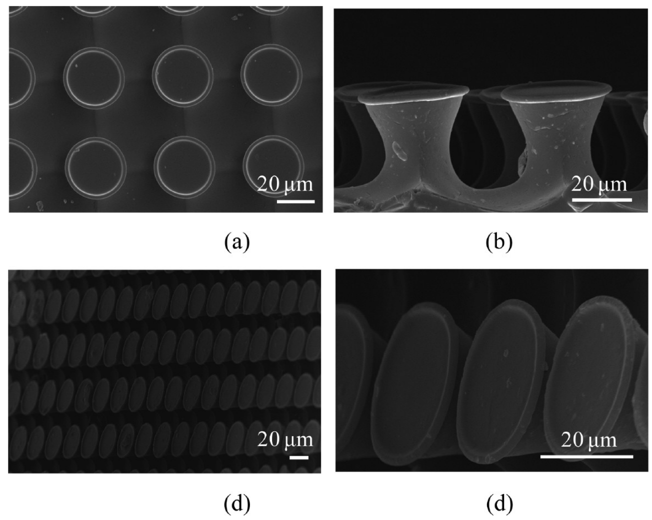


Figure 2. SEM images of the gecko-inspired surface.

To pick up light and fragile objects with a smooth upper surface, inspired by the "V" shaped gecko adhesion system, the clamp prototype in this study was designed with three legs, each leg with a small piece of gecko-inspired surface (2×2 mm^2) glued on the end of the metal leg cantilever. Accordingly, as the clamp moved vertically toward the upper surface of the object, the gecko-inspired surfaces adhered to the object surface, providing adhesive forces to withstand the gravity of the objects, as shown in Figure 3a. As the three legs moved in grip-out direction, the adhesion between the gecko-inspired surfaces and the smooth surface of the object was greatly diminished, and consequently the gecko-inspired surfaces peeled from the smooth surface of the object to release the object, as shown in Figure 3b.

According to the above design principles, the critical design parameters included the vertical adhesion force during the clamping process, the frictional force during shear and the adhesion force after shear. Thus, the vertical adhesive stress, the frictional stress, and the adhesive stress after shear were tested on a homemade friction and adhesion test apparatus,[37] as shown in Figure 4a−d. The results could provide a reference for the design of the clamp.

The friction and adhesion characterization of the gecko-inspired surface with a silicon wafer or a steel ball were done on a homemade friction and adhesion test apparatus, as shown in Figure.5. The silicon wafer (about 30 mm × 40 mm) and the steel ball (diameter of 1.2 mm) were separately fixed at the end of a double cantilever beam. The gecko-inspired surface was affixed to another double cantilever beam, using AB glue (DP420, 3 M production). The deformation displacements of the two cantilevers were detected by two eddy current sensors. With the stiffness of the cantilever springs calibrated respectively, the frictional and adhesive forces were calculated. Further, the frictional and adhesive stresses were obtained by dividing the corresponding forces by the area of the gecko-inspired surface about 5.08 mm^2. Before the experiments, the gecko-inspired surface was adjusted to be parallel to the direction of motion of the steel ball or the silicon wafer, respectively.

In the load−unload experiments, the steel ball and the silicon wafer were each adjusted to contact and press the gecko-inspired surface

 dx.doi.org/10.1021/am402815x | ACS Appl. Mater. Interfaces 2013, 5, 10137−10144

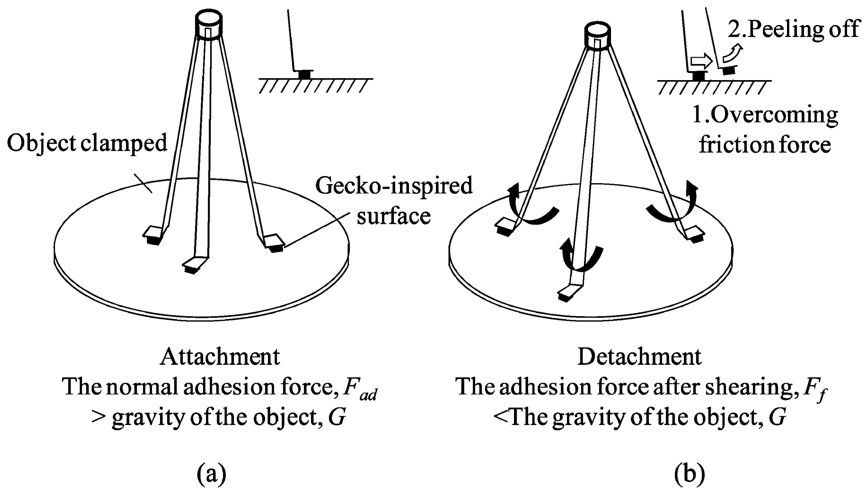


Figure 3. Working principles of the clamp: (a) gripped-in and clamped state in attachment and (b) gripped-out and released state in detachment.

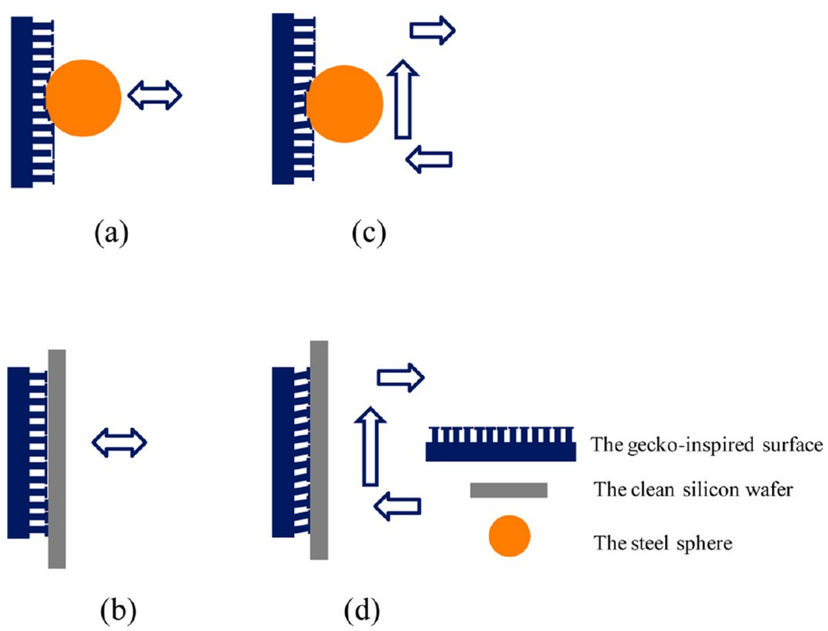


Figure 4. Adhesion and friction experiments of the gecko-inspired surfaces. The load−unload experiments to test the normal adhesive force without shear of the gecko-inspired surface with a steel ball (a) and a silicon wafer (b), respectively; the load−shear−unload experiments to test the lateral friction force and the unloading adhesive force after shear of the gecko-inspired surface with a steel ball (c) and a silicon wafer (d), respectively.

and, after several seconds, moved back to separate from the surface. For the load−shear−unload experiments, the steel ball and the silicon wafer each first contacted the surface, stayed 10 s, and then sheared for 1 mm at a velocity of 20 μm/s, retained for several seconds (called "waiting time" in the following), and finally unloaded until total separation.

3. RESULTS AND DISCUSSIONS

3.1. Tests of Adhesion and Friction of Gecko-Inspired Pillar Array Surface. The relationship between the normal adhesive stress and the preload stress without shear of the gecko-inspired surface with a steel ball or a silicon wafer in the load−unload experiments obeys the power laws as shown in Figure.6. The exponents are different because of the different contact situations, which leads to the different contact area under different preloads. Contacts with flat surfaces would give a higher normal adhesive force, as shown in Figure 6b. For the design of the clamp based on the gecko-inspired surface, the appropriate interval of adhesion stress of Figure.6b should be chosen according to the mass of the objects clamped and the total area of the gecko-inspired surface used.

The results of load−shear−unload experiments with the steel ball and the gecko-inspired surface are shown in Figure.7. The intercept of the fitting line of friction stress was not zero, which indicated that the gecko-inspired surface exhibited a finite contact and adhesion friction property. Unlike the gecko setal array, which exhibits steady adhesion friction after several hundreds of micrometers shear, the gecko-inspired surface in this study could generate adhesion friction only when the surface has just contacted the substrate. As shown in Figure 7b, the unloading adhesive force after shear increased and then decreased with increase of the preload, obeying a parabolic law, similar to the adhesion friction property of the gecko setal array. The main reason is that a larger preload could increase the number of contacted fibers, but the increase of frictional force could damage the adhesion interface. The total unloading

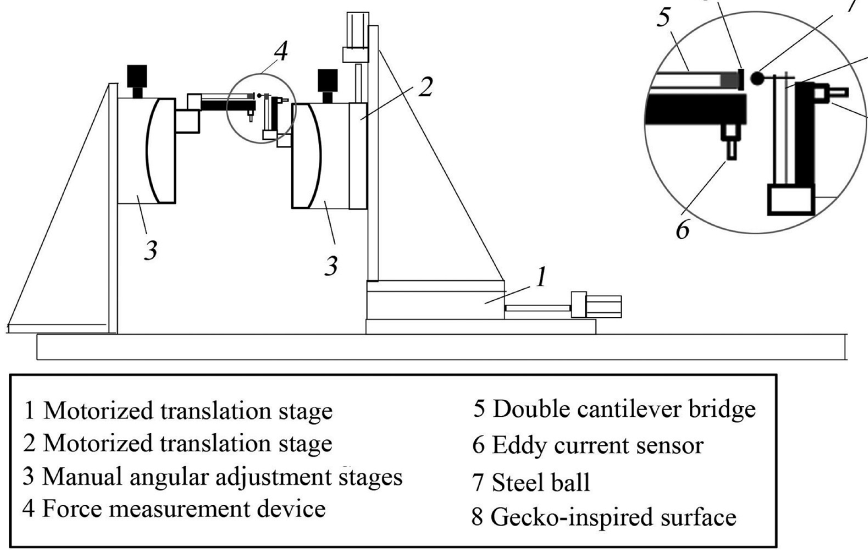


Figure 5. Schematic of the experiment setup.

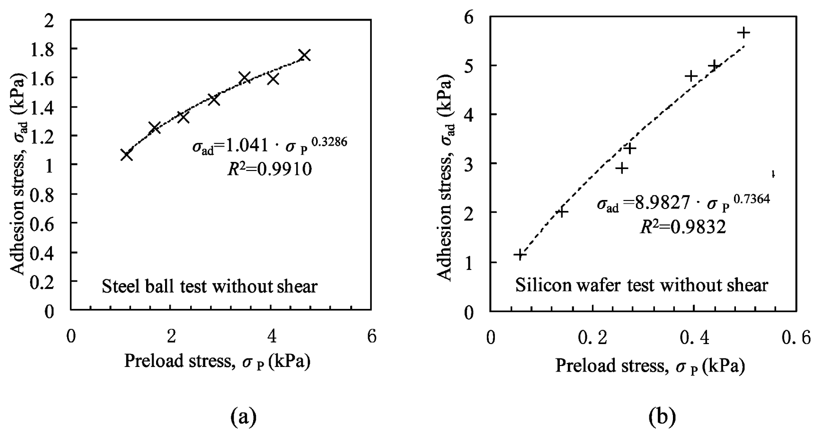


Figure 6. Normal adhesion stresses without shear of the gecko-inspired surface with different preload stress in the load−unload experiments: (a) contact with a steel ball and (b) contact with a flat silicon wafer.

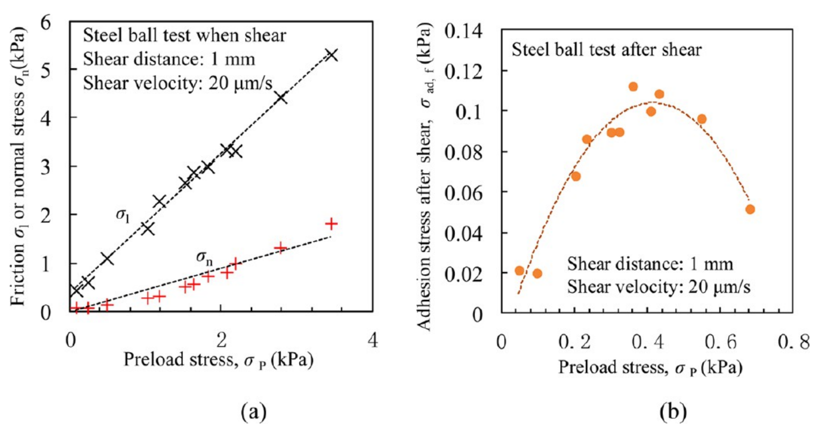


Figure 7. Friction experiments between the steel ball and the gecko-inspired surface: (a) the friction stress and the normal stress during shear and (b) the relationship between the unloading adhesion stress after shear and the preload stress.

adhesive force after shear was determined by contention between the two effects.

Figure 8 shows the results of friction between the silicon wafer and the gecko-inspired surface. Similar to the results of the experiments between the steel ball and the gecko-inspired surface, the intercept of the fitting line was not zero either. Different from that shown in Figure 7b, the adhesive force during unloading after shear monotonically decreased with the preload, as shown in Figure 8b, because the number of contact fibers to the silicon wafer remained roughly constant, showing

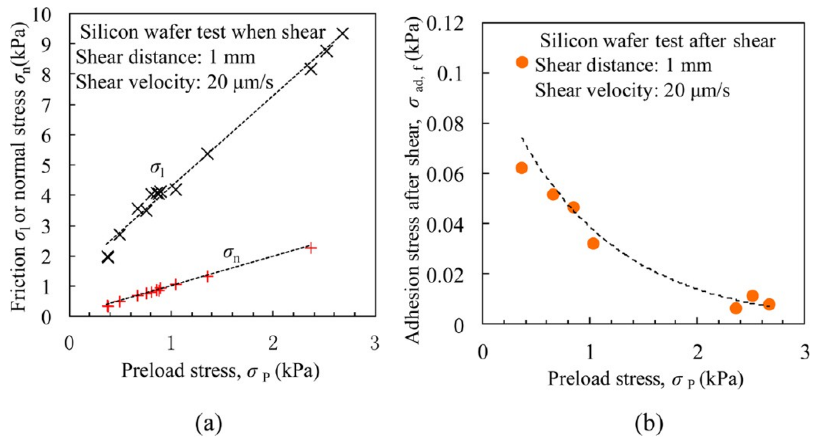


Figure 8. Friction experiments between the silicon wafer and the gecko-inspired surface: (a) the friction stress and the normal stress when shear and (b) the relationship between the unloading adhesion stress after shear and the preload stress.

that the gecko-inspired fiber array surface could adapt well to the smooth flat surface.

According to the preload stress chosen based on Figure 6b, the corresponding frictional stress could be obtained based on Figure 8a, which should be taken into account in the design of the shear force of the clamp legs during the releasing action. Furthermore, the corresponding unloading adhesive stress after shear should be checked to be much less than the mass of the objects, to ensure successful release.

The influence of waiting time on the substrate after shear on the normal adhesion stress without shear, and the unloading adhesion stress after shear, was also been observed; both obeyed the power law, as shown in Figure.9. The unloading adhesion stresses after shear were much lower than the normal adhesion stresses without shear. The results show that the shear process could damage the adhesion interface significantly, through the lateral bending of the fibers, which might decrease the contact area. According to the results, shear and peeling could be used to control the detachment of the adhered objects.

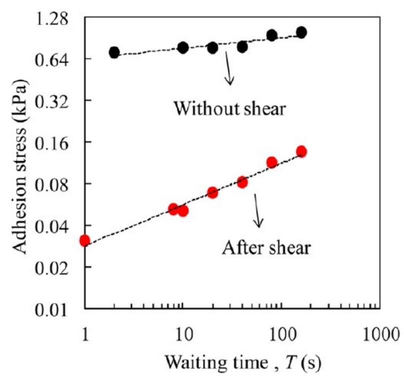


Figure 9. Normal adhesion stresses without shear and the unloading adhesion stresses after shear of the gecko-inspired surface with different waiting times.

Obvious stick−slip phenomena have also been observed in the friction experiments if the sliding distance is long enough. As shown in the friction force curves between the silicon wafer and the gecko-inspired surface in Figure 10, the first stick−slip distance increased from 0.2 to 0.4 mm as the preload increased. This result can be understood as larger preload leading to a larger elastic deformation energy being accumulated in the fibers. Therefore, a sufficiently large sliding distance should be carried out for the clamp legs to overcome the maximum friction force in the first stick−slip cycle.

3.2. Design of Three-Legged Clamp.

The basic design principles of the three-legged clamp have been introduced above in the Experiment section. A detailed description now follows. As the clamping position could not always be selected at the center of gravity of the object to prevent the object clamped overturning and consequently peeling off the gecko-inspired surfaces, the main part of the clamp was designed to have three spring steel legs installed regularly around the cylindrical holder.

The key point in controlling the action of the three legs is to switch between the states of attachment and detachment. Each leg spring was connected to a thin, strong polymer thread. The three threads all went through a guide and then were attached to a rotating shaft connected to a digital servo motor. Thus, the threads could be controlled to stretch and relax simultaneously by the motion control of the motor, producing the gripping-in and gripping-out actions of the leg springs.

Take a piece of 4′ silicon wafer with a mass of about 8 g as an example to show the design of the geometry of the clamp. Three pieces of gecko-inspired surface, each with an area of approximately 4 mm^2, were glued at the flat end of the leg springs. The fibrillar surfaces had to be kept in the same horizontal plane when the leg springs were gripped-in. According to the experiments of section 2, an adhesive force about 120 mN could be generated when the preload of the surfaces to the wafer was about 14 mN. According to the friction experiment in the section 2, the friction force of a single leg spring was about 20 mN. Also, the stick−slip distance of about 1 mm should be considered according to Figure.10. Overall, to ensure a reliable detachment, the design target was set to about 100 mN restoring force at the end of each leg spring after the restoring deformation about 1.5 mm. The fabricated clamp is shown as Figure 11.

The process by which the clamp lifted and moved the 4′ silicon wafer, controlled by computer, is shown in Figure.12. First, the clamp was gripped-in, and then it was moved down to contact the horizontally placed silicon wafer at a small preload. After several seconds, the clamp was lifted up and laterally moved to the aim position. Finally, the leg springs were relaxed to grip-out and the wafer was released. Previously, many kinds of applications of gecko-inspired surfaces were reported, which

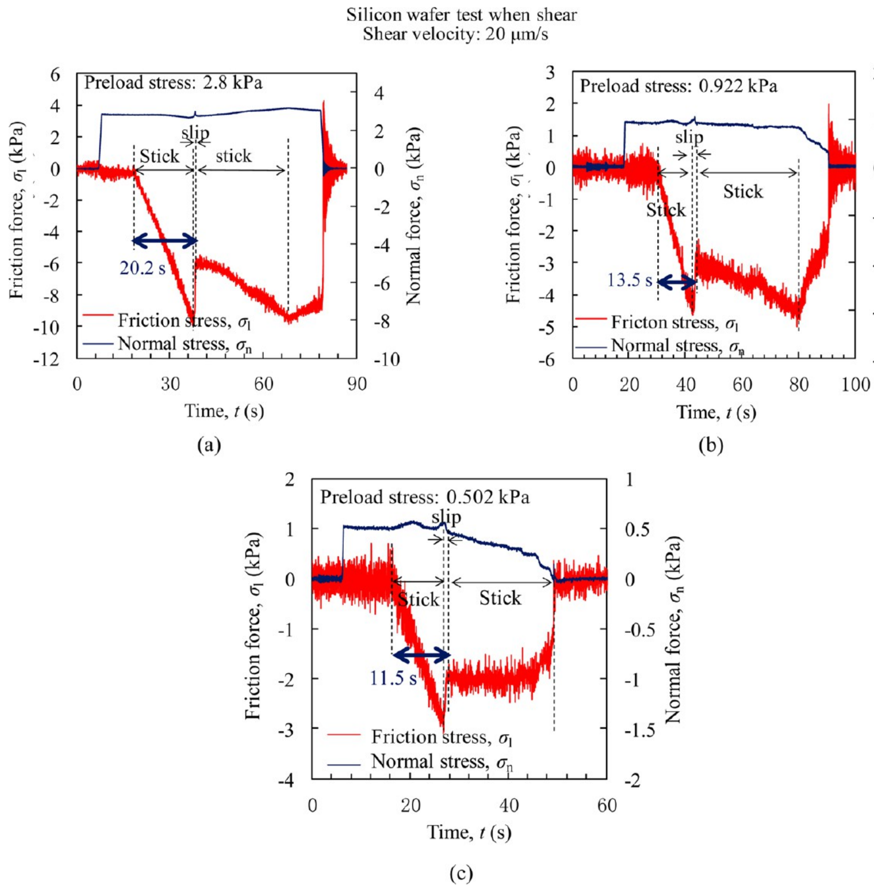


Figure 10. Stick−slip phenomenon of the gecko-inspired surface at different preload.

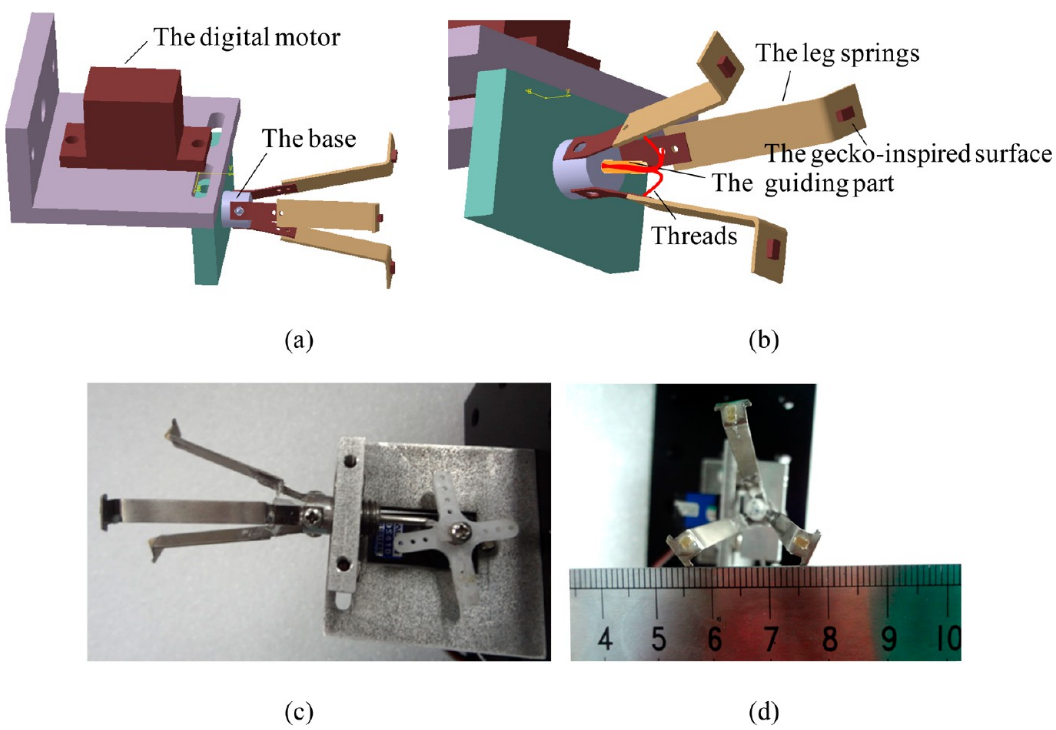


Figure 11. Design (a, b) and fabricated (c, d) the three-legged clamp.

usually used the strong friction force of the gecko-inspired surfaces. For example, Qu et al.[42] reported that a book of about 1.5 kg could be sustained by the friction force of a vertical aligned carbon nanotube array about 16 mm^2 in size. Jeong et al.[36] fabricated a kind of two-level polyurethane acrylate fiber array, which was used to move a large-area glass by anisotropic

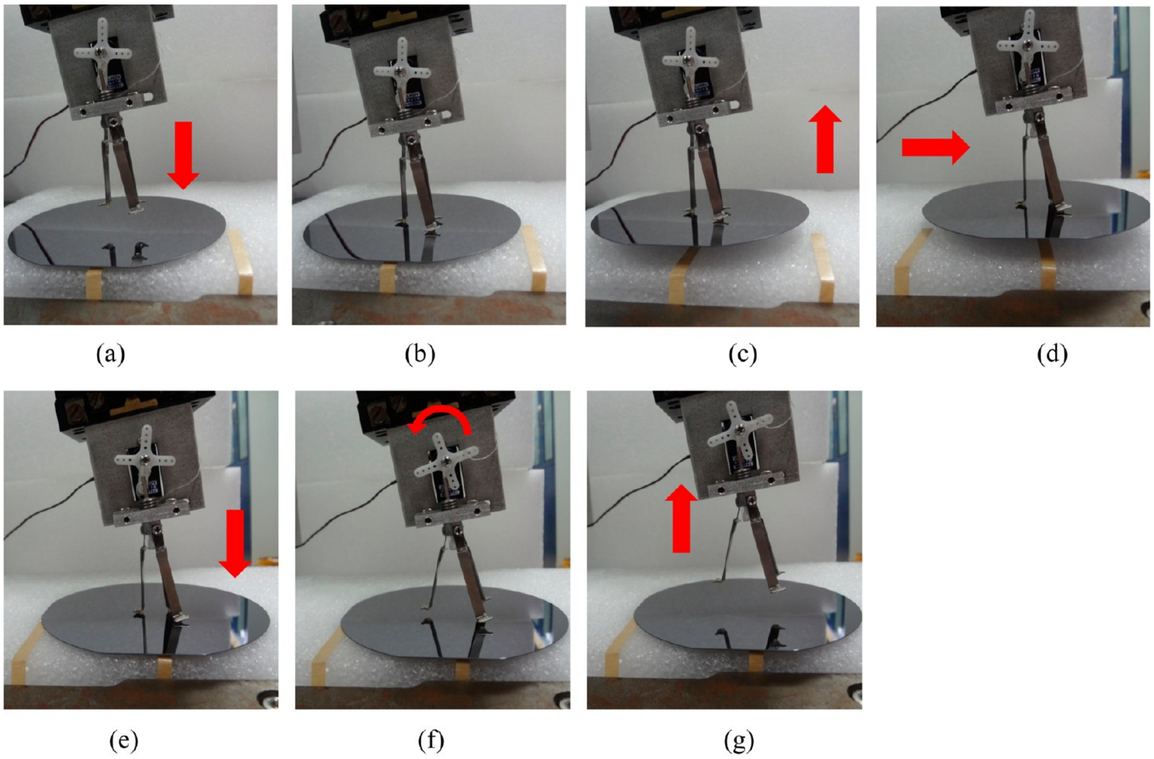


Figure 12. Process of transferring the silicon wafer by using the clamp: (a) moving toward, (b) attachment, (c) lifting up, (d) transferring, (e) moving down, (f) detachment, and (g) separation.

friction force. Lee et al.[43] used the friction force of the combined lamellae and nanofiber arrays to sustain large weights. Unlike the previous work, this kind of clamp directly controlled the adhesive force of the gecko-inspired surfaces to transfer light and fragile objects.

3.3. Discussions. Previous studies reported micromanipulation to transfer printing by using elastomeric stamps or fibers.[44−47] There were several mechanisms to control the interfacial adhesion, such as kinetically controlled,[46] shape-assisted control,[47] and shear-enhanced control.[9,44] Furthermore, it is expected to deepen this issue through scale-span integrating mechanisms. Theoretical researches have shown that the key principles of gecko attachment and detachment involved nanoscale interfacial adhesion, microscale compliance and deformation of the hierarchical structures, and further the macro-scale actuation.[5,7] For the gecko-inspired surfaces, a fracture mechanics showed that the pull-off force decreased linearly with increase of shear strain,[9] which provided an effective way to control the interfacial adhesion by the macro-scale control action.

It has been described that the two opposite feet of geckos form a Y-shaped system when climbing, and the frictional forces of these two feet enhance the attachment reliability.[47−51] Inspired by this Y-shaped geometry, the design of a three-legged clamp enabled a well-adaptable contact between the adhesive surface at the terminal legs and the substrate.[52] In the system, the total force is in the normal direction to the substrate, providing a direct way to use the adhesion force of the gecko-inspired surface in this study.

The key design principle of the three-legged clamp is to match the movement of the legs and the adhesive characters of the surfaces. For the setal arrays, it is extremely important that the normal and horizontal moving distances in the gripping-in and gripping-out directions provide appropriate deformation of the setal arrays.[52] For gecko-inspired surfaces, shear forces able to produce some sliding distance to overcome the stick−slip of the surfaces are critical. Therefore, the design in this study needed to be guided by the load−unload and load−shear−unload experiments. However, the design of the clamp needs to be improved to enhance its reliability and the stability. The durability of the clamp also requires study in future work. Besides, one of the disadvantages for the use of the standard polyurethane was that the thermal damage during fabrication or use may reduce the interfacial adhesion. It is expected that by using the conductive material, such as the carbon/polyurethane composites,[53] the thermal stability and the adhesion reliability could be improved.

Recently, much effort has been devoted to the anisotropic gecko-inspired surface.[9,37,54] These surfaces exhibited anisotropic adhesion force. Especially in ref 54, the inclined fibrillar array provided repulsive force when sheared in the gripping-out direction. The use of this kind of surface in the clamp in this study may help decrease the shear force in the releasing action and facilitate active release.[55]

4. CONCLUSIONS

In this study, the adhesion and friction of a gecko-inspired mushroom-shaped fiber array surfaces were characterized and utilized to fabricate a three-legged clamp. The results show that this gecko-inspired surface performed high adhesion when normally loaded, and low adhesion after shear. Also, stick−slip phenomena on the gecko-inspired surface were observed. On the basis of these experiments, a form of three-legged clamp was designed and fabricated, and this has been successfully used to transfer light and fragile objects with smooth flat upper surfaces, such as silicon wafer. This form of clamp has a number of advantages, such as controllable attachment and detachment, reliable attachment, easy detachment, and low clamping stress. It provides new insight into the attachment and detachment control of the adhesive force of the gecko-inspired surfaces.

AUTHOR INFORMATION

Corresponding Author

*E-mail: tianyu@mail.tsinghua.edu.cn.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This work is sponsored by the National Natural Science Foundation of China with Grant No. 51175281 and No. 51021064, and National Program on Key Basic Research Project with Grant No. 2011CB707603. D.S. would like to thank the Natural Sciences and Engineering Research Council of Canada for funding. Thanks are extended to Brendan Ferguson for the fabrication of the acrylic and silicone molds used in this work.

REFERENCES

(1) Saito, S.; Soda, F.; Dhelika, R.; Takahashi, K.; Taarada, W.; Kikutani, T. *Smart Mater. Struct.* **2013**, *22*, 015019.
(2) Chary, S.; Tamelier, J.; Turner, K. *Smart Mater. Struct.* **2013**, *22*, 025013.
(3) Autumn, K.; Liang, Y. A.; Hsieh, S. T.; Zesch, W.; Chan, W. P.; Kenny, T. W.; Fearing, R.; Full, R. J *Nature* **2000**, *405*, 681−685.
(4) Huber, G.; Gorb, S. N.; Spolenak, R.; Arzt, E. *Biol. Lett.* **2005**, *1*, 2−4.
(5) Tian, Y.; Pesika, N.; Zeng, H. B.; Rosenberg, K.; Zhao, B. X.; Mcguiggan, P.; Autumn, K.; Israelachvili, J. *Proc. Natl. Acad. Sci. U.S.A.* **2006**, *103*, 19320−19325.
(6) Autumn, K.; Hsieh, S. T.; Dudeket, D. M.; Chen, J.; Chitaphan, C.; Full, R. J. *J. Exp. Biol.* **2006**, *209*, 260−272.
(7) Zhou, M.; Pesika, N.; Zeng, H. B.; Tian, Y.; Israelachvili, J. *Friction* **2013**, *1*, 114−129.
(8) Geim, A. K.; Dubonos, S. V.; Grigorieva, I. V.; Novoselov, K. S.; Zhukov, A. A.; Shapoval, S. Y. *Nat. Mater.* **2003**, *2*, 461−463.
(9) Yu, J.; Chary, S.; Das, S.; Tamelier, J.; Pesika, N. S.; Turner, K. L.; Israelachvili, J. *Adv. Funct. Mater.* **2011**, *21*, 3010−3018.
(10) Autumn, K.; Sitti, M.; Liang, Y. A.; Peattie, A. M.; Hansen, W. R.; Sponberg, S.; Kenny, T. W.; Fearing, R.; Israelachvili, J.; Full, R. J. *Proc. Natl. Acad. Sci. U.S.A.* **2002**, *99*, 12252−12256.
(11) Huber, G.; Mantz, H.; Spolenak, R.; Mecke, K.; Jacobs, K.; Gorb, S. N.; Arzt, E. *Proc. Natl. Acad. Sci. U.S.A.* **2005**, *102*, 16293−16296.
(12) Kim, T. W.; Bhushan, B. *J. R. Soc., Interface* **2008**, *5*, 319−327.
(13) Autumn, K.; Majidi, C.; Groff, R. E.; Dittmore, A.; Fearing, R. *J. Exp. Biol.* **2006**, *209*, 3558−3568.
(14) Persson, B. *J. Chem. Phys.* **2003**, *118*, 7614−7621.
(15) Spolenak, R.; Gorb, S.; Arzt, E. *Acta Biomater.* **2005**, *1*, 5−13.
(16) Greiner, C.; Spolenak, R.; Arzt, E. *Acta Biomater.* **2009**, *5*, 597−606.
(17) Zhou, M.; Pesika, N.; Zeng, H.; Wan, J.; Zhang, X. J.; Meng, Y. G.; Wen, S. Z.; Tian, Y. *J. R. Soc., Interface* **2012**, *9*, 2424−2436.
(18) Aksak, B.; Murphy, M. P.; Sitti, M. *Langmuir* **2007**, *23*, 3322−3332.
(19) Sitti, M.; Fearing, R S *J. Adhes. Sci. Technol.* **2003**, *17*, 1055−1073.
(20) Campo, D. A.; Greiner, C. *J. Micromech. Microeng.* **2007**, *17*, R81−R95.
(21) Campo, D. A.; Greiner, C.; Arzt, E. *Langmuir* **2007**, *23*, 10235−10243.
(22) Campo, D. A.; Greiner, C.; Alvarez, I.; Arzt, E. *Adv. Mater.* **2007**, *19*, 1973.
(23) Kim, S.; Sitti, M.; Hui, C. Y; Long, R.; Jagota, A. *Appl. Phys. Lett.* **2007**, *91*, 161905.
(24) Spolenak, R.; et al. *Proc. R. Soc. A* **2005**, *461*, 305−319.
(25) Varengerg, M.; Gorb, S. *J. R. Soc., Interface* **2008**, *5*, 785−789.
(26) Creton, C.; Gorb, S. *MRS Bull.* **2007**, *32*, 466−472.
(27) Shahsavan, H.; Zhao, B. *Soft Matter* **2012**, *8*, 8281.
(28) Noderer, W. L.; Shen, L.; Vajpayee, S.; Glassmaker, N. J.; Jagota, A.; Hui, C. Y. *Proc. R. Soc. A* **2007**, *463*, 2631−2654.
(29) Bae, W. G; Kim, D.; Suh, K. Y. *Nanoscale* **2013**, DOI: 10.1039/C3NR02008H.
(30) Lee, H.; Lee, B. P.; Messersmith, P. B. *Nature* **2007**, *448*, 334−338.
(31) Lee, D. Y.; Lee, D. H.; Lee, S. G.; Cho, K. *Soft Matter.* **2012**, *8*, 4905−4910.
(32) Kustandi, T. S.; Samper, V. D.; Ng, W. S.; Chong, C. S.; Gao, H. *J. Micromech. Microeng.* **2007**, *17*, N75−N81.
(33) Greiner, C.; Arzt, E.; Campo, D. A. *Adv. Mater.* **2009**, *21*, 479.
(34) Murphy, M. P.; Kim, S.; Sitti, M. *ACS Appl. Mater. Interfaces* **2009**, *1*, 849−855.
(35) Bhushan, B.; Lee, H. *Faraday Discuss.* **2012**, *156*, 235−241.
(36) Jeong, H. E.; Lee, J. K.; Kim, H. N.; Moon, S. H.; Suh, K. Y. *Proc. Natl. Acad. Sci. U.S.A.* **2009**, *106*, 5639−5644.
(37) Zhou, M.; Liu, K.; Wan, J.; li, X.; Jiang, K. L.; Zeng, H. B.; Zhang, X. J.; Meng, Y. G.; Wen, S. Z.; Zhu, H. W.; Tian, Y. *Carbon* **2012**, *50*, 5372−5379.
(38) Lee, J. H.; Fearing, R. S.; Komvopoulos, K. *Appl. Phys. Lett.* **2008**, *93*, No. 191910.
(39) Murphy, M. P.; Aksak, B.; Sitti, M. *Small* **2009**, *5*, 170−175.
(40) Autumn, K.; Dittmore, A.; Santos, D.; Spenko, M.; Cutkosky, M. *J. Exp. Biol.* **2006**, *209*, 3558−3568.
(41) Sameoto, D.; Menon, C. *J. Micromech. Microeng.* **2010**, *20*, 115037.
(42) Qu, L. T.; Dai, L. M.; Stone, M.; Xia, Z. H.; Wang, Z. L. *Science* **2008**, *322*, 238−242.
(43) Lee, J.; Bush, B.; Maboudian, R.; Fearing, R. S. *Langmuir* **2009**, *25*, 12449−12453.
(44) Mengüç, Y.; Yang, S. Y.; Kim, S.; Rogers, J. A.; Sitti, M. *Adv. Funct. Mater.* **2012**, *22*, 1246−1254.
(45) Cheng, H.; Wu, J.; Yu, Q.; Kim-Lee, H.; Carlson, A.; Turner, K. T.; Hwang, K. C.; Huang, Y.; Rogers, J. *Mech. Res. Commun.* **2012**, *43*, 46−49.
(46) Meitl, M. A.; Zhu, Z. T.; Kumar, V.; Lee, K. J.; Feng, X.; Huang, Y.; Adesida, I.; Nuzzo, R. G.; Rogers, J. A. *Nat. Mater.* **2006**, *5*, 33−38.
(47) Kim, S.; Wu, J.; Carlson, A.; Jin, S. H.; Kovalsky, A.; Glass, P.; Liu, Z.; Ahmed, N.; Elgan, S. L.; Chen, W.; Ferreira, P. M.; Sitti, M.; Huang, Y.; Rogers, J. A. *Proc. Natl. Acad. Sci. U.S.A.* **2010**, *107*, 17095−17100.
(48) Autumn, K.; Dittmore, A.; Santos, D.; Spenko, M.; Cutkosky, M. *J. Exp. Biol.* **2006**, *209*, 3569−3579.
(49) Autumn, K.; Hsieh, S. T.; Dedek, D. M.; Chen, J.; Chitaphan, C.; Full, R. J. *J. Exp. Biol.* **2006**, *209*, 260−272.
(50) Pesika, N. S.; Tian, Y.; Zhao, B. X.; Zeng, H. B.; Mcguiggan, P.; Autumn, K.; Israelachvili, J. N. *J. Adhes.* **2007**, *83*, 383−401.
(51) Wang, Z. Y.; Song, Y.; Dai, Z. D. *Friction* **2013**, *1*, 143−149.
(52) Tian, Y.; Wan, J.; Pesika, N.; Zhou, M. *Sci. Rep.* **2012**, 3, 1382.
(53) Ferguson, B. J. Improved Gecko Inspired Dry Adhesives Applied to the Packaging of MEMS. M.S. Dissertation, Department of Mechanical Engineering, University of Alberta, AB, 2013.
(54) Jin, K.; Tian, Y.; Erickson, J. S.; Puthoff, J.; Autumn, K.; Pesika, N. S. *Langmuir* **2012**, *28*, 5737−5742.
(55) Yang, S. Y.; Carlson, A.; Cheng, H.; Yu, Q.; Ahmed, N.; Wu, J.; Kim, S.; Sitti, M.; Ferreira, P. M.; Huang, Y.; Rogers, J. A. *Adv. Mater.* **2012**, *24*, 2117−2122.