# Fabrication and Integration of Multi-Scale Compliant Elastomer Dry Adhesives with Climbing Robot Designs

**Dan Sameoto[(1)], Yasong Li[(1)], Carlo Menon[(1)], Johan Köhler[(2)]**

*[(1)] Simon Fraser University*
*Menrva Group, School of Engineering Science, 8888 University Dr. Burnaby, BC, Canada, V5A 1S6*
*dsameoto@sfu.ca, yla83@sfu.ca, cmenon@sfu.ca*

*[(2)] European Space Agency*
*TEC-MMA, ESTEC*
*European Space Agency*
*Noordwijk, The Netherlands*
*Johan.Kohler@esa.int*

## ABSTRACT

We present a new manufacturing technology to produce multi-scale compliant feet for use with a novel climbing robot. Climbing robots for space exploration missions may allow scientists to explore environments too difficult for traditional wheeled designs. These climbing robot designs should be able to grasp or adhere to a variety of surface types at multiple angles in order to be effective. To adhere to multiple surfaces, biomimetic dry adhesives based on gecko feet have been proposed. These biomimetic dry adhesives work by using multi-scale compliant mechanisms to make intimate contact with different surfaces and adhere by using Van der Waals forces. Fabrication of these adhesives has frequently been challenging however, due to the difficulty in combining macro, micro and nanoscale compliance. We present here strategies for creating multi-scale compliant mechanisms from macro to nanoscale for use with bioinspired climbing robots for eventual use in space exploration.

## INTRODUCTION

There has been an increasing interest in designing climbing robots for use in space applications ranging from inspection of surfaces on spacecraft, to exploration of planet surfaces [1]. Much of this interest has been generated from new adhesion technologies that take their inspiration from nature. Bioinspired dry adhesives are based on the foot designs of animals ranging from geckos to beetles and operate primarily based on van der Waals forces between two surfaces in close contact. The multi-scale fiber designs of the hairs on the gecko's feet are the most complex in nature, and one of the most effective at adapting a relatively stiff material (beta-keratin) into a structure that behaves as a much softer material and can make good contact with a variety of surfaces. Benefits of dry adhesives, unlike previous magnetic or active suction based climbing robots include no active power requirements, adaptability to nearly any surface and effectiveness in vacuum. Unlike conventional pressure sensitive adhesives (PSA) like tape, dry adhesives also have the potential to be self-cleaning and behave anisostropically, with different adhesion properties depending on the loading conditions. Practically however, it has been difficult to achieve the same adhesion forces that are demonstrated with geckos using synthetic dry adhesives. The best performing synthetic dry adhesives are presently made of relatively soft materials, like silicones and polyurethanes, and with specially designed fiber tips, that increase surface area and decrease the likelihood of peeling. Polyurethane based fibers have been reported in [2] and [3], while silicone based fibers have been reported in [4] among others. While most early attempts at making dry adhesives with flat tipped fibers were unsuccessful at increasing adhesion relative to unstructured polymers, the work presented in [3, 4]and [5] all demonstrated higher normalized adhesion forces with mushroom shaped or spatula tips. Previously, these adhesives have been difficult to manufacture, with those described in [3] and[4] requiring either dipping techniques or delaminated molds. The fibers fabricated in [5] can be manufactured on a larger scale, but the size of individual fibers is relatively large, which limits the contact splitting necessary to improve the adhesive performance. We have recently developed a hybrid method of producing multi-scale polymer fibers direct from a one-part mold, and a post release nanostructuring step to change the morphology of the polymer surfaces. Two types of silicone are tested as potential structural materials for dry adhesives – Sylgard® 184 from Dow Corning [6] and TC-5005 silicone from BJB Enterprises [7]. These materials are selected for their ease of molding and their low surface energies which should aid in self cleaning. Both silicones are integrated with macroscale feet which are designed to be used with a hexapod climbing robot [8] being developed at Simon Fraser University (Fig. 1).

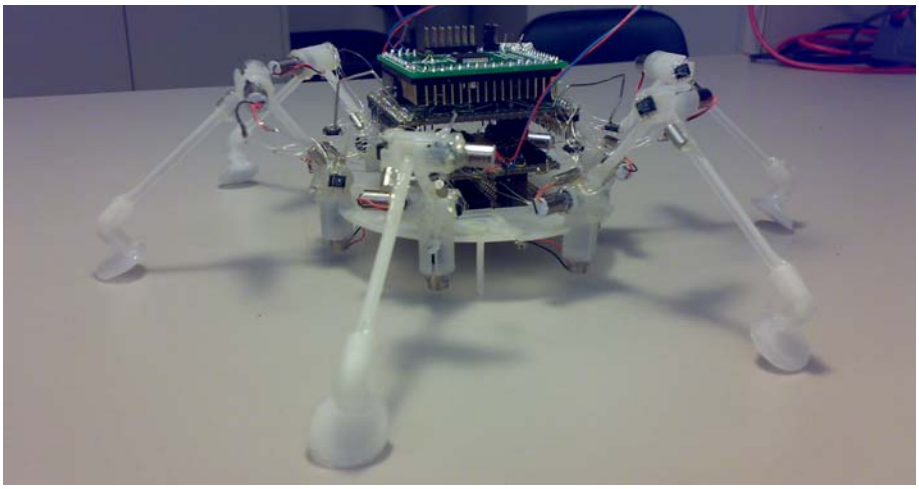

Fig. 1. Hexapod climbing robot prototype.

**FABRICATION**

The fabrication of the multi-scale compliant feet consists of three distinct steps: macro-molding of the foot structure, micromolding of the elastomer fibers, and connection of the macro-foot to the microscale fibers. Another, optional, step is the nanostructuring of the entire microfiber surface using a dry etching step in order to produce a third hierarchical level of compliance. This nanostructuring step is likely to be very important when using stiffer materials for dry adhesives, but is less critical for use with softer silicones. When producing macroscale feet, a mold is designed in SolidWorks, and fabricated using an InVision$^{TM}$ 3-D printer system. The printed material is a combination of triethylene glycol dimenthacrylate ester and urethane acrylate polymer called VisiJet® SR-200 plastic. This plastic is brittle and will soften at temperatures above 60 ºC, so low temperature curing of silicones is necessary when using these molds. Both the Sylgard® 184 and TC-5005 silicones are mixed up according to manufacturer specifications, poured into the foot molds, and degassed under vacuum for at least one hour before curing at room temperature. At ambient temperature (20 ºC), this cure takes over 24 hours. Once curing is complete, the feet are removed from the mold by hand. To aid in demolding, and for simplicity, the foot designs were circular, with an 'ankle' offset from the center which will act as a passive joint between the foot and the robot leg.

Two different manufacturing strategies are used for the microscale patterning of the silicone dry adhesives. The Sylgard® 184 is cast in a mold made of AZ9260 photoresist. An underlying layer of polymethylglutarimide (PMGI) allows for both good photoresist adhesion to the substrate, and a bottom layer that shows little adhesion to the cured Sylgard® 184 material. A similar method of fabrication was also attempted with the TC-5005 silicone, but was unsuccessful. The TC-5005 silicone frequently adhered to either the PMGI layer or the underlying substrate, and often had posts break off during demolding. The introduction of a thin gold layer on the photoresist was previously found to assist in demolding the TC-5005 series silicone [9], but greatly increased the fabrication complexity. As an alternative, polymethylmethacrylate (PMMA) molds were produced using a fabrication technique similar to that described in [10]. Rather than very thin layers of PMMA, a high molecular weight PMMA from Microchem Corp. was spun-on a gold coated silicon wafer in a 20 µm thick layer, and exposed using an inexpensive 254 nm UV source (Stratalinker 2400) [11]. In this technique, very little adhesion to the mold is observed for any of the silicones tested, but the process for making the PMMA mold cannot presently achieve the undercut necessary to cast mushroom shaped fibers. For the PMMA molds, their advantage is that the material is far more resilient compared with the AZ9260 molds, and will survive many more castings. Fig. 2 shows a basic outline of the fabrication processes for both the photoresist and the PMMA microscale molds.

The minimum feature for the Sylgard® 184 posts was 5 µm, with a center to center spacing between posts of 10 µm. For the TC-5005 series silicone, the minimum feature was 10 µm. This change was required because of the larger difference in structural stiffness between the two silicones. The TC-5005 silicone is soft enough that posts with aspect ratios of less than 2:1 will collapse during demolding, which greatly reduces the available surface area for adhesion. Casting of the silicone in the micromolds is done with the same basic steps as for the macroscale mold. After mixing and degassing, the silicones are poured on the molds and degassed again for at least one hour, followed by a room temperature cure for 24 hours. Following the room temperature cure, the thin silicone dry adhesives are demolded.

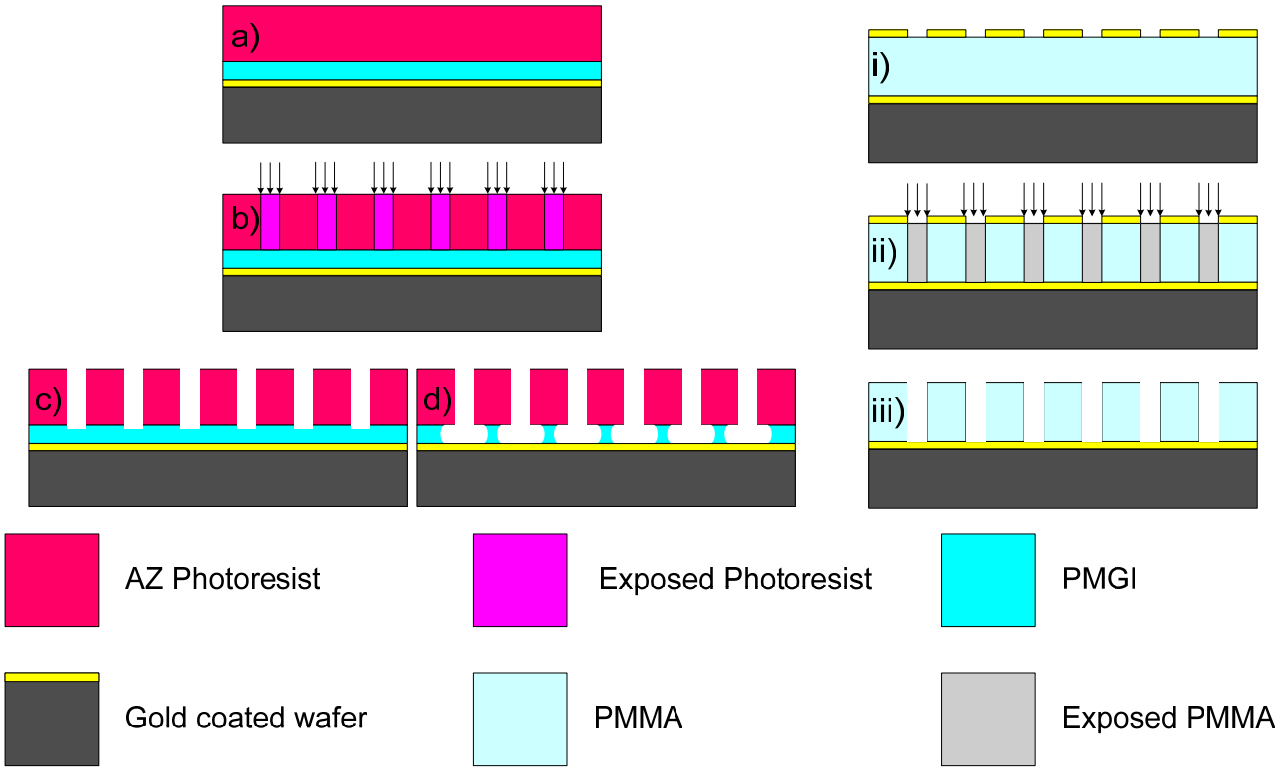


Fig. 2. Generalized process steps for producing photoresist (left) and PMMA molds (right). After spin-coating (a) and exposure (b), the photoresist can be developed to produce either flat tops (c) or mushroom shaped tips (d) after silicone molding. For the PMMA molds, a thin gold layer is patterned (i) to form a mask for 254 nm UV exposure (ii) followed by a development in a 7:3 ratio of isopropyl alcohol to water to form the finished mold (iii).

For TC-5005 silicone, this process is straightforward, as the material has very high tear strength, and will demold off of the PMMA mold with very little difficulty. When demolding the Sylgard® 184, greater care must be taken to prevent small tears at the perimeter of the adhesive from starting. Once a tear is initiated, the silicone sheet will rip very easily which can prevent a successful demolding.

After the sheet of microstructured dry adhesives is removed from the mold, a small amount of uncured silicone is used to glue the microstructured silicone to the previously cured feet. When fabricating integrated feet with TC-5005 silicone in previous work [9], placing a previously cured foot on top of the thin silicone adhesive being cured in a micro-scale mold proved to be the best option for reliability. Unfortunately, this procedure would often inhibit the cure of the thin Sylgard® 184 silicone layer. Additionally, the much thicker foot would cause a higher area of stress on the silicone film when demolding, and would often result in a tear forming around the perimeter of the foot design, which reduced the yield of the demolding procedure dramatically. Because the micromold fabrication procedure was time consuming and complex, the fabrication procedure for the Sylgard® 184 feet was designed to maximize the useful lifetime of the photoresist molds. This required gluing the feet and adhesives together with fresh silicone only after successful demolding.

For a selected number of silicone samples, a nano-patterning step was performed to test the feasibility of adding nano-hairs to the microscale structures previously cast. In earlier work [12], it was demonstrated that the presence of gold during a reactive ion etch (RIE) step was sufficient to produce high aspect ratio fibers with diameters ranging from 20 – 300 nm, through a process called micromasking. Similar results were obtained by other groups when etching polymers using glass [13], or aluminum [14] as a micromask generating material. For this work, a Trion Technologies Orion PECVD/RIE was used to etch silicone samples. The etch parameters were 160 mTorr pressure, 200W power, flow rates of 15 sccm $CF_4$ and 5 sccm $O_2$ and times of either 5 or 10 minutes. The silicone samples being etched were at least 500 µm thick, 1 cm wide, and were centered on either bare silicon, or aluminum coated silicon wafers. Placing the silicone on silicon eliminated micromasking effects, while the presence of aluminum underneath the samples was intended to provide a source of micromasking particles.

**TESTING**

To test the adhesive behaviors of each foot design, a force probe was used to record adhesion for both the adhesives by themselves and the foot designs as an integrated whole. For testing, a linear stage (Zaber Technologies T-LS28-M) controls the position of a force sensor using custom software written in LabView 8.2. The adhesion of the isolated dry adhesive is measured in the normal direction by a GSO-25 force probe from Transducer Techniques. The force probe measures adhesion between the silicone surface and a smooth silicon sample 3.6 $mm^2$ in area. After preloading the tip, the linear stage pulls away at 5 μm/second and records the maximum force.

When testing the integrated feet, a custom cantilever based force probe is used to measure the force required to pull a foot off a clean glass slide mounted vertically. The foot design is oriented with the long axis of the ankle at 90º to the floor. Light pressure is applied to the foot to achieve maximum contact area and then the foot is left for at least 10 seconds prior to being pulled. A thin cable attached to the cantilever force probe is clipped onto the ankle and pulls the foot off the wall at different angles, as shown in Fig. 3. Each foot is pulled off the wall five times, and the average pull force, $F_p$ is recorded. The normal force, $F_n$ is calculated from $F_p$ and the pull off angle. For these tests, the pull speed was set to be 1 mm/s.

**RESULTS**

After fabrication, the dry adhesives were tested for normal strength by themselves, and as an integrated structure with the macroscale foot. Images of the microscale fibers after demolding and after testing were taken to examine where failures were likely to occur during the fabrication and use of the dry adhesive feet. Effectiveness of the mushroom shaped dry adhesives was greatly dependent on the incidence of collapse. While the flat topped posts showed little to no collapse during demolding (Fig. 4a), mushroom shaped fibers would frequently be found to be stuck to one another (Fig 4b). The collapse is partially due to the closer proximity of the caps to one another than the flat tips, but can also be attributed to the effect of the posts snapping out of the mold when being released. More strain energy is required in each mushroom shaped post to remove them from the mold and this leads to each post snapping against its neighbors or the substrate after release. Both causes of collapse increase in frequency with increasing cap diameter. Despite the occasional difficulties in demolding, the mushroom shaped fibers demonstrated clear superiority in adhesion to the flat tipped fibers. The normal adhesion measurements of different Sylgard® 184 surfaces are shown below in Fig. 5.

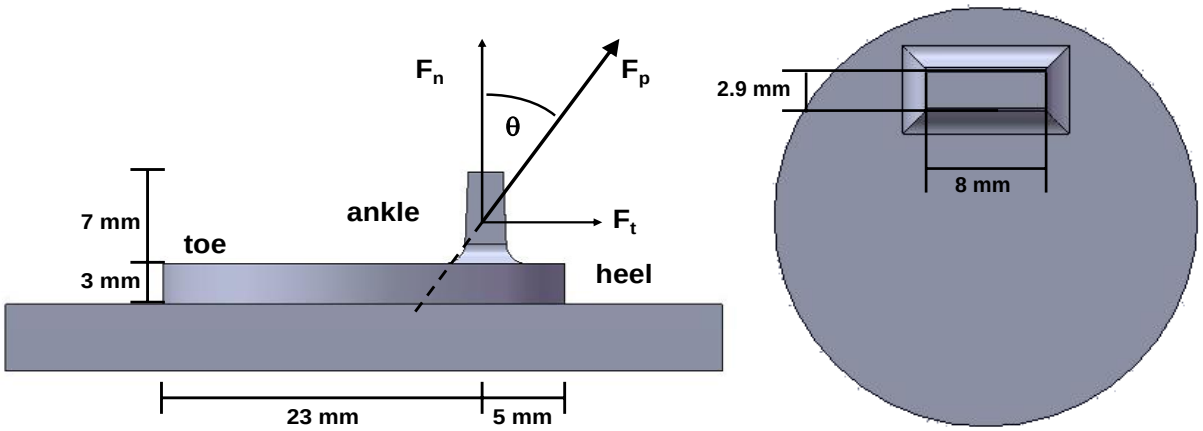


Fig. 3. Schematic of the foot designs and applied force during adhesion tests. Pulling in the direction of the heel is defined as a positive angle, while a negative angle is directed towards the toe.

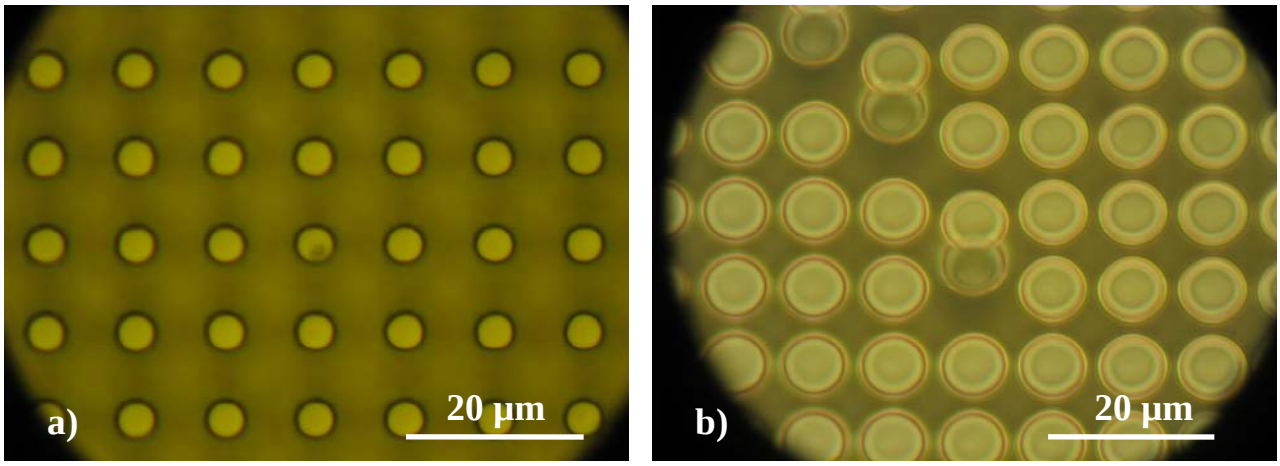

Fig. 4. Photographs of Sylgard® 184 fibers after demolding: a) flat tipped fibers, b) mushroom capped fibers.

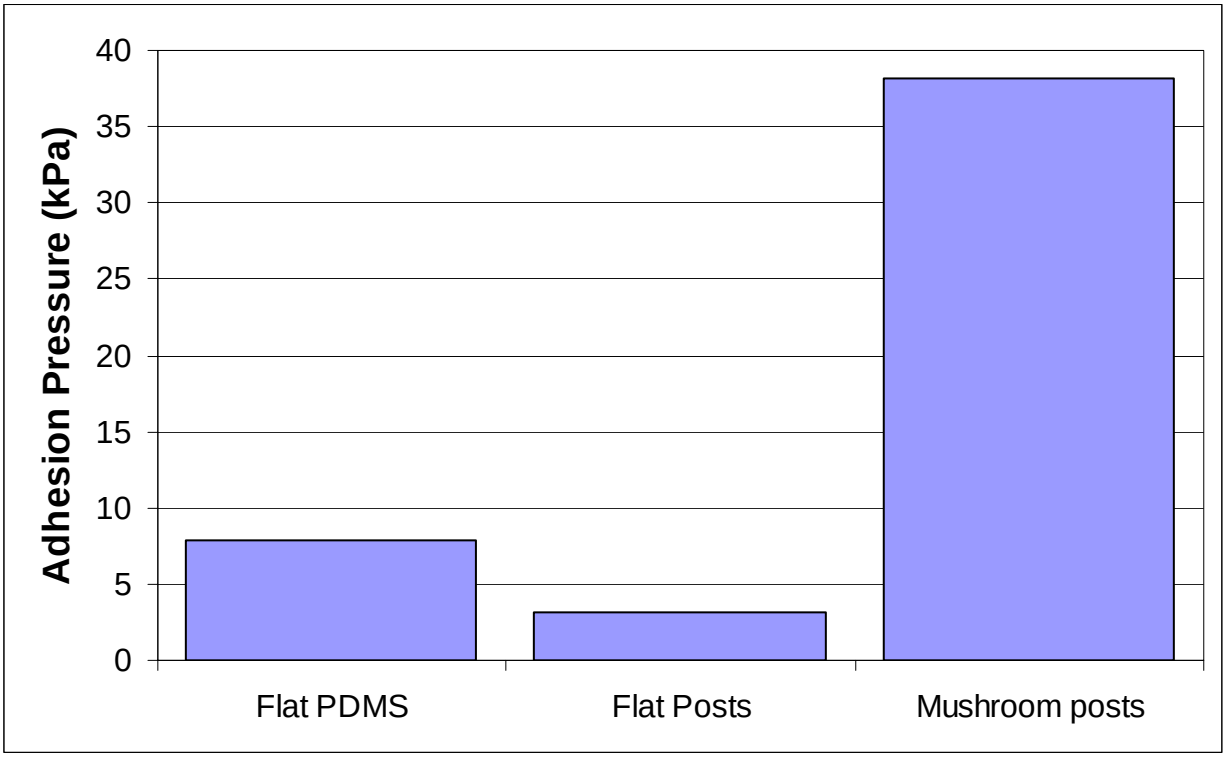

Fig. 5: Normal adhesion pressures of different Sylgard® 184 surfaces. Preload was 10 kPa for all trials.

The TC-5005 silicone demonstrated very little normal adhesion in either its fiber or unstructured form. It is possible that the much greater deformation of the TC-5005 during preloading prevented good contact between the flat force probe tip and the silicone surface. Based on these results, three different foot designs were fabricated: Sylgard® 184 feet had either flat topped or mushroom shaped fibers, or were unstructured and a TC-5005 foot was designed with an unstructured surface. These foot designs were tested at least five times each, and the average normal pull-off forces from a vertical glass surface are shown below in Fig. 6.

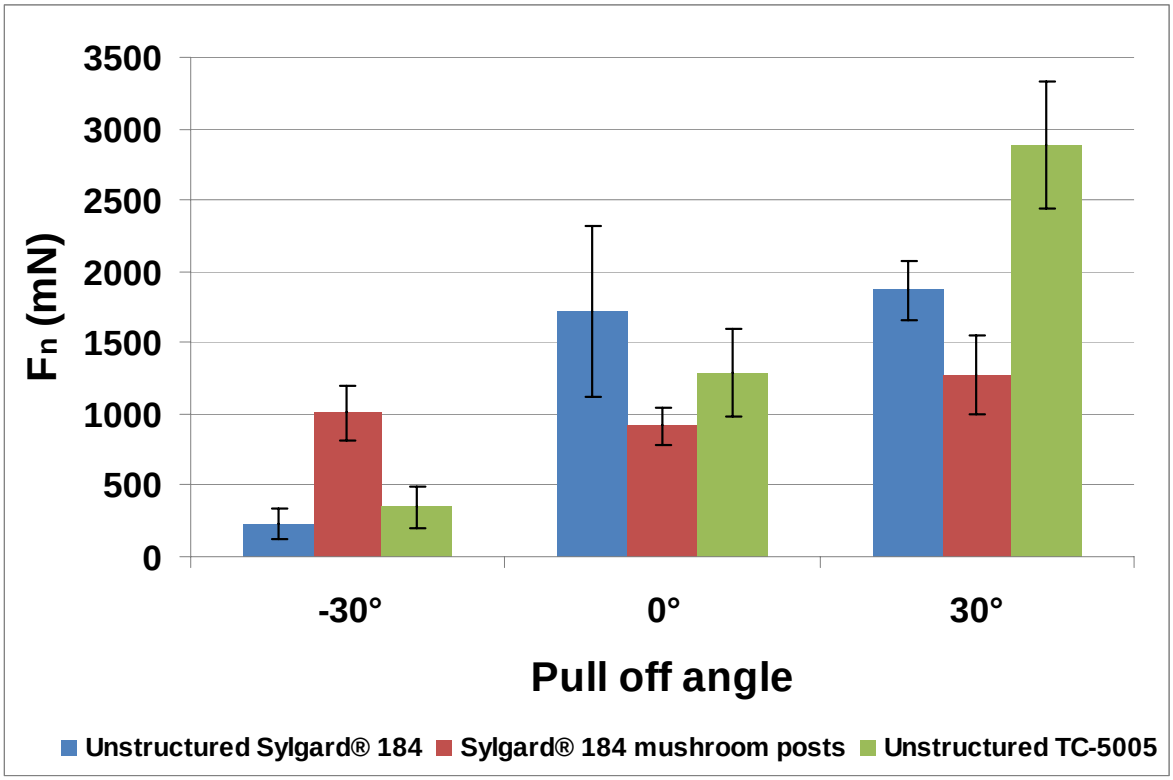


Fig. 6: Average pull off forces required to remove different silicone foot designs from a smooth glass slide.

The results in Fig. 6 show very different behaviors with the different foot materials and structures. The very soft TC-5005 silicone demonstrates a significant anisotropic adhesion with pull-off angle. This design had very little adhesion once peeling was initiated, but when the pull force was directed through the center of the foot, a passive suction cup effect appeared to occur. In this case, both peel initiation was reduced, and adhesion was greatly enhanced by the pressure differences between the atmosphere and the gap produced between the foot and the glass. For this reason, this design might work very well on smooth surfaces, with well defined loading, but would be less tolerant of transient loads in random directions. It is also likely that this design would lose most of its effectiveness in low pressure, or vacuum environments.

The unstructured Sylgard® 184 was the best performing foot design when loaded perpendicular to the glass slide, but also showed the greatest variation in pull-off force. This is because its relatively stiff structure made it more vulnerable to the start of peeling. The initiation of a crack between the glass slide and the heel of the foot lead to the foot coming off the slide almost immediately, but the force required to start this crack was highly variable. When loaded with a positive angle, the average failure force stayed relatively constant, but the variability was greatly reduced, while for negative angles, peeling from the heel occurred at a much lower force.

The most interesting result comes from the Sylgard® 184 foot with mushroom capped fibers. Although this foot was not the best performing overall, it shows a marked improvement over the unstructured designs when loaded with a negative angle. Despite the macroscale foot being at least as stiff as the other designs, it shows almost no variation between its average failure force in different loading directions making it a potentially more reliable adhesive when loaded in peel. The reduction of performance of the mushroom shaped fibers relative to the unstructured Sylgard® 184 once they were fixed to a silicone foot was confirmed qualitatively as well after fabrication. Part of this reduction in force may be fiber collapse, which reduces the effective area in contact with the surface, but another factor is likely that the base foot structure was too stiff for the thickness of the adhesive layer. If there was significant strain energy stored in the foot while in contact with the glass surface, the external force required to remove the foot from the glass would have been less. This might be avoided in the future by making the Sylgard® 184 feet thinner, and more flexible than the current designs.

The silicone samples that were etched with micromasking material were not large enough to test properly for adhesion, so several sections were coated with 10 nm of gold for viewing in a scanning electron microscope to examine the effects of the etching process. The results revealed that significant adjustments in the fabrication process need to be made for this method to produce reliable nano-hairs. The flat silicone samples with the smallest thickness (~500 µm) appeared to be very close to the desired shape after a 10 minute etch on an aluminum coated wafer. (Fig 7a, b). Thicker samples showed significantly less structuring, as did areas far away from the edge of each of the silicone samples. Additionally, the samples with nanostructuring did not demonstrate the same high aspect ratio fibers as earlier work with SU-8 as a structural material. The much lower Young's modulus of the silicone could have caused massive clumping of high aspect ratio pillars during either the etching process or the metal deposition. Future trials will be needed with different etching parameters to be certain.

For the silicone samples with microfibers, very unusual etching patterns occurred. Rather than a uniform etching of all surfaces, a shadowing effect on the etching process was observed (Fig. 7c). This shadowing was always directed towards the edge of the silicone samples. It is probable that the thicker insulating polymers charged up significantly during the etching process, and altered the electric field enough to change the speed and direction of the ions during the etching. Mushroom fibers tops appeared particularly prone to this occurrence, as they would often appear undamaged, while the rest of the fibers were significantly structured (Fig. 7d). The addition of a conducting material in the polymer, may help to prevent this charging effect for future fabrication attempts.

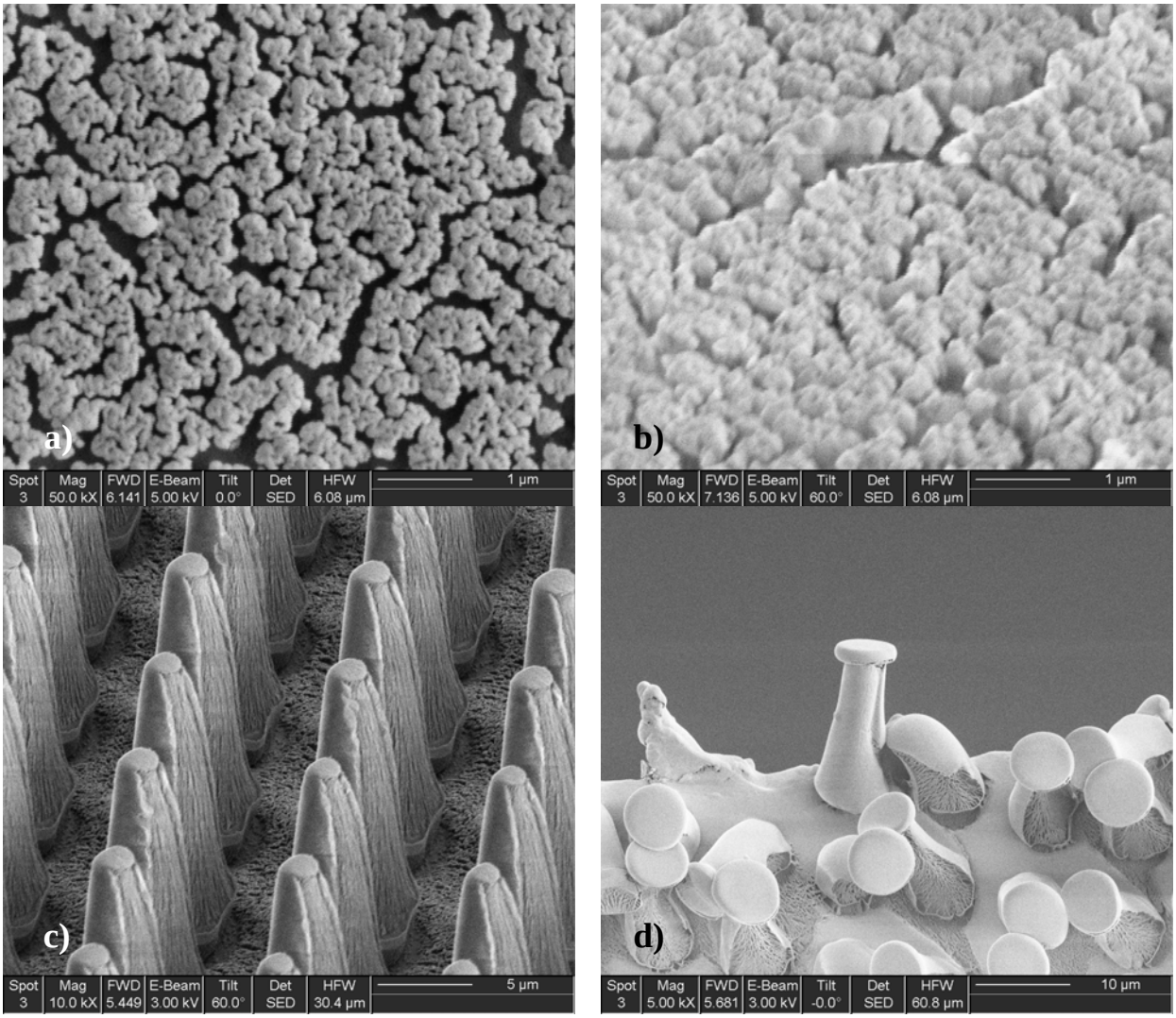

Fig. 7. a), b) Vertical and oblique views of nano-structured Sylgard® 184 after 10 minutes of etching in the presence of aluminum. c), d) Sylgard® 184 fibers showing etch shadowing effects. Etching occurs on the surface facing away from the sample edge.

## CONCLUSIONS

We have successfully demonstrated a synthetic dry adhesive integrated on a flexible foot and have explored the possibilities of adding further nano-compliance to the dry adhesive after molding. For the relatively soft polymers used for this work, the creation of the nanoscale fibers may not significantly enhance adhesion, as the majority of them collapse and act as a counter productive surface roughness. Further, it will be necessary to include some electrically conductive material either embedded in the fibers, or in a thin layer around the fibers to avoid the charging issues encountered with etching very thick polymer layers. Eventually, stiffer polymers, like polyimide may be more likely to benefit from this last level of compliant structures in order to behave as a soft material on the microscale. At the present time, the Sylgard® 184 silicone is a superior choice for the creation of dry adhesives when compared with the TC-5005 silicone primarily because it is easier to produce the mushroom shaped fibers that are demonstrated to be more effective as adhesives, and the individual fibers show far less likelihood of collapse due to their higher stiffness. Although TC-5005 silicone is a much tougher, and more resilient material than Sygard® 184 on the macroscale, its very low material stiffness makes it inappropriate for the production of reliable dry adhesives. Despite the fabrication challenges, significant advancements in the creation of large scale dry adhesives for climbing robot designs have been made. Microscale performance of the mushroom shaped fibers has been demonstrated to be better than the unstructured silicone surfaces, and nanostructuring of microhairs after demolding has been demonstrated to be a feasible direction for future improvements for stiffer structural materials to be used as dry adhesives.

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