Bioinspired pressure actuated adhesive system

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Abstract

We developed a dry synthetic adhesive system inspired by gecko feet that can switch reversibly from adhesion to non-adhesion with applied pressure as external stimulus. Micropatterned polydimethylsiloxane (PDMS) surfaces with pillars of 30 µm length and 10 µm diameter were fabricated using photolithography and moulding. Adhesion properties were determined with a flat probe as a function of preload. For low and moderate applied compressive preloads, measured adhesion was 7.5 times higher on the patterned surfaces than on flat controls whereas for high preloads adhesion dropped to very low values. *In situ* imaging showed that the increased preload caused the pillars to deform by bending and/or buckling and to lose their adhesive contact. The elasticity of PDMS aids the pillar recovery to the upright position upon removal of preload enabling repeatability of the switch. Such systems have promising properties e.g. for industrial pick-and-carry operations.

Introduction

Our previous work has demonstrated that splitting a contact into several small microscale contacts can explain strong gecko adhesion [1-2]. These observations have led the way in designing pillar surface microstructures and fabricating synthetic biomimetic adhesives, e.g. [3-9]. As opposed to a single contact by an integral solid interface, a pillar-structured surface splits the contact formation as well as detachment into multiple events. The nature of these events in time depends on the geometry and orientation of the pillars, elastic moduli of pillars and probe and roughness of probe. Especially interesting for the present study is the effect of change of applied pressure or preload on the adhesion behavior of structured surfaces. Greiner et al. [6] showed that adhesion initially increases with increasing preload and then plateaus for higher preloads. Gorb et al. [10] observed a drop in adhesion for flat as well as structured polyvinylsiloxane (PVS) pillars at high applied preload.

The gecko shows rapid attachment and detachment actions (milliseconds) during movement. Quick detachment from the attached state is inherent to such a motion. The tilted setae, by a simple change of orientation, can peel off easily from a surface [11-12]. While high adhesion strength has been obtained for artificial pillar surfaces, it is still a great challenge to mimic the specific gecko biomechanics of strong adhesion and easy release. A first example using a shape memory polymer was developed by Reddy et al. [13]. It was shown that changing the orientation of micropillars from their vertical to tilted state results in a significant loss of adhesion.

Here, we present a pressure actuated adhesive system that exploits the loss of intimate contact by change of orientation to tune adhesion. The adhesive system is composed of PDMS micropillars with aspect ratio 3 (length 30 µm and diameter 10 µm) fabricated using photolithography and moulding. We show that this system can reversibly switch between an adhesive and a non-adhesive state by applying low and high preload.

Experimental methods

Photolithography and soft moulding were used to fabricate micropillar arrays. The samples were characterized using scanning electron microscopy (SEM) and white light interferometry. The adhesion performance of the samples was measured by standard load-displacement tests on a home-built test apparatus, *Microscopic Ad-*

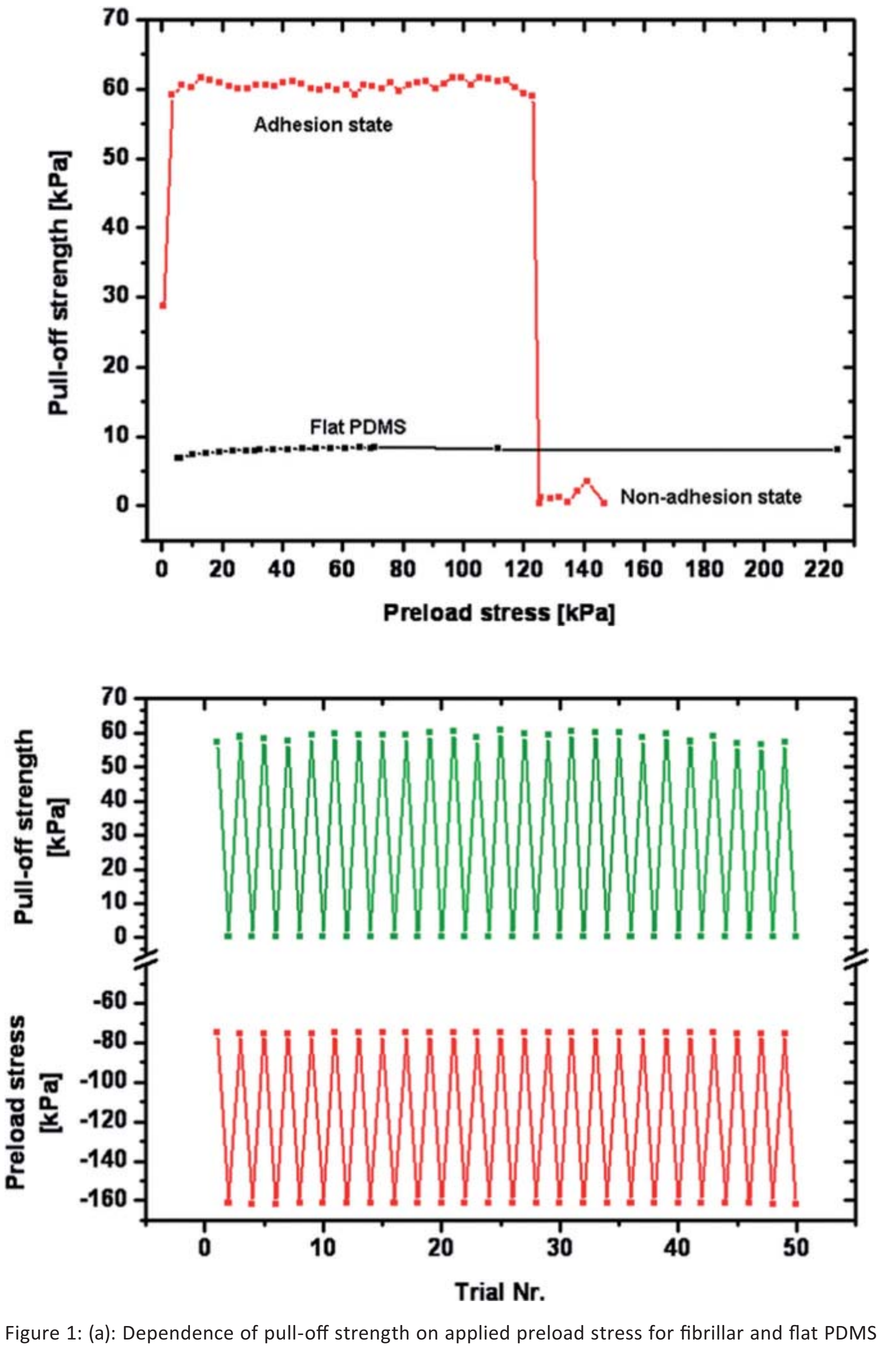

Figure 1: (a): Dependence of pull-off strength on applied preload stress for fibrillar and flat PDMS surfaces measured with MAD. Adhesion state with high pull-off strength and non-adhesion state with low pull-off strength can be distinguished. Flat controls show maximum pull-off strengths of 8 kPa. (b): Repeatability of switching between adhesive and non-adhesive state measured with MAD. Pull-off strength for 50 different adhesion trials wherein alternating high and low preload stresses were applied.

hesion measurement Device (MAD) at INM, Saarbrücken. In a standard load-displacement test, the sample was loaded against and retracted from a flat glass probe with circular cross-section (1 mm diameter) mounted on a glass spring, at a constant velocity of 1 µm/s. The deflection of the glass spring during loading and unloading was monitored via laser interferometry. A spring with a stiffness of 247 N/m was used and forces up to 0.1 N were measured with a resolution of 1 µN. Measurements were also performed with the probe tack tester at the PPMD labs, ESPCI, Paris (ESPCI tester). The ESPCI tester enabled *in situ* visualization of mechanical deformation of the PDMS micropillar array during adhesion testing. The translucent PDMS sample, mounted on a glass slide, was viewed using a long range microscope lens from the glass slide side, i.e. from the back of the sample. A polished flat steel probe with circular cross-section (6 mm diameter) was used to test adhesion. Additional experiments simulating the load-displacement adhesion test were performed using a micromanipulator in SEM to obtain in situ high resolution pillar deformation images.

Results

Figure 1a shows the dependence of pull-off strength on the applied compressive preload stress for structured PDMS as well as for flat PDMS control samples with curing conditions and dimensions similar to the structured samples. Compared to control samples (maximum pull-off strength 8 kPa) the measured pull-off strengths of structured samples were about 7.5 times higher. At low compressive stresses (0.5 kPa), the measured pull-off strength values were also low (30 kPa). With an increase in compressive stress (> 3 kPa), the pull-off strength rapidly reached a maximum of 60 kPa. The pull-off strengths were retained at maximum for an intermediate compressive stress range between 3 and 123 kPa. Increasing the compressive stress further resulted in a sudden drop to extremely low pull-off strengths (1.2 kPa). Thus, two distinct states, that of adhesion (high P_c) and that of non-adhesion (very low P_c) were realized by a change of preload stress. The repeatability of the actuated system was tested over many cycles using alternating low and high preloads and measuring the resulting adhesion. A selection of 50 cycles is shown in Figure 1b. Pull-off strengths of 60 kPa for the adhesive state and below 0.5 kPa for the non-adhesive state were recorded. Thus, the actuated adhesion system is reversible as well as repeatable over several cycles.

Figure 2 shows a representative force-time plot for an adhesion test at high preload of 5 N (177 kPa). After contact formation and lateral displacement of the pillar tops with respect to their bottoms (inset I), a rapidly propagating wave corresponding to the flipping of pillars from top contact to the side seems to occur. This is synchronous with a jump in the measured force at around 1.15 ± 0.05 N. Insets II and III show pillars lying flat after the flip. At even higher loads, the flipped pillars are seen flattened against the PDMS surface of the backing layer and touching neighboring pillars (inset IV). During unloading the pictures suggest that the pillars flip up again and show only lateral displacement with respect to their bottoms (inset V). The subsequent peel-off wave is observed to proceed much faster in comparison to that of the low preload case (inset VI).

Side view images of the loading-unloading process were obtained by adhesion experiments in the SEM. A flat Si probe (smooth side of a wafer) is brought in contact with the PDMS pillar array using a micromanipulator. The first three images from the left in Figure 3 show the loading and the picture in the right the unloading of the experiment. After contact formation the pillars bend in one direction, losing the top face contact with the probe. During unloading, the pillars regain their original upright position and partially reform contact to the probe.

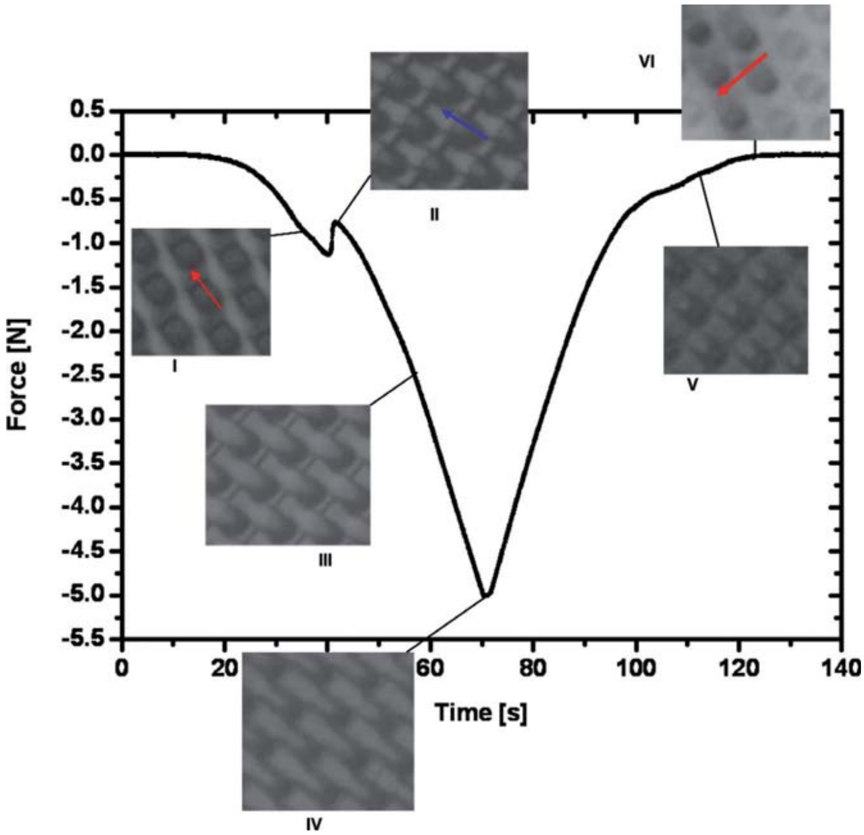

Figure 2: Force – displacement curves and top-view *in situ* videos for 5N preload. I: laterally displaced pillar tops, II: pillars flipped after jump in force (~ 1.18 N), III and IV: pillars lying flat on PDMS backing, V: apparent recovery from flip during retraction and VI: detachment with peel wave, direction indicated by arrow.

Discussion

In this study, we fabricated micropatterned PDMS surfaces, which can be switched from a state of adhesion to non-adhesion by changing the applied preload. The low pull-off strength (28.6 kPa) at low preload indicates that a certain minimum compressive preload is necessary to form intimate contact with the probe. A minimum compressive stress of 3.5 kPa is required for achieving the plateau pull-off strength of 60 kPa. The adhesion remains almost constant for further in-

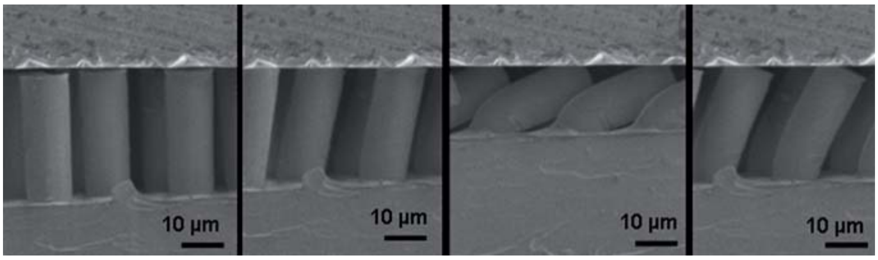

Figure 3: Side-view observations of pillars in SEM. Sequence from *in situ* load-displacement experiments simulating an adhesion test at high preload. The first three images from the left are during loading and the picture to the right during unloading.

crease in preload suggesting that there is no further increase in real contact area. For preload stresses larger than 120.9 ± 2.2 kPa, however, the sample shows a loss in adhesion with average pull-off strength as low as 1.2 ± 1.1 kPa.

The *in situ* videos from the ESPCI tester show that contact formation proceeds in wave form starting from the circumference of the probe. This suggests that the sample was slightly misaligned during the experiment. From the speed of the propagating wave, the misalignment can be estimated to be 0.2°. As the system alignment was optimized prior to the test, there are two other reasons which could explain this observation. The 6 mm diameter flat steel probe has a roughness with wavelengths much larger than the diameter of the pillars giving rise to topography effects. Secondly the PDMS sample itself is not perfectly flat. Due to this, the pillars are not exactly normal to the probe which may induce an additional shear component to the applied normal compressive forces. Consequently pillar deformation occurs under compressive shear, which may be responsible for the observed lateral displacement of the top of the pillars with respect to their bottoms. The direction of the lateral displacement seems to be dictated by the misalignment. Detachment proceeds as a peel wave in the direction opposite to that of the contact formation with the crack usually initiated at the edge of the circular contact interface between probe and sample.

High preload causes the pillars to flip at forces of 1.15 ± 0.05 N. This is related to a sudden transition from top contact to side contact of the pillar as optically observed and is accompanied by a jump in the force time curve. The 'jump' can be due to slip of the adhesive contact and/or buckling of the pillars. It is expected that the aspect ratio of the pillar and roughness of probe will play a significant role in deciding between these two mechanisms. For example, a low aspect ratio pillar is highly resistant to buckling and is more likely to slip before it can buckle, whereas a high aspect ratio pillar will buckle before it slips from top contact. For an intermediate aspect ratio, there will be a competition between the two events.

During probe retraction for measurements applying a high preload of 5 N the pillars flip up and appear to regain partial top surface contact shortly before the compressive shear stresses are completely relieved (see also Figure 3). Low pull-off forces are measured because there is no intimate contact formed between the pillar top and the probe during retraction. The flipping of the pillars is not critical for the reversibility of the system as indicated in Figure 1b.

Conclusion and outlook

- PDMS micropillars with AR 3 were tested for normal adhesion performance using standard load-displacement tests. Pull-off forces of 7.5 times higher than those of flat PDMS under the same test conditions were recorded.
- Samples were tested for switchability in adhesion performance by changing the applied preload. Two preload-defined states of adhesion and non-adhesion were found. For applied stresses between 3 and

125 kPa, an adhesion maximum of 60 kPa is realized, whereas for preloads larger than 125 kPa very low adhesion strengths of 1.2 kPa are recorded.

- The repeatability of the on-off states was tested for 50 cycles. Full switchability from adhesive to non-adhesive state by change in applied preload was found.
- We presented a qualitative understanding of the actuated adhesive system based on *in situ* videos and SEM studies of adhesion tests. The actuation mechanism mimics that of the gecko adhesive system in that the change of orientation of the micropillars is responsible for loss in adhesion. Intimate contact at pull-off from low applied preload leads to high adhesion. Loss of contact during high applied preload leads to lack of intimate contact reformation during pull-off resulting in loss of adhesion.

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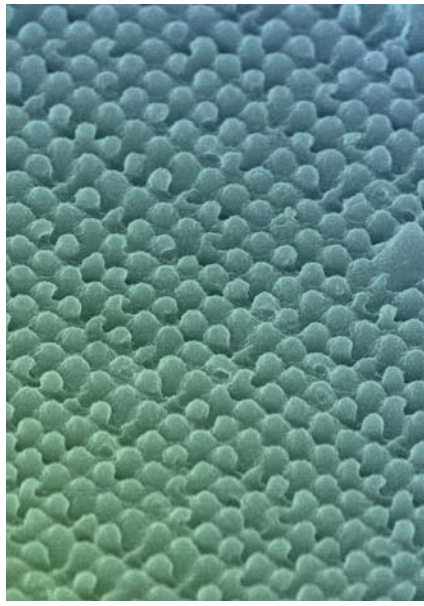

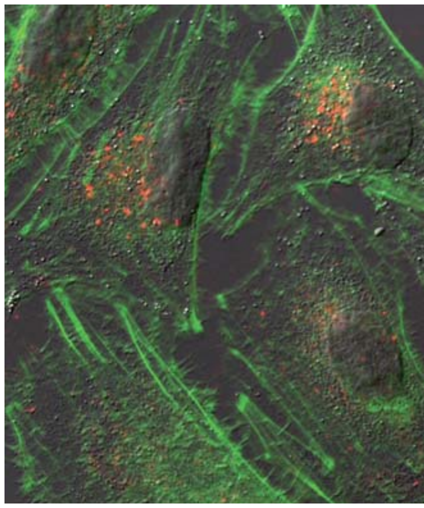

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