Switchable micropatterned adhesives exhibit high potential as novel resource-efficient grippers in future pick-and-place systems. In contrast with the adhesion acting during the “pick” phase, the release during the “place” phase has received little research attention so far. For objects smaller than typically 1 mm, release may become difficult as gravitational and inertial forces are no longer sufficient to allow shedding of the object. A compressive overload can initiate release by elastic buckling of the fibrils, but the switching ratio (ratio between high and low adhesion force) is typically only 2–3. In this work, new microfibrillar designs are reported exhibiting directional buckling with high switching ratios in the order of 20. Their functionality is illustrated by in situ optical observation of the contact signatures. Such micropatterns can enable the successful release of small objects with high placement accuracy.

1. Introduction

Micropatterned polymer surfaces that exhibit controlled temporary adhesion to objects have attracted much interest for implementing a new gripping technology in automated and robotic handling. Inspired by the astonishing clinging ability of animals in nature, such surfaces consist of well-defined fibrillar microstructures to maximize their functionality. Successful use of fibrillar arrays in pick-and-place processes has repeatedly been demonstrated; advantages over mechanical or pneumatic grippers are easy integration, scalability in object size (ranging from meters to below millimeters) and energy and resource-efficient operation. Reliable handling of objects under various conditions has been made possible by a deep understanding of the underlying contact mechanics. Examples include optimized microstructure designs to reduce interfacial stress concentrations, statistical description of detachment events to capture the collective behavior of fibrils in microstructure arrays, and the effects of misorientation between gripping surface and object. Recently, in-line optical observation of the contact area was coupled with machine learning to predict the handling performance of a fibrillar array. These studies established the sufficient adhesive capability of micropatterned polymer surfaces, on par and exceeding current handling technologies.

Driven by the miniaturization of electronic and optical components, a growing trend in the industry is the automated handling of micro-objects. Such components are typically far below 1 mm in size with a mass of a few milligrams or less. With shrinking size, the competition between surface (adhesion) and volume (inertia) effects shift increasingly to the domination of adhesion: small objects invariably tend to stick. As negligible inertial forces no longer contribute to the release of a micro-object, new release mechanisms need to be designed for accurate placement. External triggers have been used to detach macro-objects, e.g., air pressure, electric fields, temperature changes, or chemical inputs. To avoid external triggers, mechanical switching can be easily integrated into the trajectory of the gripper: the straight and intact fibrils deform compressively or even buckle when subjected to a critical overload; this is associated with a loss of contact under compression-induced buckling and facile detachment from the objects. Buckling-induced drop in adhesion has been investigated in different cases, including in air and vacuum, fibrils with different aspect ratios. The figure of merit for such a release mechanism is the switching ratio, i.e., the ratio of the maximum to the minimum adhesive force in the unbuckled and buckled state; for mechanical switching by straight and intact fibril design, it comes to lie typically between 2 and 3. This mechanism has been studied theoretically and experimentally but further improvements are required to successfully transfer this mechanism to microhandling: (i) micro-objects tend to stick to the buckled fibrils as the adhesive contact reforms during unloading; (ii) the switching ratio needs to be increased to allow the reliable placement of small and delicate objects; and (iii) elastic buckling is an uncontrolled collapse of the fibril leading to lateral deformation in random directions, which can exert forces on the object and cause imprecise placement.

In the present paper, we suggest new microfibril designs that can solve the above-mentioned challenges by enhancing the buckling behavior in controlled directions. In this way, the contact area at maximum compressive force is minimized,
leading to sharply reduced pull-off forces. The microstructures were created by two-photon lithography and replica molding. Adhesion tests were conducted after varying the maximum compressive displacement; they were accompanied by in situ optical observation of the contact area along with the fibril deformation. This contact view will be referred to as “contact signature”: it is a central claim of the paper that observations of the contact signature help deepen the understanding of the contact phenomena in fibrillar arrays.

2. Materials and Methods

2.1. Fabrication of Microfibrils

Four different microfibril designs were fabricated. All consist of six microfibrils arranged in hexagon arrays of side length of 200 µm (Figure 1). The reference cylindrical microfibrils had a flat punch geometry with a diameter of 100 µm and a length of 400 µm (Figure 1a, “standard” design). The first modified design had notches with a radius of 15 µm, placed along one third of the total length of the fibril (Figure 1b, “notch” design). Furthermore, fibrils with stalk curvature of radius 100 µm were fabricated (Figure 1c, “curve” design). Finally, the last modification exhibited 45° beveled corners at the fibril tips, which reduced the maximum contact area by 36.3% (Figure 1d, “bevel” design). The modifying feature of each fibril design was oriented to achieve radial symmetry with respect to the center of the hexagon. All microfibrillar arrays were printed with a commercial photoresist using two-photon lithography. The printed microstructure was then replica molded into polyurethane (Smooth-On PMC770, KauPo Plankenhorn e.K., Germany), as described in the previous reports.[18]
2.2. Adhesion Measurements

Adhesion tests were conducted using a custom-made setup, consisting of a 250 mN load cell (KD34s, ME Messsysteme, Germany), a six-axes hexapod (SmarPod, SmarAct, Germany), and several cameras for in situ observations (Figure 1e). For detailed description, see ref. [19]. The microfibrillar arrays were mounted to the load cell and tested against a smooth glass substrate attached to the hexapod. The approach speed was kept constant at 10 µm s⁻¹ for all experiments. Unless mentioned otherwise, retraction also occurred at 10 µm s⁻¹; to probe rate effects, some tests were run with retraction speed of up to 400 µm s⁻¹. In the test routine, the microfibrillar arrays were compressed to a certain displacement between 10 and 180 µm.

Individual measurements were done for each compressive strain, with a pause of 3 min between each measurement to allow relaxation of the material. The maximum tensile force, which leads to detachment of the array in the fully adhesive state (at a displacement of about 40 µm, corresponding to roughly 10% compression), is referred to as the “maximum pull-off force”. The pull-off force remaining after considerable compressive deformation of the structure has occurred will be called “residual pull-off force”. The respective stresses were obtained from the force values by dividing by the total cross section of the six fibrils (=47124 µm²). Finally, the ratio between the pull-off stress in the adhesive state and the residual pull-off stress will be denoted as the “switching ratio”.

3. Results and Discussion

3.1. Mechanical Behavior of the Different Fibril Designs

Figure 2 shows recorded side views and contact signatures of the four designs, together with typical stress-displacement curves. The applied displacement in compression was 120 µm (30% of the fibril height), which exceeded the linear regime in all designs. In the “standard” design, all fibrils buckled roughly in the same direction, while the exact angle of the peel front was not identical for each fibril. A minor misalignment of the sample must have predetermined the buckling direction. The stress-displacement curve (black curve) describes at first a linear response in initial compression, followed by a nonlinear buckling transition at a critical stress of 68 kPa. The residual pull-off stress recorded in a subsequent adhesion test was 21 kPa, i.e., the highest of the different designs.

The “notch” design behaved quite differently: buckling occurred in each fibril toward the periphery of the hexagon, i.e., symmetrically with respect to the center of the array. This resulted also in symmetrical contact signatures, which indicate that peeling occurred radially from the center for all fibrils. The stress-displacement curve exhibited also a linear portion with a reduced slope compared with the “standard” design. Although the “notch” design shows only minor changes compared with the “standard” design, the onset of buckling occurred at a lower stress at 57 kPa (blue curve) and the residual pull-off stress was reduced to 17 kPa, i.e., about 20% below that of the “standard” design.

The “curve” design also seemed to produce a symmetric deformation pattern and a symmetric contact signature similar to the “notch” design. Its stress response (green curve) is quite different as it exhibits only a short linear portion with the smallest slope, a monotonous stress increase and the absence of the strong nonlinearity typical of the other designs. This indicates that the design induced mostly bending without a noticeable instability as observed with a different design.\[19\] The maximum prestress was with only 30 kPa, the lowest of all designs. Also, the residual pull-off stress was most effectively reduced in this design, to about 13 kPa, representing 38% of reduction compared with the “standard” design.

Finally, the “bevel” design produced also a symmetrical deformation pattern, with two distinct stages: under gentle pressure the bottom surface came into full contact first, followed by a buckling event that rotates the contact to the beveled

Figure 2. Side views and contact signatures for the different designs, along with stress-displacement curves. a–d) Side view images of the four designs (left) and contact signatures (right) under compression of 80 µm, representing 20% of fibril height. Dark areas represent contact of the fibril with the glass substrate, the scale bar is 100 µm. e) Stress-displacement curves of the four designs. All structures were compressed by nominally 120 µm, corresponding to 30% of total fibril height. Negative maxima correspond to the residual pull-off stresses (compressive stresses are shown as positive).
surface. Figure 2d illustrates the configuration of the fibrils at this transition. Interestingly, buckling in these fibrils occurred at the highest stress of 69.5 kPa, followed by pull-off at about 18 kPa (red curve).

These results demonstrate that the variations of the fibrillar design have significant influence on their compressive behavior and on their residual pull-off stresses. Somewhat surprisingly, the strongest adhesion reduction occurred in the “curve” design. This design did not exhibit an elastic instability as evidenced by the monotonous increase of the stress-displacement curve. Its residual stress was reduced by about 40% when compared with the “standard” design (13 vs 21 kPa). The contact signatures revealed another important advantage of the modified designs over the “standard”: compressive loading led in all cases to symmetric deformation of the individual fibrils. This can be an important characteristic as asymmetric configurations can possibly exert shear forces on the object and thereby hamper precise positioning.

3.2. Detailed Analysis of the Contact Signatures: Evidence of Contact Recovery

The contact signatures recorded during the mechanical tests allow a more detailed interpretation of the performance of the different designs. It is again emphasized that except for the geometric modifications all other factors of possible influence, such as material, fibril dimensions, and array geometry were identical. We selected series of stills from the contact videos at intervals of 5% relative compressive displacement. The total contact areas (relative to the attainable maximum) were extracted from the pictures over a full attachment and detachment cycle with maximum compressive displacement of 180 µm (45% of the fibril height of 400 µm). Figures 3 and 4 show the progression of contact area values and contact signatures over compressive strain in a full cycle for all four designs, respectively.

The “standard” and “notch” designs exhibited very similar behaviors (Figures 3a,b and 4a,b): Full contact was established quickly after a relative compressive displacement of less than 5%; at about 15%, a critical load was reached causing buckling and a concomitant decrease in contact area. Beyond 25%, the contact area started to increase again, which was caused by some side contact of the fibril with the glass plate. As the displacement was reversed upon reaching 45%, the curve followed a path with slightly decreased contact area followed by increased contact area, which indicates that some recovery of the contact must have occurred. Finally, at zero compressive preload, about 94% of the contact area was recovered for these two designs (Videos S1–4, Supporting Information). A notable

![Figure 3](image-url)  
**Figure 3.** Contact area values versus compressive strain. a–d) The curves describe the progression of total contact area during compressive loading and unloading of the microstructure for different designs: a) “standard”; b) “notch”; c) “curve”; d) “bevel”. All structures were fully compressed to a maximum of 180 µm (corresponding to 45% strain relative to the fibril height of 400 µm).
difference between the two design is, as described above, the asymmetric contact signature of the “standard” design, possibly signifying lateral force exerted on the object.

Close inspection of Figure 4a,b reveals two further details: on the one hand, contact recovery occurred with some delay corresponding to about 5–10% compressive strain. It is likely that this delay was caused by the delayed establishment of full contact due to slight misalignment and possibly some viscoelastic behavior. On the other hand, stacking of contact signatures (Figure 4e, green for the first-time establishment of full contact, red for contact area after retraction to zero-preload position, and yellow for overlapping) revealed a small amount of fibril sliding at zero preload in the “standard” design (in Figure 4e), possible due to some slight misalignment. The sliding direction was away from the center of the hexagon. For the “notch” design, nearly no sliding was visible (in Figure 4f).

The other two designs showed markedly different contact signatures (Figures 3c,d and 4c,d). For the “curve” design, a steady decrease of the contact area was observed under high compression (as for the “standard” and the “notch” design), but a break of symmetry was observed when compression continued to 45% (Figure 4c): five fibrils slid toward the center, forming a pentagon and, at the same time, the sixth fibril slipping toward the center only slightly and almost staying where it was originally (Videos S5–6, Supporting Information). Another sample of the same curve design was also measured, showing a similar contact signal evolution except that all the six

![Figure 4. Contact signatures versus compressive strain. a–d) The evolutions of the corresponding contact signatures are shown with corresponding compressive strain and total contact area in %. Scale bar is 100 µm. e–h) Stacking of contact signatures from two timeframes: green for the first-time establishment of full contact, red for contact area after retraction to zero-preload position, and yellow for overlapping part of both images. Arrow points from green to red.](image-url)
fibrils slid toward the hexagonal center (Video S7, Supporting Information). Image stacking (Figure 4g) revealed sliding to an extent of nearly one fibril diameter toward the center of the hexagon. Apparently, the fibril slippage toward the hexagonal center successfully prevented the recovery of contact area such that only 10% of the contact area remained at zero load. This explains the strong reduction of the residual pull-off stress for this design as will be discussed below.

In the “bevel” design in Figure 4d, initial contact was made with the bottom face of the fibril as described above. At a compressive strain of approximately 15%, a transition to the bevel face took place. Further compression caused a decrease of contact area until the stalk areas contacted the substrate, as already observed for the first two designs (Videos S8–9, Supporting Information). The return to the compression-free state followed again a roughly mirror path, except for the final stage after which only 59% relative contact area was reformed at zero preload. Close observation did not reveal any sliding of fibrils (Figure 4h).

As all other parameters were kept constant, we conclude that the design modifications must have also influenced the recovery of the contact area. The “curve” design was particularly effective in lowering the residual pull-off stress due to the irreversibility induced by large-scale sliding (Figure 4c). In the case of the “bevel” design, the recovered contact area was reduced even without sliding (Figure 4d). The next step of our analysis was to correlate these findings with the measured pull-off stresses.

3.3. Pull-Off Stress After Varying Compressive Displacements: The Switching Ratios Achieved

To shed light on the reduction of residual pull-off stress after applying compression, correlations were established between the observed contact areas and the corresponding pull-off stresses. Data for the residual pull-off stress were normalized by the maximum pull-off stress after full contact formation; these normalized stresses are shown in Figure 5 for the different designs. Absolute adhesion force and adhesion strength are shown in Figures S1 and S2 (Supporting Information), respectively.

The pull-off stresses (squares in Figure 5) exhibit similar characteristic sigmoidal evolution for all four designs: after maximum adhesion was measured at small certain compressive strain, the residual pull-off force dropped steeply before reaching a plateau and then dropping further. The drop occurred at about 17% compressive strain for the “standard” and the “notch” design, and slightly earlier for the “curve” (14%) and the “bevel” (16%) designs. At 25% compression, the plateau values were 74%, 78%, 66%, and 83% for the respective designs. The second drop occurred at about 30–40% compression in all designs. The final values of the residual pull-off stress were 44%, 46%, 5%, and 54% for the different designs; this corresponds to switching ratios of 2.4, 2.4, 20, and 1.7. The high value for the “curve” design is remarkable and makes this design worthy of further studies.

Figure 5. Normalized residual pull-off stresses, residual contact areas (at zero preload), and contact areas measured at maximum compression in dependence of maximum compressive strains. Connection between data point only for visual guidance. a-d) For internal comparison of the four designs, the values of adhesion stresses were normalized to the maximum adhesion stress for each design and the values of contact area were normalized to maximum feasible contact area for each design. Absolute adhesion force and adhesion strength are shown in Figures S1 and S2 (Supporting Information), respectively. The normalized contact areas at maximum compression are generally smaller than residual contact areas (at zero preload) because of partial contact reformation during unloading.
Figure 5 also shows the residual contact area observed after completion of a full compression cycle (hollow stars); this contact area, denoted by “residual contact area”, reflects the elastic recovery of the contact and partial reformation of contact area during unloading. Note however that the relative loss in adhesion does not fully reflect the relative decrease of contact area in most cases: the pull-off stress drops more quickly than the observed contact area (except in Figure 5c). The reasons for this are not fully clear; a possible explanation may lie in invisible precracks existing in the interface due to the high-strain deformation history of the fibrils.

The “curve” design shows the most pronounced loss of adhesion with increasing compressive strain (Figure 5c). Over the whole range, the recovery of the contact area correlates well with the drop in pull-off stress. From the contact signatures, we know that the curved fibril shape initiates a peel front from the center of the hexagon until complete loss of contact. For the “bevel” design, the evolution in contact area reflects the additional bevel face (hollow circles in Figure 5d). At a compression of about 16%, the contact area reaches a minimum as the contact changes from the fibril bottom surface to the inclined face. At 30%, the next transition to the side surface of fibril takes place.

Further insight is obtained by plotting the normalized residual pull-off stresses in comparison with the normalized contact area at maximum displacement (hollow circles in Figure 5). It is immediately obvious that the drop in pull-off force occurs at the same displacement as the loss in contact area. The relative magnitude of the loss of contact area is, however, not fully reflected in the relative drop in pull-off force; the contact areas at maximum displacement are significantly smaller than would be expected from the measured pull-off stresses. This again confirms the assumption of partial reformation of contact during subsequent unloading, giving rise to higher residual pull-off stresses.

3.4. Effect of Retraction Speed on the Residual Pull-Off Stress

The results described above confirmed that the area of fibril surface in contact immediately before applying tensile forces plays a key role in controlling the residual pull-off stress. In addition, it was shown that material recovery leading to reformation of temporarily broken contacts was an important determinant. Depending on the deformation rate, viscoelastic effects can in principle contribute to a delay of recovery. Therefore, the influence of retraction speed was additionally analyzed.

Whereas the approach speed was kept constant at 10 µm s\(^{-1}\), the retraction speeds were varied from 10 to 400 µm s\(^{-1}\). The experiments were carried out up to the compressive strains of 10%, 25%, and 45%. The results are shown in Figure 6.

Shown in Figure 6a, when full contact was achieved at 10% compression, the pull-off stress rose with increasing retraction speed, up to 160% at the maximum speed of 400 µm s\(^{-1}\). This phenomenon may be related to the presence of viscoelasticity.\(^{[20–22]}\) Higher retraction speed would then lead to larger viscoelastic energy dissipation at the crack tip, which would result in a higher pull-off force. Plotted on a log–log graph (Figure S3a, Supporting Information), all four structures result in a straight line with a slope between 0.13 and 0.16. Further analysis of this mechanism is beyond the scope of the present paper.

The monotonic trend of increasing adhesion with increasing retraction speed disappeared at a compression of 25% (Figure 6b). Instead, a maximum pull-off stress is seen at velocities between 100 and 200 µm s\(^{-1}\) for all designs. The “bevel” design indicated the strongest decrease after the peak, with only 40% of the maximum adhesion remaining at 400 µm s\(^{-1}\).

For a compressive strain of 45%, the results show a reverse trend compared with 10% compressive strain. For designs “standard”, “notch”, and “bevel”, the slope of the log–log plot is between –0.30 and –0.36 (Figure S3c, Supporting Information). For those designs, no sliding was recognized before. The reduction is due to the viscoelastic deformation of the material. “Curve” design showed a sliding effect due to instability at high compressive strains of 45% and therefore the adhesion is already nearly zero for a speed of 10 µm s\(^{-1}\). This experiment demonstrated that the retraction speed influences the adhesion due to the material viscoelasticity. At large compression strains, very high velocities facilitate to decrease the adhesion inversely.

Overall, the crucial observation of this study is that adhesion forces in our microfibrillar arrays can be readily tuned by changing the maximum compression and/or the retraction speed.
speed. This can be important when micropatterned adhesives are to be used for robotic pick-and-place cycles: The pick action is then realized by applying slight compression to establish full contact; aided by van der Waal forces, the object can be transported; and placement is finally realized by applying larger compression. It remains to be seen whether the geometrical designs introduced in this paper will be successfully utilized in future industrial handling applications.

4. Conclusion

In the present paper, micropatterned adhesives with geometrical modifications—notch, curve, and bevel designs—were proposed to lower the residual adhesion after compressive deformation. A detailed experimental analysis including optical observation of the “contact signatures” of individual fibrils was conducted. The following conclusions can be drawn:

- The proposed designs successfully reduced the pull-off stresses after a compressive cycle, which caused directional buckling of the individual fibrils.
- The drop in adhesion occurred generally at a critical compressive displacement at which a loss of contact area was observed as well.
- One design (the “curve” fibrils) exhibited the largest switching ratio of about 20, caused by irreversible sliding of the fibrils during compression.

The demonstrated tunability of adhesion by compressive deformation and/or retraction speed points to a possible application of these effects in robotic handling of micro-objects.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

E.A. declares that he is co-owner of a start-up commercializing microfibrillar adhesives.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

controlled adhesion, directional buckling, micropatterned adhesive, microstructure design, pick and place

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