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Sliding Mechanism for Release of Superlight Objects from Micropatterned Adhesives

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Robotic handling and transfer printing of micrometer-sized superlight objects is a crucial technology in industrial fabrication. In contrast to the precise gripping with micropatterned adhesives, the reliable release of superlight objects with negligible weight is a great challenge. Slanted deformable polymer microstructures, with typical pillar cross-section 150 μ m × 50 μ m, are introduced with various tilt angles that enable a reduction of adhesion by a switching ratio of up to 500. The experiments demonstrate that the release from a smooth surface involves sliding of the contact during compression and subsequent peeling of the object during retraction. The handling of a 0.5 mg perfluorinated polymer micro-object with high accuracy in repeated pick-andplace cycles is demonstrated. Based on beam theory, the forces and moments acting at the tip of the microstructure are analyzed. As a result, an expression for the pull-off force is proposed as a function of the sliding distance and a guide to an optimized design for these release structures is provided.

1. Introduction

Automated industrial fabrication involves pick-and-place operations, including gripping, pick-up and precise placement of objects and components. Solutions for gripping are widespread and range from mechanical grippers, pneumatic suckers,^[1] jamming of granular media^[2] to magnetorheological^[3] or electromagnetic devices.^[4] The movement to a target position is often realized by robots and automated gantry systems. The present trend toward integration of miniaturized components in various industries poses numerous demands such as high-precision transport and actuation, particularly to grip and release micrometer-sized, lightweight objects during handling or transfer printing.^[5–11] To address this challenge,

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bio-inspired, micropatterned adhesive surfaces have recently been proposed,^[12-15] for a recent review.^[16] Traction between such reversible dry adhesives and a target surface primarily relies on van der Waals interactions.^[17,18] The adhesion strength can be tuned by the size, design, and mechanical properties of the microstructures.^[16,19–25] A major advantage of these deformable microstructures is their ability to mechanically switch between high and low adhesion.^[26-30] Compared to other actuation strategies, mechanical switching is most straightforward since it can be implemented in the trajectory of the handling device without requiring additional external triggers such as light, temperature, and electromagnetic fields.^[14,31-35]

Mechanical switching was proposed in

variants involving lateral and normal movements with respect to the target surface and their combinations. Lateral actuation has frequently been combined with anisotropic microstructured adhesives, resulting in unidirectional shear adhesives.^[33,36–39] However, such lateral actuation is difficult to implement in robotic operations, where vertical motion further controls the pick and place cycle of the object. Particularly for micrometersized objects, such an approach requires a high-level control over a full 3D trajectory of the microgripper. By contrast, actuation in normal direction alone reduces the complexity, as attachment, pick-up, placing, and release can all be realized by a single path normal to the target surface.

Several groups have demonstrated the switchability of elastically deformable pillar-like microstructures that undergo buckling upon passing a critical compressive load. $^{\left[12,27,32,35\right]}$ If the buckling event is accompanied by a permanent loss in contact area, it can result in controlled detachment of the target object. However, the buckling mechanism exhibits two major limitations. First, the switching ratio of high to low adhesion is often no higher than two, potentially limiting the release of lightweight objects.^[14,28,32] Second, the pillar deformation during buckling induces tangential forces on the object in an unpredictable direction, which can counteract precision during release. Both problems can usually be ignored for macroscopic, heavy objects, but can cause serious difficulties when handling micrometer-sized, lightweight objects. The switching ratio capacity of the buckling mechanism is mainly limited by the re-formation of the contact during compressive unloading ("unbuckling").[40] Such contact recovery could possibly be prevented by slippage of the microstructure during compression, which is promoted in the case of slanted microstructures, as discussed by Mengüç et al.^[12] They





report switching ratios between 26 and 35, though a detailed analysis of the proposed switching mechanism is still lacking.

Toward this end, we perform adhesion tests with individual slanted microstructures of various tilt angles. The adhesion of the microstructures is actuated by controlling the vertical displacement. Complementary to experiments, the deformation of the microstructure is analyzed by a bending beam model that allows access to forces and moments generated when pressed against the target surface. A relationship between the sliding distance and the adhesion force is obtained and a guide to optimize the design is proposed. Finally, the concept is transferred to a tripod gripper and precise handling of a superlight object is demonstrated.

2. Experimental Section

2.1. Microfabrication

The slanted microstructures were made from polyurethane (Smooth-On PMC780, KauPo Plankenhorn e.K. Germany) via replica molding, as described in previous reports.^[29,41] Master structures for the replication process were printed in an IP-S resin (Nanoscribe, Eggenstein-Leopoldshafen, Germany) using a two-photon lithography system (Photonic Professional GT, Nanoscribe, Eggenstein-Leopoldshafen, Germany). Subsequently, IP-S master structures were coated with (1H,1H,2H,2H perfluorooctyl)-trichlorosilane (AB111444, ABCR, Karlsruhe, Germany) by vapor deposition for 45 min. Then a silicone-based template (PDMS, Sylgard 184, Dow, Midland, MI, USA) was molded from the master structures.

2.2. Adhesion Testing

The custom-made adhesion test apparatus (Figure 1b) was built using three main parts: a linear actuator (Q-545.240, PI, Karlsruhe, Germany) with resolution of 6 nm, a load cell (KD45-2N, ME-Messsysteme, Henningsdorf, Germany) to record normal forces with a resolution of 0.3 mN, and two optical systems (UltraZoom, Navitar Inc., New York, NY, USA and μ Lens System Zoom 640 Aven, Ann Arbor, MI, USA), both connected with CCD cameras (DMK 33UX252, ImagingSource, Bremen, Germany) to record top and side view videos. The microstructures were mounted to a stage with two goniometers for proper alignment and the target object was a flat and smooth glass plate.

The apparatus was operated by a LabVIEW routine (National Instruments, Austin, TX, USA). First, the microstructure was brought into contact with the target surface to a set maximum compression at a velocity of 10 μ m s⁻¹. After a hold time of 5 s, the microstructure was retracted at the same velocity until detachment occurred. The maximum tensile load was defined as the pull-off force. The pull-off force obtained from the lowest compression ($u_{max} = 10 \mu$ m) was defined as adhesion force F_{ad} . For pick-and-place demonstration, a 170 μ m thick fluorinated ethylene propylene object (FEP, Bytac, Merck, Darmstadt, Germany) with edge lengths of 1.5 mm × 1.5 mm was used. The mass of the object was about 0.5 mg.

3. Results and Discussion

Microstructures were made from polyurethane using twophoton lithography and replica molding, as described in the Experimental Section. Figure 1a depicts exemplarily a 310 µm long, slanted microstructure. The rectangular cross-section was 150 μ m \times 80 μ m at the bottom and 150 μ m \times 50 μ m at the top (contact side). The top surface had a 20 µm wide and 5 µm thick extension (cap) perpendicular to the orientation of the slanted microstructure. All these dimensions were kept constant and only the tilt angle α was changed from 30° to 75° in steps of 15°. Figure 1b illustrates the adhesion experiment: the slanted microstructure was first brought into contact with a smooth object and compressed until a set displacement $u_{\rm max}$, ranging between 10 and 90 μ m, was reached. Subsequently, the microstructure was retracted until detachment occurred. Typical force–displacement curves for $u_{max} = 20 \,\mu m$ (blue curve) and $u_{\text{max}} = 90 \,\mu\text{m}$ (red curve) are depicted in Figure 1c. The blue curve shows linear compressive loading and unloading and a pull-off force of about 1.5 mN. By contrast, the red curve turned into a nonlinear regime upon passing a critical displacement of about 45 µm (step II), where the adhesive contact started to slide. At $u_{max} = 90 \,\mu m$ (step III), the slanted microstructure was S-shaped, but was still in full contact with the object. The compressive force dropped from -5 to -3.6 mN during 5 s hold time due to relaxation. During retraction, the contact remained fixed until it suddenly detached at $u = 40 \,\mu\text{m}$, even though the microstructure was still in the compressive regime (step IV). Only the edge of the microstructure remained in contact with the object, but did not result in a detectable pull-off force during final detachment (step V). In contrast to the blue curve, the red curve exhibited large hysteresis.

Figure 1d depicts the pull-off forces in terms of the maximum displacements, revealing a gradual decrease of the pull-off force from 1.8 mN down to forces below the resolution of the load cell of 0.3 mN with increasing maximum compression u_{max} . Figure 1e depicts similar trends for slanted microstructures with α of 45°, 60°, and 75°. Here, the pulloff force (normalized by the pull-off force F_{ad} at $u = 10 \,\mu\text{m}$) gradually decreased from 1 to 0.15, whereby the lower limit was always set by the resolution of the load cell. Only the most slanted microstructure with $\alpha = 30^{\circ}$ was less responsive with normalized pull-off forces ranging between 1 and 0.75. Note that comparing to buckling induced release,^[42] the detachment force decreases continuously with increasing compression displacement. Figure 1f exemplarily displays side and top views of the deformed slanted microstructure with $\alpha = 75^{\circ}$ in correspondence to the red curve shown in Figure 1c. The microstructure was first compressed and then underwent bending before sliding along the object. The microstructure then adhered at the new position until it peeled from the right edge and finally detached from the left edge. Note that sliding has led to a curved shape as seen in the top view (Figure 1f-III).

The experiments revealed that compression of the microstructure led to bending before it started to slide. However, it remains unclear how exactly sliding was induced. Therefore, we propose an analytical model to calculate the shear force ADVANCED SCIENCE NEWS _____





Figure 1. Slanted microstructure and adhesion test. a) 3D model and scanning electron images of the slanted microstructure in side and top view. b) Schematic of the displacement-controlled adhesion test apparatus. A motorized stage is used to control the displacement *u*. Normal forces F_{D2} are measured by a load cell. The target object is a smooth glass slide. c) Normal force F_{D2} versus displacement *u* for $\alpha = 75^{\circ}$ with maximum compressions of $u_{max} = 20 \,\mu\text{m}$ (blue curve) and $u_{max} = 90 \,\mu\text{m}$ (red curve). Steps (I) to (V) correspond to images from in situ observations in (f). d) Pull-off force F_p versus max. compression u_{max} for $\alpha = 75^{\circ}$. The highlighted data correspond to the curves shown in (c). The dashed line corresponds to the resolution of the load cell. e) Normalized pull-off force versus max. compression u_{max} for α of 30° (pink triangles), 45° (green triangles), 60° (red circles), and 75° (black squares). f) Side and top view images for $u_{max} = 90 \,\mu\text{m}$ displaying the deformation and sliding of the microstructure with $\alpha = 75^{\circ}$ during compressive loading. Vertical red dashed lines represent the initial lateral position of the microstructure at $u = 0 \,\mu\text{m}$ and horizontal white lines represent the initial vertical position of the contact.

and the moment acting on the tip of the microstructure in terms of varying tilt angles. The microstructure is considered as a beam of length *L* and tilt angle α , clamped at both ends (positions *O* and *A*, see **Figure 2a**). The beam is deformed by the displacement *u* normal to the object, as schematically displayed in Figure 2b. The new position *D* is exactly below *A*, as long as adhesion and friction prevent sliding. Due to the mixed mode of bending and compression, the direction of the resulting force *F* at position *D* deviates from the direction of

the beam and is given by $\alpha - \theta$, where θ is the angle between the direction of *F* and the *x*-axis. Forces along *x* and *w*-axes are then given as *F*cos θ and *F*sin θ , respectively. The elastic deformation of the beam further leads to moments M_0 and M_D at positions *O* and *D*, respectively. Balancing forces and moments provides the moment M(x) at any position along the *x*-axis as follows

$$M(x) = F\cos\theta w + M_0 - F\sin\theta x \tag{1}$$







Figure 2. Analytical model based on beam theory. a) Side view image of slanted microstructure with $\alpha = 75^{\circ}$ adhering to the object. b) Schematic of (a) where the microstructure is replaced by a beam (black). Displacement *u* of the upper end of the beam leads to elastic deformation (green line). Insets define forces and moments at position *O* and *D*. c) Experimental force–displacement curves exhibiting a linear regime with slope *K*. The inset represents *K* as function of α and $r = \alpha \frac{\pi}{180^{\circ}}$. d) Side view image of slanted microstructures for $u = 30 \,\mu\text{m}$. Symbols represent data extracted from the images using the 1–2-coordinate system. e) Comparison between the data from experiments (symbols obtained in (d)) with the analytical closed-form solution (Equation (3)) (green lines).

Introducing linear beam theory with M(x) = -EIw'', where EI is the bending stiffness of the beam, we obtain the governing equation for the beam deflection

$$w'' + \lambda^2 w = \frac{-M_0 + (F\sin\theta)x}{EI}$$
(2)

where $\lambda^2 = \frac{F \cos \theta}{EI}$. For this analysis, we assume that, to 1st

order, the beam is straight (neglecting the tapered cross-section). Furthermore, large deformations leading to nonlinear effects were ignored.^[43] Integration of Equation (2) gives the deflection of the beam as a function of x

$$w(x) = a\cos(\lambda x) + b\sin(\lambda x) + \frac{-M_0 + (F\sin\theta)x}{F\cos\theta}$$
(3)

where *a* and *b* are constants, which together with *F*, θ , and M_0 result in five variables. To solve Equation (3), we consider boundary conditions given by Equations (A.1)–(A.5) as presented in the Appendix.

Note that two Cartesian coordinate systems were introduced: The 1–2-coordinate system represents shear and normal forces, respectively. The x - w-coordinate system is used to describe the bending of the beam, where the *x*-axis follows the undeformed beam. The latter coordinate system can be transferred into the former by anticlockwise rotation of 90° – α .

To validate the model given by Equation (3), we compared the deformation of the beam with our calculations (Figure 2d,e) for $u = 30 \,\mu\text{m}$, which is slightly below the maximum compression at which sliding occurred. The calculated shapes (green lines) match fairly well with the deformed beam in the experiments for tilt angles 45°, 60°, and 75° (Figure 2e). For $\alpha = 30^\circ$, the side view images were insufficiently clear to quantify the deformation. Closer inspection of the experimental data (red symbols) reveals that the beam rotates slightly anticlockwise at position O, which violates our assumption of clamped ends (see Equations (A.3) and (A.4) in the Appendix). This rotation is most likely due to the connection of the microstructure with an elastic support (backing layer). Further discrepancies between experiment and theory may relate to the small ratio of beam length to width of ≈5 and its tapered shape with a thicker base than the tip. Despite these differences, our closed-form solution describes the deformation quite well without requiring finite element simulations and also provides practical information on forces and moments, which we discuss below.

Our experiments revealed that sliding of the slanted microstructure along the object is necessary to switch adhesion to low values. Sliding is caused by the asymmetric elastic deformation of the microstructure during compression and starts at position D, where the shear force F_{D1} and the moment M_D act at the contact (Figure 2b). First, we analyze the shear force F_{D1} that depends on the tilt angle α . **Figure 3**a shows that the calculated shear force (Equation (3)) increases with larger u and is maximum for $\alpha \approx 53^{\circ}$. To induce sliding, F_{D1} has to overcome the

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Figure 3. Force and moment analysis at position *D* before sliding. a) Calculated shear force F_{D1} in terms of tilt angle α for various displacements *u*. b) Calculated force ratio $F_{D1}/(F_{D2} + F_{ad})$ versus *u* with adhesion under dry conditions. c) Calculated force ratio F_{D1}/F_{D2} versus *u* without adhesion under wet conditions. Various symbols and colors correspond to different tilt angles α . d) Calculated moment M_D in terms of tilt angle α for various displacements *u*. e) Critical displacement u_s upon which sliding occurred in experiments under dry (red symbols) and wet (blue symbols) conditions. The inset illustrates how the microstructure with $\alpha = 30^{\circ}$ touched the object before contact sliding occurred. f) Schematic illustrating the lateral and normal forces and the moment acting on the tip of the microstructure when pressed against the target surface. The moment then induces tensile (back end) and compressive (leading end) states along the interface. g) Images of the contact at specific u_s for each of the different microstructure designs under dry conditions. The arrows highlight the location of detached regions at the back end of the contact.

(static) frictional force, $f = \mu (F_{D2} + F_{ad})$,^[44] where μ is the friction coefficient and F_{ad} the adhesion force between the microstructure and the object. The adhesion results depicted in Figure 1d provide F_{ad} of about 2 mN. Figure 3b displays the force ratio $F_{D1}/(F_{D2} + F_{ad})$ in terms of *u*. The ratio increases with larger displacements before it likely enters saturation, but it strongly varies with α . For a fixed displacement of $u = 30 \,\mu\text{m}$ (i.e., close to the displacement when sliding started in the experiments), the force ratio ranges between 0.19 and 0.51 for tilt angles of 75° and 45°, respectively. For α of 30° and 60°, similar ratios of 0.38 were calculated. Note that these values are significantly lower than typical friction coefficients ranging between 1 and 2 for elastomers on glass,^[45,46] indicating that the shear force is not sufficient to induce sliding. This discrepancy is underpinned by the results shown in Figure 3e, where the critical displacements $u_{\rm s}$, at which sliding started, is plotted versus α . The values of $u_{\rm s}$ were about 35 μ m for 45° and 60° tilt angles and 45 μ m for $\alpha = 75^{\circ}$. For $\alpha = 30^{\circ}$, no significant sliding was observed before the deformed stalk of the microstructure touched the

object at $u = 90 \,\mu\text{m}$ (see scheme in Figure 3e). These results contradict the theoretical predictions when considering the shear force alone as a source to induce sliding.

To address the discrepancy, we further analyzed the moment M_D at position D. Figure 3d depicts that the calculated moment (Equation (1) for x = OB) increases with larger u and depends on α with a maximum for $\alpha \approx 58^\circ$, which is similar to the maximum of the shear force. The moment at the tip of the microstructure has a certain relevance for sliding as it induces compression at the leading end and tension at the back end of the contact (Figure 3f). Such a change in the interfacial stress distribution is likely to reduce the effective area over which friction acts. In other words, the frictional resistance along the contact is reduced, as the moment causes the interfacial stress distribution to vary from purely compressive to compressive and tensile states at the leading and back end of the contact. Tensions on the back then even led to detachment, as depicted in Figure 3g. Therefore, the obtained trend for u_s , shown in Figure 3e, can be qualitatively described when considering the





reduced effective contact area caused by M_D in addition to the force ratio $F_{D1}/(F_{D2} + F_{ad})$. Comparing the calculated values for critical displacements $u_{\rm s}$ for α of 45°, 60°, and 75°, decreasing force ratios of 0.53, 0.37, and 0.19 were obtained, while M_D increased from 170, 196 to 240×10^{-9} Nm, respectively. Thus, with increasing tilt angles larger M_D compensate weaker force ratios to induce sliding (within the tested range $45^\circ \leq \alpha \leq 75^\circ$). For $\alpha = 30^\circ$, the force ratio was 0.67 and M_D was 242×10^{-9} Nm at $u = 90 \,\mu$ m. Both values were enhanced, but sliding was restricted to about 5 μ m as the stalk of the microstructure simultaneously touched the target surface (see inset in Figure 3e).

In addition to those results under dry conditions, we performed underwater tests, in which $F_{\rm ad}$ can be ignored, because water acts as a lubricant and reduces adhesion. Then, the force ratio reduces to F_{D1}/F_{D2} and reaches values up to \approx 3 and \approx 1 for α of 30° and 45°, respectively (Figure 3c). Such high values led to instantaneous sliding of both microstructures, as shown by the blue symbols in Figure 3e. For tilt angles of 60° and 75°, the microstructures begun to slide at $u_{\rm s}$ of 25 and 40 µm, respectively. However, note that the force ratio F_{D1}/F_{D2} decreased linearly with increasing u for all tilt angles (Figure 3c), suggesting that the shear force alone should not induce sliding for these

structures. It is therefore likely that the increasing moment M_D induced sliding.

Now we turn back to dry conditions. Passing $u_{\rm s}$ caused the microstructure to slide along the object for a distance s, but stopped immediately when the set maximum compression $u_{\rm max}$ was attained. Note that the microstructure maintained adhesive contact to the object during sliding for $u_{\text{max}} \leq 90 \, \mu\text{m}$, the upper limit in our tests. Figure 4a depicts s as a function of u_{max} depending on α . As an example for $u_{\text{max}} = 90 \,\mu\text{m}$, the sliding distance increased from 30 to 80 μ m with α increasing from 45° to 75°. Figure 4b shows that the data collapse into a single line upon dividing *s* by r^2 (with $r = \alpha \frac{\pi}{180^\circ}$), except the data for $\alpha = 30^{\circ}$ mainly because of the marginal sliding distances. Therefore, the sliding distance can be determined by $s = r^2 (0.8u_{\text{max}} - 22.7) \,\mu\text{m}$, for $r \ge \pi/4$ ($\alpha \ge 45^\circ$). Substituting this expression into Figure 1e, we obtain the relationship between the normalized pull-off force F_p/F_{ad} and the sliding distance s/r^2 , as shown in Figure 4c. For $45^\circ \le \alpha \le 75^\circ$, the data fit to the exponential function $F_{\rm p}/F_{\rm ad} = \exp(-0.0389 \,\mu {\rm m}^{-1}{\rm s}/r^2 - 0.8826)$, which expresses the exponential decrease of the pull-off force in terms of the sliding distance.

In the experiments, we observed that the microstructure remained at the new position during retraction without sliding



Figure 4. Sliding, retraction and adhesion results. a) Sliding distance s versus maximum compression u_{max} for various α . b) Sliding distance s/r^2 versus u_{max} for various α . The solid line represents a linear fit with the 0.8. c) Normalized pull-off force versus s/r^2 . The solid line represents an exponential fit $F_p/F_{ad} = \exp(-0.0389 \,\mu m^{-1}s/r^2 - 0.8826)$. d,e) Side view images displaying the relaxation of the microstructure with (d) $\alpha = 75^\circ$ and (e) $\alpha = 45^\circ$ during retraction of the object. Vertical dashed lines represent the leading end of the contact at $u_{max} = 90 \,\mu m$ after sliding.



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Figure 5. Pick-and-place demonstration. a) Scanning electron image of the tripod design the consist of three identical microstructures with $\alpha = 60^{\circ}$. b) Normal force F_{D2} versus displacement *u* with maximum compressions of $u_{max} = 20 \ \mu\text{m}$ and $u_{max} = 90 \ \mu\text{m}$. c) Pull-off force versus maximum compression u_{max} . d) Side views show the complete pick-and-place handling cycle including (I) approach, (II) attachment to the FEP object, (III) lifting, (IV) microstructure sliding during compression, and (V) detachment and separation. e) Bottom view of the FEP sheet with green contour line before the test and after the 5th (yellow contour line) and 10th (red contour line) pick-and-place cycle.

backward until detachment occurred. This can be explained by a decreasing shear force at the tip with decreasing displacement and the relaxation of the microstructure by releasing stored strain energy. When sliding occurred during compression, complete relaxation occurred before $u = 0 \,\mu\text{m}$ was reached. When the object was further retracted, this led to stretching of the microstructure and a moment at the tip, opening the leading end of the contact by peeling. The peeling then led to a drastic reduction of the contact area and the microstructure receded to its original position, where it easily detached at a much lower pull-off force. The process further explains the dependence of the pull-off force on the sliding distances as shown in Figure 4c. However, note that the pull-off force depends on the peeling resistance which could be altered, for example, by tip modifications.

Seeking to demonstrate such slanted microstructures in handling applications, we created a tripod gripper made of three identical microstructures with $\alpha = 60^{\circ}$ in an axisymmetric arrangement (**Figure 5**a). Figure 5b depicts the force–displacement curves of the gripper tested on glass object and a perfluorinated FEP object. The adhesion of the tripod gripper to the FEP object is ≈ 2.8 mN (dark green), which is 3.5 times lower than the adhesion to the glass object with 10 mN (dark

blue). For $u = 90 \,\mu\text{m}$, pull-off forces were below the resolution of the load cell of 0.3 mN in both cases (light green and blue). Figure 5c depicts the gradual decrease of the pull-off force as a function of the maximum displacements. It was similar for the glass and FEP object and similar to the results of the single pillar studies discussed above (Figure 1e). In Figure 5d, the successful pick-and-place handling of a thin FEP object is depicted by several snapshots including I) the approach, followed by II) the attachment, III) the lifting of the object, IV) the microstructure sliding during compression, and finally V) the detachment and separation (Movie S1, Supporting Information). The FEP object had an edge length of 1.5 mm and a thickness of 180 μ m. The mass of the object was 0.5 mg, corresponding to a gravitational force of 5 μ N, leading to the conclusion that the adhesion force upon sliding was below 5 μ N.

An important performance parameter of a release structure is the ratio between the high and low adhesion values, i.e., the switching ratio. Comparing 10 mN (obtained against glass) and 0.3 mN (the lowest detectable force due to load cell resolution) gives a switching ratio of 33, which is an order of magnitude larger compared to previous reports of buckling-induced detachments from straight pillars.^[14,28,32] This value is similar to that reported by Mengüç et al.^[12] For the FEP object, the



maximum pull-off force of about 2.8 mN, when compared to the weight of the object of 5 μ N, results in a switching ratio of about 500. However, note that this value represents an upper bound as it neglects any interaction between the object and the lower substrate. The large improvement of the switching ratio is most probably caused by the fact that the sliding prevents the re-formation of the contact during unloading, which has frequently been observed in unbuckling of straight pillars. Another difference is the gradual loss of adhesion with compression, compared to a more sudden switching due to the elastic instability during buckling. The resulting differences will very likely require modifications in robot control algorithm, which is beyond the scope of this paper.

Another limitation of the sliding-induced release mechanism may be the accuracy of positioning the object. All three legs of the tripod have to slide similarly, despite possibly varying local friction conditions, wear of the tips, and so on. To evaluate the accuracy of our tripod, the pick-and-place cycle was repeated ten times and positions of the placed object were measured after the 5th and 10th cycle and compared to the original position by overlaying the contours (Figure 5e). The object was found to slightly rotate anticlockwise, while the upper left corner shifted by about 50 μ m to the left. Within this tolerance, the tripod arrangement of the microstructures proved to be efficient in avoiding displacement of the object. Overall, the successful demonstration of precise pick-and-place handling opens up a new possibility for handling super-lightweight objects, meeting the growing demands of ongoing component miniaturization.

4. Conclusions

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In the present work, we report on a new release mechanism for superlight objects with a weight of few μ N using slanted microstructures. We have shown that an optimized tilt angle enables high switching ratios. The following conclusions can be drawn.

- Compression resulted in lateral sliding of the slanted microstructures followed by a peeling process during retraction. This mechanism reduced the adhesion strength by a factor of up to 500, which can be utilized in the detachment of superlight objects.
- Based on a theoretical analysis, we found that sliding occurred because of the interplay of a shear force and a moment acting at the interface between the microstructure and the object. The sliding mechanism was optimized for a tilt angle α of 53° and 58°, which was also explained by calculations of shear force and moment.
- During retraction, the microstructures preferentially peeled from the leading end due to the acting bending moment. As a consequence, the contact area decreased strongly, which in turn led to low adhesion.
- The mechanism was demonstrated to enable sliding-induced detachment at low forces for a thin fluorinated FEP object with a weight of about 5 μN.
- Under wet conditions, the microstructures started sliding immediately following compression (provided the tilt angle was smaller than 45°). The optimized tilt angle will therefore depend on the level of adhesion.

Appendix

To solve Equation (3), we consider the following boundary conditions. For x = 0, the deflection of the beam is zero, which gives

$$a = \frac{M_0}{F\cos\theta} \tag{A.1}$$

The deformed beam at position *D* corresponds to a projected distance from position *O* to *B* on the original beam of length, $I_{OB} = L - u \sin \alpha$. For $x = I_{OB}$, the deflection of the beam $w = u \cos \alpha$, resulting in

$$w(x = l_{OB}) = a\cos(\lambda l_{OB}) + b\sin(\lambda l_{OB}) + \frac{-M_0 + (F\sin\theta)l_{OB}}{F\cos\theta} = u\cos\alpha \quad (A.2)$$

We further assume that the tilt angle α remains constant at both ends during deformation of the beam. This assumption is reasonable, as both ends are clamped before any detachment or sliding occurs; thus

$$w'(x=0) = b\lambda + \tan\theta = 0 \tag{A.3}$$

$$w'(x = I_{OB}) = -a\lambda\sin(\lambda I_{OB}) + b\lambda\cos(\lambda I_{OB}) + \tan\theta = 0$$
(A.4)

Finally, the force F is given as

$$F = \frac{F_{D2}}{\sin(\alpha - \theta)} \tag{A.5}$$

where F_{D2} is the normal force component recorded by the load cell during the tests. Figure 2c displays F_{D2} versus displacement *u* for the initial compression of the slanted microstructure before sliding. The compressive forces increased linearly with different slopes *K*, representing the effective stiffness of the beam in normal direction and, thus, $F_{D2} = Ku$. The inset in Figure 2c depicts that *K* increased linearly with the tilt angle of the microstructures $r = \alpha \frac{\pi}{180^{\circ}}$. A linear fit provides $K = \left(\frac{780}{\pi}r - 122\right)\frac{N}{mm}$. Substituting the expression for *K* into Equation (A.5) gives $F = \left(\frac{780}{\pi}\frac{N}{mm}r - 122\frac{N}{mm}\right)u/\sin(\alpha - \theta)$. Finally, considering Equations (A.1)–(A.5), Equation (3) can be solved numerically for given displacements *u*.

Supporting Information

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

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Conflict of Interest

Eduard Arzt declares that he is co-owner of a start-up commercializing robotic systems.

Data Availability Statement

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

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bioinspiration, microhandling, micropatterned adhesives, release of superlight objects, two-photon lithography

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