Suction component in adhesion of mushroom-shaped microstructure

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To shed light on the role of suction in adhesion of microstructure with mushroom-shaped terminal elements, we compared pull-off forces measured at different retraction velocities on structured and smooth surfaces under different pressure conditions. The results obtained allow us to suggest that suction may contribute up to 10 per cent of the pull-off force measured on the structured surfaces at high velocities. We therefore conclude that the attachment ability of this biomimetic adhesive must not be solely based on van der Waals forces. Our experiments also suggest a change in visco-elastic properties of the structured surfaces compared with the bulk material. Based on the results obtained, it is assumed that this adhesive may be suitable in dynamic pick-and-drop processes even under vacuum conditions at which sufficiently high adhesive capability is maintained.

Keywords: biomimetics; surface patterning; polymer; adhesive; vacuum

1. INTRODUCTION

Adhesion between solid bodies relies on various physical forces, such as intermolecular forces, capillary forces, electrostatic attraction and suction [1,2]. These forces may also contribute to the attachment of biological and biomimetic microstructured surfaces [3–9], such as in recently reported mushroom-shaped adhesive [10] inspired by the morphology of tarsal hairs of male Chrysomelidae beetles [11,12].

Tribological properties of mushroom-shaped geometry were intensively investigated during the last few years [6,10,13–19], and a combination of intermolecular van der Waals forces and a geometry preventing crack propagation was supposed to be responsible for their effective performance. However, close visualization of the contact formation and breakage led to the assumption that these mechanisms may also be superimposed by a suction effect [17,18]. Later on, considering the fact that reducing the ambient pressure should decrease the suction effect if it is present, this assumption was seemingly disproved by observing no reduction in the attachment ability of mushroom-shaped microstructure placed inside a vacuum chamber [20,21].

The present study was carried out in order to adjust the above differences and eventually shed light on the role of suction in adhesion of microstructure with mushroom-shaped terminal elements. This was performed by comparing pull-off forces measured at different retraction velocities on structured and smooth surfaces under reduced and atmospheric pressure conditions.

2. MATERIAL AND METHODS

Biomimetic mushroom-shaped adhesive microstructure was made of polyvinylsiloxane (PVS), and consisted of uniformly distributed micropillars of about 100 μm in height terminated by thin contact plates of about 50 μm in diameter which cover about 43 per cent of the apparent contact area ([10,14,17–20]; figure 1). Performance of six structured and six smooth PVS discs of 2 mm in diameter and 1 mm in height was characterized in contact with smooth glass.

Pull-off force measurements were performed with a home-made microtribometer [19,22] using a self-aligning system of sample holders to measure contact forces in a flat-on-flat contact scheme. The pull-off forces were determined after applying a preload of 60 mN, while withdrawing the glass substrate from the contact at velocities of 100, 400 and 800 $\mu\text{m s}^{-1}$. In order to perform measurements at different ambient pressures, the apparatus was encased in a glass chamber connected to a vacuum pump V700 equipped with a V850 pressure controller (Büchi AG, Flawil, Switzerland). Each sample was tested at atmospheric pressure (996 mbar), then at reduced pressure (20 mbar) and again at atmospheric pressure. The temperature and relative humidity in the laboratory were 24°C and 25 per cent, respectively.

The data analysis of the vacuum experiment was performed separately for structured and flat samples. This is justified by previous studies referring to this mushroom-like microstructure indicating an about twice higher pull-off force for the structured surface compared with the smooth surface (e.g. [10]) making a comparison dispensable and keeping the data analysis

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Figure 1. Biomimetic mushroom-shaped adhesive microstructure made of polyvinylsiloxane. CP, contact plate. Scale bar, 100 μm .

more simple. We used two-way repeated measures ANOVA to investigate for both factors: pressure regime and retraction velocity. For both evaluations, structured and smooth surfaces, the assumption of normal distribution was violated. A non-parametric alternative to the two-way ANOVA with repetitions is not common in statistics and of less power than the parametric analysis [23]. The two-way ANOVA with repetition was, however, performed. It is said to be robust particularly against violation of normal distribution and only has minor effect on the informational value especially when all other assumptions are fulfilled [24], which applies here.

3. RESULTS AND DISCUSSION

Suction force F_{suc} is a function of the difference between the outer and inner pressures Δp acting on the suction device of an area A ($F_{\text{suc}} = \Delta p \cdot A$), so reducing an ambient pressure should reduce this force. This provides the ability to examine the contribution of suction to the overall pull-off force developed by our mushroom-shaped PVS adhesive. To exclude the possibility of pressure-induced changes in PVS properties, we first compared the results obtained before and after the ambient pressure reduction (figure 2). No statistically significant differences between the pull-off forces measured at these pressure regimes were observed for both types of samples (table 1). As a consequence of these results, further analysis was done with the data obtained at two first pressure steps only.

Figure 3 shows the pull-off forces obtained from force–distance curves (figure 4) of mushroom-shaped microstructures and smooth surfaces at different retraction velocities and ambient conditions. Smooth surfaces, which cannot rely on the suction effect, behave as expected. They show no effect of ambient pressure but the pull-off force increases along with increasing velocity, which is attributed to visco-elastic properties of the PVS. Structured surfaces behave in an opposite and much more complex way. First of all, we can clearly see the statistically significant effect of

Figure 2. Mean pull-off forces of the structured (hatched bars) and smooth (white bars) samples measured on glass at a withdrawal velocity of 100 $\mu\text{m s}^{-1}$. Experiments were carried out at an atmospheric pressure before and after ambient pressure reduction.

pressure reduction at the velocities of 400 and 800 $\mu\text{m s}^{-1}$ (table 1), which means that though adhesion of mushroom-shaped microstructures is mainly powered by dispersive interactions, suction indeed slightly contributes to the pull-off force. Interestingly, the suction contribution scatters about 10 per cent of the overall pull-off force at the two higher velocities tested and is seemingly absent at the lower velocity, which requires an explanation.

We believe that this velocity dependence arises from non-perfect sealing of the contact elements owing to surface roughness, loose particles and imperfections at the edges of thin contact plates. At low velocities, the voids formed below the contact plates (figure 5) grow slowly enough, so the surface imperfections at the sealing lips allow the ambient air to leak into these voids and instantaneously balance the pressure difference. At higher velocities, however, the leaking air does not succeed keeping pace with the growing voids, so the pressure inside the voids drops and a certain pressure difference gives rise to the suction effect is established. This explanation also suggests that the suction effect will be measurable at lower retraction velocities as well for more viscous surrounding fluids (e.g. water), which fits well with our underwater tests [17]. A similar consideration was also put forward in studying cell adhesion [25].

Yet another observation to be mentioned is that no statistically significant difference was found between the pull-off forces measured on structured samples at different velocities within any of the two pressure regimes studied (table 1). A certain trend, however, can clearly be seen, which allows interpreting these results. It is well known that adhesion of visco-elastic

Table 1. Statistical significance of differences between pull-off forces measured under different conditions.

pressure	sample	velocity ($\mu\text{m s}^{-1}$)	significant difference
atmospheric before versus after reduction	smooth	100	no ($p = 0.219$) ^a
atmospheric before versus after reduction	structured	100	no ($p = 0.556$) ^b
atmospheric versus reduced	smooth	all	no ($p \geq 0.679$) ^c
atmospheric versus reduced	structured	100	no ($p = 0.362$) ^c
atmospheric versus reduced	structured	400	yes ($p = 0$) ^c
atmospheric versus reduced	structured	800	yes ($p = 0$) ^c
atmospheric	smooth	100 versus 400	yes ($p = 0$) ^c
atmospheric	smooth	100 versus 800	yes ($p = 0$) ^c
atmospheric	smooth	400 versus 800	yes ($p = 0$) ^c
atmospheric	structured	100 versus 400	no ($p = 0.128$) ^c
atmospheric	structured	100 versus 800	no ($p = 0.030$) ^c
atmospheric	structured	400 versus 800	no ($p = 0.454$) ^c
reduced	smooth	100 versus 400	yes ($p = 0$) ^c
reduced	smooth	100 versus 800	yes ($p = 0$) ^c
reduced	smooth	400 versus 800	yes ($p = 0$) ^c
reduced	structured	100 versus 400	no ($p = 0.139$) ^c
reduced	structured	100 versus 800	no ($p = 0.166$) ^c
reduced	structured	400 versus 800	no ($p = 0.919$) ^c

^aTested using Signed Rank Test (not normal data distribution).

^bTested using paired *t*-test (normal data distribution).

^cTested using two-way repeated-measures ANOVA.

Figure 3. Pull-off forces of the structured and smooth samples measured on glass at different withdrawal velocities and ambient conditions. Ambient pressure: dark grey bar, atmosphere; light grey bar, reduced. Sample: hatched bar, structured; unfilled bar, smooth.

materials to rigid substrates may first increase and then decrease with increasing retraction velocity [26]. Changing mechanical properties by structuring the surface of PVS may result in a shift of the adhesion peak to another velocity range. So the same increase in velocity will lead to an increase in the pull-off force on smooth surfaces and to a decrease in the pull-off force on structured ones. The latter can indeed be seen under the conditions of reduced pressure, where the suction

Figure 4. Representative force–distance curves for different specimens and pressure states. Black line, atmospheric pressure; grey line, reduced pressure.

effect does not contribute to adhesion. This speculation, however, calls for further verification.

4. CONCLUSION

The experiments performed in this study lead us to conclude that attachment ability of the biomimetic mushroom-shaped adhesive microstructure must not be solely based on van der Waals forces. At sufficiently high retraction velocities, a suction effect contributes to the overall pull-off force of this particular microstructure by about 10 per cent, making each microstructure act as a passive sucker. Therefore, this glue-free

Figure 5. High-speed video stills showing the detachment process of the mushroom-shaped contact element of a single microfibre. Dark areas represent real contact zones between polymer and glass. (a) $\Delta t = 0$ ms; (b) $\Delta t = 7$ ms; (c) $\Delta t = 9$ ms; (d) $\Delta t = 10$ ms; (e) $\Delta t = 11$ ms; (f) $\Delta t = 12$ ms.

reversible adhesive may have potential in applications where attachment forces have to be maintained even under dynamic loads, such as in pick-and-drop processes in wafer manipulation. Since the suction effect is rather low, this biologically inspired adhesive can be potentially used under vacuum conditions, such as space applications or object manipulation in vacuum chambers.

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