On/off switching of adhesion in gecko-inspired adhesives

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Abstract

In this study, the adhesion-detachment behaviour of a gecko-inspired adhesive pad was investigated to understand the on/off switching mechanisms of adhesion in gecko feet. A macroscopic spatula model was fabricated using silicone rubber, and adhesion tests combining lateral sliding and vertical debonding were conducted. It was observed that the contact state and the adhesion force of the pad vary considerably with the direction of lateral sliding prior to debonding, and that the pad achieves adhesion during debonding even when it loses contact due to excess lateral sliding. These results explain the mechanisms behind the on/off switching and stable adhesion of gecko feet, and suggest the possibility of developing new-generation adhesives capable of switchable adhesion.
I. INTRODUCTION

Geckos are able not only to walk on the ground, but also to climb up walls and to hang upside-down on ceilings\textsuperscript{1} - \textsuperscript{3}. As geckos walk under a small or negative normal load in such situations, they must attach their feet onto a substrate firmly, and detach from the substrate quickly\textsuperscript{3} - \textsuperscript{6}.

Microscopic observations and adhesion experiments involving the fine structures of gecko feet have revealed that van der Waals attractive forces between the substrate and the pad at the edge of the feet play a major role in adhesion\textsuperscript{7}, similar to other conventional adhesive systems\textsuperscript{8}. Moreover, different aspects, such as a slender geometry and asymmetric structures, contribute to quick adhesion and detachment\textsuperscript{9}. In fact, many studies have regarded gecko feet as microscopic arrays of fine hairs, and researchers have fabricated gecko-inspired adhesives with fibres or pillars on the surface\textsuperscript{10} - \textsuperscript{18}.

In addition, recent theoretical studies\textsuperscript{19} - \textsuperscript{21} have highlighted the importance of the geometry with a tilted pad attached to a curved beam and have successfully explained some of the superior properties of gecko feet. In particular, Zhao and co-workers\textsuperscript{19} discussed that in such a structure, the adhesion of the pad depends strongly on the operation conditions before debonding, i.e., strong adhesion is achieved when the pad is pulled laterally before vertical debonding, and quick release is realized when the pad is pushed laterally before the debonding. With these lateral operations in addition to the vertical debonding, it was expected that on/off switching of the adhesion can be easily performed. Furthermore, Yamaguchi and co-workers\textsuperscript{20} showed that the adhesive pad geometry of gecko feet contributes to the generation of a negative normal force during sliding friction and yields stable motion without unexpected detachment from the substrate; this is caused by repetitive stick-slip motions and the coupling between the vertical and horizontal forces of a curved beam. Bio-inspired designs resembling gecko feet in terms of adhesion and friction are considered to be important for creating bio-inspired, stimuli-responsive, soft interfacial devices\textsuperscript{22} - \textsuperscript{28}.

However, micro-mechanical studies involving adhesion experiments and in-situ visualiza-
tion for the development of gecko-feet-like asymmetric slender structures remain inadequate. Although several trials have been conducted thus far, it remains difficult to fabricate arrays of fine and well-controlled structures having the aforementioned geometry [29].

In this study, we fabricated a macroscopic analogue of a gecko-inspired tilted adhesive pad attached to a curved beam, and observed the adhesion/detachment behaviour of a single pad. During adhesion testing, we combined vertical compression-debonding motions with lateral sliding motions. This type of testing geometry is known as frictional adhesion [3, 5, 6, 20, 30–35], in which the coupling between adhesion and friction is important, and materials with strong adhesion and high friction are normally used [34]. As discussed subsequently, the adhesion properties strongly depend on the precursory lateral sliding motions, and on/off switching of adhesion is possible with lateral sliding in addition to vertical debonding.

II. EXPERIMENT

A. Sample

A schematic of a sample is depicted in Fig. 1(a). The sample, having the structure of a single curved beam with a tilted pad on the tip, was prepared by curing silicone prepolymer (SILPOT184 prepolymer, TORAY DOW CORNING, Japan) with a curing agent (SILPOT184 CAT) in a Plexiglass mould, with a weight ratio of 9:1 at 90°C for 5 h.

B. Substrate

In this study, we aimed to reproduce realistic situations involving microscopic gecko pads and to understand the underlying mechanisms using a macroscopic analogue (our adhesive pad model). Here, we considered the following assumptions:

- The adhesion energy $E_{\text{adhesion}}$ and the stored elastic energy $E_{\text{elastic}}$ are the main factors controlling the functioning of the pad.
The deformation of a microscopic gecko pad (and a spatula) and a macroscopic analogue model are similar to each other (i.e., the strains are the same in the two systems).

Based on these assumptions, we can deduce that the adhesion energy is proportional to $L^2$ (where $L$ is the system size), while the stored elastic energy is proportional to $L^3$. Furthermore, to reproduce the same mechanics between gecko feet and our model, we assumed that the ratio between the adhesion energy and the stored elastic energy is the same in gecko feet and our model.

\[
\frac{E_{adhesion}}{E_{elastic}} \propto \frac{\gamma}{EL} \\
\sim \frac{10^{-2} J}{10^9 Pa \times 10^{-6} m} \quad (gecko) \\
\sim \frac{\gamma_{model}}{10^6 Pa \times 10^{-1} m} \quad (model),
\]

where $\gamma$ is the surface energy between a pad and a substrate, and $E$ is the Young’s modulus of the pad. The values for gecko feet were obtained from the literature \[30\] and those for our model were estimated through rheological measurements. Based on Eq. (11), the surface energy must be as large as $\gamma_{model} \sim 1 J$, which cannot be reached as long as the original glass surface is used ($\sim 10^{-2} - 10^{-1} J$). To enhance the stickiness of the glass, we coated silicone rubber with 3wt% of a curing agent (SILPOT184, TORAY DOW CORNING, Japan) and cured it at 90°C for 5 h.
The experimental setup for the adhesion test is illustrated in Fig. 1(b). The sample was attached to the head of the tensile testing machine (MST-1, Shimadzu, Japan), and the substrate was fixed onto the horizontally moving stage (SGSP80-20ZF, Sigma-Koki, Japan).

In the first series of experiments, we examined the on/off switching of the adhesion properties. To achieve this, we combined lateral motions with compression/tension during the adhesion test, as illustrated in Fig. 2. Before the experiment, we separated the sample from the substrate by 2.5 mm. Then, we applied a compressive force on the sample in the vertical direction for 5 s at 2 mm/s; thus, the compression displacement after contact was 7.5 mm. After the compression, we translated the substrate either to the left or to the right at 1 mm/s or maintained the position (at 0 mm/s) for 10 s. Thereafter, we pulled the sample in the vertical direction at 2 mm/s until the sample detached from the substrate completely. The vertical tensile force was measured as an adhesion force using a load cell.

In the second series of experiments, we investigated how excess sliding and vertical compression affect the debonding behaviour: after applying compression at 2 mm/s, we translated the bottom substrate only to the left by 20 mm; then, we pulled the sample in the vertical direction at 2 mm/s until complete detachment, in the same manner as in the first series of the experiments. However, in the second series of experiments, we controlled
the vertical compression displacement from 4 to 8 mm and changed the lateral sliding speed from 0.01 to 1 mm/s.

III. RESULTS AND DISCUSSION

A. On/off switching behaviour

Fig. 3 shows the time evolutions of the vertical tensile forces for the three different testing protocols in the first series of the experiments. When the substrate was translated to the right (R) or was kept at the same position (Keep) in the lateral sliding phase, no tensile force was generated during the final debonding phase. In contrast, when the substrate was translated to the left (L), a tensile force was generated during the final debonding phase. These results clearly show that the generation of the tensile force depends strongly on the precursory lateral sliding motions.

To explain the mechanisms behind the large differences in the debonding force, we show snapshots of the deformation states in the right panel of Fig. 3. When the compression was applied (A), the entire surface of the pad did not attach to the substrate; only the toe did. The reason for this imperfect contact is that the pad rotates in the counter-clockwise direction due to the buckling of the stem (curved beam). However, the differences in the deformation state appeared after the lateral sliding: as the substrate was translated to the left, the pad started to rotate in the clockwise direction, and the entire surface of the pad became attached, as shown in B. Once perfect contact was attained, a strong vertical tensile force was generated, and this force detached the pad from the substrate, as shown in the left panel of Fig. 3. In contrast, when the substrate was translated to the right or when it was kept at the same position during the lateral sliding phase, the contact states immediately before debonding were C and A respectively, and almost no tensile force was generated. In both cases, the imperfect contact produced an edge in the contact region, and this edge caused a stress concentration during debonding. This resulted in the weak adhesion force.
These results suggest that geckos achieve on/off switching of the adhesive force by performing translation in the horizontal direction, in addition to the vertical direction.

B. Effects of compression displacement and sliding distance

As discussed above, the lateral sliding produces additional rotation of the pad and controls the contact state. However, the aforementioned setup was special in terms of the vertical compression displacement and lateral sliding distance, which were 7.5 mm and 10 mm, respectively. In actual situations involving gecko feet, this corresponds to fine control of the displacements on a micron scale, which founds to be impossible or difficult for geckos.

We investigated the effects of excess vertical compression and lateral sliding. In the second set of the experiments, we changed the compression displacement from 4 to 8 mm and set the sliding distance as 20 mm, which is the twice that in the on/off switching experiment. The results are illustrated in Fig. 4. Here, the differences are coming from the differences in the compression displacement.

When the applied compression displacement was 4 mm (Fig. 4(a)), almost no tensile force was generated during lateral sliding, except at the early stage. The mechanism behind
the generation of the weak force was that the pad formed partial contact only at the toe, as shown in the right panel of Fig. 4(a). In contrast, when the compression displacement was 6 mm (see Fig. 4(b)), the situation changed drastically: a strong adhesion force was generated at the initial phase of the lateral sliding, and adhesion forces were successively generated during the subsequent phases. This was due to the near-perfect contact between the pad and substrate during the lateral sliding, as seen in the right panel of Fig. 4(b). However, when the compression displacement was 7.5 mm (Fig. 4(c)), A tensile force was generated at the early stage, and almost no force was generated thereafter; this is similar to the case of the small compression displacement (4 mm). However, an adhesion force was again generated in the final debonding phase. This can be explained by the snapshots in Fig. 4; during the lateral sliding, the heel of the pad attained contact, but in the debonding phase, the pad rotated in the counter-clockwise direction and formed perfect contact before complete debonding was achieved.

These behaviours are similar to the sliding friction of a block against a compliant gel[34]; the angle of the inclined block strongly affects the contact state and stick-slip motions, due to the bi-material effect.

A summary of the results of the second series of experiments with excess lateral sliding is depicted in the phase diagram in Fig. 5.

Evidently, the compression displacement strongly affects the dynamical behaviour of the pad, while the sliding speed affects the behaviour only when a small compression displacement is applied. Interestingly, the phase boundary between the strong adhesion phase (Fig. 4(b)) and the phase with the final contact recovery (Fig. 4(c)) is not sensitive to the sliding speed, but depends only on the compression displacement.

IV. CONCLUSION

In this study, we investigated the effects of the geometry of a gecko-inspired adhesive pad on the adhesion/debonding properties. We found that the debonding behaviour strongly depends on the direction of lateral sliding, and that such systems are robust in terms of
FIG. 4: Time evolutions of vertical forces for sliding distance of 20 mm at sliding speed of 0.1 mm/s. Applied compression displacements are (a) 4 mm, (b) 6 mm, and (c) 7.5 mm. The snapshots are the images captured at respective times described in the right panel.

FIG. 5: Phase diagram of sliding and debonding behaviour in second series of experiments. The cross, filled triangle, and filled circle symbols correspond to those in Fig. 4.

excess sliding and vertical compression. These results highlight the importance of optimal shape design for individual pillars in terms of the adhesion properties for synthetic gecko-like adhesives. Although some new findings were obtained through this study, several aspects remain to investigated. These include validation of the results of this study based on in-situ electron microscope observation of gecko feet, fabrication of gecko-inspire adhesives having fine multiple structures of adhesive pads attached to a curved beam, and optimization of the pad in terms of adhesion performance. Moreover, in the adhesion test conducted in this...
study, only the vertical tensile force was measured to evaluate the adhesion performance of the pad. It would be worthwhile to measure the tensile and friction forces simultaneously. We intend to focus on these topics in future studies.

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