Biomimetic surfaces with controlled direction-dependent adhesion

Luciano Afferrante* and Giuseppe Carbone

Dipartimento di Ingegneria Meccanica e Gestionale, TriboLAB, Politecnico di Bari, V.le Japigia 182, 70126 Bari, Italy

We propose a novel design of a biomimetic micro-structured surface, which exhibits controlled strongly direction-dependent adhesion properties. The micro-system consists of parallel elastic wall-like structures covered by a thin layer. Numerical calculations have been carried out to study the adhesive properties of the proposed system and to provide design criteria with the aim of obtaining optimized geometries. A numerically equivalent version of the double cantilever beam fracture experiment is, then, simulated by means of finite element analysis to investigate the anisotropic adhesion of the structure. We find that, because of inherent crack trapping properties of these types of structures, the wall-like geometry allows us to strongly enhance adhesion when the detachment direction is perpendicular to the walls. On the other hand, when the detachment occurs parallel to the walls, the system shows low adhesion. This controlled direction-dependent adhesive property of the proposed structure solves one of the key problems of biomimetic adhesive surfaces, which usually show very strong adhesion, even larger than biological systems, but are not suitable for object manipulation and locomotion, as detachment always occurs at high loads and cannot be controlled.

Keywords: adhesion; anisotropy; biomimetic surfaces; crack trapping

1. INTRODUCTION

Micro-patterned surfaces, inspired by the observation of natural systems [1], have been attracting strong scientific interest as a consequence of their enhanced adhesive [2–6], or superhydrophobic [7–11] properties. Because of their relevance in (i) medical adhesive bands [12,13], (ii) gecko-inspired robots [14–16], (iii) gecko tyres [17], (iv) adhesive gloves and suits [17], several efforts have been made to fabricate fibrillar surfaces that may replicate the adhesive properties of geckos and insects [18–21]. The amazing adhesion of such man-made biomimetic surfaces has been considered as a sort of magic, until very recent studies have shed light on the fundamental physical mechanisms providing their micro- and nano-structured surfaces with optimized adhesive properties [3,5,6,22,23]. In actual systems, roughness can be detrimental to the adhesive strength, because it hampers the ability of mating surfaces to make intimate contact. In fact, both the mean pull-off force and the work needed to detach the surfaces decrease with increasing roughness, and may even vanish above a certain roughness threshold [23,24]. However, it has been also shown [23,25–27] that, if the contacting bodies are relatively soft in comparison with the surface energy and roughness length scales, the adhesion forces and the effective interfacial energy may, unexpectedly, increase when roughness is present, provided the contacting surfaces are not too rough. Indeed, in such cases, the adhesion forces may easily deform the elastic bodies to pull them into full contact with the substrate, thus increasing the contact area and the strength of adhesion. Moreover, optimized fibrillar structures may show enhanced adhesive properties when compared with flat surfaces, even though this behaviour is strongly dependent on the distribution and local shape of the microstructures, and on the presence of interfacial defects or air bubbles [5,6,28,29]. Indeed, increased adhesion may not always be observed in experimental tests [19,20,30] because the fibrils tend to be fragile, to buckle or to laterally adhere with the others. Because of these controversial conclusions, additional investigations have been developed and finite element simulations have been carried out [31] to define the conditions that make a fibrillar interface ‘stronger’ than a non-fibrillar one. Improved adhesion may be obtained when a terminal plate is added at the fibrils end, with the aim of reproducing the flexible terminal spatula observed in many lizards and insects [32,33], or by adding a continuous thin sheet as in the case of the setal system of the insect Tettigonia viridissima [34–36]. Experimental and theoretical investigations have shown a strong enhancement in the effective adhesion energy from one to two orders of magnitude compared with the flat control sample.

However, in these systems, there is not any preferential direction of the strength of adhesion and, therefore, they do not perfectly fit those engineering applications (e.g. robot locomotion and object manipulation), where enhanced adhesion is desired in one direction to support

*Author for correspondence (l.afferrante@poliba.it).

Received 7 June 2012
Accepted 21 August 2012

3359 This journal is © 2012 The Royal Society
2. PROBLEM FORMULATION

We assume that the system is loaded with an external bending moment $M$ in the $x$–$y$ plane and applied to the left edge of the structure (figure 2). The thickness of the backing layer is also assumed significantly larger (up to 10 times) than the fibrils height to correctly reproduce the size of the micro-structure with respect to the supporting layer of a real geometry. The thin film covering the walls makes contact with a rigid flat surface, and a crack is assumed extending on (a plane parallel to the walls ($y$–$z$ longitudinal plane).

The contact zone between the thin film and the flat rigid substrate is considered, as suggested by some experiments [37], in sticking friction. This condition is taken into account by properly constraining the nodes of the adhering surface to the substrate. We also assume that the structure is much longer (along the $x$-axis) than the existing crack to neglect border effects, and that detachment follows the mode I debonding of the adhering surface to the substrate. We also taken into account by properly constraining the nodes of the crack from the edge. Different rupture mechanisms such as mode II or mode III debonding will be discussed later in §3.1. Note that in the current context, $d U_\text{tot}$ is the change in the elastic energy stored in the system and $d U_s = \Delta y b dl$ is the change in the surface energy, where $\Delta y = y_1 - y_2 - \Delta y_2$ (the so-called work of adhesion [38]), $y_1$ being the surface energy of solid 1, $y_2$ the surface energy of solid 2 and $\Delta y_2$ the surface interaction energy when the two surfaces are in direct contact. Recalling that the energy-release rate $G$ at the crack tip is defined as [38]

$$G = \frac{\partial (U_\text{tot} - U_s)}{\partial A},$$

where $A = bl$ is the detached area (with $b$ the constant linear size of the system along the $y$-axis, and $l$ the crack length), spontaneous evolution of the system will occur when

$$d U_\text{tot} = -(G - \Delta y) b dl \leq 0.$$  

If $G > \Delta y$, the above inequality (2.3) requires $dl > 0$ and the crack will spontaneously advance, causing the detachment of the system. If $G < \Delta y$, the crack should recede. We observe that the strain energy-release rate $G$ can be written as

$$G(l) = \frac{1}{b} \left( \frac{\partial U_\alpha}{\partial l} + \frac{\partial U_P}{\partial l} \right) \bigg|_{M=\text{const}}$$

Thus, under constant applied bending moment $M$, the quantity $G$ is related to the variation of the system compliance $C = 1/K$, which occurs as the crack advances of a unit length. When the crack moves perpendicularly to the walls, i.e. along the $x$-axis, the periodic geometry of the system will force the energy-release rate $G$ to vary periodically with the spatial period $\lambda$. Therefore, recalling that $\Delta U_\alpha = -1/2 \Delta U_P$, the average value of $G(l)$ is

$$G_{\text{ave}} = \frac{1}{\lambda} \int_{\lambda} G(l) dl = \frac{1}{b \lambda} (\Delta U_\alpha + \Delta U_P) = \frac{\Delta U_\alpha}{b \lambda},$$

the load, and no enhancement or a reduction in adhesion is desired along other directions to facilitate system detachment. In this study, we focus on this last aspect of the problem, and propose a new architecture constituted by parallel wall-like structures, as shown in figure 1, which present very high adhesion when the detachment direction is normal to the walls ($x$–$y$ transversal plane) and can be easily removed by applying a bending moment in a plane parallel to the walls ($y$–$z$ longitudinal plane).
where $\Delta U_e$ is the change in stored elastic energy that occurs when the crack advances of a spatial period $\lambda$. On the other hand, when the crack moves parallel to the walls, i.e. along the $y$-axis, the energy-release rate $G(l)$ cannot change and therefore it remains constant.

A finite element analysis has been carried out, with the aid of the commercial software ANSYS [39], to evaluate the variation in energy-release rate that occurs during the crack propagation. Two-dimensional quadratic plane strain elements have been adopted to mesh the overall geometry. The material is assumed to be nearly incompressible with Poisson’s ratio $\nu = 0.5$ and elastic modulus $E = 3 \, \text{MPa}$.

3. RESULTS AND DISCUSSION

In this section, we present the results of the numerically simulated test described in §2. First, we will discuss the case of a crack propagating along the $x$-axis, and latter the case of a crack moving parallel to the walls (i.e. along the $y$-axis).

3.1. Crack propagating perpendicularly to the wall-like structures

Figures 3 and 4 show the variation in the ratio $(G/G_{\text{flat}})$ between the energy-release rate $G$ of the proposed micro-structured system and the energy-release rate $G_{\text{flat}}$ of the flat control sample, as a function of the dimensionless crack length $l/\lambda$, for different values of the geometrical parameters. As expected and already mentioned, in this case, $G/G_{\text{flat}}$ is a periodic function of $l/\lambda$.

The variation of $G$ with the crack length $l$ is positive (d$G$/d$l > 0$) when the crack is located underneath the wall. In this case, energy flows from the system to the crack tip, and the crack tends to spontaneously advance. On the other hand, when the crack tip is in-between two adjacent walls, crack trapping (i.e. d$G$/d$l < 0$) occurs: the crack stops and cannot propagate, thus enhancing the adhesive strength, in agreement with some experimental observations [34] and other previous calculations [40]. Notice that the maximum value of $G$ occurs when the crack tip is located below the wall, where the stiffness of the system is higher. This means that crack trapping may occur only in those regions where the system is sufficiently compliant, i.e. in-between two consecutive walls. The limiting case is obtained when the thin film covering the walls is interrupted. This should provide the structure with amazing crack tapping properties, as already observed in microstructures based on a similar principles, as those constituted by a regular distribution of mushroom-shaped pillars [5,6,32,37], where the lack of continuity between the thin plates covering each pillar completely inhibits mode I crack propagation, thus strongly enhancing the adhesive properties. In figures 3 and 4, we also analyse the influence of several geometrical parameters (the thickness $t$ of the thin film, the spacing $\lambda$ between the walls, the thickness $s$ and height $h$ of the walls) on the adhesive properties of the system. Because crack propagation occurs without interruption only when $G_{\text{min}} > \Delta \gamma$, one concludes that those modifications of the geometry that determine an increase in the system compliance in-between two adjacent walls, such as a reduction of $t$, a decrease in $s$ or rather an increase in $\lambda$, are strongly beneficial because they lead to a significant reduction in the minimum value $G_{\text{min}}$ of the energy-release rate (i.e. to an enhancement of the crack trapping properties of the structure). We observe in figure 4a that the influence of $h$ is instead much less important, although increasing $h$ is still advantageous.

In view of the above arguments, one concludes, for example, that if the thickness $t$ of the film becomes vanishingly small, the minimum $G_{\text{min}}$ of the energy-release rate also vanishes and crack propagation is completely inhibited. In this case, a very high applied moment $M$ would be necessary to detach the system. In reality, by increasing $M$, large tensile stresses develop beneath the walls and the interface fails because either the mode II debonding mechanism is activated (as observed in the
Biomimetic surfaces with controlled adhesion  L. Afferrante and G. Carbone

The variation in the energy-release rate $G$ of the proposed system, normalized with respect to that of a flat control sample $G_{\text{flat}}$, as a function of the dimensionless crack length $l/\lambda$. Results are presented for different wall heights $h$ ($t = 2 \mu m$; $s = 4 \mu m$; $\lambda = 95 \mu m$), (a); and different wall thicknesses $s$ ($t = 2 \mu m$; $h = 85 \mu m$; $\lambda = 95 \mu m$), (b). $E = 3$ MPa, $v = 0.5$. Applied moment: $M = 9.5 \times 10^{-2}$ Nm m$^{-1}$. (Online version in colour.)

The new architecture proposed in this paper, if compared with other structures made of a regular pattern

where $2a$ is the defect size, and $E^* = E/(1 - v^2)$ is the composite Young’s modulus. Assuming $2a = 20 \text{ nm}$ and $\Delta \gamma = 16 \text{ mJ m}^{-2}$, $E = 3 \text{ MPa}$ and $v = 0.5$, we get $\sigma_{\text{II}} \approx 3.17 \text{ MPa}$. We notice that, for soft adhesives, the stress $\sigma_{\text{II}}$ is always much less than the theoretical van der Waals contact strength $\sigma_{\text{II}} = \Delta \gamma/\rho$, where $\rho \approx 1 \text{ nm}$ is the typical range of van der Waals forces. One can easily calculate the bending moment $M_0$, which activates crack propagation from the edge (i.e. mode I debonding mechanism) by enforcing the condition $G_{\text{min}} = \Delta \gamma$, and using equation (2.4), which gives

$$M_0 = \sqrt{\frac{2\Delta \gamma h}{\partial C/\partial l_{\text{min}}}}.$$  

(3.2)

Recalling that the system is linearly elastic, the moment, $M_{\text{II}}$ needed to activate the mode II debonding mechanism, associated with the growth of interfacial defects underneath the walls, can be calculated as

$$\frac{M_{\text{II}}}{M} = \frac{\sigma_{\text{II}}}{\sigma},$$  

(3.3)

where $M$ is the value of the applied moment and $\sigma$ is the corresponding stress in the walls.

Figures 5 and 6 show the critical bending moment $M_c = \min\{M_0, M_{\text{II}}\}$ necessary to fully detach the fibrillar structure as a function of the geometrical parameters: (i) film thickness $t$, (ii) wall spacing $\lambda$, (iii) wall height $h$ and (iv) wall thickness $s$. Results are normalized with respect to the debonding moment $M_{\text{flat}}$ necessary to detach the flat control sample. Notice that, thanks to the crack trapping properties of the fibrillar structure, the adhesion strength, for the test cases considered in the present study, is increased up to about 15 times when compared with the flat control case. We observe that mode I or mode II debonding may be both activated, depending on the geometry of the system. Therefore, it is not beneficial to increase $M_0$ beyond the value $M_{\text{II}}$ because, in this case, the mode II debonding mechanism is the one that limits the performance of the system, i.e. the optimal geometry maximizes $M_c$ subjected to the constraint $M_0 = M_{\text{II}}$.

3.2. Crack propagating parallel to the wall-like structures

Figure 7 shows the critical ratio $M_{\text{C}} = M_{\text{flat}}$ necessary to fully detach the system as a function of the film thickness $t$ (figure 7a) and wall thickness $s$ (figure 7b), when the fibrillar structure is loaded in the $y$–$z$ plane, so that crack propagation occurs parallel to the wall-like structures.

This time $M_c$ is reduced by more than 15 times when compared with the values obtained in figure 6b. The system can be very easily detached, even easier than the flat control sample. Moreover, the influence of $t$ and $s$ is almost negligible. In this case, the only possible detaching mechanism is the mode I. Crack trapping cannot occur because the compliance of the system increases linearly with the $z$ coordinate, i.e. the energy-release rate remains constant during the crack propagation.

The new architecture proposed in this paper, if compared with other structures made of a regular pattern
of pillars, has the significant merit of guaranteeing both high adhesion, when the detachment direction is perpendicular to the micro-walls, and easy release when the detachment direction is parallel to the micro-walls. This property may turn out very successful in applications such as manipulation systems, mobile-robots, climbing gloves and suits, where anisotropic adhesion is required to prevent the system from remaining stuck to the substrate.

4. CONCLUSIONS

In this work, we have presented a new architecture for biomimetic micro-structured adhesives that possesses anisotropic adhesion properties. The proposed system comprises micro-walls covered by a thin layer, and presents high debonding strength when detachment occurs perpendicularly to the micro-walls, whereas it is very easy to detach when detachment occurs parallel to the micro-walls. The reason for such strong adhesion anisotropy is easily explained: in the former case, the microstructure enables crack trapping, thus preventing crack propagation. In the latter case, crack trapping cannot occur and a crack may easily propagate fed by a constant flux of energy per unit area. Such considerations are well supported by the results of numerical calculations carried out to simulate a double cantilever beam-like test, and by some experimental observations. We have also investigated the influence of geometry on the adhesive performance of the proposed system. In particular, a modification of the geometrical quantities leading to an increase in the compliance in the regions located between micro-walls, determines a stronger ability of the system to stop and trap cracks. These changes

Figure 5. The variation of the critical bending moment $M_C$, necessary to fully detach the fibrillar structure, normalized with respect to that of a flat control sample $M_{flat}$, as a function of the film thickness $t$ with $s = 4 \mu m; h = 85 \mu m; \lambda = 95 \mu m$, (a); and wall spacing $\lambda$ with $t = 2 \mu m; s = 4 \mu m; h = 85 \mu m$, (b). $E = 3$ MPa, $\nu = 0.5$. Work of adhesion: $\Delta y = 16$ mJ m$^{-2}$.

Figure 6. The variation in the critical bending moment $M_C$, necessary to fully detach the fibrillar structure, normalized with respect to that of a flat control sample $M_{flat}$, as a function of the wall height $h$ with $t = 2 \mu m; s = 4 \mu m; \lambda = 95 \mu m$, (a); and wall thickness $s$ with $t = 2 \mu m; h = 85 \mu m; \lambda = 95 \mu m$, (b). $E = 3$ MPa, $\nu = 0.5$. Work of adhesion: $\Delta y = 16$ mJ m$^{-2}$.
Biomimetic surfaces with controlled adhesion
L. Afferrante and G. Carbone

REFERENCES


in the geometry only slightly affect the behaviour of the system when detachment occurs parallel to the walls. This, in turn, allows us to design microstructures that mimic the direction-dependent adhesion properties of some biological systems, and may be successfully exploited in a countless number of engineering applications such as in biomedical devices, gecko-inspired robots, spy robots, industrial manipulation, gecko tyres, adhesive gloves and suits, where anisotropic adhesive properties are a prerequisite for the correct functioning of the device.

The authors are grateful for the financial support of Regione Apulia (Italy) within the agreement ‘Accordo di Programma Quadro in Materia di Ricerca Scientifica—Il Atto Integrativo’ project TRASFORMA code no. 28 signed on 3 December 2009.

Figure 7. The variation in the critical bending moment $M_c$, necessary to fully detach the fibrillar structure (this time the detachment direction is parallel to the walls), normalized with respect to that of a flat control sample $M_{bat}$, as a function of the film thickness $t$ with $s = 4 \mu m$; $h = 85 \mu m$; $\lambda = 95 \mu m$; (a); and wall thickness $s$ with $t = 2 \mu m$; $h = 85 \mu m$; $\lambda = 95 \mu m$, (b). $E = 3$ MPa, $\nu = 0.5$. Work of adhesion: $\Delta G = 16$ mJ m$^{-2}$.