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# Roles of discontinuities in bio-inspired adhesive pads

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Morphological intricacies of the biological attachment pads generate considerable interest owing to their remarkable ability to control adhesion to various surfaces. Motivated by the adhesive microstructures of insects, we examine the behaviour of adhesion and crack propagation in patterned adhesive films. These films are made of silicone elastomers that were patterned with lateral, longitudinal or crosswise incisions from which a thin silanized glass plate was removed in a displacement-controlled peel experiment. The behaviours of crack propagation on these patterned adhesive films are controlled by simple incision patterns, their depths and spacing. With the crosswise incisions, significant enhancement ($\times$10–20) of fracture energy has been achieved. These findings point towards an important mechanism by which of biological organisms might enhance adhesion, and provide a simple design principle for manipulating the interfacial fracture in a variety of artificial attachment devices.

**Keywords: patterned adhesive film; interfacial fracture toughness; bio-mimetic adhesion**

Biological attachment pads, which present a variety of microscopically textured surfaces, are abundant in nature (Ruibal & Ernst 1965; Autumn *et al.* 2000, 2002; Scherge & Gorb 2000, 2001; Federle *et al.* 2001). Their structural morphologies endow exceptional ability to biological species in creating strong attachment to, and easy detachment from, various surfaces. The design principles of the adhesive pads of motile biological species are in contrast to those of man-made adhesives, in which the roles of viscoelasticity and chemical interactions predominate. While chemical interactions and viscoelasticity effectively enhance adhesion strength, they either lead to irreversible bonds and/or increase the interfacial relaxation time to such an extent that they are not optimum for biological adhesion and locomotion. Apart from the fact that the viscoelastic adhesives are prone to fouling by particulate contamination, its greatest drawback might be that the adhesion strength is rate dependent, thus requiring a nonlinear control of locomotion in order to achieve desired speeds. Nature has devised ways (Scherge & Gorb 2001; Autumn *et al.* 2002) to optimize adhesion using the simplest denominators of material properties of adhesives—elasticity and van der Waals forces coupled with structural morphology—in that the attachment and detachment processes could be controlled linearly by manipulating the mode (e.g. peel angle, shear versus normal traction) of remote loading.[1]

A particular kind of attachment pad is found in the bush cricket (Scherge & Gorb 2000, 2001), which is segmented and exhibits hexagonal symmetry (see figure 3). Despite considerable interest generated in this and other types of structural morphologies found in the insect world, we know little about the mechanisms of crack initiation and propagation with such textured surfaces.

Recently, motivated by the exquisite structural morphologies of insect adhesive pads, we studied the behaviour of the initiation and propagation of cracks in thin elastomeric films (shear modulus $\mu$, thickness $h$) endowed with sharp discontinuities (Ghatak *et al.* 2004). A brief summary of the previous observations and the main results are given in the following paragraph. When a flexible glass plate is removed from a bonded thin PDMS (polydimethylsiloxane) film having an edge crack, the moment ($M$) on the cantilever increases with displacement ($\Delta$) almost linearly up to the point of crack initiation. Concomitantly, bubbles are formed (Ghatak & Chaudhury 2003; Ghatak *et al.* 2004) just behind the film edge (figure 1), which grow and coalesce to form two viable cracks. When one of these cracks is annihilated at the free edge of the film, the applied moment drops, as the other crack continues to propagate on the smooth part of the film accompanied with a wavy undulation (Ghatak *et al.* 2000) of the contact line.

Before describing the motivation and the details of the current studies, it would be instructive to consider figure 1, which summarizes the results of a peel experiment very much like those reported previously (Ghatak & Chaudhury 2003; Ghatak *et al.* 2004), but with some important further insights. In particular,

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[1]A positive effect of mild viscoelasticiy of certain insect adhesive pads leading to better conformity with rough surfaces has, however, been reported by Scherge & Gorb (2001, ch. 11). We thank A. Jagota for the discussion on viscoelastic adhesion.

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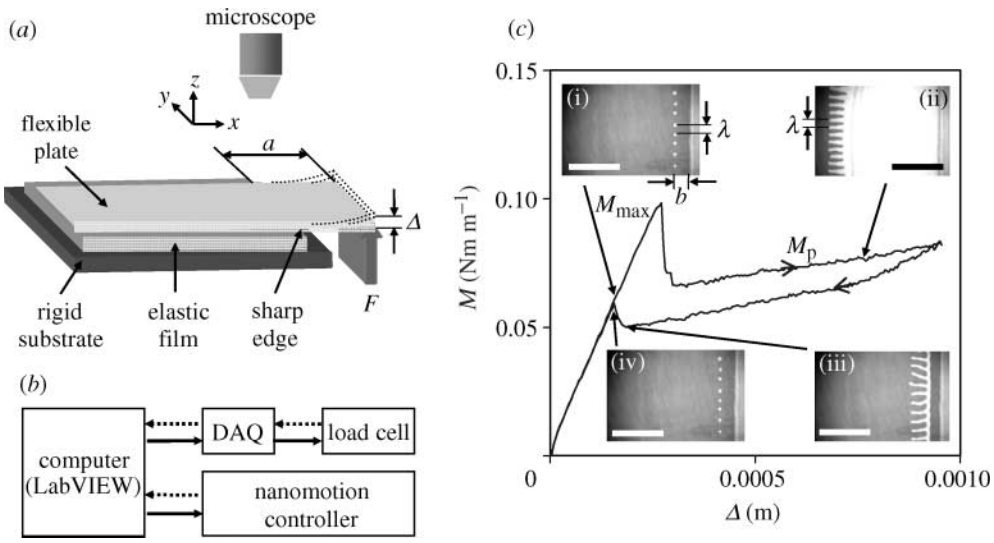


Figure 1. ($a$), ($b$) Schematic of the displacement controlled peel experiment (($a$) is reproduced from Ghatak *et al.* 2004) in which the free edge of a flexible plate adhering to the elastomeric (PDMS) film is delaminated at a constant rate of 5 μm s$^{-1}$. The elastomeric film bonded to the lower rigid substrate may have either a sharp edge or be decorated with incision (see figure 3). ($c$) illustrates the moment–displacement ($M$–$\Delta$) data of a thin silanized glass plate of flexural rigidity 0.05 Nm peeling from a PDMS film (thickness 150 μm, shear modulus 0.9 MPa) having an edge crack. During the delamination cycle, bubbles first nucleate (i) at a distance $b$ inside the sharp edge, followed by their growth and coalescence as reported in Ghatak *et al.* (2004). At the onset of crack propagation, $M$ reaches its maximum value ($M_{max}$). Once the crack opens up, it propagates (ii) on the smooth adhesive film with a lower $M$ ($M_p$). The slight upward slope of $M$ is owing to the fact that the energy release rate in this phase is not entirely given by the bent plate, but contributed by the shear deformation of the PDMS film as well. The above sequence can be reversed by decreasing the plate displacement $\Delta$ (iii,iv). The degree of the reversibility of the crack opening and closing are illustrated in the $M$–$\Delta$ plots. The scale bars in ($c$) are 3 mm.

when a silanized glass plate of flexural rigidity ($D$) is removed from the PDMS film, the moment ($M$) rises sharply and then falls as the crack continues to propagate. Here, we also report the healing of the crack resulting from the decrease of the external moment. We note that the morphological features of the instability and its evolution from cavitation bubbles to fingering patterns are also reversible. The crack opening and healing, however, exhibit a small hysteresis of the peeling moment giving rise to the corresponding fracture energies ($\sim M^2/2D$) of 55 and 36 mJ m$^{-2}$, respectively. The fact that these fracture energies are close to its thermodynamic work of adhesion ($\sim$44 mJ m$^{-2}$; Vorvolakos & Chaudhury 2003) indicates that the interfacial fracture toughness is essentially reversible with only a small dissipation. The significant hysteresis in the overshoot of the peeling moment during the initiation and final disappearance of the crack, on the other hand, is mechanical and not entirely interfacial. An important objective of the current study is to augment and sustain this dissipation in order to achieve an overall enhancement of fracture toughness.

Ghatak *et al.* (2004) already pointed out that multiple incisions in the adhesive film cause interfacial delamination to occur in an intermittent manner involving sequential events of initiation, propagation and arrest of crack. It was conjectured that the spacing between the incisions should be smaller than the characteristic length ($k^{-1}$) of stress decay (Dillard 1989) for the enhancement of fracture toughness. In this paper, we redress the problem by studying more carefully the mechanisms of the initiation and propagation of crack on PDMS films by systematically varying the spacing of the incisions in the lateral and longitudinal directions. Once the relevant length-scales are identified, we use them to create crosswise incision patterns and study how the fracture toughness can be further enhanced by varying the thickness of the PDMS film.

Before describing the details of these experiments, it would be instructive to consider the profiles of the stress ($\sigma$) that develop in thin films along the length of the cantilever by solving the beam equation:

$$\sigma = D\xi_{xxxx}. \tag{1}$$

Here, $\xi$ is the displacement of the plate–film interface from its undisturbed state as a function of $x$, measured parallel to the interface from the edge of the film, and $D$ is the flexural rigidity of the plate. The plate–film interface is represented by $x<0$, and that of the free plate as $x>0$. $\xi_{xxxx}$ indicates the fourth derivative, $\mathrm{d}^4\xi/\mathrm{d}x^4$. The above equation needs to be solved in conjunction with the following sets of equations (see Dillard 1989; Ghatak *et al.* 2004, and the references therein):

$$\xi_{xxxxxx} - \frac{12\mu}{Dh^3}\xi = 0 \quad \text{for } x<0, \tag{2}$$

$$\xi_{xxxx} = 0 \quad \text{for } 0<x<a, \tag{3}$$

subject to the following boundary conditions: the displacement, slope, bending moment, vertical shear force and pressure at the edge and incisions are continuous; the pressure vanishes at the edge, incisions and at infinity; the pressure gradient vanishes at infinity, and the integral of the stress in the plate $\int_{-\infty}^{0}\sigma\,\mathrm{d}x$ yields the force $F$ applied at its end ($x=a$). We begin by defining a dimensionless system parameter ($sk$), which is the ratio of the separation distance between lateral incisions ($s$) to the stress decay length $k^{-1} = (Dh^3/12\mu)^{1/6}$. The condition $sk = \infty$ implies the limiting case of a single edge discontinuity for which the normal traction exhibits alternating regions of tension and compression (figure 2). The traction attains a maximum positive value at a distance $b$ from the edge, where bubbles cavitate. With large incision spacing ($sk = 2$), cavitating bubbles still appear at the same distance behind the incision (figure 1$b$). The regular spacing of the bubbles is, however, determined by another periodic stress profile that develops in the film at $x = -b$ owing to its geometric confinement in the $y$ direction.[2] This stress profile is $\sigma \approx \sigma_m + (Ev/h)\sin(2\pi y/\lambda)$, where $\sigma_m$ is the maximum tensile stress at $x = -b$, $v/h$ is the ratio of the amplitude of deformation to the thickness of the film, and $\lambda$ is the wavelength of perturbation that characterizes the instability in terms of cavitation spacing and fingering width. As a result of the superposition of the above two, the resultant stress profile at the film–substrate interface is two-dimensional, with pressure cusps lining up parallel to the edge at $x = -b$. Interfacial migrations of bubbles (figure 2$c$) nucleated occasionally from random defect sites to specific locations at $x = -b$, providing evidence for the existence of these minimum pressure cusps.

When the incision spacing becomes comparable to, or less than, the stress decay length ($sk = 1.0$ and $0.5$), the stress profile (along $x$) is altered dramatically, in which the distance $b$ is restricted by the spacing of the incisions. Evidently, (figure 2$a$) the maximum tensile stress produced for $sk = 0.5$ is lower than for $sk = \infty$ with the same amount of applied external moment. Thus, in order to raise the tensile stress to the level required for crack propagation, a moderately larger external moment would be required for $sk = 0.5$ than for $sk = \infty$. Figure 2$b$ summarizes the crack initiation and propagation results for $sk = (0.5, 10$ and $\infty)$. While the crack propagates in a saw-tooth manner for $sk = 10$ (figure 2$b$), we see stick–slip behaviour for $sk = 0.5$ that involves saw-tooth-like peaks with much smaller amplitudes. In the latter case, the bubbles cavitate between the incisions but, as they coalesce, they grow laterally rather rapidly as the peeling continues. Nevertheless, because of the close proximity of the next