CANTILEVER PEEL MEASUREMENTS ON PATTERNED SURFACES: CHARACTERIZING THE EFFECT OF PATTERN GEOMETRY AND VOID SPACE†

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Introduction

Many naturally occurring adhesives, such as the foot pads of insects, and famously the gecko, rely on microstructural and hierarchical patterning to enhance the fracture toughness of the adhesive interface.[1-4] However, there is limited knowledge regarding the structural mechanisms responsible for enhanced fracture toughness. Developing adhesion metrologies which are less qualitative and more reliant on fundamental mechanics of the materials involved is critical to the design of advanced functional surfaces. Many naturally occurring adhesives rely on surface texture or mechanical property gradients to increase fracture toughness without manipulating surface chemistry. Without relying on chemical mechanisms, textured adhesives are able to exhibit reversible, directionally-dependant adhesion.

Chemically and physically patterned surfaces, anisotropic adhesives, and long-life stimuli-responsive adhesives are all areas of focus that cannot be adequately characterized with the adhesion tests commonly available. Our objective is to develop a model of the microstructural factors affecting adhesion and delamination focusing on geometric shape, size scale, and orientation of physical patterns. To understand the effect of interface morphology on adhesion, a suite of patterned surfaces was created varying the interfacial contact area and the profile of the crack tip. Positive and negative arrays of simple geometrical shapes were used as test surfaces. The fracture toughness and crack-tip morphology between patterned polydimethylsiloxane (PDMS) surfaces and glass slides was measured using a cantilever peel test and in-situ optical microscopy.

In order to accomplish our objective we measured fracture toughness of interfaces with controlled adhesive heterogeneity induced through surface patterning and manipulation of sub-surface structure, thus revealing critical design elements for advanced adhesives. This method offers many advantages in the research and design of advanced adhesives. We have pushed our investigation into adhesives that are microstructurally designed similar to many naturally occurring adhesive surfaces.

Experimental‡

The cantilever peel test, similar in many ways to a tape test, employs a rigid cantilever fixed to the adhesive interface to be measured. By knowing the cantilever stiffness and measuring the load required to peel the cantilever, the fracture toughness of the adhesive interface is calculated. The geometry of the cantilever peel test differs from the 90° tape test, as the delamination occurs at a very shallow angle (≈1°) and the rigid cantilever is only deformed elastically, as compared to the mechanical loss due to plastic deformation of the peeling tape. A custom cantilever peel apparatus was built based on the descriptions of experimental procedures by Chaudhury and coworkers.[5,6]

The cantilever peel testing apparatus is shown schematically in Figure 1. The adhesion specimen is an elastic film which is strongly bonded to a rigid substrate. The elastic film must have a sharp edge or a defect or incision which will serve as the initiation point for adhesive delamination. A flexible plate is adhered to the elastic film and a tensile machine controls the vertical displacement of the flexible plate. Dynamic delamination experiments were performed at a constant displacement rate where the flexible plate is raised at a controlled speed. An optical microscope with video recording capability was used for visual characterization of the delamination event; including the morphology of the crack front upon initiation and during crack growth. The displacement rate of the flexible plate was held at 5 µm/s. The flexural rigidity (D) of the flexible plate can also be described by equation 1 where (P) is the load on one end of the plate (L) is the length of the plate, b is the plate width, Δ is displacement of the plate. By measuring the tensile stress applied, the rate of the force, and the rate of crack advancement, moment-displacement curves were constructed which illustrate the energy input to the system and how that translates to strain energy release rate.[5]

$$D = \frac{PL^3}{6\Delta b} \qquad (1)$$

PDMS films were used as the elastomeric adhesive. PDMS was cast against photo-lithographically patterned silicon master templates. Sylgard 184 was used with 10 % mass fraction curing agent. PDMS was cured in a 70 °C oven for 4 h. The silicone test surfaces were irreversibly adhered to glass substrates through exposure to oxygen plasma. Thin, flexible glass cantilevers with thicknesses of either 0.22 mm or 0.13 mm were reversibly adhered to the patterned side of the silicone test surfaces. Fracture

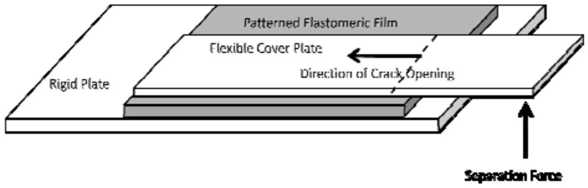

Figure 1. Schematic of the cantilever plate experiment.

toughness of this adhesive interface was measured through the controlled delamination of the glass cantilever.

Results and Discussion

The adhesion of physically patterned PDMS surfaces was measured using the cantilever peel test. Patterns consisting of arrays of squares with varied size and spacing were tested. Likewise, adhesion behavior of triangle based patterns and arrays of parallel lines were also measured. (Schematically shown in Figure 2.) The size scale of pillars that were examined was over the range of 50 µm to 500 µm, as this is on the same order of the many naturally occurring patterned adhesives.

One unique aspect of the triangle based pattern is that the adhesion measurement can be arranged such that the apex of the shape intersects the advancing crack edge or such that the base of the shape intersects the advancing crack edge. This surface pattern demonstrates adhesive anisotropy based on the direction of delamination. Such a system has potential to directionally control delamination through preferential initiation and propagation events.

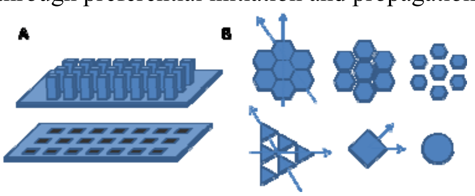

Figure 2. (A) Schematic of positive and negative pattern of square pillars. (B) Schematic array in which size and spacing of pillars is varied; two directions of crack opening are indicated by arrows.

By creating mechanical property discontinuities and gradients at a microstructural level, it is possible to alter the interfacial stress profile prior to crack initiation, thus altering the energy cost for delamination. Geometric shape and orientation of surface texture were also varied to create anisotropic fracture behavior. Our initial surfaces have displayed up to 40% reduction in load required to initiate delamination based on solely on changing the direction of crack propagation.

Conclusions

A study of patterned adhesive interfaces is presented to examine the role orientation and spacing of surface defects on the adhesive behavior at interfaces. Correlation between the geometry and chemistry of the test surface and the fracture toughness of the interface will provide insights to material design especially with regard to bio-mimetic surfaces. Examining the mechanisms of energy dissipation and the morphology of crack growth will outline the limits of constructive property interactions and can also illicit antagonistic combinations of surface properties. Dominant interactions will be revealed by the effects of surface chemistry, roughness and film patterning. With a thorough understanding of the scientific principles underlying the unique behavior of nature's adhesives, new materials and surfaces can be fabricated with tunable properties including but not limited to anisotropic fracture toughness, universal (wet or dry) adhesives, and self-cleaning extended-lifetime adhesives.

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‡ *The equipment and instruments or materials are identified in the paper in order to adequately specify the experimental details. Such identification does not imply recommendation by the National Institute of Standards and Technology, nor does it imply the materials are necessarily the best available for the purpose.*

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