Biomimetic Wet Adhesion of Viscoelastic Liquid Films Anchored on Micropatterned Elastic Substrates

Sandip Patil, Rahul Mangal, Abhinav Malasi, and Ashutosh Sharma*

Department of Chemical Engineering, Indian Institute of Technology, Kanpur-208016, U.P., India

ABSTRACT: Inspired by the natural adhesives in the toe pads of arthropods and some other animals, we explore the effectiveness and peel failure of a thin viscoelastic liquid film anchored on a micropatterned elastic surface. In particular, we focus on the role of the substrate pattern in adhesion energy of the liquid layer and in allowing its clean separation without cohesive failure. Peel tests on the microfabricated wet adhesives showed two distinct modes of adhesive (interfacial) and cohesive (liquid bulk) failures depending on the pattern dimensions. The adhesion energy of a viscoelastic liquid layer on an optimized micropatterned elastic substrate is ~3.5 times higher than that of a control flat bilayer and ~26 times higher than that of a viscoelastic film on a rigid substrate. Adhesive liquid layers anchored by narrow microchannels undergo clean, reversible adhesive failure rather than the cohesive failure seen on flat substrates. An increase in the channel width engenders cohesive failure in which droplets of the wet adhesive remain on the peeled surface.

INTRODUCTION

Natural adhesives and the micronano architecture of the feet of some arthropods and other animals produce an excellent ability to adhere strongly to any type of surface and detach easily, often cleanly. The attachment of geckos and some other animals to rough surfaces is more effective2 when the attachment pad is often rough, taking the form of microdomains separated by channels or grooves filled with a biofluid. Persson3 has considered some interesting aspects of the wet adhesion. However, the importance of dry versus wet adhesion in different species and their detailed mechanisms are still the subject of some debate.

Inspired by examples of wet adhesion in nature, we examine the slow peel failure of a thin film of a mildly cross-linked viscoelastic liquid that fills the microchannels of a micropatterned soft elastic substrate and also covers its surface in the form of a thin film, as shown in Figure 1. In particular, we explore whether confinement and anchoring of a soft liquid by a rough substrate offers any advantages for the peel strength and ease of clean separation. To this end, arrays of fully cured, elastic polydimethylsiloxane (PDMS) pillars were microfabricated in various sizes (Figure 1a) to explore the roles of pillar and channel dimensions (shown as dimensions a and b, respectively, in Figure 1b). The channels were filled with a partially cross-linked PDMS liquid, a thin film of which also completely covered the surface. Because of its small surface tension, PDMS liquid wets almost any surface, whereas its viscoelasticity allows a moderate peel strength because of viscous dissipation.

Debonding of topographically patterned elastic films has been investigated, where increased elastic compliance and crack arrest produce a higher adhesive strength. Contact instability and the formation of surface patterns in the debonding of single elastic films, debonding of single...
viscoelastic films and elastic bilayers on flat and topographically patterned substrates have been investigated. However, so far there are no studies related to the adhesive strength of thin liquid layers and their modes of failure on topographically micropatterned elastic substrates.

**EXPERIMENTAL SECTION**

**Fabrication of Master Stamp on SU-8 Photoresist.** An epoxy-based negative photoresist (2015 Microchem, U.S.) was used for photolithography and Sylgard-184 PDMS, a two-part thermo curable PDMS elastomer (Dow Corning, MI), was employed for making the PDMS layers. Propylene glycol monomethyl ether acetate (PGMEA) (Microchem, U.S.) was used as a solvent for developing SU-8. First, SU-8 was spin-coated with a thickness of 40 μm on a clean glass substrate. After spin-coating, the prepared photoresist samples were soft baked at 60 °C for 1 h and exposed (using a maskless photolithography system (Intelligent Micro Patterning). The soft baked at 60 °C for 1 h and exposed (using a maskless photolithography system (Intelligent Micro Patterning).36 The exposed photoresist films were subsequently developed in a PGMEA solvent. After development, the samples were rinsed with isopropyl alcohol and blown dry with nitrogen. A schematic of the photoresist negative master stamp was used with an area of 280 mm² (L = 28 mm and W = 10 mm) is shown in Figure 1a, step 1.

**Fabrication of PDMS Elastic Patterned Surfaces.** After preparation of the SU-8 negative master stamp, the commercially available PDMS (sylgard 184) with a cross-linking agent was used for the adhesive film preparation. The elastomer and cross-linking agents were mixed in a ratio of 100:10 w/w (or 10% cross-linked PDMS) and 100:1 w/w (or 1% cross-linked PDMS) separately in a clean glass beaker and degassed under vacuum to remove dissolved air from the PDMS solution. First, the 10% cross-linked PDMS solution was cast between a glass plate and the master stamp (step 2, Figure 1a). The patterns on the master stamp were thus transferred onto a cast layer of PDMS; a uniform thickness was obtained by inserting spacers of known thickness between the master and the confining glass plate. The sample was then placed in an oven for curing at 85 °C for 24 h. Cured samples were dipped into acetone for 30 min to swell PDMS, after which it could be separated slowly starting from one end by hand. Following this process, the positive PDMS replica could be peeled from the master but remained bonded to the rigid glass, which served as its substrate. A typical optical micrograph of the patterns on the elastic PDMS surface with thickness 50 ± 2 μm is shown in Figure 1b.

The height of the PDMS pillars was 40 μm with a 10 μm backing layer. Three types of 10% cross-linked PDMS micropatterned substrate were created: set 1, patterns with a fixed channel width (b = 15 μm) but variable pillar widths (a = 15, 45, 90, 225, and 450 μm); set 2, patterns with a fixed pillar width (a = 15 μm) but variable channel widths (b = 15, 45, 90, 225, and 450 μm); and set 3, patterns where the pillar and channel widths are equal (a = b = 15, 45, 90, 225, and 450 μm).

**Liquid Film Coating on Patterned Elastic Surfaces.** The PDMS solution with 1% cross-linker was used to fill in the patterned cavities by spin-coating at slow speeds, leaving a thin layer ~20 μm thick on top of the patterned surface. The PDMS gel was again cured at 85 °C for 48 h to yield a viscoelastic liquid film on top of the filled grooves. The uniformity of the top layer thickness was confirmed by optical microscopy by focusing at various points on top of the pillars. The measured average thickness was 20 ± 2 μm. Step 3 in Figure 1a shows the final elastic micropatterned substrate with filled channels and supporting an excess 20 μm layer of PDMS liquid on top. During fabrication, we followed a previous protocol for bilayer adhesive in which smooth PDMS bilayers with two different cross-linker concentrations and elastic properties were fabricated for adhesion experiments and their structural integrity was verified by atomic force microscopy.35 Note that the bottom layer was fully cross-linked before the top viscoelastic layer was added. Our experimental observations thus preclude the possibility of any anomalous interfacial alterations during the preparation of the PDMS layers.

**Storage (G') and Loss (G'') Moduli of the Liquid Film and Substrate.** The rheological response of the prepared PDMS smooth films was measured by the oscillatory parallel plate method (Anton Paar MCR-501). Rheology tests were performed on four different PDMS samples and averaged with less than 2% variation in the results. Figure 2 shows a typical rheology response for the 1% cross-linked liquid PDMS.
PDMS and 10% cross-linked PDMS materials used in this study. The rheology response for the 10% cross-linked PDMS (Figure 2) shows a higher storage modulus ($G'$) as compared to its loss modulus ($G''$) and indicates a nearly frequency-independent response that exhibits nearly elastic solid behavior. In contrast, the rheology response for the 1% cross-linked PDMS shows that the loss modulus is substantially higher than the storage modulus, thus indicating largely viscous response in the slow peel experiments. Although the liquid layer behaves as a viscous liquid in slow peel experiments, the main advantage of 1% cross-linking is a substantially increased loss modulus (viscosity), which is helpful in carrying out the debonding experiments with an increased work of adhesion.

**Peel Test.** To understand the modes of adhesive failure and work of adhesion, a small angle peel test was performed on the liquid adhesive layer supported on the micropatterned substrate by using the setup shown in Figure 3. We first mounted the glass plate with the prepared adhesive on a fixed platform. A flexible microscopy glass cover plate with octadecyltrichlorosilane (OTS) monolayer coating with water contact angle 103 ± 2° was then brought into complete contact with the adhesive surface and separated by a micromanipulator from its hanging edge with a speed of 3 μm/s (Figure 3). The movement was controlled by a stepper motor mounted on the linear stage interfaced with an RS 232 computer interface.

The flexural rigidity of the cover plate ($D \approx 0.02$ N m) was selected so as to allow little bending for a more precise estimation of the work of adhesion. The peel test was performed on four different samples with the same pattern geometry to verify reproducibility. The estimation of the work of adhesion using the peel method is explained in the next section of this Article.

During separation, the force–displacement ($F-\Delta$) curve was recorded by a strain gauge load cell attached to the micromanipulator.

**RESULTS AND DISCUSSION**

Figure 4a–c depicts typical $F-\Delta$ curves for the three sets of surface patterns (varying pillar width, channel width, or both). Curve 1 in Figure 4a corresponds to a control sample prepared by depositing the 1% PDMS visco-elastic liquid at a thickness of...
20 μm on a uniform, nonpatterned 10% PDMS elastic backing layer 50 μm thick. This flat bilayer provides a reference point for judging the effect of substrate patterning. In this control bilayer sample, debonding was initiated by the formation of viscous fingers followed by the formation of fibrils, with some qualitative similarities to the observations of Carelli et al. As shown in the Figure 5, crack initiation occurs in the control uniform bilayer by the formation of broad, unconfined fingers along a line normal to the direction of peeling. On propagation of the crack line, the fingers meander, develop side undulations, and merge. The liquid bridges formed with the contactor rupture cohesively to leave liquid residue on the peeled surface. Single films of 1% cross-linked PDMS deposited directly on the glass slides with layer thicknesses of 20 and 70 μm also showed similar cohesive failure. Typical F−Δ curves for 1% cross-linker smooth films on glass with two different thicknesses are shown in curves 2 and 3 of Figure 4a for comparison. For these relatively thick films, only a slight thickness dependence appears because of the lack of the confinement effect on the cohesive failure. Supporting the top liquid layer on a uniform elastic layer improves the adhesion (curve 1) by increasing the compliance of the system, as was also observed previously. However, detachment in both the control bilayer with smooth surfaces and single liquid films on rigid substrates continued to occur by cohesive failure. The separation in such cases was not clean; some adhesive material transferred to the detached surface. The adhesive layer after separation became uneven because of its cohesive rupture. In such cases, the layer showed reduced adhesive strength if used again within a few hours of its first use.

Next, we focus on the same viscoelastic liquid films on patterned substrates to understand the conditions that encourage clean, interfacial detachment (adhesive failure) occurring at the liquid film–contactor interface, rather than bulk cohesive failure. In such a case, the liquid film snaps back to its microgrooved substrate, and no residue could be observed on the peeled surface. The effect of substrate patterns on the work of adhesion is also assessed. The three different sets of micropatterned elastic PDMS substrates were used as outlined in the Experimental Section.

**Variation of Pillar Width.** We consider first the results for a fixed channel width (b = 15 μm) and variable pillar widths (a = 15, 45, 90, 225, and 450 μm). This case offers highest lateral confinement of the liquid in the channels during peeling. The F−Δ curves for these cases are shown in Figure 4a. Interestingly, for all pillar widths of 225 μm or less, clean interfacial separation between the glass plate and the liquid layer was observed without any residue remaining on the peeled surface. However, at the largest pillar width of 450 μm, some cohesive failure of the liquid layer occurred mainly by the failure of bridges formed between the liquid in the channels and the contactor surface. It is interesting to note that the periodicity of unconfined fingers in the control bilayer on nonpatterned substrates is ~300 μm. Thus, very broad pillars would offer the possibility of propagation of multiple meandering fingers per pillar, thus losing the confining and guiding effects offered by the pattern. In view of the further discussion below, this could be the reason for a shift in the mechanism of debonding from adhesive to cohesive failure on very wide pillars.

The crack morphology during debonding on patterned substrates showed a completely different behavior as compared to the control sample. A typical sequence of finger progression and liquid detachment is shown in a video (Supporting Information). Figure 6a shows a representative view of debonding in the cases when a clean adhesive failure occurred. Lighter shades represent the liquid film adhering to the glass plate, and the darker shades are debonded regions with the liquid film covering the patterned substrate. Periodicity of the advancing fingers (detached regions) is now governed by the periodicity of the underlying pattern on the substrate, and the progression of fingers from one row of pillars to the next row remains ordered and unidirectional without splitting or merging of the fingers. The liquid bridges to the glass plate are now highly confined in the channels. The initial debonding occurs by detachment of the film from the glass contactor on top of the pillars where the film thickness is minimum. At this stage, the viscous liquid fingers forming bridges with the contactor are confined in the channels. Eventually, the narrowing liquid bridges also snap back to the film. Interestingly, reduced pressure in the liquid film ahead of the main crack also causes cavitations and detachment on top of the pillars as evident in the appearance of somewhat irregular contact lines around the couple of rows of pillars ahead of the main crack (Figure 6a). In all of the cases of adhesive failure, the width of intersurface
bridges that debonded last was less than the channel width so that only a single bridge was confined in a channel during the final phase of debonding. This morphological pathway of debonding, however, becomes different when cohesive failure was seen as discussed below for the Figure 6b.

For large pillar widths, $a = 450 \, \mu m$, local cohesive failure began because at this large pattern size, the liquid layer above the wide elastic pillars acts more like the unconfined control bilayer on a smooth elastic base. Thus, the presence of narrow (channel width = $15 \, \mu m$) channels is found to be sufficient to anchor and stabilize the adhesive upper layer despite long stretches of flat interface that tend to encourage cohesive failure, as in the control bilayers. The force–displacement analysis in Figure 4a also shows that the maximum debonding force and the plateau in the force–displacement curves depend on the pillar size. For the smallest pillar width, which is comparable to a channel width of $15 \, \mu m$ (curve 4), the maximum debonding force is $\sim 2$ times higher than that of the control surface (curve 1), and a much wider constant force plateau is observed, signifying a slower crack propagation phase. With further increases in the pattern width from 15 to 225 $\mu m$ (curves 4–7), the maximum debonding force decreases, but the plateau region becomes increasingly more defined. Finally, the behavior changes again at a pillar width of 450 $\mu m$ (curve 8) with the onset of cohesive failure as discussed. The energy release rate varies spatially because of the different stress fields created by the differences in the heights of elastic base and the liquid film. This results in a pattern directed sinusoidal crack propagation as shown in Figure 6a where debonding occurs first on top of the pillars followed by debonding over the channels. The plateau seen in the $F–\Delta$ curves of Figure 4 indicates the extent of viscous dissipation during peeling, which becomes more prominent as the pillar and the channel widths decrease.

**Variation of Channel Width.** We consider here the results for a fixed smallest pillar width ($a = 15 \, \mu m$) and variable channel widths ($b = 15, 45, 90, 225$, and $450 \, \mu m$). The $F–\Delta$ curves for these cases are shown in Figure 4b. For a small channel width of $15 \, \mu m$, the liquid film underwent adhesive failure from the contacting surface only if the pillars were very wide ($\sim 450 \, \mu m$) as discussed above. However, for wider channels starting at $45 \, \mu m$, cohesive failure in the liquid film was always observed regardless of the pillar width. Clearly, a small channel width plays a more prominent role than the pillar width in stabilization of the liquid film against cohesive failure and its clean separation from the adhering surface. A representative view of debonding by cohesive failure for wider channel widths is depicted in Figure 6b, and a video representing the progression of debonding is shown in the Supporting Information. Clearly, debonding proceeds by the formation of multiple fingers, cavities, and bridges in every channel. Also, unlike the case shown in the Figure 6a, the progression of the multiple crack fronts is no longer guided unidirectional by the pattern. Figure 6b for wider pillar widths ($225 \, \mu m$) shows multiple fingers per pillar, but for small pillar widths, for example, $15 \, \mu m$, the only difference was that a single finger as shown in the Figure 6a formed covering the debonded pillar, but multiple meandering crack fronts formed in the wide channels. Cohesive failure occurred in the multiple bridges formed in the channels.

The $F–\Delta$ curves in Figure 4b show that increasing the channel width decreases the maximum debonding force for the onset of crack propagation and the adhesion energy (area under the $F–\Delta$ curves). For large channel widths, cohesive failure engendered a more prominent constant-force crack-propagation plateau regime, as shown in curves 3 and 4.

**Variation of Pattern Dimensions with Equal Pillar and Channel Widths.** Here, we present results for the case when both the channel and the pillar dimensions are kept equal (pillar width = channel width). The $F–\Delta$ curves for this case are shown in Figure 4c. In agreement with the results in Figure 4a and b, clean adhesion failure was observed for pillar width or channel width <45 $\mu m$, but for channel width >45 $\mu m$, cohesive failure occurred. As discussed earlier, representative views of the adhesive and cohesive failures are as shown in Figure 6a and b.

Important observations from these results are that the presence of narrow channels below a critical width and areal number density on the substrate prevents cohesive rupture of the overlying viscoelastic liquid adhesive film and increases the debonding force for crack initiation and the work of adhesion. Two possible mechanisms may play a role. The first is the capillary adhesion model,8,42–44 which seeks to explain the debonding of a surface having capillaries filled with a liquid adhesive. If the debonding liquid film separates to form trapped meniscus in the channels, the Laplace pressure deficit of the viscoelastic liquid within the grooves is $\sim \gamma/b$, where $\gamma$ is the surface tension of PDMS liquid and $b$ is the width of the groove or channel between the neighboring pillars. The pressure in the receding liquid meniscus of the film is $\sim \gamma/t$, where $t$ is the thickness of the liquid adhesive layer, which is in the range of $20–60 \, \mu m$ on top of the pillars and on the channels, respectively, in our experiments. According to this mechanism,8 cohesive failure may occur when $b > t$, and the liquid tends to flow out of the grooves rather than being pulled back. However, the capillary model8 is a great simplification of our situation in which a liquid film exists at the top of the pillars and in the channels, and the shape of the meniscus may be complex. It also does not account for dynamic effects. The second known mechanism is the blunting of a propagating crack and increased energy dissipation when it encounters low modulus regions such as air pockets.18,19 Further, sudden expansion or contraction of flow areas and recirculating flows in the confining channels as a crack passes by can greatly increase the viscous dissipation and thus lower the crack propagation energy near the substrate. A greatly increased viscous dissipation could thus contribute to preventing cohesive failure and increasing the work of adhesion. Finally, another possibility in conjunction to the above is the anchoring effect of the grooves on the liquid bridges formed between the separating surfaces. This may stabilize the fibrils against break up.

**Work of Adhesion.** Next, the work of adhesion was estimated from the $F–\Delta$ curves. The integrated area under the $F–\Delta$ curves divided by the total contact area of 100 mm$^2$ yields the work of adhesion required to debond the flexible glass plate from the adhesive surface. Estimated work of adhesion includes the bending energy of the flexible cover plate and the interfacial energy of adhesion. However, as shown in the $F–\Delta$ plot of Figure 4, the remaining load on the bent flexible glass plate becomes negligible at the end of the experiment after detachment of the film. This shows a very small quantity of stored elastic energy in the plate. The maximum bending energy of the cover plate was found to be 21 mJ/m$^2$ by bending the plate to the maximum displacement of $\Delta = 2$ mm without an adhesive layer. The same protocol of the peel test has been extensively used and discussed earlier.12,13,17,27,29,39,40 The method has the advantage of obtaining the adhesion strength.
without the need of any specific model of the composite viscoelastic layer. To present our results, we report separately the crack initiation energy (nonshaded area, Figure 7) and the crack propagation energy (shaded area, Figure 7). The latter is the area from the point of maximum force (i.e., crack initiation point) to the point of complete separation. The work of adhesion required to separate the two surfaces, including the viscoelastic energy dissipation in the film, is reported. The details and interpretation of the peel test can be found elsewhere. The energy of adhesion for both crack initiation and crack propagation are increased by the introduction of the patterned substrate, as shown in Figure 8. Below, we focus on the work of adhesion for crack propagation; in the subsequent discussion, \( G \) refers only to this part of the work of adhesion. A uniform elastic layer with 10% cross-linking has a very low total work of adhesion (\( \sim 60 \) mJ/m\(^2\)) and negligible work of adhesion for crack propagation. However, these can increase substantially by the creation of crack-trapping incisions in the elastic layer. The plateau seen in the \( F-\Delta \) curves of Figure 4 is correlated to the viscous dissipation during peeling, which becomes more prominent as the pillar and the channel widths decrease. Figure 8b shows that when both channel width and pillar width are small (=15 \( \mu \)m), the work of adhesion for crack propagation part (\( G = 2799 \pm 199 \) mJ/m\(^2\)) on the patterned substrate is \( \sim 3.5 \) times higher as compared to the control bilayer (\( G = 812 \pm 59 \) mJ/m\(^2\)) with smooth interfaces and about \( \sim 26 \) times higher as compared to the 1% cross-linked PDMS films (\( G = 110 \pm 26 \) mJ/m\(^2\)). As either the pillar width or the channel width is increased, the adhesion energy decreases and becomes nearly constant at higher pattern dimensions. As compared to the 1% cross-linked PDMS film on a rigid glass substrate, supporting the viscoelastic film on a smooth elastic substrate increases the work of adhesion by a factor of \( \sim 7 \). However, it is important to note that debonding in both of these cases occurs by cohesive failure, leaving some residual liquid on the peeled surface. The work of adhesion is maximum for the smallest channel width and the maximum pillar density, but decreases with an increase in the pattern sizes (both pillar width and channel width). An interesting observation is that the work of adhesion remains significantly higher on the narrow-channeled substrates (channel width = 15 \( \mu \)m) as compared to the smooth bilayer, regardless of the pillar width, even when cohesion failure occurs. This factor indicates the importance of dynamic effects in the form of increased liquid friction or dissipation and crack blunting caused by the channels. The volume of the viscoelastic liquid decreases with increasing pillar width and increases with the channel width.
However, in both of these cases, the work of adhesion is reduced. The work of adhesion here is mainly contributed by the viscous losses in the liquid layer, and thus a correlation with the effective elastic modulus of the substrate is not expected. As discussed earlier, dynamic effects leading to increased viscous losses and crack blunting \( \sim \) on patterned substrates are the likely causes of the increased adhesion. For example, increased adhesion by crack arrest in debonding of patterned elastic adhesives in air is well-known.14,17

Admittedly, our work is only loosely inspired by the wet adhesion in tree frogs. Although the minimum pillar width in this study is comparable to the domain size on tree frog pad \((\sim 10 \mu m)\), the channel widths and the liquid film thickness in some biological settings may be about an order of magnitude lower \((\sim 1 \mu m)\). However, as shown by our results, a smaller channel width is in fact more effective in stabilization of liquid film against its cohesive failure. A thinner liquid film is also expected to encourage adhesive rather than cohesive failure as compared to a thick film. Thus, it would seem that thinner liquid films confined in narrower channels could be even more stable than the ones considered here. However, it is conjuncture that needs to be explored by future studies.

**CONCLUSIONS**

We studied the adhesion failure of a thin viscoelastic liquid layer supported on micropatterned elastic substrates, which loosely mimics the scenario of natural adhesives in the toe pads of animals. The work of adhesion as measured by a peel test is very low for the same viscoelastic layer supported on a rigid substrate, but increases by a factor of \( \sim 7 \) with the introduction of a smooth soft elastic substrate. The liquid layer on a uniform elastic substrate undergoes cohesive failure by unconfined growth of multiple meandering crack fronts. The work of adhesion of the liquid layer can be further enhanced by a factor of \( \sim 3.5 \) by micropatterning the elastic substrate with narrow channels as compared to the control bilayer. Increasing the channel and/or pillar widths both decrease adhesion, but the channel width plays a far more significant role. At small channel widths, cohesive failure of the liquid adhesive is suppressed, indicating clean interfacial adhesive separation and minimal adhesive loss. In such cases, the underlying substrate pattern confines and guides the progression of crack pattern with a single bridge forming between the film and the peeled surface per channel. Channel widths substantially in excess of the film thickness produce cohesive rather than adhesive failure in the film. This is accompanied by the unconfined growth of multiple crack fronts in a channel. Thus, micropatterns provide an effective strategy for stabilization of thin adhesive liquid layers during debonding, enhanced reusability, and increased work of adhesion. As an example of wet adhesion in nature,11 the toe pad surface of a tree frog is patterned with an array of epithelial cells with typical widths of \( \sim 10 \mu m \) separated by narrow channels or grooves of width \( \sim 1 \mu m \) and depth \( \sim 10 \mu m \) that contain mucous secretions. While the channel dimensions and the liquid film thickness considered here are much larger than the tree frog toe pad characteristics, a smaller channel width should in fact further encourage stabilization of the liquid film against cohesive failure. Our results may thus also partially explain the minimal loss of natural adhesives that are anchored on the microtextured adhesive pads during locomotion. It may, however, be noted that whether failure is adhesive or cohesive should depend also on the film thickness and the properties of the surface from which detachment occurs (roughness and adhesion energy), so that a generalization is probably not warranted.

**REFERENCES**


