International Journal of Adhesion and Adhesives 79 (2017) 102–110

Contents lists available at ScienceDirect

International Journal of Adhesion and Adhesives

journal homepage: www.elsevier.com/locate/ijadhadh

A finite element study of adhesion of soft thin elastic films cast on rough surfaces

Satish Mishra, Hemalatha Annepu, Jayati Sarkar*

Department of Chemical Engineering, Indian Institute of Technology Delhi, New Delhi 110016, India

ARTICLE INFO

Keywords:
Self organization
Patterning
Instabilities
Corrugated surfaces

ABSTRACT

Contact instability of thin elastic films rigidly bonded to patterned substrates, in comparison to those bonded to smooth substrates, were found to form highly miniaturized patterns at their free surfaces. Through finite element simulations, we have found that irrespective of the widely varying substrate patterns used (step, sinusoidal, sawtooth and noisy sinusoidal, with different substrate parameters), the salient miniaturized surface features engendered in these films are found to be same for identical *RMS* substrate-roughnesses. Columns formed at the film-contactor interfaces of these patterned-substrate films are found to be very slender with larger contact area and are comparatively able to bear very high stresses (responsible for higher peak debonding forces). These columns simultaneously display higher stress release during debonding that leads to almost identical snap-off distances and consequentially, higher work of adhesion is observed. Additionally, work of adhesion also increases for higher debonding velocities. The *RMS* substrate roughnesses promote these films to perform as potentially better adhesives and, their influence on pattern miniaturization can be harnessed to enhance other surface properties.

1. Introduction

In the seminal work by Mönch and Herminghaus [1] it was shown that an initially smooth, free surface of an elastic film bonded to a rigid substrate, undergoes morphological patterning whenever the destabilizing interactions between the film and a contactor surface exceed a critical value. These patterns help in creating adhesive contact zones between the film and the contacting surface. The patterns persist during withdrawal of the contactor up to snap off distance, where the contact zones again reduce to zero. Since the snap-off distances are much higher than the critical distances where the instabilities first set in, these films perform as adhesives. The length scales of the engendered patterns play a crucial role in determining the adhesive strength of the film. In case of smooth substrate and contactor assembly, the length scales (λ) of the morphological patterns depend on the geometry ($\lambda \sim 4h$ and $3h$ for single films of thickness h, in peel geometry as shown by Ghatak et al. [2], and on adhesive geometry as reported by Mönch and Herminghaus [1], Shenoy et al. [3], Sarkar et al. [4–6], respectively).

Topologically patterned thin film surfaces are useful for making pressure sensitive adhesives (as can be understood from Chivers work [7] set to illustrate how for skin applications, microstructures in PSAs are used in decreasing peel off forces). Structured film surfaces are also useful in various other applications like in flexible printed circuits: where optimized perforated substrate geometries are used to manufacture robust stretchable flex devices as shown by Taylor et al. [8]. Other useful application of patterned thin film is in sensors/biosensors, an overview of which can be obtained from the review article presented by Rajesh et al. in [9]. Burton and Bhushan in their work [10] on MEMS/NEMS have demonstrated that the usage of structured surfaces can tailor adhesion and friction in these devices. Structures created on soft polymeric surfaces can also be used to develop in-situ medical diagnostics and high efficiency light-emitting diodes (as shown through experiments by Macaya et al. [11] and Lee et al. [12] respectively). Pattern formations in soft elastic thin films by self-organization are interesting for the advantages they offer in: characteristic patterns formed at small length scales, low costs involved and the relative ease in scaling up the process. The challenge, however, lies in further densification of the patterns, which is anticipated to further enhance surface properties like adhesion.

In the past decade much work has been done with this objective and smaller length scales of $\sim 0.5h$ have been reported with elastic bilayers by Mukherjee et al. [13] and, Annepu et al. [14]. In the studies [15–17] it has been shown by Sarkar et al. that pattern length scales as low as $\sim 0.3h$ can be achieved in elastic films cast on patterned substrates. Previous investigations performed on the elastic films cast on patterned substrates have been restrictive on two counts: they were all limited to

* Corresponding author.
E-mail address: jayati@chemical.iitd.ac.in (J. Sarkar).

http://dx.doi.org/10.1016/j.ijadhadh.2017.09.013
Accepted 3 September 2017
Available online 28 September 2017
0143-7496/

the initial stages of adhesion when the contactor was just approaching the film and, secondly, only two geometrically well-defined and limited substrate topographies were investigated (refer to Mukherjee et al. [18] and Sarkar et al. [15–17]). In the existing work on well-defined pre-patterned substrates, the length scales are a strong function of the substrate surface roughness amplitude. However, the inherent roughness present in a real substrate may not conform to any of these regular geometries. Also, hard lithographic techniques are used to create these regular patterns on substrates, which are very costly and time-consuming. This defeats the very purpose of the present self-organization route to produce miniaturized pattern formation.

In the present work we address the question that can the inherent roughness of any substrate be employed, without further patterning it, and tapped to produce reduced-scale features. If so, how does one predict the length scales obtained in the absence of any defining substrate amplitude? A unifying study is performed on the various substrate roughnesses of both regular and irregular geometries that can be very instrumental in designing novel materials without demanding mesoscale smooth surfaces or pre-patterned substrates to build on. With the help of Finite Element Analysis we explore these possibilities, observe the engendered surface topology in 3D and also predict the debonding force, snap-off distance and work of adhesion for these soft, thin elastic films rigidly bonded to regularly patterned and irregularly patterned substrates during adhesion-debonding from an external contactor. This work also reveals how to produce highly miniaturized patterns utilizing the inherent roughness of the substrate without resorting to pre-patterning of the substrate to a definite regular form and how the miniaturized length scales help these films to behave as better adhesives.

2. Mathematical modeling

To facilitate mathematical modeling and to mimic the real situation a geometrical setup as shown in Fig. 1 is considered. It depicts the schematic of an initially stress-free, soft (shear modulus, $\mu < 1$ MPa), thin (mean film thickness, $h < 10$ μm), incompressible elastic film cast on various topographically patterned rigid substrates. The Cartesian coordinate system with co-ordinates (x_1, x_2) used for the analysis is shown in Fig. 1A. The film is unbounded in x_1-direction and for mathematical treatment a portion of the film of length L is taken which is considered to be periodic at $x_1 = 0$ and at $x_1 = L$. The patterned substrate morphology is defined by the pattern amplitude β_p ($= \beta \times h$) and wavelength λ_p ($= L/n_p$: n_p being the number of the crests/troughs present in the substrate pattern). The types of substrates considered for the present study are illustrated in Fig. 1B–E, where Fig. 1B–D respectively, denote a step-substrate, sinusoidal-substrate, sawtooth-substrate having substrate amplitude in the range of $0.1 \times \beta h - 0.7 \times \beta h$ and a noisy sinusoidal substrate (Fig. 1E), having random roughness in the range of $\pm\, 0.1\beta h$ imposed on a base sinusoidal profile.

The roughness of the substrates can be characterized by the root mean square (RMS) value as defined by:

$$RMS = \sqrt{\frac{1}{L}\int_0^L |f(x_1)|^2 dx_1} \tag{1}$$

where, $f(x_1)$ is the topology of the substrate profile. The calculated non-dimensional RMS roughness $RMS' = RMS/h$) for the step, sinusoidal and sawtooth profiles are β, $\beta/\sqrt{2}$ and $\beta/\sqrt{3}$ respectively, making step substrate the roughest substrate amongst these three. The noisy sinusoidal profile is comparatively rougher than the smooth sinusoidal profile. The top surface of the film at $x_2 = 0$, is considered to be adjacent to a contactor at a mutual separation distance d which is also referred to as the gap distance. The contactor velocity during adhesion phase is v_a and in debonding phase is v_d.

2.1. Energetics of the elastic film

The governing thin film (Navier's) equation obtained by performing a force balance over a thin differential volume is given by:

$$\vec{\nabla}.\sigma + \vec{\mathbf{F}} = \rho\frac{\partial^2\vec{u}}{\partial t^2} \tag{2}$$

where ρ is the density, $\sigma = p\boldsymbol{I} + \mu(\vec{\nabla}\vec{u} + (\vec{\nabla}\vec{u})^T)$ is the stress tensor prevalent inside the film, $\vec{u}$ is the displacement vector, p is the pressure, $\boldsymbol{I}$ the identity matrix and $\boldsymbol{F}$ is the body force (per unit volume) arising because of the presence of the contactor, μ is the shear modulus of the film and t is the time unit. For incompressible films the governing equation can now be written as:

$$\mu\nabla^2\vec{u} + \vec{\nabla}p + \vec{F} = \rho\frac{\partial^2\vec{u}}{\partial t^2} \tag{3}$$

Now, the most common interactions between two molecules (atoms) are van der Waals forces, which originate when the contactor is brought closer to the film. As the distance between the film and the contactor decreases, the van der Waals interactions lead to affinity of the film towards the contactor. This spontaneous deformation of the film surface is countered by the elastic stiffness of the film. When the van der Waals interactions exceed a critical value at a gap less than the critical gap distance d_c, the film undulates at a wavelength. The undulation wavelength is determined by the film, substrate and contactor parameters together (as reported by Mönch and Herminghaus [1], Shenoy and Sharma [3], Sarkar et al. [4,5,15] and Annepu et al. [16,17]). It may be noted that when the contactor is below the critical distance the deformations are spontaneous because of the elastic nature of the film, and the R.H.S of Eq. (2) and (3) are practically negligible.

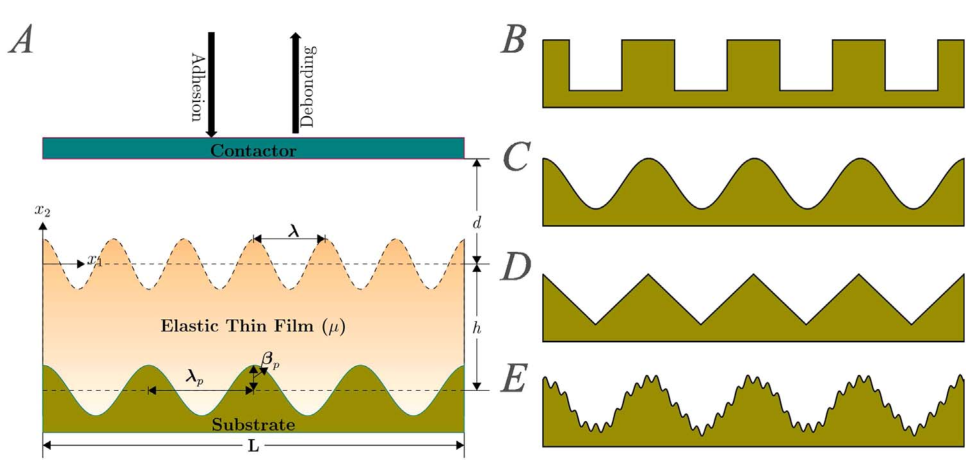

Fig. 1. (A) Schematic of a soft, incompressible elastic film in contact proximity with an external contactor and rigidly bonded to a smooth sinusoidal substrate (B) step patterned substrate (C) smooth sinusoidally patterned substrate (D) sawtooth substrate and (E) noisy sinusoidal substrate. The mean thickness of the film is h, shear modulus μ and is of length L. The contactor position is denoted by the gap distance d it makes with the stable flat surface of the elastic film. The substrate pattern is defined by the amplitude βp and wavelength λ_p.