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# Peeling behavior of a thin-film on a corrugated surface

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ABSTRACT

The peeling behavior of a thin-film perfectly adhering on a corrugated substrate is investigated theoretically. Unlike the usually adopted average method of introducing an effective adhesion energy, the effect of substrate roughness is considered directly in this paper and an accurate closed-form solution to the peel-off force under quasi-static peeling process is achieved. Comparing to the results obtained by the average method and those of a smooth substrate case shows that the peel-off force in the present model varies periodically, similar to the roughness of substrates. Furthermore, it is interesting to find that the peeling strength (defined by the maximal peel-off force) of the corrugated interface can be significantly improved with the increase of substrate roughness, while the peel-off force obtained by the average method was found to decrease monotonically or increase first and then decrease with the increasing surface roughness. Spontaneous detachment happens locally at the valley or crest of each asperity when the substrate roughness is large enough, but it does not influence the enhanced trend of the maximal peel-off force. The effect of mode-mixity dependent interface adhesion energy on the peel-off force is also considered, by which the interface peeling strength is further improved. The results in this paper should be helpful for deep understanding of the interface behavior between a film and a rough substrate and be useful for the design of film/substrate interfaces with high interface quality in nano-devices.



## 1. Introduction

Adhesion and peeling mechanisms of thin-films on substrates have been attracting considerable attention because film/substrate systems are ubiquitous in many applications and other technologies, such as automobiles, micro-electromechanical systems, coating technology as well as biological adhesion (Kim et al., 1989; Peng and Chen, 2011, 2012; Peng et al., 2010; Pesika et al., 2007; Sauer, 2011; Thouless and Jensen, 1992; Tian et al., 2006). The interface adhesion strength and adhesion energy are two important properties for materials protecting, connecting and strengthening as well as designing of high-quality interfaces (Wei and Hutchinson, 1998). Peel-test, as a classical technique, is one of the efficient method for assessing the interface mechanical properties (Spies, 1953).

The peeling behaviors of thin-films on substrates have been widely investigated experimentally and theoretically (Chen et al., 2013; Kim et al., 1989; Kinloch et al., 1994; Sauer, 2011; Thouless and Jensen, 1992; Wei and Hutchinson, 1998). One of the most widely used theoretical models for elastic thin-films is the classical Kendall's peeling theory (Kendall, 1975), which shows the peel-off force depends not only on the interface adhesion energy but also on the elastic deformation of films as well as the peeling angle. It has provided a direct measuring method to achieve the interfacial properties with the help of the peel-off force, for example, the adhesion strength and adhesion energy. Based on such a pioneer work, extensive studies including the adhesion mechanism of elastic–plastic thin-film (Kim and Kim, 1988; Kinloch et al., 1994; Wei and Hutchinson, 1998), visco-elastic thin-film (Chen et al., 2013; Loukis and Aravas, 1991), heterogeneous thin-film (Xia et al., 2012, 2013) have been carried out. Recently, the peeling model has also been applied in the field of bio-inspired study on gecko adhesion (Peng and Chen, 2012; Peng et al., 2010; Pesika et al., 2007; Sauer, 2011; Tian et al., 2006).

However, most of the works focused on thin-films adhering on smooth and flat substrates. As we know, natural surfaces, even highly polished ones, possess roughness in many different length scales. Significant influence of surface roughness on adhesion between thin-films and substrates has been found (DelRio et al., 2007; Fuller and Tabor, 1975; Persson, 2002). The pioneering study was carried out by Fuller and Tabor (1975), in which a theoretical model was established based on a Gaussian distribution assumption of surface asperity and the whole contact force was obtained using the JKR model (Johnson et al., 1971) for each individual asperity. It was found that relatively small surface roughness could

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reduce or even remove adhesion. Later, an average method by introducing an effective adhesion energy $\Delta\gamma_{eff}$ was proposed by Persson (2002), Persson and Gorb (2003), Persson and Tosatti (2001) and Palasantzas and De Hosson (2003a,b) with $\Delta\gamma_{eff}A_0 = \Delta\gamma A - U_{el}$, where $A_0$ is defined as a nominal contact area, $A$ the true atomic contact area, $U_{el}$ the elastic bending energy and $\Delta\gamma$ the adhesion energy of a smooth and flat surface. It was shown that whether the surface roughness increases the adhesion force depends on the competition between the increasing adhesion energy $\Delta\gamma(A - A_0)$ and the bending elastic energy $U_{el}$ stored in films. Inspired by gecko adhesion on rough surface, the present authors studied a model of nano-thin films with finite length in adhesive contact with a sinusoidal surface and the results consist well with the experimental findings (Peng and Chen, 2011). From above, one can see that the average method actually equalizes a rough surface to a flat one by adopting the effective adhesion energy $\Delta\gamma_{eff}$. Although the average method provides valuable insights on the adhesion of thin-films on rough surfaces, detailed peeling process is neglected. Recently, numerical calculations have been carried out to simulate the peeling behaviors of thin-films on rough substrates. For example, molecular dynamics simulation was used to study the peeling process of a graphene sheet on a corrugated surface (Chen and Chen, 2013), in which the peeling force varies with surface roughness during the peeling process and the maximum of the peeling force is much larger than the average one. Finite element calculation was carried out to simulate the peeling behavior of thin-films bonded on substrates of different surface morphologies, including a flat surface, a sinusoidal one and a wavy surface with two-level sinusoidal characteristics (Zhao et al., 2013), where the interface strength (maximum of the peeling force) can be significantly improved by the substrate roughness, especially in the hierarchical case. Another noticeable field related to thin-films on corrugated substrates is the stretchable electronics (Feng et al., 2007; Jiang et al., 2007; Khang et al., 2008; Meitl et al., 2006; Wu et al., 2011). When a thin-film is deposited onto a pre-strained elastomeric substrate or compress a structure that consist of a thin-film on a complaint substrate, this can create, through nonlinear buckling process, well-defined sinusoidal distributions of surface topography with the thin-film completely adhering on the substrate (Jiang et al., 2007; Khang et al., 2008). Most of the recent experimental and theoretical researches have focused on understanding and controlling thin-film buckling to form a corrugated interface (Bowden et al., 1998; Chung et al., 2011; Hendricks et al., 2010; Jiang et al., 2007). Few studies focus on the adhesion behaviors between the buckling thin-film and substrate. Chan et al. (2008) and Lin et al. (2008) respectively measured the adhesion force between a corrugated compliant substrate and a glass probe, but opposite results are derived. Therefore, systematically theoretical analysis of the detailed peeling process for such an interface is still lacking.

In this paper, a theoretical model of a thin-film in adhesive contact with a sinusoidal rough surface is established and the effect of substrate roughness on the peeling behavior is considered directly with different peeling angles. Influence of the mode-mixity dependent interface adhesion energy on the peel-off force is also investigated in the corrugated model. The results derived in the present paper are further compared with those predicted by the average method and those in a flat substrate case.

## 2. Theoretical model of a thin-film peeling from a corrugated substrate

Considering an elastic thin-film peeled quasi-statically from a rough substrate with sinusoidal surface morphology as shown in Fig. 1. The film adheres perfectly on the rough substrate with a length $l$ and the length $L - l$ of the film is peeled-off at a peeling angle $\theta_F$ under a peeling force $F$ acted at the left end of the film. The length of the thin-film $L$ is assumed to be long enough so that the tangential angle at the left end of the film is always equal to the peeling angle, i.e., $\theta_L = \theta_F$. The tangential angle of each point on the film is defined as $\theta$ with respect to the horizontal plane. $E$ and $h$ denote the Young's modulus and thickness of the thin-film, respectively. Without loss of generality (Chen and Chen, 2013; Liu et al., 2007; Peng and Chen, 2011; Zhao et al., 2013), the surface roughness is assumed to abide by a sinusoidal function $y = a - a\cos(kx)$, where $a$ is the amplitude of the roughness, $k = 2\pi/\lambda$ the wave number and $\lambda$ the wavelength.

The potential energy of the film/substrate system at the state shown in Fig. 1 can be expressed as,

$$E = \int_0^l \frac{D}{2}\theta'^2 ds + \int_l^L \frac{D}{2}\theta'^2 ds + \int_l^L \frac{1}{2}E\varepsilon^2 h ds - \vec{F}\cdot\vec{u}_F - \int_l^L F\varepsilon ds - \int_0^l \Delta\gamma ds \quad (1)$$

where the first and second terms on the right hand side of Eq. (1) are the bending elastic energy, and $D$ is the bending stiffness of the film, $s$ is the arc-length of the film from the origin $o$. The third term on the right hand side is the tension strain energy, where the elastic strain of the film is $\varepsilon = F\cos(\theta - \theta_F)/(Eh)$. The fourth and fifth terms are the potential of the external applied force $\vec{F}$, and the last term is the interfacial adhesion energy. The corresponding displacement $\vec{u}_F$ of the loading point can be given as (Xia et al., 2013),

$$\vec{u}_F = \int_0^L \begin{pmatrix} \cos\theta - \cos\theta_F \\ \sin\theta - \sin\theta_F \end{pmatrix} ds \quad (2)$$

which is measured relative to a reference position at

$$\begin{pmatrix} L\cos\theta_F \\ L\sin\theta_F \end{pmatrix} \quad (3)$$

The elastic bending energy of the film in the perfectly bonding region $(0, l)$ can be obtained explicitly as,

$$U(l) = \int_0^l \frac{D}{2}\theta'^2 ds = \int_0^{x(l)} \frac{D}{2}\left(\frac{\partial^2 y}{\partial x^2}\right)^2 dx = \frac{Eh^3}{24}\int_0^{x(l)} a^2k^4\cos^2(kx)dx = \frac{Eh^3}{48}a^2k^4\left\{x(l) + \frac{1}{2k}\sin[2kx(l)]\right\} \quad (4)$$

where the bonding length $l$ is a variable with $l = \int_0^{x(l)}\sqrt{1 + a^2k^2\sin^2(kx)}dx$. Substituting Eqs. (2) and (4) into Eq. (1) yields,

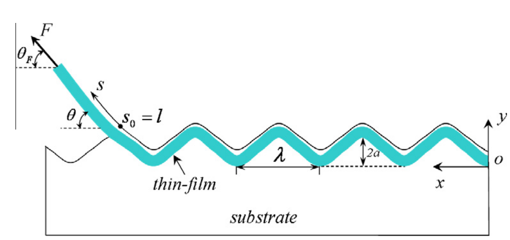


**Fig. 1.** Schematic of an elastic thin-film peeled from a sinusoidal rough substrate. The segment $(0, l)$ of the film adheres perfectly on the rough substrate, and the part $(l, L)$ is peeled-off under a peeling force $F$ at a peeling angle $\theta_F$. $\theta$ is the tangential angle of each point on the film with respect to a flat referred surface, $\lambda$ is the wavelength and $a$ is the amplitude of the roughness.