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ADHESIVE MECHANISMS OF A BIO-INSPIRED NANO-FILM

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ABSTRACT

Inspired by geckos' spatulae, the adhesive behavior of a finite nano-film is investigated theoretically and numerically in this paper, considering the effects of adhesive length as well as surface roughness. It is found that (1) an effective adhesive length controls the peeling-off force, beyond which the peeling-off force will keep a constant for a determined peeling angle; (2) An intermediate surface roughness exists, at which the normal adhesion force between a finite nano-film and the rough surface achieves the weakest. All the results are qualitatively consistent with the experimental observations, which may be helpful for understanding geckos' micro-adhesion mechanisms.

Key Words: gecko; spatula; finite nano-film; adhesive length; surface roughness

INTRODUCTION

Understanding the adhesion mechanisms of biological systems may not only provides insights into the biological attachment systems but also yield general principles employed in nature as inspiration and guidance for development of biomimetic adhesive devices. Several creatures including insects, spiders and geckos have unique abilities to climb and detach from rough ceilings and vertical walls using their attachment systems. Due to the largest weight, gecko has attracted many scientists' interests. Experiments have found that one toe of geckos includes several lamellas which contain millions of setae. Each seta is about 30 - 130 μm long, 4.2μm in diameter, and it further branches into hundreds of spatula pads through several stalks. Each pad is about 200nm in length and width, and 5nm in thickness, which looks like a nano-film with finite scale [1]. The special climbing ability of geckos has been found experimentally to be due to the van der Waals forces [2] between substrates and the hierarchical adhesive system. What is the microscopic reversible mechanism adopted by geckos' spatulae? Recently, Huber el al. [3] found that the adhesion force of a gecko spatula does not increase or decrease monotonically with surface roughness, but is strongly reduced at an intermediate substarte roughness ranging from 100nm to 300nm. How does the surface roughness influence the adhesion of a so small spatula? All these questions will be investigated in this paper using adhesive models of nano-films with a finite length scale, though many

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researchers have tried to give the answers using the classical Kendall's model, in which the length of the film is assumed to be infinite.

THE EFFECT OF FINITE ADHESIVE LENGTH

A peeling model, as shown in Fig.1, was proposed to analyze the peeling behaviors of a bio-mimetic nano-film using finite element method (FEM) [4]. The influence of the nano-film's adhesion length on the peeling force is mainly considered.

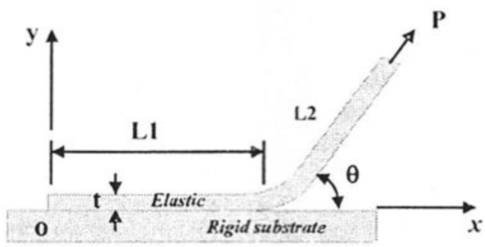


Figure 1. Peeling model of a finite nano-film in adhesive contact with a substrate.

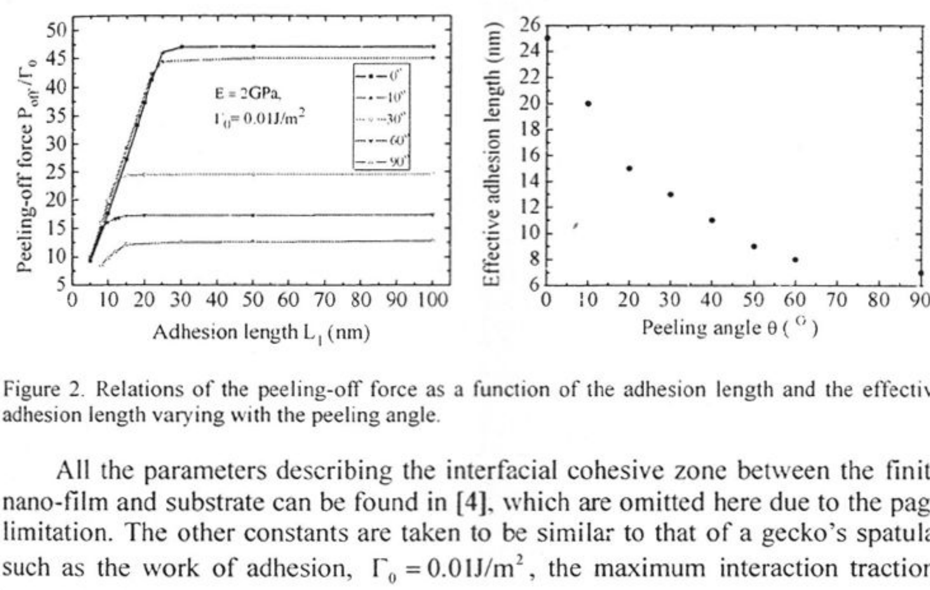


Figure 2. Relations of the peeling-off force as a function of the adhesion length and the effective adhesion length varying with the peeling angle.

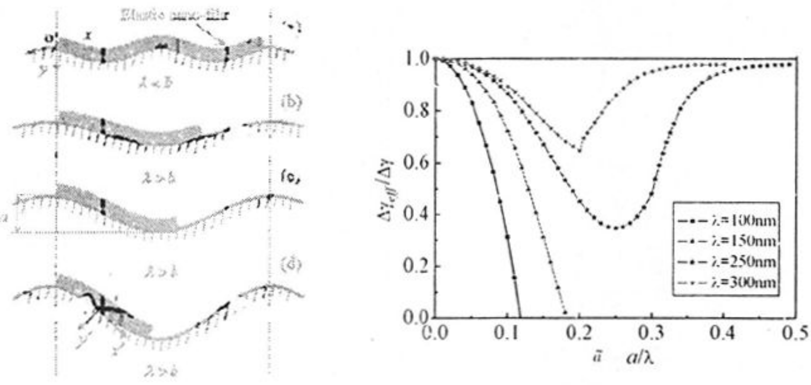
All the parameters describing the interfacial cohesive zone between the finite nano-film and substrate can be found in [4], which are omitted here due to the page limitation. The other constants are taken to be similar to that of a gecko's spatula, such as the work of adhesion, $\Gamma_0 = 0.01\text{J/m}^2$, the maximum interaction traction, $\sigma_0 = 20\text{MPa}$, the maximum separation distance in the normal and tangential direction, $\delta_n^c = \delta_t^c = 0.5\text{nm}$, and the Young's modulus of nano-film, $E = 2\text{GPa}$.

For a nano-film with length 50nm, Fig. 2 clearly indicates that the peeling-off force varies with the adhesion length of the nano-film. When the adhesion length is small, the peeling-off force increases with an increasing adhesion length. A critical adhesion length (effective adhesion length) exists, beyond which the peeling-off force keeps a constant for a determined peeling angle. Furthermore, the critical adhesion length as well as the peeling-off force decreases with an increasing peeling angle.

Even the longest critical length is much smaller than the real one of a gecko's spatula, 200nm. Also, the critical size in the present peeling model is much smaller than the one in the tension model [5]. It can be inferred that the whole length of geckos' spatula is not designed to achieve flaw tolerant adhesion under peeling behavior. Why do geckos overbuild the length of a spatula pad? It is a known fact that surfaces in nature can not be perfectly smooth. The area of intimate adhesion will be reduced due to the surface roughness, which will decrease the adhesion force.

THE EFFECT OF SUBSTRATE SURFACE ROUGHNESS

In order to explain an interesting observation reported by Huber et al. [3] that the adhesion force of a spatula is strongly reduced at an intermediate roughness, a theoretical model of an elastic nano-film in adhesive contact with a rough surface is established as shown in Fig. 3(a).



(a) (b)

Figure 3. (a) Schematic of a finite nano-film in adhesive contact with a rough surface; (b) The effective interfacial energy as a function of the substrate surface roughness.

The nano-film has a finite length scale similar to a gecko's spatula. The surface roughness is represented by a simple sinusoidal profile $w = y = a - a\cos(kx)$, where a is the amplitude of the substrate surface roughness, $k = 2\pi/\lambda$ the wave number and λ the wavelength. Sinusoidal profile has been often used to describe the surface roughness in literatures without losing problem's essence. Due to the influence of bending behavior of the nano-film on a rough surface, the effective interfacial energy $\Delta\gamma_{eff}$ can be written as

$$\Delta\gamma_{\rm eff} b_0 = \Delta\gamma b - U_{\rm el} \quad (1)$$

where $\Delta\gamma = \gamma_1 + \gamma_2 - \gamma_{12}$ is the change of the interfacial energy (per unit area) when perfect flat surfaces are brought into contact. $U_{\rm el}$ is only the bending energy necessary to make atomic contact at the interface, b is the true atomic contact area and b_0 the nominal contact area between surfaces.

Figure 3(b) indicates the effective interfacial energy normalized by the interfacial energy of a flat interface as a function of the substrate roughness a/λ, for a set of values of $b = 200\text{nm}$, $h = 5\text{nm}$, E=2GPa, $\Delta\gamma = 0.01\text{J/m}^2$ and different wavelengths. One can see that when the length b of the nano-film is larger than the wavelength, the effective interfacial energy decreases monotonically with increasing surface roughness. While the effective interfacial energy decreases first and then increases if the length of the nano-film is smaller than the wavelength. Comparing to the experimental measurement [3] on a gecko's spatula, we find that the present results agree well with the experimental observation qualitatively that the adhesion force of a gecko's spatula is strongly reduced at an intermediate roughness. When the surface roughness is small, the nominal contact area is almost equal to the real contact area, which results in less elastic energy stored in the film. Similar explanation should also be true for the case of a surface with large roughness. For an intermediate roughness, more elastic energy stored in the bending film leads to a reduced effective interfacial one, and thus a reduced adhesion force.

CONCLUSION

A finite nano-film is used to simulate gecko's spatula. Adhesive contact models are established considering the effect of adhesive length and substrate surface roughness. The results show that there is a critical adhesive length, beyond which the peeling-off force achieves maximum and keeps a constant for a determined peeling angle; As for the effect of the substrate surface roughness, an intermediate roughness similar to the experimental observations is found, at which the adhesive force of the contact interface will be strongly reduced. The findings in this paper should be useful for the designs of advanced adhesives and reversible adhesive devices.

ACKNOWLEDGEMENTS

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