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Experiments of the adhesion behavior between an elastic beam and a substrate

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ABSTRACT

Adhesion between the lower surface of an elastic beam and the flat surface of a substrate during a loading–unloading cycle is experimentally investigated. In the presence of adhesion, it has been theoretically explained that the force curve for the loading and the unloading coincides with each other because reversible thermodynamic work of adhesion, which is the work to separate a unit area of the adhered surfaces, is considered. In the experiment, however, the work of adhesion was apparently different between the approaching (loading) and the receding (unloading), and the force curves did not coincide with each other. Therefore, the theory is modified considering the difference of the apparent work of adhesion between them. Maximum tensile force is theoretically obtained as a function of the displacement at the transition point from approaching to receding.

1. Introduction

To determine a surface energy of mica, Obreimoff carried out an interesting splitting test and theoretically discussed using simple beam theory [1,2]. With the development of micro electro mechanical systems (MEMS) technology, micro-cantilever beam has been used to estimate the work of adhesion of microstructures in the same manner as Obreimoff's experiment [3]. Another contact model of a cantilever beam, which considers attachment to and detachment from a substrate, has been introduced to discuss the adhesion force of hair structure materials [4], the idea of which comes from gecko's foot hair.

Gecko utilizes adhesion in order to climb walls and move on ceilings easily, quickly, and repeatedly. Mechanism of gecko adhesion has the potential to be used in re-adhesive and strong adhesive materials, which can be applied for adhesive grippers, re-adhesive tapes, and wall climbing robots, etc [5–10]. Gecko has hierarchical micro-/nano-hair structure, called seta and spatula, on its foot to adhere to surfaces. By the development of MEMS, the accurate pull-off force of a gecko's single seta was measured [11] and the mechanisms of the seta have been theoretically discussed [12,13]. Also the effect of the pulling orientation of a single seta on the pull-off force has been justified using finite elements modeling (FEM) [14].

When focusing on the tip of each seta, a myriad of spatulas exist. Tape peeling theory, such as Kendall's thin film peeling model [15], has been popularly applied as analytical and numerical models to discuss the pull-off force of each spatula [16–18]. The elongation, i.e. the stretching, of a film has been considered in these models but the bending has been neglected. Although, Kendall model is in good agreement with the experiments of thin film peeling [15], it has been suggested that the effect of the bending stiffness on the pull-off force cannot be negligible in the case of the adhesion of the gecko's spatula [19]. As for an analytical model considering the bending, we have proposed an adhesion theory of an elastic beam [4]. In this theory, the elastic energy due to the bending has been considered and the elastic energy due to the elongation has been assumed as negligible. The force at equilibrium has been obtained as a function of the displacement.

In this paper, experiments were carried out to investigate the adhesion between the elastic beam and a substrate and discussed based on the adhesion theory of the elastic beam [4]. The hysteresis of the force change in the presence of the adhesion was observed between the approaching and the receding, where it is a significant deviation from the theory. The difference of the work of adhesion during the approaching and the receding segments is a well-known phenomenon of elastomer interface [20–24]. Therefore, the theory has been modified taking account of the hysteresis.

2. Summary of relevant theoretical results

In the earlier article [4], adhesion contact between an elastic beam and a rigid substrate during a loading–unloading cycle was

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considered as shown in Fig. 1. The elastic beam with the length L, the width W, and the thickness H approaches the substrate at a constant angle θ. First, only the edge of the beam contacts to the substrate. Then the lower surface of the elastic beam adheres to it. Finally, the elastic beam recedes from it until the separation occurs. The work of adhesion, $\Delta\gamma$, is the energy required to separate a unit area of adhered surfaces. It is given as $\Delta\gamma=\gamma_1+\gamma_2-\gamma_{12}$, where γ_1 and γ_2 are the surface energies of each surface and γ_{12} is the energy of the interface. The displacement at the fixed end of the elastic beam, d, is negative for the upward direction. Thus, the distance from the fixed end to the substrate is $-d$. The linear beam theory has been used to discuss the deformation of the elastic beam, and so the angle $\theta \ll 1$ [rad], an aspect ratio $H/L \ll 1$, and small deflections have been assumed in the theory [4]. Also, friction between the elastic beam and the substrate has been neglected. In reality, the friction would not be zero and the normal force may distribute in the contact area as well as the elastic beam in this area may be deformed. But under friction free condition assumed in the theory, tangential contact force is zero and no deformation occurs in the contact area. Thus, a normal force can be substituted for a concentrated load at a peeling front as well as the elastic beam is considered strait-lined.

The relation between the force, f, and the displacement, d, was determined as

$$\tilde{f}=\frac{\tilde{d}+\theta}{4} \tag{2.1}$$

when only the edge of the elastic beam contacts to the substrate, and

$$\tilde{f}=\frac{8\Gamma^3\tilde{d}}{(\sqrt{\theta^2-12\Gamma\tilde{d}}-\theta)^3}+\frac{2\Gamma^2\theta}{(\sqrt{\theta^2-12\Gamma\tilde{d}}-\theta)^2} \tag{2.2}$$

when it adheres to it, where f, d, and $\Delta\gamma$ are normalized as $\tilde{f}=f/(12EI/L^2)$, $\tilde{d}=d/L$, and $\Gamma=\sqrt{6\Delta\gamma L^2/EH^3}$, respectively [4]. Because $\theta \ll 1$ is assumed, the trigonometric functions are approximated as $\sin\theta\approx\theta$, $\cos\theta\approx 1$, $\tan\theta\approx\theta$. Eq. (2.2) is derived from two equations. One is the relation among the force, the displacement, and the length of non-adhesion area, which can be obtained from the linear beam theory;

$$\tilde{f}=\frac{\tilde{d}}{\tilde{l}^3}+\frac{\theta}{2\tilde{l}^2}, \tag{2.3}$$

where l is the length of non-adhesion area and is normalized as $\tilde{l}=l/L$. The other is equilibrium length of non-adhesion area, which can be obtained from the minimal total energy in the same manner as the Johnson–Kendall–Roberts (JKR) theory [25];

$$\tilde{l}=\frac{\sqrt{\theta^2-12\Gamma\tilde{d}}-\theta}{2\Gamma}. \tag{2.4}$$

The relation between the normalized force and the normalized displacement is shown in Fig. 2 in the case of $\Gamma/\theta=3$.

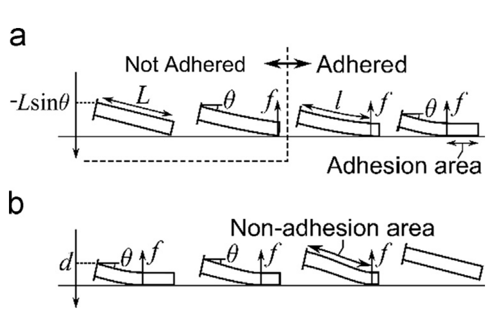

Fig. 1. Schematic picture of (a) approaching (loading) and (b) receding (unloading) processes.

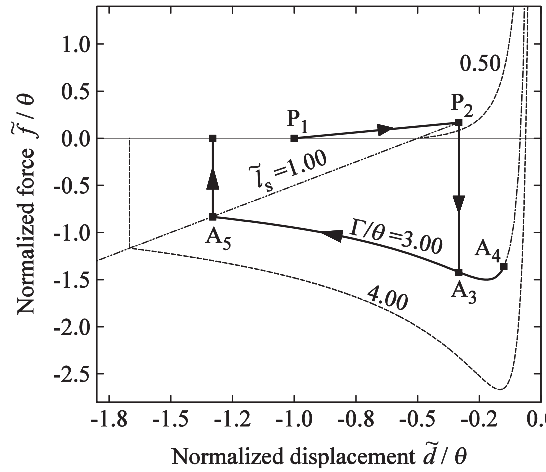

Fig. 2. The relation between the normalized force and the normalized displacement when considering the reversible thermodynamic work of adhesion.

On approaching, the elastic beam starts contacting at P_1 and the force linearly increases to P_2 without adhesion. At P_2, the lower surface of the elastic beam starts adhering to the substrate and the contact area increases to equilibrium. Therefore, it moves from P_2 to A_3. This phase of the process is irreversible. With more approach, the force changes from A_3 to A_4 following the equilibrium force curve, i.e. the curve of Eq. (2.2). During the receding, the force changes from A_4 to A_5 following the equilibrium curve until the contact area becomes zero at A_5, which is the separation point.

3. Experimental preparation

3.1. Experimental equipment

The experimental setup is schematically illustrated in Fig. 3a. The inclined elastic beam was moved upward and downward using a motorized linear stage (SURUGA SEIKI K101-20 MS). The force was measured using an electronic scale of load cell (SARTORIUS, TE153S), which has a resolution of 0.1 mN; since the maximum applied force was of the order 0.01 to 0.1 N. A glass plate was used as a substrate. In the theory [4], the friction between the elastic beam and the substrate is considered zero. However, it would not be negligible in the experiments. Therefore, steel spheres as shown in Fig. 3b were put under the substrate to decrease the friction. In the experiments, gel (TANAC Co., Ltd. CRG-T1502, Fig. 3c) and silicone rubber (Kyowa Industries, Inc. SI-10, Fig. 3d) were used as elastic beams. Elastic moduli were measured using tensile test machine (SHIMADZU EZ-S) as 1.4×10^5 Pa (the gel) and 3.3×10^5 Pa (the silicone rubber), where they were obtained using the least-squares method with the data in the range of the extension from 100 to 102% (see Fig. 4). The size of the elastic beams was determined as $L=0.015$ m, $W=0.010$ m, and $H=0.002$ m. The angle was set to $\theta=13°$. The room temperature was set to 23 °C.

3.2. Experimental procedure

First, the elastic beam was moved to the initial position, i.e. point P_1. Then, the stage was moved downward with a constant speed. After it stopped approaching, the process was suspended until the measurements of the force became stable. The dwell time was about 20–50 min, where it was depended on how fast the contact became stable. Finally, it was moved upward with the constant speed until the separation occurred. The speed was the