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The effect of substrate roughness on tape peeling

Alaettin Ozer *

Department of Mechanical Engineering, Bozok University, Yozgat, Turkey

A R T I C L E I N F O

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A B S T R A C T

This study explores the effect of substrate roughness on peel force for tape peeling. In order to assess the effect of substrate roughness on peel force for tape peeling, a new approach based on a peel zone model was established, including rough surfaces as substrate. This approach is applicable for rough surfaces and accomplished by using contact and adhesion theories. Experimental values were used to calculate peel forces for surfaces with a different level of roughness. The results indicated that the peel force for a rough substrate for the same peel angle is smaller than the one for a flat substrate and that increasing root mean square roughness decreases the peel force. This study is a different approach to prove conclusions that may be proved with experiments by using real animals such as Gecko, lizard, etc. Also, this theory is useful for explaining how some animals such as Gecko peels-off from rough surfaces more easily and quickly than from smooth ones.

1. Introduction

Surface roughness is an important phenomenon in interface science that affects many physical properties such as friction, wear and adhesion. By applying the energy theory of fracture to an elastic film peeling from a rigid substrate, an equation for the peel force including a term depending on the elastic modulus and thickness of the film material was obtained by Lindley [1] and Kendall [2]. Kendall showed that the force required to peel an elastic film from a rigid substrate depends on both adhesive surface energy and the elastic deformation term [2].

A study about the adhesion between elastic solids describing the effect of roughness in reducing the adhesion was published by Fuller and Tabor [3]. They determined the strength of adhesion by using a smooth rubber sphere in contact with a rough flat surface and found that relatively small surface roughnesses are enough to reduce the adhesion to low values.

Pesika et al. [4] developed a tape-peeling model based on the geometry of the peel zone (PZ). Their model predicts the peeling behavior of adhesive tapes from a glass substrate at peel angles at 90° or less without considering substrate roughness. Pesika's PZ model adds an angle-dependent multiplier to the Kendall equation [8]. A more widely applicable PZ model including large deformation and pre-strain of the backing layer was presented by Molinari and Ravichandran [5].

Persson [6] developed a theory of adhesion between an elastic solid and a hard randomly rough substrate. His adhesion theory posits that partial contact may occur between the solids on all length scales.

Persson and Gorb [7] investigated the influence of surface roughness on the adhesion of elastic plates using self-affine fractals by examining plate-substrate pull-off force as a function of the surface roughness.

Yu et al. [8] measured adhesion and friction forces between microfabricated tilted PDMS flaps and rough SiO_2 surfaces created by plasma etching using modified surface forces apparatus. They found that increasing the surface roughness decreases the adhesion forces.

However, a PZ model including peel angle change and rough surface substrate has not yet been presented. In this study, an extended PZ model including a rough, self-affine substrate was developed. Rough surface includes self-affine spherical asperities which have the same radius.

2. Theoretical background

2.1. Peeling

One of the most commonly used peeling models, the Kendall peel model [9] uses energy balance to show that the force required to peel an elastic film from a rigid substrate depends on the adhesive surface energy. The elastic deformation term is defined as:

* Tel.: +90 354 2421001; fax: +90 354 2421005.
E-mail address: alaettin.ozer@bozok.edu.tr

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$$\left(\frac{F}{b}\right)^2 \frac{1}{2dE} + \left(\frac{F}{b}\right)(1 - \cos\theta) - \gamma = 0 \tag{1}$$

where F is the peeling force, b is the width of the tape, d is the thickness of the tape, E is the elastic modulus of the tape, θ is the peeling angle, and γ is the adhesive energy required to fracture unit area of the interface.

For higher peel angle values, F/b peel strength is given by the equation

$$\frac{F}{b} = \frac{\gamma}{(1 - \cos\theta)} \tag{2}$$

However, in cases of decreased peel angle, the peel strength is approximated to

$$\frac{F}{b} = (2Ed\gamma)^{1/2} \tag{3}$$

A tape peeling model based on the geometry of the PZ was derived by Pesika et al. [4] to predict the peeling behavior of adhesive tapes at peel angles less than or equal to 90°. They found that the peel strength of an adhesive tape is approximately proportional to the length of the PZ. That is

$$\frac{F_\perp}{b} = \gamma \frac{S}{S_0} \tag{4}$$

where $F_\perp$ is the perpendicular component of the peel force, γ is the adhesion energy, S is the length of the PZ at a specific peel angle, and S_0 is the length of the PZ at 90°. The total peel force per unit width of tape F/b as function of the peel angle is given as:

$$\frac{F}{b} = \frac{F_\perp}{b \sin\theta} \tag{5}$$

The PZ model adds an angle-dependent multiplier to the Kendall equation that takes into account the geometrical changes within the PZ as:

$$\frac{F(\theta, \varphi_0)}{b} = \gamma\left[\frac{\theta}{\varphi_0}\right]\left[\frac{1 - \cos\varphi_0}{1 - \cos\theta}\right]\left[\frac{1}{\sin\theta}\right] \tag{6}$$

2.2. Effect of substrate roughness on peeling

In this study, we assume that the curvature of the tape backing is approximately circular in all the important local regions of the PZ (stationary point to leading edge), and the length of the PZ on the surface is equal to the arc length of the tape backing. First assumption was given in this study is in order to assess that the length of the peel zone on the rough surface is equal to the length of the tape backing. The second one was given to assess also that the stretch of tape is not significant. We also assume that the tape is composed of a backing material which has a large stretch modulus.

For a hemispherical asperity and a purely elastic case, the diameter d of the contact area with a flat substrate without adhesion is given by Hertz [11]

$$d^3 = \frac{12R_h F}{E^*} \tag{7}$$

where R_h is the radius of the hemisphere and E^* is the average plain strain modulus given by

$$\frac{1}{E^*} = \frac{1 - \vartheta_1^2}{\pi E_1} + \frac{1 - \vartheta_2^2}{\pi E_2} \tag{8}$$

When Hertz theory is extended to include adhesion, the diameter of the contact area according to Johnson–Kendall–Roberts (JKR) [10] becomes

$$d^3 = \frac{12R_h}{E^*}\left\{F + 3\pi R_h\gamma + \left[6\pi R_h\gamma F + (3\pi R_h\gamma)^2\right]^{1/2}\right\} \tag{9}$$

where γ is the adhesion energy per area. JKR theory is more generally used for biological and artificial attachments systems. This theory was used in this study in order to make comparisons with other studies.

At zero applied load the radius of contact becomes

$$a^3 = \frac{9\pi\gamma R_h^2}{E^*} \tag{10}$$

For self similar scaling, consider n contacts of diameter R_h. The areal density of contacts can be expressed as [12]:

$$N_A = \frac{n}{D^2} = \frac{1}{s^2} \tag{11}$$

where n is the number of contacting asperities, s is the contact size and D is the size parameter. The diameter of contact under zero applied load for an asperity becomes $d=2a$ (Fig.1). Then, total length of contact for a peel angle for an asperity on a rough substrate is given as:

$$S = \sum d \tag{12}$$

and

$$S_0 = \sum d_0 \tag{13}$$

where S_0 is the length of the PZ and d_0 is the total length of the contact diameter length and a_0 is the radius of contact length at 90° peel angle for an asperity on a rough substrate. Finally, the peel force strength is obtained for self-affine rough surfaces by moving S and S_0 to Eq. (4).

3. Results and discussion

This paper is concerned with the peeling of an elastic tape from a hard, self-similar rough surface. In order to demonstrate the effect of substrate roughness on peel force for tape peeling, a new approach was established based on Pesika's [4] PZ model by extending it to include rough surface as substrate. This approach is especially applicable for rough surfaces and accomplished by the application of contact and adhesion theories. Due to the difficulty involved in making experiments and obtaining data to confirm

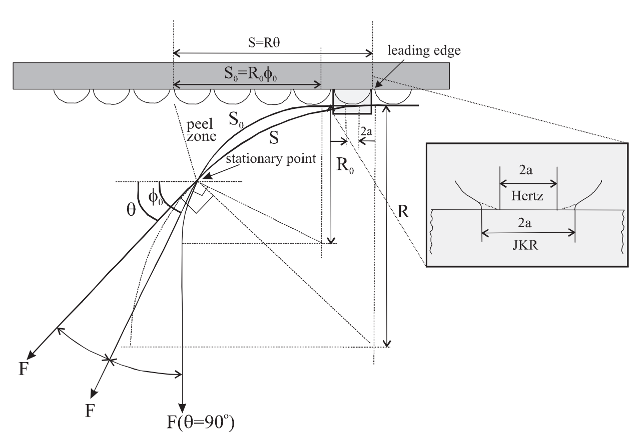

Fig. 1. Contact of rough substrate for tape in peel zone model (Partially adapted from Ref. [4]).