THE EFFECT OF PEELING RATE AND PEELING ANGLE ON THE PEELING STRENGTH

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THE EFFECT OF PEELING RATE AND PEELING ANGLE ON THE PEELING

STRENGTH

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Thesis

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ABSTRACT

Peeling force is an important property to characterize adhesion of materials. This force is defined as the force required to remove the adhesive film from a substrate. According to Dr. Alan N. Gent and Dr. K. Kendall's research, this debonding process is an energy driven process, and three terms contribute to the energy change: a surface energy term, a potential energy term, and an elastic energy term. Energy conservation analysis shows that peeling strength, peeling force per width, of the film is dependent on the peeling rates, peeling angle and elastic modulus. To continue their research, the influence of these variables on peeling force was studied. Polyisoprene was used as the testing material, and an effective instrument was set up to test peeling force. Peeling forces at different peeling rates and angles were tested separately. The relationship of peeling strength with peeling rates, peeling angles, and elastic modulus is discussed. The adhesive energy is calculated based on Kendall's model. Then Kendall's model is used to fits the relationship of peeling strength with peeling angles. A corrected model for rubber based on Kendall's model is proposed.

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CHAPTER I

INTRODUCTION

Adhesives are widely used materials to bond separate parts and different materials together. The history of using adhesives is so long that it is difficult to pinpoint their origin. In the present, the application of adhesives is not restricted to everyday life. They can be found in tissue engineering, precise instrument, and aerospace manufacture. In most cases, the performance of adhesive is of vital importance. The performance of adhesives includes different aspects, which can be characterized by different properties. As one of these characterizations, peeling strength is related to viscoelasticity and rheology of the material, and can give us both information on stickiness and removability.¹⁻⁵ In 1975, Dr. Kevin Kendall published a paper on the elastic term of thin-film peeling.⁶ In this paper, he proposed the mechanism of elastic adhesive layers peeling off from a rigid substrate. This paper provides further understanding of the how peeling rates and peeling angle influence peeling strength. My research will study the relationship of peeling force with peeling rates, peeling angles, and elastic modulus based on his paper.

CHAPTER II

BACKGROUND

2.1 Adhesives and Adhesion Mechanism

Adhesives are used to bond separate materials or small parts together. They are widely used in our daily life, industrial manufacturing, and scientific research. The bonding process is achieved by the joint work of cohesion in the adhesive layer and adhesion between adhesive layer and substrate.² Cohesion is the interaction between molecules in the adhesive layer. Adhesion is the interaction between molecules of adhesive layer and substrate. Cohesion and adhesion are both important for a good adhesive, because the failure of the adhesive joints is caused by the weaker one of the two interactions. That is to say, both cohesion failure and adhesion failure will cause failure of the adhesive joints. In comparison, adhesion interaction takes the dominant role in the performance of adhesives.

Although the earliest application of adhesives is hard to track, researches related to the adhesion phenomenon can be dated back to the beginning of the 20th century. Scientists showed great interests in the adhesion phenomenon. Till now, scientists have proposed many mechanisms to explain the origin of adhesion phenomenon, and some of them have been experimentally proven and widely accepted, such as absorption theory, diffusion theory, mechanical theory and electrostatic theory.^{2 - 9} In the absorption theory, adhesion is caused by the molecular interaction between adhesive and substrate, such as hydrogen bonding, Van der Waals force, and covalent force. In some physical-adhered system this interaction can be characterized by contact angle. The diffusion theory is mostly used to explain the adhesion between polymer materials. The diffusion is caused by the thermodynamic motion of molecules and polymer segments at the interface. With this diffusion, the interface between the adhesive and substrate gradually disappear, and an adhesion occurs. The mechanical theory is mostly applied in the substrates with rough, porous interface. The adhesives diffuse into the holes of the substrate at the interface. After solidification or gelation, the substrate and adhesives interlocks. In electrostatic theory, adhesion is attributed to the electrostatic force, which is caused by the form of double electrical layers.

2.2 Adhesion Characterization

The performance of adhesives is affected by many factors. These factors can be classified into three categories: the intrinsic property of adhesives, processing method, and external conditions.^{1, 2} The intrinsic properties of adhesives have a large effect on the performance of the adhesive, such as the chemical compound, molecular structure, crosslinking, crystallinity, viscoelasticity, strength, and other physical properties. A good adhesive should have a balance of these properties. Besides, adhesion is the interaction between adhesive and substrate. For a specific adhesive, its adhesion varies with different substrate. So the compatibility of adhesive and substrate should be

considered in the selection of adhesives. Another important factor is the processing method. A typical process to apply adhesive to substrate includes surface processing of the substrate, coating adhesives, bonding, and solidification or gelation of the adhesive. All the procedures should be well controlled to acquire optimized adhesion strength. Besides, external conditions, such as humidity and temperature, also should not be neglected because of their influence on the performance of adhesives.

There are many methods to characterize whether an adhesive is a good one or a bad one. Three most widely used characterizations are tensile strength, shear strength, and peeling force.² Tensile strength is the maximum strength the adhesive joints can bear per area at vertical direction of the interface before failure. Tensile stress larger than tensile strength will lead to either cohesion or adhesion failure. Tensile testing is one of the most traditional tests in adhesive characterization. Tensile strength testing instrument for adhesives is different from the traditional tensile strength testing instrument. ASTM D2095 clevis grips adhesive tensile tester is one of the most widely used and precise instrument to obtain tensile strength for adhesives.^{2, 9} In this instrument, samples are prepared into bars and rods. Two movable fixtures clip two ends of the sample. This method can ensure that the direction of the tensile stress and the axis of the sample are in line. Compared with the traditional instrument, this instrument is much more accurate.

Shear strength is another traditional characterization for adhesives. Shear strength is the maximum strength the adhesive joints can bear per area at parallel direction of the

interface before failure. When shear stress is larger than the shear strength, adhesive and substrate will slide over each other within the adhesive layer or at the interface.

When a tensile force is concentrated at one edge of the adhesive, the adhesive layer will peel off from substrate. This tensile force is the peeling force. In other words, peeling force is the force required to remove adhesive film from a substrate.¹ Peeling force is not a maximum load. Peeling force is the force at equilibrium state. This force is sensitive to experimental conditions, such as peeling rate and peeling angle. More detailed information will be shown in Chapter 2.3.

There are also some other important characteristics which influence adhesives, such as fatigue strength, impact strength, yield strength, durability and so on. The requirements of these properties vary in different applications. These properties all have their own specific testing methods and unique characterization criteria.²

2.3 Peeling Strength Analysis in Kendall's Model⁶

In 1976, Dr. K. Kendall published a paper, *thin-film peeling, the elastic term.*⁶ This paper established a model in which an elastic thin film peels off from a rigid substrate and illustrates how elastic modulus and other variables influence the peeling strength in this model. Peeling an adhesive layer from substrate is an energy driven process. Therefore this debonding process can be analyzed by the energy conservation law. In this research, we assume a peeling system, shown in Figure 1, as the example. An elastic adhesive thin layer adheres to a rigid substrate, such as a glass plate. This adhesive layer peels off from the substrate. The adhesive layer's thickness is d, width is

b, and elastic modulus is G. The applied peeling force is F, and peeling angle is $\boldsymbol{\theta}$. We assume that in this peeling off process, the peeling edge moves from A to B, with a movement of *l*.



Figure 1 Peeling system illustration. The adhesive layer has a thickness of d, width of b, and elastic modulus of G.

According to Dr. K. Kendall's research, in this peeling off process, the energy change can be classified into three categories. The first one is attributed to the surface energy change. This energy change is equal to the energy required to create new surfaces. For the convenience of analysis, here a new variable, adhesive energy, R, is defined as the energy required to create new surfaces per area. So the surface energy term can be expressed in Equation (1):

$$\Delta E_1 = -R(bl) \ (1)$$

It should be noted that R is dependent on peeling rate.

The second term is a potential energy change. This energy change is attributed to the work done by the movement of peeling force. Simply, we assume that the adhesive film is not extensible. This allows the potential energy change to be equal to the peeling force multiplied by its movement at the direction of the peeling force. So the potential energy change can be expressed in Equation (2):

$$\Delta E_2 = F(1 - \cos\theta)l \quad (2)$$

However, in the peeling off system the adhesive layer is actually elastic. It will gradually extend in the peeling off process. Therefore there should be another energy change component which is attributed to the elastic term. For the convenience of calculation, we assume that the region AB extends with a length of Δl in the direction of the peeling force. The elastic energy change can be divided into two parts. The first part is attributed to the work done by the peeling force in stretching region AB. Its value can be expressed in Equation (3):

$$\Delta E_{3(1)} = F \Delta l \quad (3)$$

When region AB is stretched and extended, energy will be stored. Here we regard the extensible layer as a spring. According to Hooke's Law, the stored energy caused by the extended region AB can be expressed in Equation (4):

$$\Delta E_{3(2)} = -\frac{1}{2}kx^2 = -\frac{1}{2}\frac{F}{\Delta l} \times \Delta l^2 = -\frac{1}{2}F\Delta l \ (4)$$

So the overall value of the elastic energy change is:

$$\Delta E_{3} = \Delta E_{3(1)} + \Delta E_{3(2)} = F \Delta l - \frac{1}{2} F \Delta l = \frac{1}{2} F \Delta l$$
(5)

Elastic modulus is the ratio of stress and strain. According to this definition, we can conclude the relationship between elastic modulus G and ΔI :

$$G = \frac{\sigma}{s} = \frac{\frac{F}{bd}}{\frac{\Delta l}{l}} (6)$$
$$\Delta l = \frac{Fl}{bdG} (7)$$

Equation (6) and Equation (7) can be combined, so the elastic energy change can be expressed in Equation (8):

$$\Delta E_3 = \frac{F^2 l}{2bdG}$$
(8)

Back to the energy conservation law, the sum of the surface energy change, potential energy change, and elastic energy change equals 0. Combining Equation(1), Equation(2), and Equation(8), we can conclude:

$$-R(bl) + F(1 - \cos\theta)l + \frac{F^2 l}{2bdG} = 0$$
(9)

After simplification, this equation can be expressed in Equation (10):

$$\left(\frac{F}{b}\right)^2 \frac{1}{2dG} + \left(\frac{F}{b}\right) (1 - \cos\theta) - R = 0 \quad (10)$$

Equation $\left(\frac{F}{b}\right)^2 \frac{1}{2dG} + \left(\frac{F}{b}\right) (1 - \cos\theta) - R = 0 \quad (10)$ can be manipulated to be a quadratic equation with a new variable $\left(\frac{F}{b}\right)$. Here we define this new variable $\left(\frac{F}{b}\right)$ as peeling strength. It characterizes peeling force per width of the adhesive layer. We can conclude that peeling strength increases as the peeling angle decreases and adhesive energy increases.

2.4 Measurement of Peeling Force

Peeling test geometry has a large influence on experiment results. The three most widely used peeling test geometries are the 180° peeling test, the 90° peeling test,

and the T peeling test.¹¹ Nowadays, several instruments can obtain peeling strength with different peeling rates at 90° , 180° , or T-peeling geometry. However, peeling tests with other peeling angles are not so easy with the traditional instruments. Specific instrument are needed to satisfy the specific peeling geometry at different angles.^{5, 10-14}

2.5 Influencing Factors of Peeling Force

Peeling strength is sensitive to intrinsic properties.¹ As a kind of characteristics of adhesion, peeling force is greatly influenced by the chemical nature of the adhesive layer, such as its chemical structure, molecular weight, crosslinking degree, and impurity percentage. Peel strength is related to the viscoelastic and rheological properties of the material, so the influence of molecular weight can be attributed to the influence of modulus. An increasing molecular weight leads to an increasing modulus. On one hand, when modulus increases, more energy is required to create new surfaces, so peeling strength increases. On the other hand, increasing modulus leads to low chain mobility and diffusion rate, which lowers peeling strength. The influence mechanism for crosslinking degree is slightly different. In general, a high degree of crosslinking causes low tack, which leads to low peeling strength; while a low degree of crosslinking causes high cohesion interaction, which lead t high peeling strength. All these properties compete to determine the adhesive's overall peeling strength.

Besides, thickness and width of the adhesive layer also have a large influence on peeling strength. Increase of the adhesive layer's thickness or width will increase the energy required for peeling, so the peeling strength increases as the adhesive layer's thickness or width increases. Besides, peeling strength is also sensitive to the flaws and defects at the interface. Bubbles and impurities will largely decrease peeling strength. In the experiments, their influence on peeling force should be minimized.

Experimental condition, such as temperature, and humidity, peeling geometry, are also factors affecting peeling strength. In experiments, the experiment conditions should keep the same for the data accuracy and preciseness.

2.6 Statement of Purpose

Peeling strength is an important property to characterize adhesion of materials. This characteristic is of great help in surface science in physical chemistry, technology, and biology. Besides, the study of peeling force is good for further understanding the adhesive mechanism of materials. Based on Kendall's analysis in thin film peeling, influence of peeling angle, peeling rates and elastic modulus to peeling strength is studied for further understandings in peeling.

CHAPTER III

EXPERIMENT

3.1 Sample Preparation

Polyisoprene, NATSYN 2200 from Goodyear Chemical, was used as the testing material. Impurities in adhesives have unneglectable influence on peeling strength. Synthetic rubber consists of little impurities, so their influence to the experiment results can be minimized.

Before the peeling tests, samples should be molded into thin long narrow pieces. There are two methods to prepare thin adhesive rubber films: hot melting and solution casting.11 In my research, hot melting is used. In the hot melting method, the polyisoprene sample was filled in a spacer plate with a thickness of 1 mm. Then the spacer plate with the polyisoprene sample was sandwiched by two pieces of Mylar films. This geometry is shown in Figure 2. The Mylar films were used to protect the adhesive polyisoprene surface from dust. The molding temperature was 200° F. The molding pressure was 3 MPa. The molding time was 3 hours. The molding condition should keep the same in all sample preparation processes.^{11-13,15} After molding, a thin adhesive polyisoprene film bonded with two protective Mylar films was formed. This

thin polyisoprene film should be cut into long narrow test pieces with the same width of 1 cm. The test pieces were stored at room temperature.



Figure 2 Polysioprene sample preparation illustration.

Before the peeling tests, one protective Mylar film was quickly peeled off. Instead, a new clean glass plate was immediately pressed against the smooth rubber surface in this side. Pressure was applied to make the glass plate and polyisoprene film perfectly adhered with each other with little bubbles. This pressure should keep the same in all experiments to avoid its influence on peeling strength. Then the other Mylar film was gently peeled off. Another 30 minutes were required before the peeling test to avoid the influence of contact time between adhesive and substrate to peeling strength.

3.2 Elastic Modulus Tests

Elastic modulus of the sample was obtained in the Instron 5567. The pressed-molded polysioprene film should initially cut into dumbbell test pieces with a necking width of 3 mm and length of 80 mm. Then the test piece's two ends were clipped by two chucks in the Instron 5567. When the instrument was operated, the two chucks moved apart with a speed of 100 mm/min. The relationship between

tensile stress and strain was recorded by a connected computer. At least three parallel experiments were required to ensure the precision of the tests.

3.3 Rubber Modification

To study the influence of elastic modulus to peeling tests, the polyisoprene sample should be modified. The polyisoprene sample with 1% dycumyl peroxide (DCP) was blended at a mixing mill for about 30 minutes. After blending, a sheet of hardened rubber was obtained.

3.4 Peeling Tests

An inclined plane with adjustable slope angle was used to test peeling force in the research. The glass plate with the polyisoprene test piece was fixed beneath the slope, with the polyisoprene test piece at the bottom. This geometry is shown in Figure 3. When the test piece peeled off from the lower edge to the higher edge, the peeling angle equaled to 90° minus slope angle, shown in Figure 3(a). When the test piece peeled off from the higher edge to the lower edge, the peeling angle equaled to 90° plus the slope angle, shown in Figure 3(b). The slope angle could be freely adjusted from 0° to 90°, so that the peeling angle could be controlled from almost 0° to 180°. A ruler was vertically fixed beside the inclined plane to provide location information of the peeling point at different times.

In the peeling test, calibrated weights were hung at one edge of the polyisoprene test piece. With the gravity of the calibrated weights, the adhesive test piece slowly peeled off from the glass plate. This peeling off procedure was videoed, so the peeling rate could be calculated.



Figure 3 Peeling test instrument geometry illustration. Figure 3(a), the test piece peeled off from the lower edge to the higher edge; Figure 3(b), the test piece peeled off from the higher edge to the lower edge.

CHAPTER IV

RESULTS AND DISCUSSION

4.1 Elastic Modulus

The complete stress – strain curve of the test pieces is attached in Appendix A. For rubber materials, strain is not linearly correlated with stress, so elastic modulus cannot be calculated by the ratio of stress and strain. In general, the deformation of rubber is characterized by extension ratio λ :

$$\lambda = \frac{l + \Delta l}{l} = 1 + \frac{\Delta l}{l} = 1 + \epsilon$$
(11)

where ϵ is the strain of the rubber.

The equation of state for rubber is written in the form of Equation (12):

$$\frac{F}{bd} = \sigma = G(\lambda - \frac{1}{\lambda^2}) \quad (12)$$

where σ is the stress applied to the rubber film, and G is the elastic modulus of rubber.

Equation (12) gives the method to calculated elastic modulus in non-linear elastic materials. In ideal case, stress σ is linearly correlated to $(\lambda - \frac{1}{\lambda^2})$, and elastic modulus equals to the slope of the $\sigma - (\lambda - \frac{1}{\lambda^2})$ curve. In peeling test, several rubber test pieces were selected randomly, and their extension ratio were measured separately. Their extension ratios range from 1.02 to 1.06. Here, data with a strain smaller than

1.2 were selected, and their $\sigma - (\lambda - \frac{1}{\lambda^2})$ curves were plotted in Figure 4. So the average elastic modulus is 0.46 MPa with a standard deviation of 0.09 MPa. Data are attached in Appendix B.



Figure 4 Stress strain curve of the unhardened test pieces.



Figure 5 Stress strain curve of the hardened test pieces.

Figure 5 shows the $\sigma - (\lambda - \frac{1}{\lambda^2})$ curve of the test pieces after modification by 1% DCP. The average elastic modulus is 0.75 MPa with a standard deviation of 0.14 MPa. The stress-strain curve shows that the polyisoprene sample hardens and elastic modulus significantly increases after 1% DCP was added.

4.2 Machine Test and Data Calculation

The peeling off procedure was recorded by a video. A video example is attached in supporting information. In the film, different time points with same intervals were selected, shown in Figure 6. Their vertical location information is directly obtained by a ruler separately. With time and location information, their rates were calculated separately. It should be noted that this rate is the vertical component rate of the peeling rate. The peeling rate is obtained after trigonometric transformation.

Peeling rates at different peeling points with the same time intervals were selected and calculated separately, and the results are shown in table 1. According to the results, we can find that these peeling rates are similar. It proves that this peeling-off procedure could be seen as a constant motion. This result is a proof that when the peeling rate is not too small, the influence of small perturbation and the weight of the peeled-off film can be neglected. The peeling force roughly equals to the gravity of the calibrated weights. The result further proved that this instrument can be used for peeling tests.



Figure 6 Selection of different time points with same time intervals. Their vertical location information is directly obtained by a ruler on the right side.

Time (s)	Location (cm)	Displacement (cm)	Velocity (cm/s)
45	4.60		
47.5	4.30	0.30	0.12
50	4.03	0.27	0.11
52.5	3.71	0.32	0.13
55	3.45	0.26	0.10
57.5	3.13	0.32	0.13

Table 1 Calculation of peeling rates at different time points

4.3 Effect of Peeling Rate on Peeling Strength

Figure 7 shows the relationship between the peeling rates and the peeling strength. In Figure 7, the unhardened test pieces with a peeling angle of 135^o is plotted in the black line with dot marks, while the unhardened test pieces with a peeling angle of 80^o is plotted in the red line with triangle marks, and the hardened test pieces with a peeling angle of 135^o is plotted in blue line with diamond marks. Data are attached in Appendix C.



Figure 7 Relationship between peeling rate and peeling strength. Peeling angle is 135° or 85° .

Increasing peeling strength leads to increasing peeling rate. Peeling rates are positively correlated to adhesive energy, as the adhesive energy required is larger when the cracking velocity increases. Compared the black curve and the red curve, we can find that increasing peeling angle leads to decreasing peeling strength. This fact supports the relationship in Equation (10) in Chapter 2.3. Compared the black curve and the blue curve, we can find that increasing elastic modulus leads to increasing peeling strength. The possible reason is that when elastic modulus increases, more energy is needed to peel the adhesive test piece off.

4.4 Adhesion Energy Calculation

When peeling rate is fixed in a specific peeling system, adhesive energy is a constant. Therefore, the relationship between peeling rate and adhesive energy can be studied. Equation (10) is expressed in the form of Equation (13) after transposition:

$$R = \left(\frac{F}{b}\right)^2 \frac{1}{2dG} + \left(\frac{F}{b}\right) \left(1 - \cos\theta\right)$$
(13)

When peeling angle, elastic modulus, film width and thickness are known, adhesive energy R can be seen as a function with the only variable of peeling strength $(\frac{r}{b})$. As one peeling strength corresponds to a specific peeling rate, so the relationship between adhesive energy and peeling rate can be obtained. Here the peeling strength data with a fixed peeling angle of 135° in Chapter 4.3 were used to calculate adhesive energy. The curve of the calculated adhesive energy versus corresponding peeling rate is plotted, shown in Figure 8. Data are attached in Appendix C.

It is obvious in this figure that when adhesive energy increases with increasing peeling rates. This means more energy is required to peel a film off when peeling rate increases.



Figure 8 Relationship between adhesion energy and peeling rate. Peeling angle is 135° .

4.5 Effect of Peeling Angle on Peeling Strength

Peeling strength is sensitive to peeling angle. To study the relationship between peeling angle and peeling strength, peeling rate should be fixed. The fixed peeling rate should be moderate. If the peeling rate was too small, the influence of small perturbations cannot be neglected, which influence accuracy of the experiment. When the peeling rate is too large, the precision of the results will be influenced. In this research, 2.5 mm/s was used as the fixed peeling rate. Initially the inclined plane is fixed at an angle. Calibrated weights with different mass were applied to the test pieces, and their peeling rates were calculated separately. The mass of calibrated weights was adjusted until the peeling rate is equal to 2.5 mm/s. Then the peeling angle was changed and this process was repeated.

The relationship between peeling strength and peeling angle at fixed peeling rates is plotted in Figure 9, marked with dark dots. Data are attached in Appendix D. At the same peeling rate, increasing peeling angle leads to increasing peeling strength. Larger peeling force is required to peel the thin film off from the substrate.



Figure 9 Relationship between peeling strength and peeling angle. Peeling rate is 2.5 mm/s. Fitting curve is based on Kendall's model.

Adhesive energy is not dependent on peeling angle, so the calculated adhesive energy in Chapter 4.4 with a fixed peeling angle of 135° is applicable when the peeling angle changes. According to the results in Chapter 4.4, when peeling rate is fixed at 2.5 mm/s, adhesive energy is equal to 11.8 J/m². Applying its value into Equation (10), we can get a function with two variables of peeling strength $(\frac{F}{b})$ and peeling angle $(1 - \cos\theta)$. The curve of this function is also plotted in Figure 9 in red line with cross marks (fitting curve 1). Compared this fitting curve with the

experimental data, we can find that although the measured peeling strength is smaller than the fitted value in the red curve, the experimental data and the fitted curve have the similar changing trend. This means that Kendall's model can reveal the relationship between peeling strength and peeling angle. The calculated adhesive energy is not accurate as many variables influence its calculation in Equation (13).

Therefore, an adhesive energy that better fits the experimental data should be found. Here, Equation (10) was used to approximate the best fitted adhesive energy and find the best fitted curve. As discussed in the previous part of this Chapter, if we apply a specific adhesive energy into Equation (10), a function with two variables of peeling strength $\left(\frac{F}{b}\right)$ and peeling angle $(1 - \cos\theta)$ can be obtained. By changing the value of adhesive energy, we can get a series of functions with two variables of peeling strength $\left(\frac{F}{b}\right)$ and peeling angle $(1 - \cos\theta)$. The correlation coefficients of the experimental data to these functions were calculated separately. The maximum correlation coefficient corresponds to the best fitted adhesive energy. The best fitted adhesive energy is 6.4 J/m^2 , with an R-square coefficient of determination of 0.9155. This fitting curve is plotted in blue line with triangle marks (fitting curve 2). Fitting curve 2 fits experimental data well at small peeling angles. At large peeling angles, the fitted peeling strength is smaller than the measured peeling strength. The Kendall's model should be modified.

4.6 Correction of Kendall's Model

Peeling strength analysis in Chapter 2.3 assumes that the adhesive film is linear elastic material and neglects its extension in peeling. However, as discussed in Chapter 4.1, the strain is not linearly correlated to stress in rubber, and its extension cannot be neglected. So the peeling strength analysis should be corrected.

We assume that an adhesive thin rubber film adheres to a rigid substrate, with the same peeling geometry shown in Figure 1. The extension ratio λ is used to characterize the deformation of rubber, and elastic modulus is obtained by the state equation for rubber (12). When the adhesive thin rubber film peels off from the rigid substrate, the value of surface energy term does not change:

$$\Delta E_1 = -R(bl) (1)$$

For potential energy term, we cannot assume that the adhesive film is not extensible here. Considering the extension of rubber film in region AB, the value of potential energy term is corrected in Equation (14):

$$\Delta E_2 = F(\lambda - \cos\theta)l \ (14)$$

As the stress is not linearly correlated with strain, Hooke's law is not applicable in the calculation of the elastic term. Rubber elasticity origins from entropy elasticity. When the rubber film is stretched, energy is stored because of the increasing entropy. With the introduction of affine deformation assumption, the value of the elastic term is expressed in Equation (14):

$$\Delta E_3 = -\left(\frac{NkT}{2}\right)\left(\lambda^2 + \frac{2}{\lambda} - 3\right) = -\left(\frac{Glbd}{2}\right)\left(\lambda^2 + \frac{2}{\lambda} - 3\right) (15)$$

Combining Equation (1), Equation (14), and Equation (15), we can conclude:

$$-R(bl) + F(\lambda - \cos\theta)l - \left(\frac{Glbd}{2}\right)\left(\lambda^2 + \frac{2}{\lambda} - 3\right) = 0 \quad (16)$$

After elimination and transposition, we can conclude the relationship between peeling strength and peeling angle, extension ratio, and adhesive energy in Equation (17):

$$\frac{F}{b} = \frac{\left(\frac{6d}{2}\right)\left(\lambda^2 + \frac{2}{\lambda} - 3\right) + R}{(\lambda - \cos\theta)}$$
(17)

Combining Equation (13) and Equation (17), peeling strength can be eliminated, and Equation (18) is obtained:

$$\lambda - \frac{1}{\lambda^2} = \frac{\binom{Gd}{2} \left(\lambda^2 + \frac{2}{\lambda} - 3\right) + R}{Gd(\lambda - \cos\theta)}$$
(18)

Elastic modulus and width of the film are known constant. If we fix peeling angle and adhesive energy, extension ratio λ can be solved in Equation (18). Then we apply the value of extension ratio λ into Equation (13) to calculate the corresponding peeling force. If we only change peeling angle with fixed adhesive energy and repeat this process, a series of peeling strength at different peeling angles with a fixed adhesive energy can be obtained. A curve representing the relationship between peeling angle and the calculated peeling strength at the fixed adhesive energy in the corrected model can be plotted.

To compare the difference of the corrected model and Kendall's model, the best fitted adhesive energy in Kendall's model, 6.4 J/m^2 , is applied into Equation (18) to plot the curve representing the relationship between peeling strength and peeling angle in the corrected model. This curve is plotted in Figure 10 in red line with square marks (fitting curve 3).



Figure 10 Relationship between peeling strength and peeling angle. Peeling rate is 2.5 mm/s. Fitting curve is based on the corrected model.

Compare the experimental data with fitting curve 3, we can find that data with a peeling angle ranging from 30° an 50° fits the fitting curve 3 greatly. When the peeling angle is smaller than 30°, the fitted peeling strength is larger than the measured value. When the peeling angle is larger than 50°, the fitted peeling strength is smaller than the measured value. Compare the fitting curve 2 in Kendall's model and fitting curve 3 in the corrected model with the same adhesive energy, we can find that at large peeling angles, the two fitting lines are close to each other, which means that fittings of the two models are similar when peeling angle is large. However, the difference of the two fitting curve enlarges as the peeling angle decreases. Peeling strength in the corrected model is larger than that in Kendall's model at the same peeling angle. The possible reason is that the influence of elastic modulus is neglected at large peeling angles. When peeling angle decreases, the influence of elastic

modulus cannot be neglected. Kendall's model assumes that the adhesive film is not extensible, so peeling strength in Kendall's model is smaller than that in the corrected model at the same peeling angle.

By changing the value of adhesive energy, we can get different series of peeling strengths at different peeling angles. The best fitted curve is also plotted in Figure 10, in green line with diamond marks (fitting curve 3), and the best fitted adhesive energy is 3.4 J/m^2 . Fitting curve only fits experimental data at small peeling angles. At large peeling angles, the fitted peeling strength is much smaller than the measured value. The fitting is not satisfactory, and the model should be further improved.

CHAPTER V

CONCLUSION

The experiment results show that the instrument in this research can be used to test peeling strength. The peeling strength and peeling rate are positively correlated at the fixed peeling angle. However, when the elastic modulus of the sample increases, the peeling rate decreases at the same peeling strength. Besides, the relationship between peeling angle and peeling strength is studied. Based on the relationship between peeling angle and peeling strength, two models, Kendall's model and the corrected model, are used to approximate adhesive energy and fit the relationship of peeling strength and peeling angle at fixed peeling rate. Both models can predict the changing trend of peeling strength at different peeling angle, but the precision of the two models should be improved.

The peeling test instrument in this research has limitations. When adhesive film peels off from substrate, perturbations are unavoidable. This problem is extremely obvious when the peeling rate is large. However, when the peeling strength is too small, the weight of the film that has peeled off cannot be neglected. The precision of this instrument should be improved.

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APPENDICES

APPENDIX A

COMPLETE STRESS – STRAIN CURVE

Unhardened Test Pieces



Hardened Test Pieces



APPENDIX B

ELASTIC MODULUS CALCULATION DATA

Unhardened Rubber Test Pieces

test piece	slope	sum of squares for error	coefficient squared error
1	0.6287	0. 2374	0. 9679
2	0.4024	0. 0267	0. 9924
3	0.3861	0. 1089	0. 9733
4	0.4183	0.079	0. 9817
5	0.4831	0. 1371	0. 9677

Hardened Rubber Test Pieces

test piece	slope	sum of squares for error	coefficient squared error
1	0.8862	3.691	0. 5541
2	0.6169	0.114	0.984
3	0.7474	1.139	0. 8581

APPENDIX C

PEELING RATE AT DIFFERENT PEELING STRENGTH DATA

Unhardened Test Pieces at 135°

Load (g)	Peeling Strength F/b (N/m ²)	Peeling Rate 1 (10 ⁴ um/s)	Peeling Rate 2 (10 ⁴ um/s)	Peeling Rate 3 (10 ⁴ um/s)	Average Peeling Rate (10 ⁴ um/s)	Standard Deviation (10 ⁴ um/s)	Adhesive energy J/m²
6	5.88	0.14	0.11	0.14	0.13	0.02	10.08
7	6.86	0.28	0.25	0.21	0.25	0.04	11.77
8	7.84	0.49	0.40	0.49	0.46	0.06	13.46
10	9.80	0.78	0.72	0.82	0.77	0.05	16.84
12	11.76	0.89	1.02	0.88	0.93	0.08	20.24
14	13.72	1.07	1.13	1.09	1.10	0.03	23.65
16	15.68	1.60	1.70	1.70	1.66	0.06	27.06
18	17.64	1.98	1.95	1.84	1.92	0. 07	30. 49
20	19.60	2.26	2.23	2.29	2. 26	0. 03	33. 92

Unhardened Test Pieces at 80°

Load (g)	Peeling Strength F/b (N/m ²)	Peeling Rate 1 (10 ⁴ um/s)	Peeling Rate 2 (10 ⁴ um/s)	Peeling Rate 3 (10 ⁴ um/s)	Average Peeling Rate (10 ⁴ um/s)	Standard Deviation (10 ⁴ um/s)
10	9.80	0.19	0.17	0.21	0.19	0.02
15	14.70	0.24	0.22	0.22	0.23	0.01
16	15.68	0.24	0.24	0.28	0.26	0.02
17	16.66	0.26	0.28	0.34	0.29	0.04
18	17.64	0. 28	0.37	0. 34	0.33	0.05
20	19.60	0.45	0.56	0.47	0.49	0.06

Hardened Test Pieces at 135°

Load (g)	Peeling Strength F/b (N/m ²)	Peeling Rate 1 (10 ⁴ um/s)	Peeling Rate 2 (10 ⁴ um/s)	Peeling Rate 3 (10 ⁴ um/s)	Average Peeling Rate (10 ⁴ um/s)	Standard Deviation (10 ⁴ um/s)
6	5.88	0.17	0.15	0.11	0.14	0.03
8	7.84	0.14	0.16	0.14	0.15	0.01
10	9.80	0.46	0.30	0.30	0.35	0.09
15	14.70	0.75	0.77	0.71	0.74	0.03
20	19.60	1.43	1.37	1.68	1.49	0.16

APPENDIX D

Peeling Angle	Load 1 g	Load 2 g	Load 3 g	Average Load g	Peeling Strength F/b (N/m)
100	63	60	60	61.00	59. 78
20°	50	49	52	50. 33	49. 33
30 °	42	45	45	44.00	43. 12
40°	27	28	27	27. 33	26. 79
50°	20	19	19	19. 33	18.95
80°	17	16	15	16.00	15.68
135•	7	6	8	7.00	6.86

PEELING STRENGTH AT DIFFERENT PEELING ANGLE DATA