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Peeling behavior of a viscoelastic thin-film on a rigid substrate

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ABSTRACT

In order to study the adhesion mechanism of a viscoelastic thin-film on a substrate, peeling experiment of a viscoelastic polyvinylchloride (PVC) thin-film on a rigid substrate (glass) is carried out. The effects of peeling rate, peeling angle, film thickness, surface roughness and the interfacial adhesive on the peel-off force are considered. It is found that both the viscoelastic properties of the film and the interfacial adhesive contribute to the rate-dependent peel-off force. For a fixed peeling rate, the peel-off force decreases with the increasing peeling angle. Increasing film thickness or substrate roughness leads to an increase of the peel-off force. Viscoelastic energy release rate in the present experiment can be further predicted by adopting a recently published theoretical model. It is shown that the energy release rate increases with the increase of peeling rates or peeling angles. The results in the present paper should be helpful for understanding the adhesion mechanism of a viscoelastic thin-film.

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1. Introduction

In recent years, investigations on the physical mechanism of interface have been attracting considerable attentions because of the great significance not only for the widely applications of thin-films and coatings in engineering (Kim et al., 1989; Thouless and Jensen, 1992; Wei and Hutchinson, 1998) but also for deeper understanding of the extraordinary adhesion ability of biology, such as gecko (Peng and Chen, 2011; Peng et al., 2010; Pesika et al., 2007; Tian et al., 2006). The adhesion strength and adhesion energy are 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).

With regard to the problem of an elastic thin-film on a rigid substrate, the classical Kendall's model shows that the peel-off force not only depends on the adhesion energy but also on the elastic deformation of the film as well as the peeling angle (Kendall, 1975). As a pioneering work, it provides a direct method to find the interfacial properties, for example, adhesion energy, by measuring the peel-off force. While for a ductile thin-film, such as a metal film, the measured energy release rate is often much larger than the interfacial adhesion energy due to the plastic dissipation. Bending models were widely adopted to analyze the plastic dissipation (Kinloch et al., 1994; Thouless et al., 1997) following the work of Kim and his coworkers (Kim et al., 1989; Kim and Aravas, 1988; Kim and Kim, 1988).

What is about a viscoelastic thin-film? It is well known that each material has a viscoelastic feature, which is weak in some materials, e.g. metals, but strong in some other ones, e.g. polymers and biomaterials. Adhesion mechanism of a viscoelastic material on a substrate has been widely investigated theoretically, numerically and experimentally (Andrews and Kinloch, 1973b; de Gennes, 1996; Derail et al., 1997, 1998; Gent and Schultz, 1972; Hui et al., 1992; Kaelble, 1964; Marin and Derail, 2006; Rahulkumar et al., 2000; Xu et al., 1992), the corresponding force is often a function of the loading rate and temperature. Gent and Petrich (1969) studied the effects of peeling rate and temperature on adhesion of a viscoelastic thin layer on a rigid substrate by T-peeling experiment over a wide range of temperature and peeling rate, a single master relation was yielded in terms of the peeling rate when the temperature was reduced to a reference one by means of the Williams, Landel and Ferry's (WLF) rate-temperature equivalence. Derail et al. (1997, 1998) and Renvoise et al. (2007) experimentally studied the failure criterion of pressure sensitive adhesives at 90° peeling angle and obtained a transition rate from cohesive to interfacial failure. Chivers (2001) studied easy removal techniques of a medical pressure-sensitive adhesive tape for skin application, in which both physical and chemical approaches were introduced to achieve reversible adhesion of the medical adhesive tape. The effect of a flexible substrate on the peeling behavior of a medical pressure-sensitive adhesive tape was studied by Steven-Fountain et al. (2002), which was found to be different from the case of a rigid substrate. The viscoelastic effect of a polymeric film was analyzed

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by Loukis and Aravas (1991), in which the thin-film was modeled as a cantilever beam subjected to a purely bending moment. Based on the work (Loukis and Aravas, 1991), Chen et al. (2013) further investigated the viscoelastic peeling problem theoretically considering both the tensile and bending effects. Poulard et al. (2011) investigated the role of micro-patterning in adhesion properties of a soft deformable PDMS/acrylic adhesive interface, in which it was found that the adhesion energy could be successfully tuned by varying the pattern size.

Though many studies related to the peeling behavior of viscoelastic material exist, the peeling force with a 90° peeling angle was mainly focused on. The peeling mechanism of a viscoelastic thin-film from a substrate at an arbitrary peeling angle is unclear.

Peeling experiment of a viscoelastic thin-film on a rigid substrate is carried out firstly in the present paper. The effects of peeling angle, peeling rate, film thickness, surface roughness as well as the interfacial adhesive on the peeling force or the interfacial adhesion strength are mainly considered. Then, the variation of the viscoelastic energy release rate in our experiment is further predicted with the help of a recently published steady-state peeling model for viscoelastic thin-films on rigid substrates.

2. Peeling experiment of a viscoelastic thin-film on a rigid substrate

2.1. Materials in experiment

3 M Vinyl Electrical Tape (3 M #1500) made of polyvinylchloride (PVC) is used as thin-film in the present experiment. The width w and thickness h of PVC film are 18 mm and 0.13 mm, respectively, with a length of 50 mm. In all the experiments, the interfacial adhesive is polyacrylic acid with a thickness h_1 that is much smaller than the thickness of the thin-film h. Glass slides with a smooth or a rough surface are used as substrates. All the substrates are cleaned two times with ethyl alcohol followed by two times cleaning of acetone, then rinsed with distilled water.

2.2. Peeling experiment

In order to achieve a nearly perfect adhesion interface between the thin-film and glass substrate and avoid air bubbles entrapped at the interface, a hand roller is used to roll the thin-film on the glass surface five times in both directions. Then, the specimens are placed at a room temperature (about 25° C) for 4 h. All the experiments are conducted with a standard tensile machine as shown in Fig. 1, where a special peel-rig is made in order to vary the peeling angle conveniently. A three-dimensional schematic of the film/substrate system under a peeling load is shown in Fig. 2. The glass substrate is fixed to the rig, with the help of which the peeling angle can be tuned from 15° to 165° (the interval is 15°). To decrease the deviation of a determined peeling angle during peeling process, a thin nylon thread with one meter in length connects one end of the film to the force sensor installed on the crosshead of the tensile machine. Since the length of the thread is much longer than that of the thin-film (50 mm), the peeling angle will approximately keep a constant and the deviation of the peeling angle is about ±1.4° during peeling. The relationship between the peeling rate and the speed of the crosshead can be described as $v_{ch} = (1 - \cos\theta)v$ during steady-state peeling process, where θ is the peeling angle, v_{ch} is the velocity of the machine's crosshead and v is the peeling rate. A long focus Questar microscope is used to observe the images of the interface cohesive zone when the peeling behavior becomes steady-state. All the experiments are carried out at a room temperature 25° C with a relative humidity about 44%.

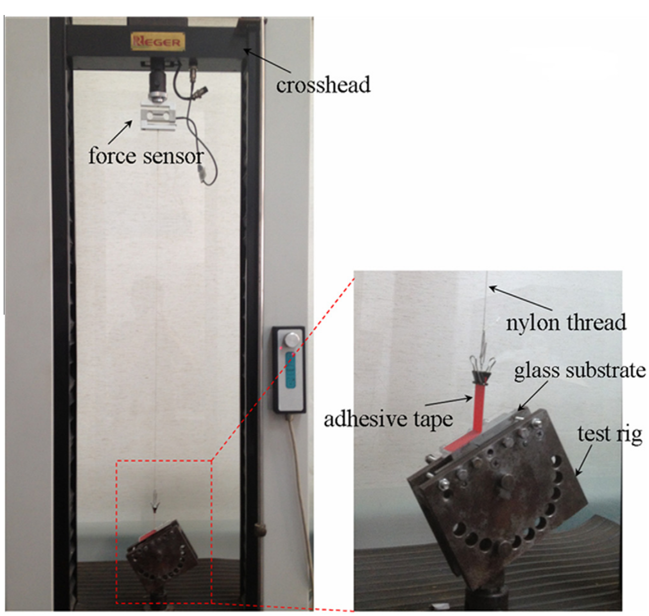

Fig. 1. A standard tensile machine and a rig made specially for tuning the peeling angles from 15° to 165° with an interval 15°.

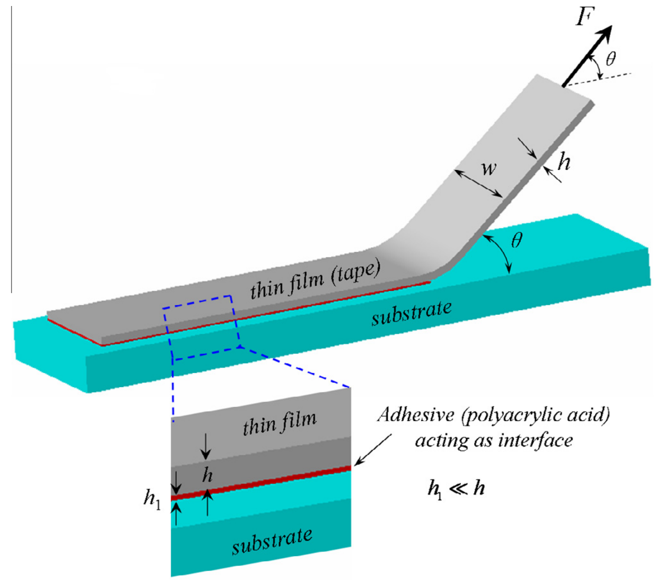

Fig. 2. Schematic of the peel-test with dimension illustrations of the adhesive tape (thin-film), interface (polyacrylic acid) and the substrate.

3. Experimental results and discussion

3.1. The effect of peeling rate on the peel-off force

Due to the viscoelastic properties of the PVC material, the peeling rate should show a significant effect on the peeling behavior. Typical curves of the peeling force vs. peeling distance are measured and exhibited in Fig. 3, where different peeling rates and different peeling angles are considered. Each curve in Fig. 3 shows three distinct regions: (i) the peeling force increases initially up to the onset of interface propagation; (ii) once the interface starts propagating, a slight drop is found in the peeling force; (iii) then it follows a steady-state peeling process and the peeling force approximately remains a constant, which is recorded conveniently and defined as the peel-off force in our experiment. Comparing the peel-off force in the steady-state process, it is reasonable to find

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