# Adhesive Failure Peak in Peel Spectra

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ABSTRACT: Peel force spectra for pressure-sensitive adhesive tapes provide a peel peak in the adhesive failure region. The observed peak behavior is coincident with calculation based on a viscoelastic peel model. It turns out that the origin of the peak is significantly associated with viscoelasticity or short relaxation time of the adhesive. © 1999 John Wiley & Sons, Inc. J Appl Polym Sci 74: 264-266, 1999

**Key words:** peel spectra; adhesive failure peak; viscoelastic peel model; pressuresensitive adhesive tapes

The nonstationary peel method has been used for peel testing of a variety of pressure-sensitive adhesive (PSA) tapes.<sup>1–4</sup> By use of the peel tester, a wide peel spectra, including some of the cohesive, adhesive, or interfacial failures and the peel transition, can be measured with a short-length sample tape during a relatively short time.<sup>2-4</sup> The stick-slip behavior appearing as a discontinuous change for ordinary peel tests<sup>5,6</sup> has been found as a hysteresis of accelerating and decelerating peels. We have additionally observed a peel peak in the adhesive failure region. In this article, origin of the peel anomaly is examined from the peel angle dependence, a video observation on peeling, and a theoretical treatment based on viscoelastic model.

Peel measurements were carried out for a PSA tape with a  $30-\mu$ m-thick rubber-based adhesive. The tape backing is a  $25-\mu$ m-thick poly(ethylene-terephutalate) film. Sample tapes were cut into a 10 mm width. The tape adhered on a clean Pyrex glass substrate<sup>2</sup> was kept for a day at ambient

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## THEORY

A viscoelastic analysis based on Hata's peel model<sup>7</sup> was done in order to interpret the observed peel spectra. An improved model consists of two Maxwell elements connected in parallel with each other and a hook with the defined work of adhesion  $W_a$  in series with their elements. Two relaxation times  $\tau_1$  and  $\tau_2$ , defined by elastic moduli  $G_j$ and viscosities  $\eta_j$  of j = 1, 2, if  $\tau_2 > \tau_1$  are associated with viscoelasticity of the components of polymeric chains and short molecules in the PS

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temperatures in an air-conditioning room because of steady-state adhesion. The peel tester<sup>3</sup> was operated at room temperature in air, under peel angles of 30, 50, and 90°. The peel test was run in accelerating and decelerating peels, along with stationary peel; the accelerating peel rate  $V_p$  was varied with peel length L according to  $V_p = V_1 \exp(bL)$ , where  $V_1 = 0.01 \text{ mm s}^{-1}$  and  $b = 0.08 \text{ m}^{-1}$ .<sup>3</sup> The stationary or decelerating rates are obtained by substituting b in the  $V_p$  into zero or -b. The maximum rate was 30 mm s<sup>-1</sup> in this measurement.



**Figure 1** Peel force  $F_p$  against the logarithm of peel rate  $V_p$  at three peel angles of 30, 50, and 90° for rubber-based PSA tapes. Note that values are made two (×2), three (×3), and four (×4) times for the explicit peak.

adhesive. No extension to multiple relaxation times was made for simplicity.

The model analysis was performed by assuming three basic criteria for deforming fibrils of the adhesive; the volume invariance for deforming fibrils, leading to the effective ratio of cross-sectional area  $R = (1 + \text{strain})^{-1}$ , the uniform stress distribution<sup>8</sup> for all fibrils in the deformation region approximated to an isosceles triangle and no interaction among fibrils. When a fibril during deformation stored the deformation energy comparable with  $W_a$ , the fibril is broken at the interface between the adhesive and substrate. Thus, the relation between the peel force per unit tape-width  $F_p$  and peel rate  $V_p$  is given as

$$F_p = (1/2)g^2 L_0 \log(1 + e_b)s_p, \tag{1}$$

where  $L_0$  is the initial thickness of the PS adhesive, g is the peel angle  $\theta$  factor defined by  $g^{-1}$ =  $\sin(\theta/2)$ ,  $e_b$  is the fracture strain and  $s_p$  is the peel stress;  $s_p = \eta_j [v_i \{1 - \exp(-t_b/\tau_j)\}]$ ; j = 1, 2with the initial strain rate  $v_i$  of a fibril arrived at the peel point and the fracture time  $t_b$  corresponding to  $e_b$ . The strain rate is readily transformed by multiplication of  $(1/2)gL_0$  into the peel rate  $V_p$ . The peel acceleration  $A_p$ , which does not appear explicitly in eq. (1), is similarly given with  $A_p = dV_p/dt = (1/2)gL_0a$  with a strain acceleration a; the  $A_p$  or a is available for accelerating peels.

### **RESULTS AND DISCUSSION**

Figure 1 shows the accelerating peel spectra at peel angles of 30, 50, and 90° for rubber-based PSA tapes. The peel mode was adhesive failure over the measured rate range. The peel force, increasing with peel rate, lowered at a rate, and formed a peel peak. The peak was similarly observed in the decelerating spectra without peel hysteresis. The peel angle dependence indicated the decreasing trend of the peak rate and strength as the peel angle rose. A broadening of the peak was also exhibited at greater angles.

The side-view profile of adhesives on peeling was taken with a video television system. Fibrillation of the adhesive on deformation was confirmed before adhesive failure. From still images, the average fracture strain was estimated as a function of strain rate; the results gave a relatively steep lowering around a characteristic strain rate. Although the lowering rate region tends to be broader with increase in peel angle, the characteristic rate remains almost constant. It appears that the invariant rate corresponds to



**Figure 2** Strain estimated for a 90° peel in a logarithmic peel rate  $V_p$  region.



Figure 3 Calculated peel force  $F_p$  against the logarithm of the peel rate  $V_p$  at three peel angles of 30, 50, and 90°, according to eq. (1). Constants used are given in the text.

the inverse short relaxation time of the adhesive. For reference, the estimated strain for a 90° peeling over a peel rate range is given in Figure 2.

Numerical calculation of the peel force from eq. (1) was performed by use of normal values of  $W_a = 3 \text{ N} (\text{mm})^{-2}$ ,  $\tau_1 = 15 \text{ ks}$ ,  $\tau_2 = 3 \text{ ms}$ ,  $\eta_1 = 900 \text{ Ns} (\text{mm})^{-2}$ , and  $\eta_2 = 0.08 \text{ Ns} (\text{mm})^{-2}$  at a peel acceleration of  $A_p = 0.1 \text{ mm s}^{-2}$ . Figure 3 shows the calculated curves for peel angles of 30, 50, and 90°. The spectra, as the whole, are coincident with the observed ones; a similar change of the peak against peel angle is recognized. The lowering in the peak rate is likely due to the g factor included in  $V_p = (1/2)L_0gv$ . In other words, the peak shift should be proportional to  $\sin^{-1}(\theta/2)$ . When, instead of the peel rate, the peel force is replotted

against the strain rate, it is confirmed that the peak appears at a definite rate, corresponding to the inverse short relaxation time. This implies that the peak is deeply associated with the adhesive itself. In addition, the lowering in the peak strength is similarly explained from the change of  $g^2$  in eq. (1); obviously, the peel angle dependence should be stronger than that of the peak rate. Otherwise, no broadening of the peak was seen for spectra in calculation, while the broadening in observation was emphasized at greater angles. It appears that such broadening is chiefly related to excess strain of tape backings. In addition, the overall behavior in peel force measured, that is, the so-called force-baseline, except for the peak, shows an increasing trend with peel rate compared to a flat baseline in the theoretical curve. A major origin of the difference is seemly due to the multiple distribution of relaxation times; a preliminary calculation after consideration of a set of wedge- and box-type distribution of relaxation times significantly explains such an experimental tendency.

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