Viscoelastic Analysis of Shear Adhesion Test for Pressure-Sensitive Adhesive Tape

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A new shear adhesion tester of a pressure-sensitive adhesive tape is developed, by which the slippage of the tape under shearing force can be measured as accurately as 1 μm or 0.1 μm per digit by the aid of a linear variable differential transformer. When shearing force is exerted on a tape applied on an adherend, two kinds of slippages are expected, that is, the one between the surface of the adhesive and the adherend and the other of the shearing strain of the adhesive. In order to separate the two kinds of slippages, slippage under shearing force and the recovery displacement after removing the force are measured. Analysing the results of measurements it becomes clear that viscoelastic models of Voigt units connected in series are suitable for both of the slippages.

KEY WORDS Boundary and cohesive slippage; pressure-sensitive adhesive tape; shear adhesion test; test apparatus; Voigt model.

1 INTRODUCTION

In order to analyse viscoelastically shear adhesion tests of a pressure-sensitive adhesive tape (PSA tape), a new testing apparatus has been developed. The shear slippage can then be measured as accurately as 1.0 or 0.1 μm per digit. A viscoelastic model of slippage is consequently proposed.

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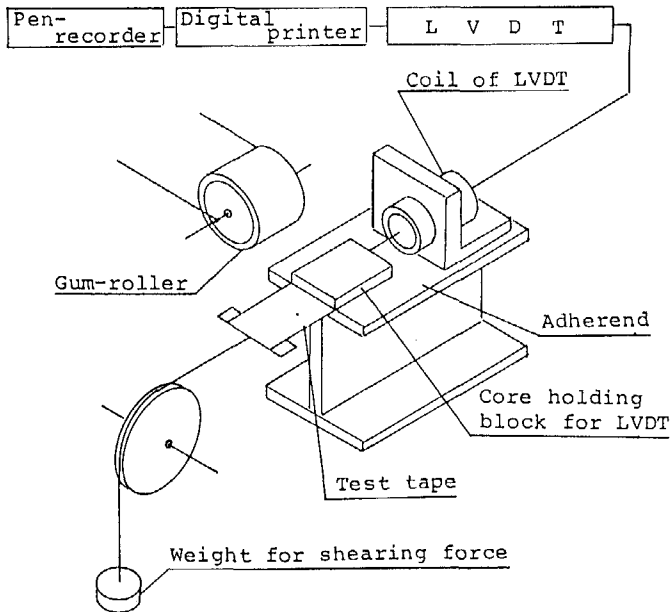
FIGURE 1   Schematic diagram of a device developed for shear adhesion.

2   TESTING APPARATUS

A schematic diagram of the apparatus is shown in Figure 1. The specimen is applied on an adherend made of stainless steel plate in the way prescribed by JIS (Japanese Industrial Standard). Shearing force is applied by a dead weight. A block with a core of a LVDT (Linear Variable Differential Transformer) is put on the specimen. The core is inserted into a detector of the LVDT, so that the slippage of the specimen is detected and recorded by a digital printer or a pen recorder.

3   VISCOELASTIC MODEL OF THE SHEAR ADHESION TEST

When shearing force is applied to the tape, there arise two kinds of displacement of the tape, that is, the cohesive slippage inside the adhesive and the boundary slippage between the adhesive and the

FIGURE 2   Generalized visco-elastic model of shear adhesion.

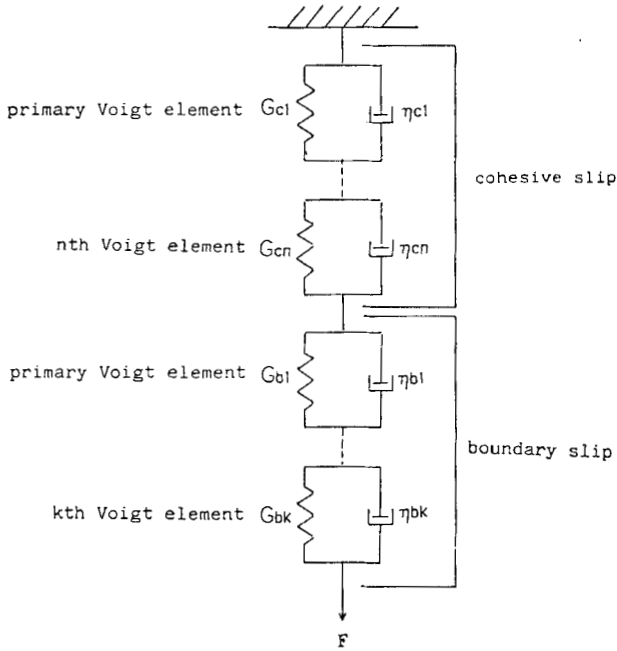adherend. Therefore, a viscoelastic model is expressed by a series of Voigt units in both kinds of slippage, as shown in Figure 2, where the model of boundary slippage has unrecoverable elements of springs and dampers, because the boundary slippage does not recover practically. As is shown in Figure 2 the model of cohesive slippage has n Voigt units, the elements of which are denoted by G_{ci} and η_{ci} of the springs and dampers respectively, and that of the boundary slippage has k Voigt units in which the elements of the units are denoted by G_{bj} and η_{bj} in a way similar to the cohesive slippage.

4 THEORETICAL ANALYSIS OF THE MODEL

When the shearing force F (gf) is applied to the specimen, both cohesive and boundary slippage ε_c and ε_b (mm) take place and the

two kinds of slippages are given by the following equations:

$$\varepsilon_c = F \sum_i^n (1/G_{ci})\{1 - \exp(-t/\tau_{ci})\} \qquad (1)$$

$$\varepsilon_b = F \sum_j^k (1/G_{bj})\{1 - \exp(-t/\tau_{bj})\} \qquad (2)$$

where $\tau_{ci}:(\eta_{ci}/G_{ci})$ and $\tau_{bi}:(\eta_{bj}/G_{bj})$ are the relaxation time of ith and jth unit of the Voigt model shown in Figure 2. The total slippage is thus given by the following equation;

$$\varepsilon = \varepsilon_c + \varepsilon_b \qquad (3)$$

If the shearing load is removed after a lapse of time t_1 from its application, the boundary slippage stops, for no shearing force for the boundary slippage exists but, on the other hand, the cohesive slippage begins to recover owing to the elongation of springs in the Voigt units. The recovering displacement ε_r is given by the following equation;

$$\varepsilon_r = \sum_i^n Ai \exp\{(t - t_1)/\tau_{ci}\} + F \sum_j^k (1/G_{bj})\{1 - \exp(-t_1/\tau_{bj})\} \quad (4)$$

where A_i is the initial condition of recovering displacement at time t_1 of the Voigt unit, and the second term means the boundary slippage during the application of the shearing load. The boundary slippage can be obtained through the recovering displacement at sufficiently long time after removal of the load.

When the slippage of the tape under the shearing load and the recovering displacement free from the shearing load are measured, the viscoelastic constants of the Voigt elements shown in Figure 2 can be determined by the aid of the least squares method.

5 MEASUREMENT OF THE SLIPPAGE

The experimental results for a polyester tape coated with polyacrylate adhesive are shown in Figure 3 for 30 min in loading time and 30 min in recovering time. The measuring conditions are as follows: 25×25 mm in adhesion area, 100 gf in shearing load, 0, 20, 40 and
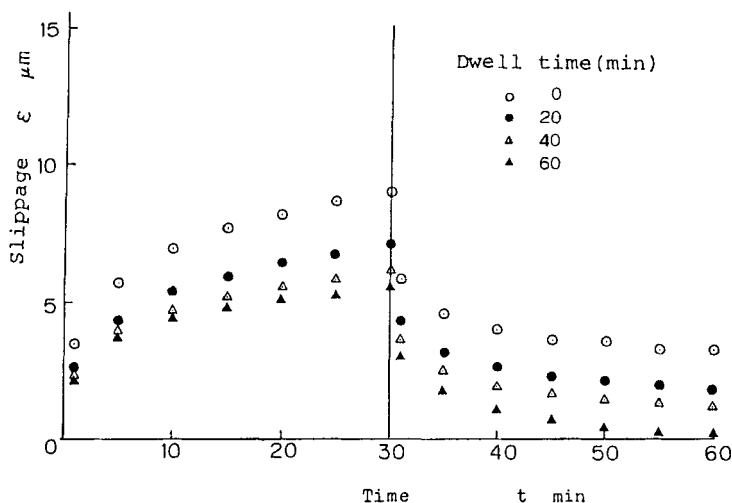
FIGURE 3 Slippage under shear adhesion test and viscoelastic recovery after unloading.

60 min in dwell time and $23 \pm 0.5°C$ and $65 \pm 5\%$ RH as the atmospheric condition.

6 RESULTS OF EXPERIMENTS

From the recovering displacement the model of cohesive slippage can be determined. The number of Voigt units is determined by increasing the number from 1 to 3 and the variance of residuals is successively tested by the F-test. The number of 2 is confirmed to be sufficient. The constants of the units are proved to be independent of dwell time by the aid of the analysis of variance. Relaxation time of the units is shown in Table I.

As the slippage under shearing force includes cohesive slippage, the effect of cohesive slippage is eliminated by substituting the constants of the cohesive units and the pure boundary slippage is obtained as shown in Figure 4. In a similar way to the case of the cohesive recovery, the number of the Voigt units of 2 and its constants are determined, which are shown in Table II.

TABLE I
Constants of Voigt units of cohesive slippage

Coefficient	
G_{c1} 10^6 Pa·m	0.413
G_{c2}	0.326
η_{c1} 10^6 Pa·s·m	4.878
η_{c2}	133.8
τ_{c1} s	11.32
τ_{c2}	410.4

In Figure 4 the pure boundary slippage, experimentally determined, is shown and it is observed that the boundary slippage decreases as the dwell time increases. At a dwell time of 60 min no boundary slippage is recognized and the velocity of slippage is higher at the beginning of slippage, becoming slower until it is constant. The initial transient phenomena disappear when the dwell
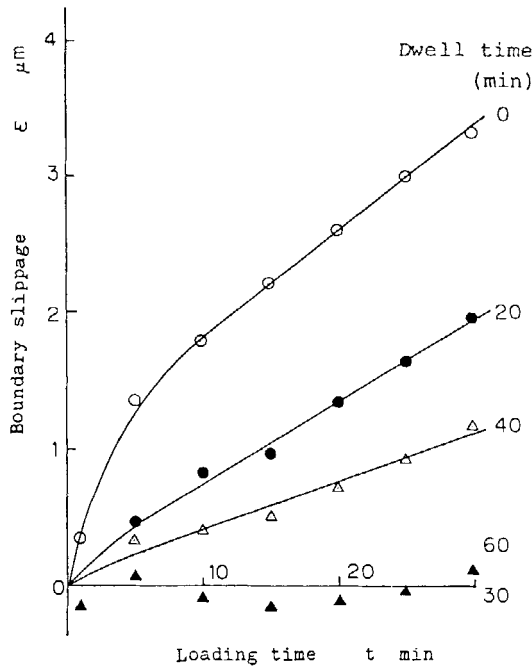

FIGURE 4   Relationship between loading time and boundary slippage.

TABLE II
Constants of Voigt units of boundary slippage

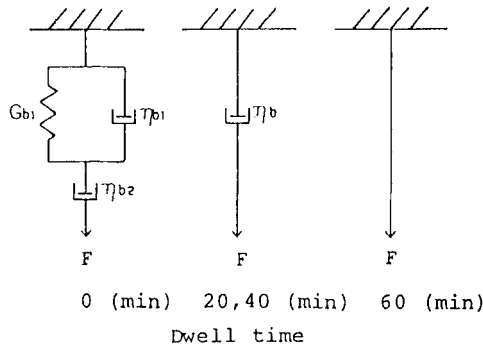| Coefficient	Dwell time T min		
	0	20	40
G_{b1} 10^6 Pa·m	0.938	7.175	16.76
G_{b2}	0.102	0.056	0.046
η_{b1} 10^6 Pa·s·m	189.8	234.8	643.5
η_{b2}	672.8	919.1	1630
τ_{b1} s	202.3	32.72	38.40
τ_{b2}	6596	16413	35200

FIGURE 5 Simplified models of boundary slippage.

time is longer. Determining the constants of the Voigt elements by the aid of the least squares method, the model of a boundary slippage can be simplified as is shown in Figure 5 with respect to dwell time.

7. CONCLUSIONS

A new shear adhesion tester of high accuracy and precision was developed. A polyester tape coated with a polyacrylate adhesive was tested using this tester. Viscoelastic models of boundary slippage and the cohesive slippage of the adhesive were analysed by introducing a combination of Voigt units in series. The results are

briefly summarized as follows:

1) Two kinds of slippages in the shear adhesion test are separated by measuring the slippage under shearing force and the recovering displacement after removing the force.

2) Viscoelastic characteristics of the adhesive can be determined by introducing a model of two Voigt units in series and the constants of the units are determined. They are not influenced by dwell time.

3) Two Voigt units connected in series are also successfully applied in the analysis of boundary slippage. The models of the slippage are greatly influenced by the dwell time.