Nonstationary Peeling Apparatus

HIROYOSHI OBORI,[1] MITSURU TAKENAGA,[2,*] ANIWAR ABDULLA,[2] and AKIRA NAKAMURA[2]

[1]Product and Technology Department, Teraoka Seisakusyo Co. Ltd., 1-4-22 Hiromachi, Shinagawa, Tokyo 140 and [2]Department of Applied Physics, Faculty of Science, Science University of Tokyo, 1-3 Kagurazaka, Shinjuku, Tokyo 162, Japan

SYNOPSIS

A piece of apparatus for measuring the peel adhesion behavior of pressure-sensitive adhesive tapes was developed. The apparatus allows peel rates to be varied as any functions of time or peel distance. In a cycle run of the accelerating and decelerating peel processes, nonstationary peeling was investigated over a wide range of peel rates using relatively short-length samples. The resultant behavior in nonstationary peeling indicated that in the interfacial failure regime, a good agreement with the normal stationary peeling can be obtained. This nonstationary peeling apparatus is expected to be useful for evaluation of peel adhesion.

INTRODUCTION

In peeling of pressure-sensitive adhesive (PSA) tapes, it is important to know the peel spectrum over a wide peel rate range. Most of the spectra have been constructed in terms of an assembly of data from the stationary methods. Such procedures make it quite time consuming to complete the spectrum. They are also inconvenient for use with a very long sample, particularly in a high-rate peeling test.

Peeling testers that made active use of a nonstationary method have been reported: these include the soft-machine testing by Andrews, Khan, and Majid[1,2] and the compound pendulum type tester.[3] By use of the former machine, the low energy peeling was detected in addition to the normal high energy one; this means that two kinds of peel forces exist at the same peel rate. On the other hand, the latter tester could give the peel behavior over a wide range of peel rates in a half cycle of rotation of the pendulum. However, it was difficult to do a systematic study on nonstationary peeling because of the utilization of gravity.

In the transition regime between the cohesive and interfacial failures, a characteristic peak of the peel force appeared in stationary peelings[4]; in nonstationary peel testings, a peel hysteresis in a cycle run of the increasing and decreasing rates was observed.[3] Furthermore, the occasional occurrence of the oscillation phenomenon suggests unstable peelings as a result of the complex failure behavior.

A nonstationary peeling apparatus was developed in order to obtain useful information on nonstationary peeling; the test results, which can be available for the peel evaluation, were obtained for some PSA tapes.

APPARATUS

Figure 1 shows the schematic diagram of the nonstationary peel adhesion apparatus, mainly classified with the control system based on a personal computer and the peel mechanical system. At the outset, tapes to be measured were adhered to substrates; then the peel angle at the separation point was set up by changing the position of the third pulley. The flexible belt connected with one end of the sample tape was linked to the substrate via three pulleys, each of whose positions was adjusted so that slight tension acted on the belt. When the head moved as a certain function of variable peel rates, the peel angle remained constant on peeling because of constancy in the angle of the polygon formed in the initial setting. One of the characteristics of the apparatus is that peel rates can be varied as any func-

* To whom correspondence should be addressed.

Journal of Applied Polymer Science, Vol. 53, 993-998 (1994)
 CCC 0021-8995/94/080993-06

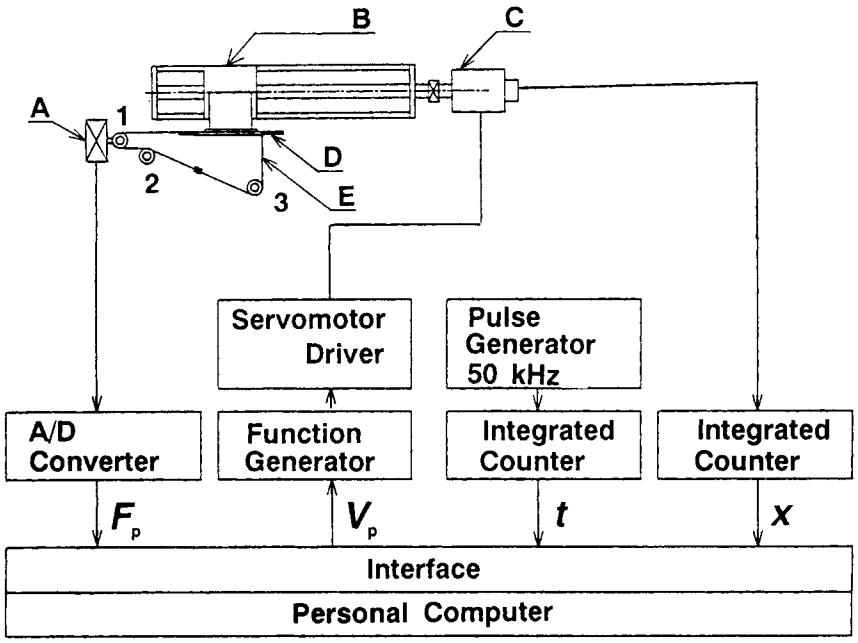

Figure 1 Schematic diagram of a system of peel adhesion apparatus for measuring stationary and nonstationary peelings of PSA tapes: (A) load cell; (B) slide head; (C) servomotor; (D) substrate; (E) sample tape; 1, 2, and 3, pulleys.

tion programmed in the computer. Ordinarily, the nonstationary peel measurement is carried out in a successive cycle of the accelerating and decelerating peel processes.

Control System

The present measuring system was constructed of a personal computer with a 10-MHz clock pulse, an analog–digital (A/D) converter, two integral counters, a 50-kHz pulse generator, and a variable-frequency pulse generator. In Figure 1, the arrows indicate the sense of flowing of signals related to the peel force F_p, peel rate V_p, time t, and peel distance x.

Data of peel force from the load cell were stored in the computer memory through the A/D converter. Peel rates varying as some function of time or peel distance were output in pulses through the pulse generator into the motor driver to gain the power for moving the actuator head. The practical peel rate was calculated from the time elapsed while the tape was peeled for a constant length of 0.1 mm. The distance of movement of the substrate fixed on the actuator head was checked by the number of pulses generated in the servomotor. As the reference timer, a set of the pulse generator and counter were used; these controlled all devices connected with the computer. Data processing was performed in real time during the waiting time between runs; the relationship between peel force and peel rate was displayed on a CRT.

Mechanical System

Plate substrate to which a given sample tape was adhered were fixed to the movable head of the actuator (LM-GUIDE, THK Co., Ltd). The head board moved linearly by means of the mechanism for transforming the rotational motion of the servomotor to the linear movement; the head speed was varied with the pulse frequency, proportional to rotational angles of the servomotor. In the present system, the lower limit of the speed was 10^{-6} mm/s in the approximately continuous change. On the other hand, the upper limit, concerned with the maximum rpm of the servomotor, was 2×10^2 mm/s. The precision in the linear movement was 0.01 mm. The transnational driving force of the head was 200 N.

The peel force was detected by a load cell connected with the first pulley. The capability of the load cell with the sensitivity of 3 mV/V ranged from 10 to 100 N. The dynamic range with a strain gauge amplifier was 10 kHz. The peel angle was varied from a few to 180° by adjusting the position of the

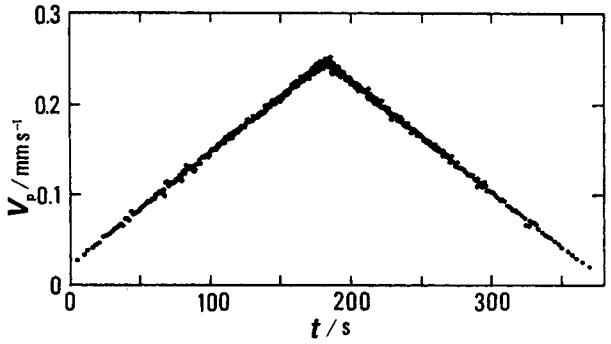

Figure 2 Peel rate V_p plotted against elapsed time t for testing the constant acceleration and deceleration process. The varying rates agree with eq. (2) with $a_p = 1.2\ \mu m/s^2$, $V_1 = 0.025$ mm/s. See text about the deceleration.

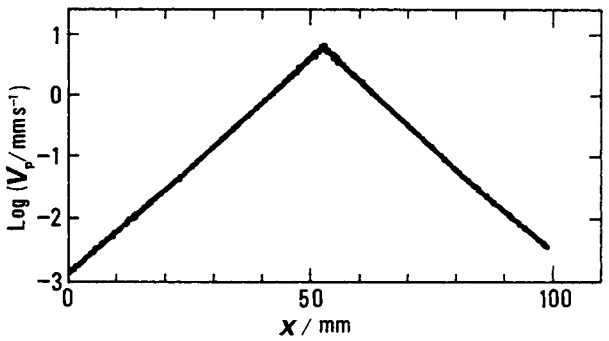

Figure 3 Peel rate V_p plotted against peel distance x for testing the rate process based on eq. (3). The acceleration varies with bV_p^2, where $b = 0.074\ mm^{-1}$; $V_2 = 0.0013$ mm/s. See text about the deceleration.

third pulley, along with fine adjustment of the other two pulleys. Note that in 180° peeling the third pulley was not necessary.

In the present peel test, three kinds of the rate modes were used. One was the stationary mode of constant rate process, corresponding to normal peel testing. The other two were the nonstationary modes that involve the accelerating and decelerating peel; they were the rate processes of the constant and rate-dependent acceleration and deceleration. Each peel rate V_p is expressed with respect to elapsed time t or peel distance x:

$$V_p = V_0 \tag{1}$$

$$V_p = V_1 + a_p t \tag{2}$$

$$V_p = V_2 \exp(bx) \tag{3}$$

where V_0 is the constant rate, V_1 or V_2 are the initial rates, a_p is the constant acceleration, and b is a constant relating to the acceleration, whose magnitude varies with bV_p^2.

The decelerating peel based on eq. (2) was represented by the same function form with $a_p = -a_p$ and the initial rate $2V_m - V_1$, from the maximum rate $V_m (= V_1 + a_p t_m)$ at the final time t_m in the accelerating peel. Figure 2 shows the test results of the constant acceleration and deceleration processes. It was confirmed that the rate varied at the constant acceleration or deceleration with the slope of a_p or $-a_p$, respectively. Notice that the total time in a cycle runs was twice t_m, and the range in varying rates was only two decades in the present peel condition. This process was useful for investigating the acceleration or deceleration dependence of peeling.

The decelerating peel of eq. (3) is given by a function with a form similar to that of eq. (3), but with $b = -b$ and the initial rate $V_2 \exp(bx_m)$, where x_m is the maximum distance peeled on a cycle run. The test results shown in Figure 3 are in accord with the behavior that the logarithm of the peel rate varies in slope b with the peel distance, from the initial rate V_2 to the maximum rate $V_m \{= V_2 \exp(bx_m/2)\}$, and in slope $-b$ from V_m downward to V_2. The utility of this process was to be able to measure the peel behavior over a wide peel rate range with short-length samples; in addition, data on peel rate was obtained in the equivalent intervals on the logarithmic scale. It is noted that the range of varying rates was from four to six decades, depending on the value of b.

Table I Characteristics of PSA Tapes and Substrates

Samples (PSA Tapes)	Adhesives (30-μm Thick)	Backing (25-μm Thick)	Substrate
A	Rubber type	PET	Glass
B	Acrylic type	PET	Glass
B′	Acrylic type	PET	Release liner
C	Silane type	PET	Glass

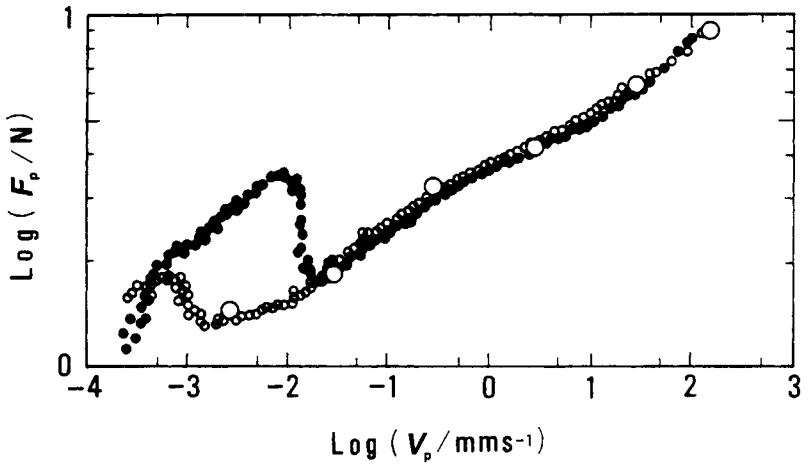

Figure 4 Relation between peel force F_p and peel rate V_p for sample A of 10-mm width, using the rate process based on eq. (3) with $V_2 = 10^{-4}$ mm/s, $b = 0.11$ mm^{-1}, $V_m = 100$ mm/s. Open circles, decelerating peel; solid circles, accelerating peel; large open circles, stationary peel.

EXPERIMENTAL AND RESULTS

Nonstationary peeling of a variety of PSA tapes was investigated, in addition to the test of performance of the apparatus. The PSA tapes have backing consisting of polyethyleneterephthalate (PET) film of 25-μm thickness. As listed in Table I, three kinds of adhesives were used. The sample tape was cut into strips 10-mm wide. The tape length necessary for a cycle of runs is around 100 mm. Pieces of Pyrex glass whose surfaces were clean-treated were used as the substrate. After adhered to the substrate, the sample was kept at room temperature for more than a day because of stationary adhesion. All measurements were made at room temperature in an atmosphere of air. The peel adhesion spectra were measured in 180° peeling using this apparatus.

Figure 4 shows the results of sample A in the rate process based on eq. (3), along with values in stationary peeling. The interfacial failure peeling oc-

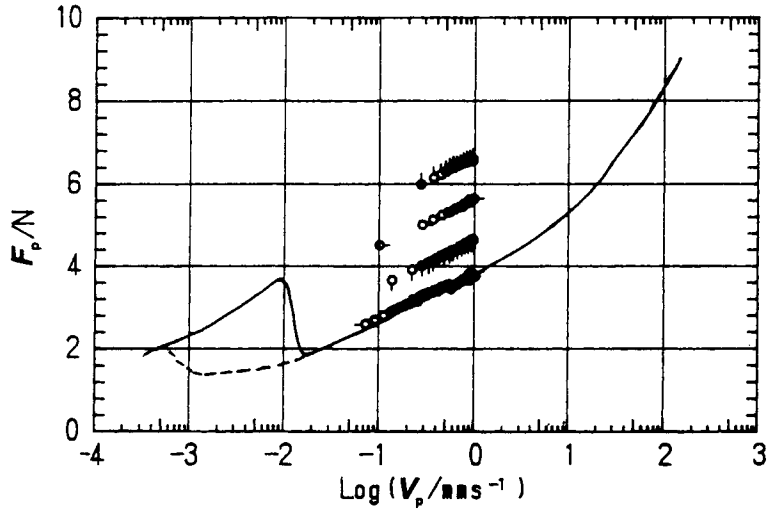

Figure 5 Relation between peel force F_p and peel rate V_p for sample A in the constant process at various accelerations a_p [mm/s^2]: (—○), 0.02; (○), 0.15; (○—), 0.2; (○), 0.3. Curves at three higher accelerations are shifted upward for clarification. Tape width is 10 mm.

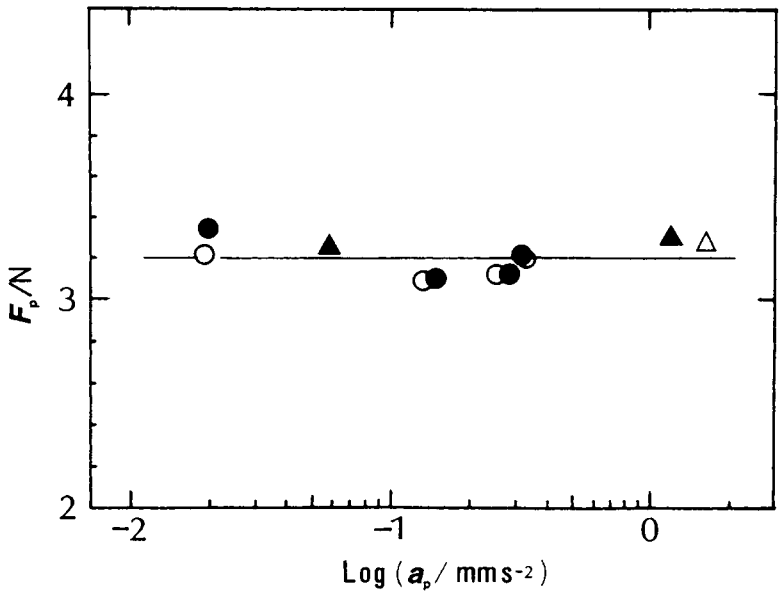

Figure 6 Peel force F_p plotted against the magnitude of a_p, at a rate of 0.5 mm/s in the interfacial failure region of sample A. Tape width is 10 mm. Open symbols, decelerating peel; solid symbols, accelerating peel. Circles, constant process; triangles, variable process; line, mean value.

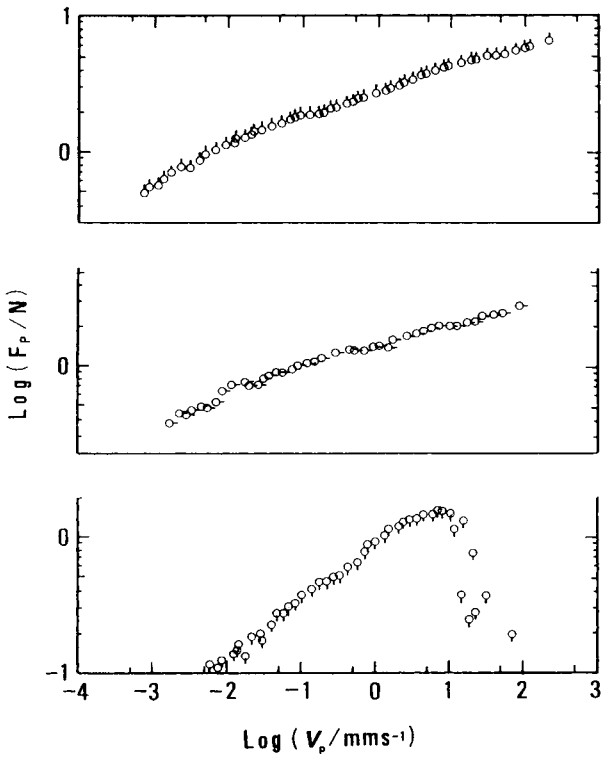

Figure 7 Peel force F_p versus peel rate V_p for PSA tapes with a variety of adhesives, in the accelerating peel of the rate process based on eq. (3). (♁) sample B; (○—) sample C; (♀) sample B′. Each tape width is 10 mm.

curred at the overall rates, although a cohesive failure regime was included at low rates, in particular in the accelerating peel; the transition regime between cohesive and interfacial failures was also observed as a hysteresis in a cycle run. Values in stationary peeling were consistent with the peeling curve, particularly in the decelerating peel.

The consistency between stationary and nonstationary peelings was further confirmed in the constant acceleration process of eq. (2). Figure 5 shows the results at different magnitudes of acceleration, along with the variable process curve. The change in one decade in acceleration hardly influenced the peel behavior. So the peel force in the interfacial failure regime was expected to be almost independent of the acceleration (Fig. 6). This means that the peeling by the nonstationary method may be regarded as quasistationary one.

Figure 7 shows peel force spectra over the wide rate range for samples B, C, and B′, in the accelerating peel of the rate process based on eq. (3); similar behavior was obtained in the decelerating peel. The peel behavior gave the interfacial failure for all samples if the stick–slip phenomenon for the B′ sample appeared at high peel rates. It is obvious that the difference between the results for the B′ and B samples is characterized by the different sorts of substrates. In view of other test results not given here,

the nonstationary peeling apparatus was expected to be available for investigating peel characteristics of test tapes under development and of practical tapes under various peeling conditions because of simple operation and use of short-length tapes. Among other advantages, a cycle run of relatively short measuring times readily gives the peeling behavior over the wide peel rate range, along with existence of the failure transition and peel anomalies. A viscoelastic model will be proposed elsewhere for explaining the nonstationary peeling.

CONCLUSIONS

It was reported that the nonstationary peel apparatus is useful to study the peel behavior of PSA tapes over a wide peel rate range, at varying peel angles, in a variety of substrates, and at a cycle of the accelerating and decelerating peel processes. The peel measurement in the decelerating peel gave quasistationary peelings, which may be regarded as the normal peeling by the conventional tester.

REFERENCES

1. E. H. Andrews, T. A. Khan, and H. A. Majid, *J. Mater. Sci.*, **20,** 3621 (1985).
2. E. H. Andrews and T. A. Khan, *J. Appl. Polym. Sci.*, **41,** 595 (1990).
3. H. Obori, M. Takenaga, and A. Kasai, *J. Appl. Polym. Sci.*, **46,** 553 (1992).
4. A. N. Gent and R. P. Petrich, *Proc. Roy. Soc.*, **A310,** 433 (1969).

Received October 15, 1993
Accepted January 26, 1994