Spatiotemporal patterns formed by deformed adhesive in peeling

Yoshihiro Yamazaki
Department of Physics, Waseda University, Okubo, Shinjuku-ku, Tokyo 169-8555, Japan
E-mail: yoshy@waseda.jp

Akihiko Toda
Faculty of Integrated Arts and Sciences, Hiroshima University, Kagamiyama, Higashi-Hiroshima, Hiroshima 739-8521, Japan
E-mail: atoda@hiroshima-u.ac.jp

Abstract. Dynamical properties of peeling an adhesive tape are investigated experimentally as an analogy of sliding friction. An adhesive tape is peeled by pulling an elastic spring connected to the tape. Controlling its spring constant $k$ and pulling speed $V$, peel force is measured and spatiotemporal patterns formed on the peeled tape by deformed adhesive are observed. It is found that there exist two kinds of adhesive state in peeling front. The emergence of multiple states is caused by the stability of a characteristic structure (tunnel structure) formed by deformed adhesive. Tunnel structures are distributed spatiotemporally on adhesive tape after peeling. Based on the spatiotemporal distribution, a morphology-dynamical phase diagram is constructed on $k$-$V$ space and is divided into the four regions: (A) uniform pattern with tunnel structure, (B) uniform pattern without tunnel structure, (C) striped pattern with oscillatory peeling, and (D) spatiotemporally coexistent pattern.

1. Introduction
Peeling an adhesive tape bears similarity to pulling a slider when their dynamical behaviors are focused on. Comparing these two dynamical systems as shown in Fig. 1, it is found that the peeling front of an adhesive tape corresponds to the contact surface between a slider and a plate. Physical and mathematical treatment for sliding friction system is then applicable to peeling system [1]. So far, we have carried out an experiment about dynamical behaviors of peeling [2, 3]. Our experimental setup is shown schematically in Fig. 1 (a). Two-ply adhesive tape was stuck on a flat solid plate and the top tape was connected to an elastic spring. Its spring constant is denoted by $k$. The elastic spring was pulled upward at constant speed $V$. In our case, the adhesive tape was peeled not from the surface of the solid plate but from the back surface of the bottom adhesive tape. We used a commercially available adhesive tape composed of a cross-linked natural rubber and a tackifier. The width of the tape was 25 mm. The backing tape film was a PET film of 25 $\mu$m thickness. The thickness of the adhesive was 28 $\mu$m. We varied $k$ and $V$ as controlling parameters. Peel force was measured, and a peeling front and a pattern formed by deformed adhesive on the tape after peeling were observed. A precise explanation of the setup is given in a previous paper [3].
Figure 1. (a) An experimental setup of peeling an adhesive tape. (b) A spring-slider system.

2. Tunnel Structure
In the experiment presented here, the adhesive was not left on the back surface of the bottom tape after peeling. This type of peeling is called adhesive separation (or adhesive failure). In the range of peel speed we controlled ($0.3 \text{ mm/min} \leq V \leq 10 \text{ mm/min}$), two typical types of peeling front were observed as shown in Fig.2. These snapshots were taken from the direction of the thick black arrow in Fig.1(a). Peeling proceeds from top to bottom in the figure. The state of the deformed adhesive in the peeling front became either of the two types. The white arrows indicate the detachment lines explained in Fig.1(a): (a) sinusoidal curve and (b) roughly meandering curve. The oval morphology seen in Fig.2(a) is the cross section of a tunnel structure formed by air invading into the adhesive from the direction of the white arrow. At the onset of the tunnel structure formation, fingering instability occurs for a straight detachment line. Due to the instability, the straight detachment line is undulated with a characteristic period [4, 5]. The undulation is considered to trigger the tunnel structure formation. The formation of tunnel structure is considered to be the same as the case reported by Urahama [6, 7]. We call this peeling state “peeling with tunnel structure”. The tunnel structure can be unstable depending on $V$, and “peeling without tunnel structure” is realized as shown in Fig. 2(b).

Figure 2. Two typical states of deformed adhesive in the peeling front. The white arrows in (a) and (b) point at the detachment lines. (a) $V = 0.4 \text{ mm/min}$, $k = 8.4 \times 10^3 \text{ N/m}$. (b) $V = 3.0 \text{ mm/min}$, $k = 8.4 \times 10^3 \text{ N/m}$. 
3. Morphology and Dynamics

3.1. Speed-Force Curve

The stiffness of the elastic spring affects a dynamical behavior of peeling. Time sequence of peel force essentially changes by varying $k$ even if $V$ is fixed. Figure 3 shows two examples of speed-force curve. The value of $k$ in (a) is smaller than that in (b). Open circles show the values of peel force and indicate peeling with constant peel force. The vertical lines show the amplitude of peel force which fluctuates in time. It is found from Fig.3(a) that the speed-force curve is classified into the following three regions A, B, and C, depending on $V$: A: peeling with constant force at low speed, B: peeling with constant force at high speed, and C: peeling with oscillating force in time. A typical time sequence of oscillating peel force is shown in Fig.4(a).

We call the peeling state in region C “oscillatory peeling” state. As $k$ increases, it is confirmed that region C becomes narrow and vanishes. Instead, the speed region spreads where peeling proceeds with almost constant peel force as shown in Fig. 3(b) [2, 3]. This speed region is called region D. It is noted that peel force decreases monotonically as $V$ increases. Fig.4(b) shows a time sequence of peel force in region D.

![Figure 3](image1)

Figure 3. Speed-force curves for different $k$: (a) $2.9 \times 10^2$ N/m and (b) $2.4 \times 10^4$ N/m.

![Figure 4](image2)

Figure 4. Time sequences of peel force in (a) region C and (b) region D. The vertical axises indicate the fluctuation in peel force from its average.
3.2. Morphology-Dynamical Phase Diagram
The peeling front is considered as a one dimensional system for creating tunnel structure, and is always normal to the direction of peeling. Then, the state of peeling at any position in the peeling front at any time is recorded on the peeled adhesive tape as a (1+1) dimensional pattern formed by the spatiotemporal distribution of tunnel structure. Based on the spatiotemporal patterns, morphology-dynamical phase diagram for peeling the adhesive tape was obtained as shown in Fig.5. The diagram is divided into the four regions. The regions with open circles, filled circles, double circles, and triangles correspond to the four peeling states A \sim D explained in sec.3.1, respectively.

![Figure 5. The morphology-dynamical phase diagram for peeling the adhesive tape.](image)

3.3. Spatiotemporal Patterns
Figure 6 shows spatiotemporal patterns which are obtained in each region of the morphology-dynamical phase diagram. Peeling proceeds from top to bottom for all patterns in this figure. Patterns obtained in regions A and B of the diagram are shown in Fig.6(a) and (b), respectively. White stripes in Fig.6(a) represent tunnels vertically aligned. Split, creation, and annihilation of tunnels occur by small fluctuations originating from inhomogeneity of the adhesive. In region B, peeling without tunnel structure is realized. Then, Fig.6(b) shows that there is no characteristic pattern left on the tape. In region C, a striped pattern is obtained as shown in Fig.6(c). Black and white regions alternate with each other in time. The white region represents the array of tunnels, while tunnels are not formed in the black region. Consequently, the striped pattern indicates periodic change of the state of the peeling front in time. Due to the difference in the required force for peeling in those states, the periodic change of the peeling state causes oscillation in peel force shown in Fig.4(a). In region D, peel force becomes almost constant in time. Following the above discussion, a uniform peeling state (and pattern) may be expected in region D. However, the pattern obtained in region D is far from uniform as shown in Fig.6(d). Black and white domains coexist in a peeling front, and their positions fluctuate in time. We call the pattern “spatiotemporally coexistent pattern”. The black and white domains represent the states of peeling without and with tunnels, respectively.
Figure 6. Snapshots of the spatiotemporal pattern left on the adhesive tape peeled in regions (a) A, (b) B, (c) C, and (d) D. Peeling proceeds from top to bottom.

4. Discussion
Interestingly, distribution of tunnel structure in region D varies spatiotemporally although peel force is almost constant. Regarding the relationship between spatiotemporally coexistent pattern and peel force, it has been known that peel force has a linear dependence on the occupation ratio of tunnel structure in a peeling front. We have confirmed that the ratio is a monotonically decreasing function of $V$. Since peel force with tunnel structure is larger than that without tunnel structure at each $V$, peel force is found to decrease as $V$ increases [3].

5. Conclusion
We have shown that peeling an adhesive tape causes formation of tunnel structure, and that various spatiotemporal patterns are formed by distribution of the tunnel structures on the peeled tape. The features of the spatiotemporal patterns depend on peel speed (pulling speed $V$) and stiffness of the peeling system (spring constant $k$). It is important that the dynamical properties of peel force can be identified from image analysis of the spatiotemporal patterns on the peeled adhesive tape.

Acknowledgments
This work was partly supported by a Grant-in-Aid for Scientific Research from the Japan Society for the Promotion of Science, the Waseda University Grant for Special Research Projects (No. 2003A-872), and the Ministry of Education, Science, Sports and Culture, Grant-in-Aid for Young Scientists (B), 17740257, 2005.

References
[1] Persson B N J 1998 Sliding Friction (Berlin: Springer)
[2] Yamazaki Y and Toda A 2002 J. Phys. Soc. Jpn. 71 1618
[3] Yamazaki Y and Toda A 2006 Physica D 214 120
[4] Shull K R, Flanigan C M and Crosby A J 2000 Phys. Rev. Lett. 84 3057
[5] Ghatak A, Chaudhury M K, Shenoy V and Sharma A 2000 Phys. Rev. Lett. 85 4329
[6] Urahama Y 1989 J. Adhesion 31 47
[7] Urahama Y 1991 Nitto Gihou 29 1 (in Japanese)