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Spatio-Temporal Patterns in an Adhesive Tape at Peeling

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Abstract

We investigated the dynamical behavior of an adhesive tape at peeling. And a dynamical-morphological phase diagram as functions of peel speed and spring constant was obtained. The spatio-temporal patterns turn out to be classified roughly into four types; low-speed pattern, high-speed pattern, oscillatory pattern, and spatio-temporal intermittent pattern.

keywords : adhesion, dynamical phase diagram, stick-slip motion, fingering instability, spatio-temporal intermittency

Introduction

Adhesion is a common phenomenon in our daily life and is characterized as a mechanical behavior when we separate two materials sticking to each other. It is, however, considered to be difficult to understand adhesive behaviors quantitatively since we must take into account not only a microscopic change of surface properties but also a macroscopic deformation of an adhesive itself [1]. In order to characterize the mechanical properties of an adhesive, speed-load curve is measured by peeling an adhesive tape. This measurement has been carried out as an industrial test in general. Furthermore this measurement is also important from the viewpoint of soft matter physics.

Recently, the dynamical properties of an adhesive tape has been studied by observing the morphology of a peeling front of adhesive [2]. In the case of adhesive failure which means that the adhesive does not remain on the surface of the substrate after peeling, two sorts of morphologies are observed depending on the peel speed and load. In one state, adhesive undergoes a large deformation and forms a tunnel-like morphology. The large deformation causes the energy dissipation and peel speed becomes low. In the other state, adhesive failure occurs before the large deformation of adhesive. Therefore the peel speed is larger than that of the former state, and no morphology is observed. The interesting point is that there is an

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oscillatory region between these two states with respect to peel load. If the experiment with a constant speed within the intermediate region is carried out, then these two states emerge alternately in time. We expect that this oscillatory motion in an adhesive tape is also able to understand within the common physical framework to other stick-silp phenomena [3] such as dry friction of granular matter [4], paper-paper slip [5], earthquake [6], and melt fracture in polymeric liquid [7].

In this Letter, we report the results of our experiments for the further investigation and try to understand the peeling behavior by constructing a dynamical phase diagram.

Experimental Setup

The experimental setup is shown schematically in Fig.1. A two-ply adhesive tape was sticked on a solid plate and the top tape was connected to an elastic spring whose spring constant is denoted by k in this figure. The elastic spring was pulled upward at one end with a constant speed V. Therefore the peeling angle in our experiment is 90°. It is noted that we consider the peeling of an adhesive tape not from the surface of a solid plate but from the back surface of the other adhesive tape. We used an adhesive tape with cross-linked adhesive (No.31D, Nitto Denko Corporation). The width of the tape is 25mm and the substrate is a PET film with 25 μm thickness. The temperature was 25 ± 1 °C and humidity was not controlled. It is known that moisture has little effect on the property of adhesive we used [8]. As control parameters we changed k and V, and we measured the peel load F and observed the patterns left on the surface of a peeled tape.

Results

Speed-load curves in three different cases, namely, $k = 2.9 \times 10^2$, 2.9×10^3, and 2.4×10^4 N/m are shown in Fig.2. From Fig.2(a), it is found that two stationary regions represented by a set of white circles (region A: $V < 0.8$ mm/min, region B: $V > 2.0$ mm/min) exist. In each region, peel load increases as peel speed becomes high. The strength of the peel load in these regions seems to be independent of the spring constant. In the intermediate region between regions A and B, oscillatory motion occurs as shown in Fig.2(a). The speed-load behavior in Fig.2(a) is consistent with the experimental results by Urahama [2]. In addtion we found that the intermediate oscillatory region becomes narrower and finally vanishes as k increases (see Fig.2(b) and (c)). We also confirmed that the fluctuations in peel load from the average are gradually diminished as k increases at a fixed peel speed. Therefore we expect that there exists a critical spring constant as a function of peel speed at which a Hopf bifurcation occurs.

The difference between region A and region B emerges not only in a speed-load curve but also in a morphology of adhesive during peeling. Figure 3 shows the typical failure front of an adhesive tape in peeling process. Figs. 3(a) and (b) are failure fronts in the case of regions A and B, respectively. The direction of peeling is down. In the case of region A, it is found that oval holes aligning regularly are formed in front of the failure front. These holes represent cross sections of tunnels made of adhesive as pointed out by Urahama. On the other hand, in the case of region B, no hole is formed and the failure front becomes rough. The difference in the failure front between these two regions is considered to be caused by the visco-elastic behavior of adhesive. In region A, peel speed is low and adhesive is able to deform largely. In region B, however, peel speed is so high that the failure occurs without large deformation in most part of adhesive. Instead of a tunnel formation as in the case of region A, fibrils are formed by the large deformation only in the limited local part of adhesive. These deformations in both speed regions occur in the vicinity of the failure front and remain even after peeling. Therefore, we can identify a peeling process by observing an adhesive tape after peeling.

Figure 4(a) and (b) show the typical patterns in a peeled adhesive tape in regions A and B, respectively. In Fig.4(a), a striped pattern is seen. White lines represent tunnels of adhesive, and some defects exist where a white line is terminated or is splitting into two or three lines. The splitting of a white line occurs due to the tip splitting of an oval air hole in Fig.3(a) induced by fingering instability [9]. In contrast, no pattern is observed in Fig.4(b) because large deformation occurs only in a limited local region of adhesive.

In the intermediate speed region between two regions A and B, we found two characteristic pattens depending on the spring constant as shown in Fig.5. In these figures, peeling progresses from top to bottom. Morphologies observed in the case of regions A and B are seen as white and black regions in Fig.5, respectively. Figure 5(a) is a striped pattern alternating morphologies in the case of region A and B, and this striped pattern is obtained in the case where the spring constant is small. It is found that this pattern is spatially uniform and periodic emergence of two morphologies causes the oscillation of peel load. As the spring constant becomes bigger, spatial uniformity in the pattern is lost and black and white regions vary not only temporally but also spatially as shown in Fig.5(b). In the case of a hard spring, the deviation of peel load must be reduced and a steady state in peel speed and load is realized. The crucial point from Fig.5(b) is that a steady state is realized not by emergence of a new morphology formed by peeled adhesive but by coexistence of two morphologies obtained in the case of region A and B. Therefore, if we change a peel speed, a new steady state is achieved by changing the ratio of white region to black region as shown in Fig.6.

Then, It turns out to be that the spatio-temporal patterns can be classified into four types; low-speed pattern, high-speed pattern, oscillatory pattern, and spatio-temporal intermittent pattern. Actually the dynamical-morphological phase diagram in V-k space was obtained as shown in Fig.7. Low-speed and high-speed patterns correspond to morphologies in the case of regions A and B, respectively. And oscillatory pattern is characterized as a spatially uniform striped pattern.

Summary and Discussion

We investigated the dynamical behavior in the peeling process of an adhesive tape from a morphological viewpoint. The features are summerized as follows.

(i) By constructing a dynamical-morphological phase diagram in V-k space the spatio-temporal patterns of a peeled adhesive tape can be classified into four types; low-speed pattern ($V < V_{\mathrm{L}}$), high-speed pattern ($V > V_{\mathrm{H}}$), oscillatory pattern ($V_{\mathrm{L}} < V < V_{\mathrm{H}}$, $k < k_{\mathrm{c}}(V)$), and spatio-temporal intermittent pattern ($V_{\mathrm{L}} < V < V_{\mathrm{H}}$, $k > k_{\mathrm{c}}(V)$). V_{L} is the upper limit speed for the low-speed pattern, and V_{H} is the lower limit speed for the high-speed pattern. k_{c} is the upper limit spring constant for a spatially uniform striped pattern.

(ii) From a speed-load measurement, a transition from a steady state to an oscillatory state occurs at a critical spring constant k^*. k^* is expected to be a Hopf bifurcation point. The relation between k_{c} and k^* is not clear.

(iii) A steady state in a speed-load curve in the case of $V_{\mathrm{L}} < V < V_{\mathrm{H}}$ and $k > k^*$ is realized by controlling the rate of a spatial occupation of morphologies in low-speed and high-speed patterns at a time. And this ratio depends on the peel speed.

The failure front in a spatio-temporal intermittent pattern is shown in Fig.8. The peeling process progresses downward. It is found from this figure that the failure in high-speed region occurs in the middle region of the front line and two kinds of failure fronts as shown in Fig.3 coexist. The important point is that the positions of the failure fronts in two states are different from each other. Therefore this difference is considered to have an influence on the morphologies in the vicinity of the interface between two states. In constructing a model for the dynamical behavior of an adhesive, we must take into account not only the effect of spring as a global interaction but also the spatial variation of the failure front as a local interaction.

Acknowledgments

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References

[1] C. Gay and L. Leibler. *Physics Today*, 52(11):48–52, 1999.

[2] Y. Urahama. *J. Adhesion*, 31:47–58, 1989.

[3] B. N. J. Persson. *Sliding Friction.* Springer-Verlag, Berlin, 1998.

[4] S. Nasuno, A. Kudrolli, A. Bak, and J. P. Gollub. *Phys. Rev. E*, 58:2161–2171, 1998.

[5] F. Heslot, T. Baumberger, B. Perrin, B. Caroli, and C. Caroli. *Phys. Rev. E*, 49:4973–4987, 1994.

[6] J. M. Carlson and J. S. Langer. *Phys. Rev. Lett.*, 62:2632–2635, 1989.

[7] K. Sato and A. Toda. *J. Phys. Soc. Jpn.*, 68:77–85, 1999.

[8] Y. Urahama. private communication. 2001.

[9] M. Rabaud, S. Michalland, and Y. Couder. *Phys. Rev. Lett.*, 64:184–187, 1990.

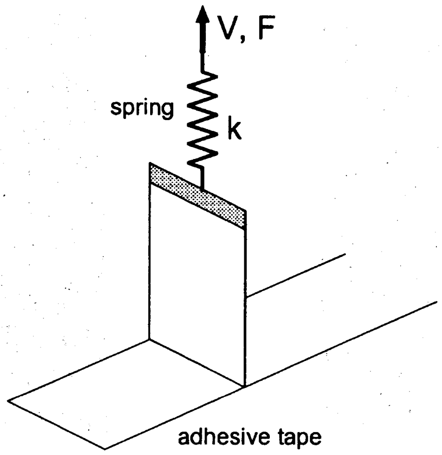
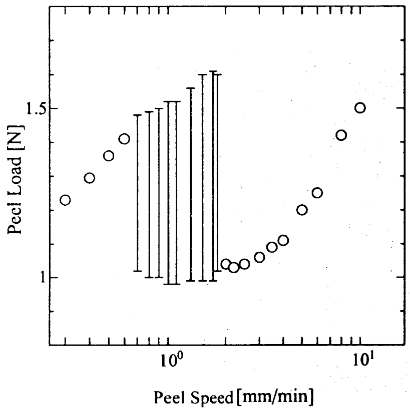
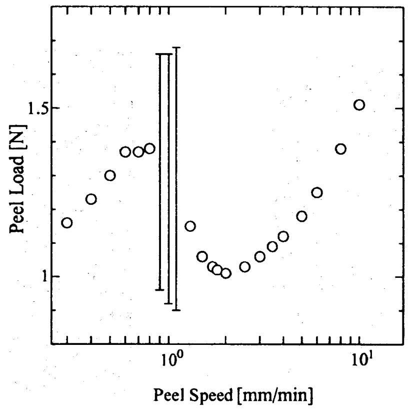


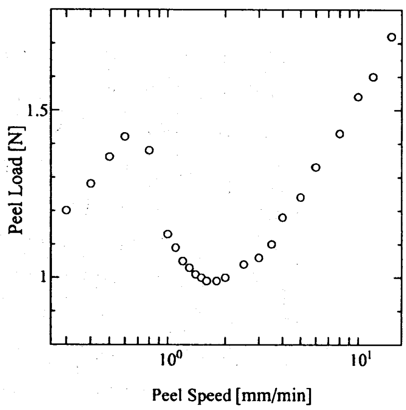
Figure 1: Schematic representation of the experimental setup.



(a) k= 2.9×10^2 N/m



(b) k=2.9×10^3 N/m



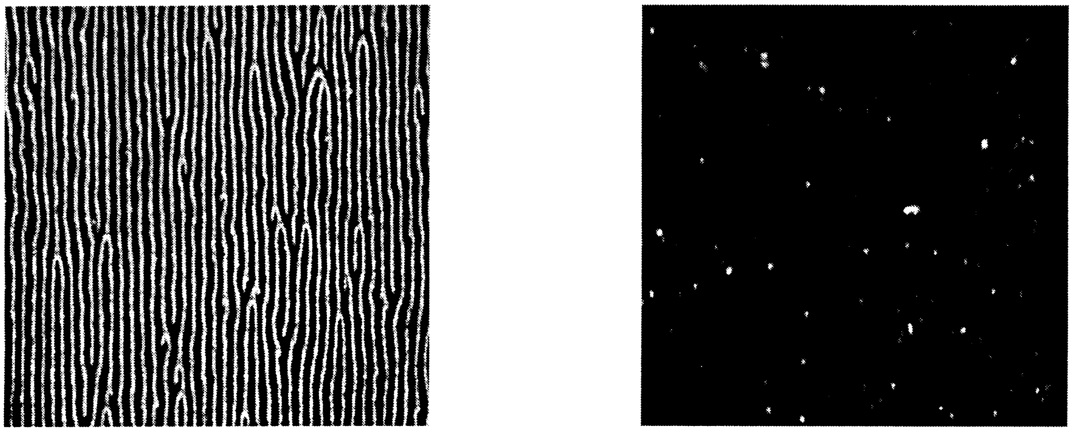
(c) k=2.4×10^4 N/m

Figure 2: Peel load as a function of peel speed V in three cases with a different spring constant. (a) k=2.9×10^2 N/m, (b) k=2.9×10^3 N/m, (c) k=2.4×10^4 N/m. The bar represents the amplitude of the oscillatory motion in peel load at each fixed peel speed.

(a)

(b)

Figure 3: Failure fronts at peeling. Peeling progresses from top to bottom. (a) the morphology of adhesive in the case of region A. (b) the morphology of adhesive in the case of region B. The actual size of these figures is 440 μm$\times$ 290 μm.



(a) (b)

Figure 4: Snapshots of typical patterns in a peeled adhesive tape. (a) the case of region A. (b) the case of region B. The actual size of these figures is 5.0 mm $\times$ 5.0 mm.

(a) (b)

Figure 5: Snapshots of typical patterns in the intermediate regions of peel speed between region A and B. (a) oscillatory pattern; $k = 2.9 \times 10^3$ N/m, $V = 0.8$ mm/sec. (b) spatio-temporal intermittent pattern; $k = 2.7 \times 10^3$ N/m, $V = 1.6$ mm/sec. The actual size of these figures is 25 mm $\times$ 19 mm.

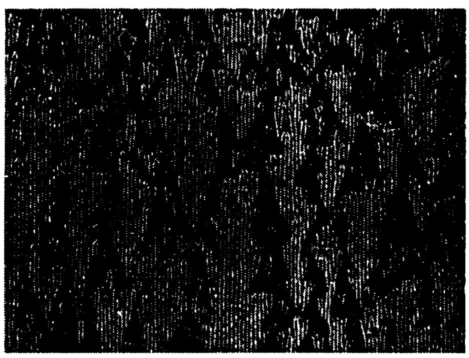


Figure 6: Another example of a spatio-temporal intermittent pattern with a different condition from Fig.5(b). The actual size of this figure is 15 mm $\times$ 11 mm.

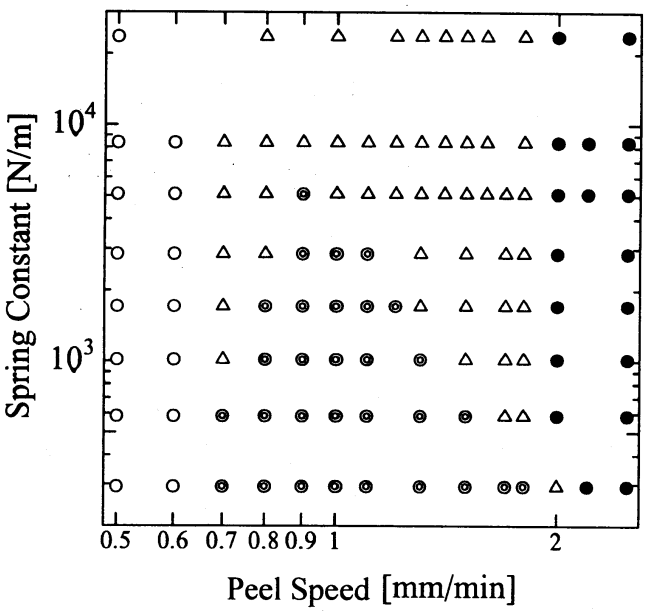


Figure 7: Dynamical-morphological phase diagram in V-k space.

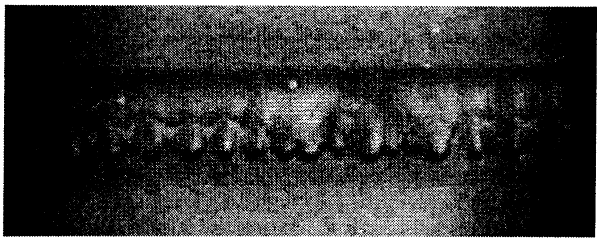


Figure 8: A failure front in the case of a spatio-temporal intermittent pattern. Two kinds of failure morphologies, namely, morphologies in low-speed pattern and high-speed pattern coexist. The actual size of this figure is 1.9 mm $\times$ 0.75 mm.