Experimental study of the stick-slip effects in adhesive peeling: instability range as a function of velocity

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We report an experimental study of the problem of the stick-slip dynamics associated to adhesive tape peeling. We will vary the peeling velocity by pulling the tape from the original roll using a commercial rotating tool and detecting the instability with a thermographic infrared camera. The aim is to detect the limits of the instability regions and compare with the values of Dalbe *et al.* [1]. The results match relatively well with previous experiments. Several modifications will be proposed to improve the experimental setup.

I. INTRODUCTION

Adhesive peeling is an interesting fracture phenomenon [2], [3], [4], [5], [6] which occurs when adhesive tape is removed from a substrate. Not only does this phenomenon occur in everyday situations, but also happens in industrial environment (lettering, packaging) and more recently, in nanoscience and nanotechnology applications, such as nano adhesive polymers [7] or graphene exfoliation [8]. The study of peeling dynamics has been of research interest in the last decades. Peeling can be understood as an advancing fracture front in which air penetrates the adhesive film. The advance of the fracture front is not always smooth, but in contrast, it occasionally might show instabilities.

From an energetic point of view, the energy input from the external work performed by the peeling force at the free end of the tape, is used to break the adhesive polymer chemical bonds, being eventually transformed into heat. Part of the work can also be temporary stored and released as elastic energy in the already detached tape. Eq. 1 shows the energies involved in tape peeling. [2]

$$-bR\Delta c + F(1-\cos\theta)\Delta c - E_{elastic} = 0 \qquad (1)$$

The first term comes from the creation of a new free surface of adhesive when peeling. b is the tape width, Δc is the length of the peeled segment whereas R is the fracture energy per unit surface. The second term corresponds to the work performed by the applied force F. θ is the angle between the applied force and the original adhesion surface. Finally, the third term comes from the elastic energy $E_{elastic}$ stored in the detached tape when strengthened in the direction of the applied force [2]. In some geometries, this term does not play a role when the peeling is smooth and stationary, although it might have an influence when the process accelerates or decelerates.

Nevertheless, the advancement of the fracture front is not always smooth. On a regular basis, the energy needed for the fracture to proceed is higher at high velocities. Therefore, the front advances smoothly with a speed proportional to the applied force. This occurs both at low and very high speeds. Yet there is a range of velocities for which the fracture energy decreases with the velocity. In this range, the front becomes unstable, it advances jerkily, and the peeling occurs as a sequence of stick-slip events.

A peeling experiment can be performed subject to different geometries: the tape can be stuck either to a flat surface or to a roll; the peeling can be driven both by applying a constant force at the end of the tape or by forcing a constant mean velocity V; the peeling angle might be kept constant or not, etc. In many situations, studies have detected unstable regions $\left(\frac{\partial F}{\partial V} < 0\right)$ when the external force versus mean velocity is plotted, as indicated in Fig.1**.** In the unstable region, the instantaneous front velocity oscillates between the nearest two stable solutions V_{min}, V_{max}, while in the stable regions, the peeling velocity matches with front peeling velocity.

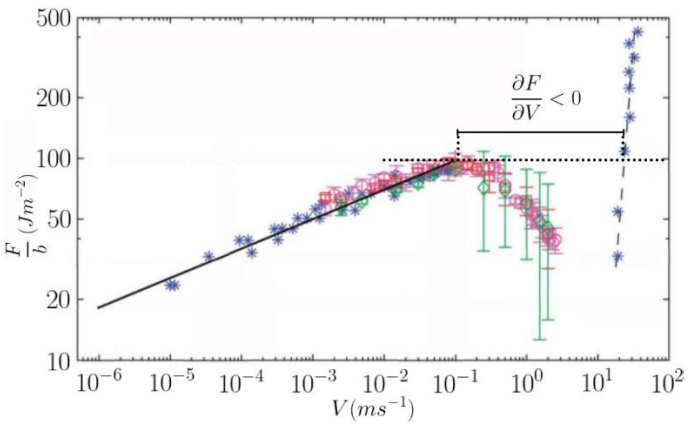

Figure 1. Mean value of the peeling force F (divided by the tape width, F/b), as a function of mean velocity V for different experiments and 3 different tape lengths L. The solid line and dashed line are power law fits to the low and high velocity stable branches respectively. Error bars represent the standard deviation of the force fluctuations during one experiment. Data extracted from [1] and [3].

Dalbe *et al.* found that when increasing peeling velocity, the instability starts in ~10^{-1} m/s and finishes near ~20^{1} m/s. However, when decreasing velocity, the instability starts at ~10 m/s and goes down to ~10^{-6} m/s (approx. 0 m/s). A hysteresis phenomenon can be appreciated due to the curve

behaviour; consequently, the instability should end at a higher velocity when accelerating than it starts when decelerating. In these regions, the stick-slip instability occurs, and the oscillations of the peeling front can be measured with a thermographic camera. Recent studies [5] suggest that the instability is a multiscale phenomenon, where not only the peeling front advances jerkily but also the fracture advances transversal (for instance from left to right) to the tape also as a sequence of microfractures.

This TFG is the third on this subject in the Physics Faculty of UB. Previous works have studied acoustic emission of peeling adhesive tapes [9] and thermal characterization of tape peeling [10], however, both of them at low velocities. Our purpose is to increase the velocity enough to detect the stick-slip instability. In section II the experimental setup will be presented. Results are detailed at section III and finally, the conclusions are given in section IV.

II. EXPERIMENTAL SETUP

A commercial roll of adhesive tape has been used in this experiment (3M Scotch® 600, made of a polyolefin blend backing coated with a layer of a synthetic acrylic adhesive [11]). The adhesive tape has been mounted on an office tape dispenser inclined 50º so as to prevent the tape from tilting its axis when high velocities are imposed.

We have used a commercial rotating tool (Dremel® 4000-1/45) to unroll the tape. The tape was unwound from its original support, while wounding around the rotating tool's axis.

A total of 6 experiments have been conducted, of which only 2 have provided reliable data. Each experiment consists of increasing the velocity from 0 m/s up to a maximum value V_{max}. Subsequently, the velocity is decreased back to 0 m/s in order to see the stick-slip effects twice: the first one accelerating, and the second one when decelerating.

Once the rotating tool is connected, it takes around 0.5 s to reach constant angular velocity ω_{max}. When ω_{max} is reached, it is kept constant for ~1.5 s. After this time, the rotating tool angular velocity is slowly decreased manually using a variable resistor that changes the power from 100% to 0% in ~1 s. The total duration of each experiment is ~3 s. One should take into account that along this process the rotating tool axis diameter increases every lap due to the increase of the rolled tape thickness. Consequently, when angular velocity reaches a constant value ω_{max}, linear velocity will not. A more accurate discussion will be presented in part III.

The acquisition of the temperature map near the peeling front has been done by an InfraTec® ImageIR 8800 thermographic camera (S/N 88173812) with the IRBIS-3.1 software. The camera recorded 160x256 pixel frames every 1.06 ms (947 fps). In typical experiments, sequences of 10 seconds were taken (9470 frames) in order to ensure that the 3 s of the experiment were captured. Experimental setup can be seen in Fig.2 (a).

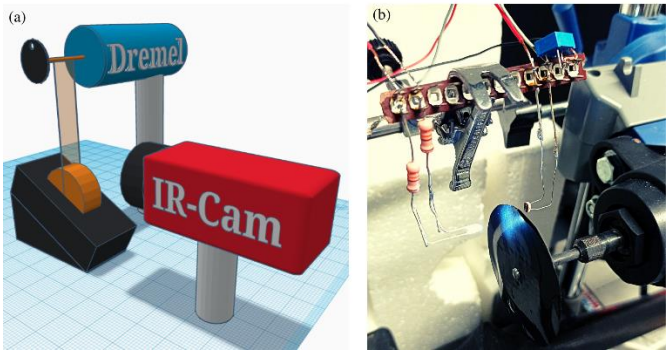

Figure 2. (a) Schematic representation of the experimental set up showing the tape, the tape dispenser, the IR-Cam and rotating tool. (b) Detail of the electronic circuit used to measure the peeling speed.

A light dependent resistance (LDR) has been used to measure the rotating tool period. A black disk with a hole aligned with the LED and the LDR has been mounted on the rotating tool axis, as shown in Fig.1(b). Every time the rotating tool finishes a lap, the hole intersects the line between the LED and the LDR. The electronic signal from the sensor is measured with an oscilloscope (Tektronix MSO44, 200 MHz, 6.25 GS/s). The detail of the electronic circuit as well as an example of the signal measured by the oscilloscope can be seen in Fig.3.

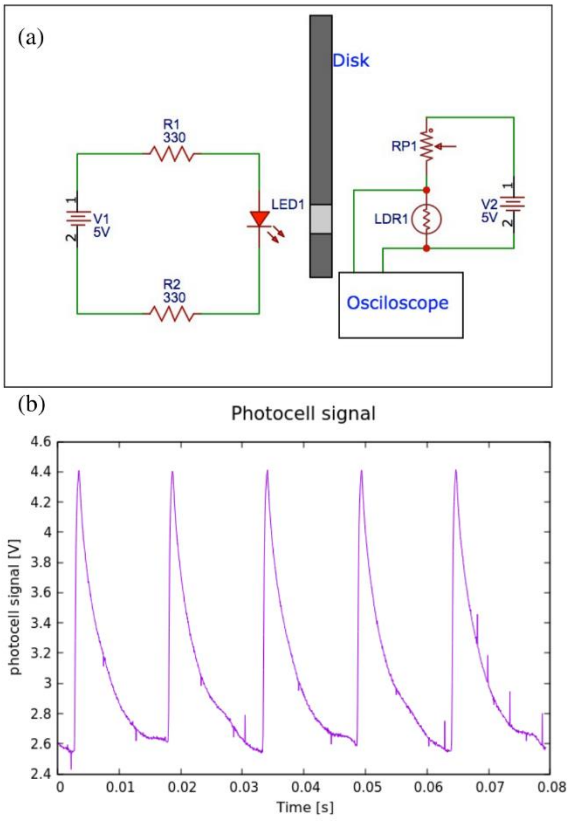

Figure 3. a) Electronic circuit used to measure the rotating tool period. b) Example of signal measured by the oscilloscope. Each peak corresponds to a lap of the rotating tool axis. An arbitrary time has been used to represent the signal.

The IRBIS-3.1 software has enabled the synchronisation of the beginning of the recording by the camera and the time scale in the oscilloscope. A switch connected to an IR-Cam input has been used to trigger the recording of the images at a safe distance from the tape in order to avoid thermal noise. Moreover, the whole experiment has been covered with insulating material so as to avoid reflexions of external radiation.

Thus, for the experiment to start, several coordinated steps must be taken.

1. IR-Cam calibration. A non-radiative background must be placed in front of the lens to fix all the pixels at the same temperature level.
2. Start the IR-Camera. The camera is ready for the acquisition but, as previously described, the recording will not start until a manual switch is activated.
3. Start the oscilloscope recording, set to last for 15 s.
4. Turn on manually the switch which activates the camera. The camera, then, sends a square signal every time a frame is recorded.
5. Connect the rotating tool. The tape will start unrolling.
6. After ~2 s, decrease the value of the variable resistor which controls the power of the rotating tool.
7. Wait until the oscilloscope ends the recording and save the data for its posterior analysis.

III. EXPERIMENTAL RESULTS

The data recorded by the oscilloscope is analysed in order to measure the angular velocity of the rotating tool. Knowing the initial and final diameter of the tape rolled to the tool and the number of laps done, it is possible to represent the mean lineal velocity at every lap *i*,

$$V_i = \omega_i * r_i \qquad (2)$$

where r_i can be obtained by

$$r_i = \frac{\phi_0}{2} + \frac{i(\phi_f - \phi_0)}{2N} \qquad (3)$$

and where $\phi_0$and ϕ_f are the initial and final diameter of the rolled tape in the rotating tool axis, *N* is the total number of laps and ω_i is the angular velocity of each lap *i*.

Fig.4 represents the measured angular velocity of the rotating tool and the corresponding peeling velocity.

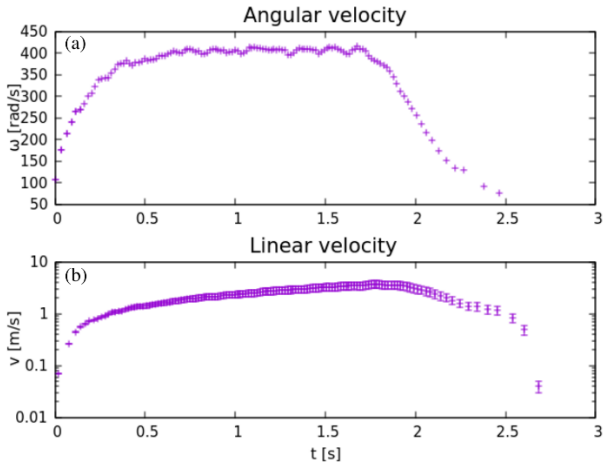

Figure 4. (a) Angular velocity of the rotating tool axis. It reaches a constant value after 0.5 s, showing a manual slow deceleration afterwards. (b) Linear peeling velocity of the tape. A logarithmic axis has been used to have a better representation of the zone of interest.

The IR-Camera provided a set of synchronised images where the presence of instability was detected. Although it seems easy to spot the difference between a frame with lines from another with none, in practice the determination of the change is somewhat diffuse. The first and last images with evident lines have been taken as the start and end of the stick-slip instability.

Fig.5 shows example of images of stick-slip instability (a) and smooth peeling (b).

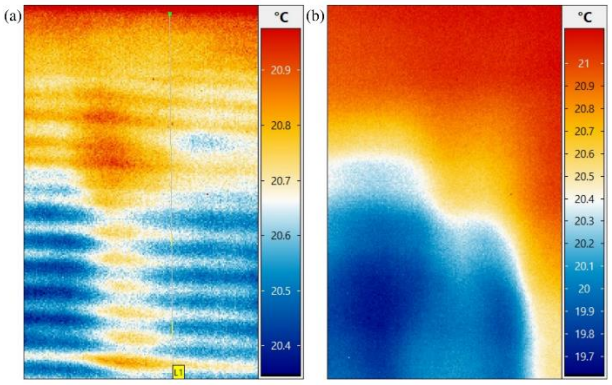

Figure 5. (a) Frame of a zone with stick-slip instability. (b) Frame of a zone with no instability. The temperature variations in this frame are caused by the heating of the tape due to the force applied.

Comparing the time of each frame with the data plotted in Fig.4 it is possible to represent the zones where the instability occurs, which are represented with yellow boxes in Fig.6.

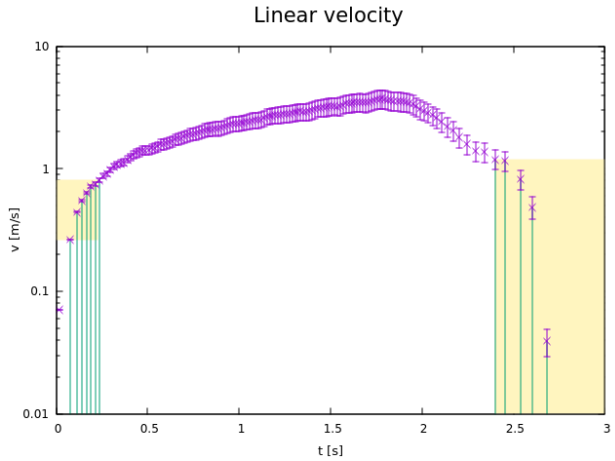

Figure 6. Peeling velocity as a function of time with vertical logarithmic axis. Green lines indicate the laps for which instability has been detected. Yellow boxes represent the initial and final velocity for each instability zone, when accelerating and decelerating.

We have found that when accelerating instability lines appear at 0.26±0.05 m/s and disappear at 0.8±0.05 m/s. When decelerating, instability lines appear at 1.2±0.3 m/s and do not disappear until the tape has stopped.

The experimental error comes mostly from the velocity determination. The linear velocity is the product of the angular velocity times the radius, as can be seen in Eq. (3). The determination of angular velocity is quite accurate due to the resolution of the oscilloscope, although the determination of the radius assumes that the tape rolls perfectly to rotating tool axis. The commercial specifications of the tape report the thickness of the tape to be 38 μm while our measurements give a value of 64±1 μm. Consequently, an error of ±15 μm is added to the radius r_i value at every lap.

IV. DISCUSSION AND CONCLUSSIONS

In this paper, we report a peeling experiment of an adhesive tape from its roll. We have focused on the detection of stick-slip instability by using an IR-camera.

The instability is detected between 0.26±0.05 m/s and 0.8±0.05 m/s when accelerating and between 1.2±0.3 m/s and 0 m/s when decelerating. These values are lower than the ones reported in the literature [1]. However, the qualitative behaviour of the instability matches with what was expected. There are two different instability regions, one corresponding to acceleration and one to deceleration. The instability zone shows hysteresis.

As it was presented in section III, problems in the determination of r_i might have caused the measurement of the velocities to be higher than the real one.

We can propose some modifications in order to improve future experiments. The experiments conducted reach higher velocities than the ones of interest. In future experiments, peeling velocity should be increased more slowly towards a smaller maximum value (approx. 2 m/s), yet still big enough to ensure the observation of instabilities. The stretching should be done with a more controllable device, such as a servo motor or stepper motors. The rotating tool is too powerful for this experiment. Moreover, the system used to measure the angular velocity is quite accurate, but it could be improved a lot by digging some more holes in the black disk. Finally, we have measured the peeling velocity in the rotating tool axis although one could measure the unrolling velocity at the roll axis by using a similar method (black disc, LDR and LED). This will allow us to correct the fact that the peeling angle is changing.

To conclude, we have determined stick-slip instabilities during the peeling of an adhesive tape. Despite experimental limitations, results are rather accurate and reliable. Agreement with previous data in the literature is qualitative. A series of modifications of the experiment have been proposed in order to improve the results.

Acknowledgments

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