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# Multi-scale stick-slip during the peeling of adhesive tape

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## Résumé :

*Nous avons étudié l'instabilité de stick-slip lors du pelage d'un adhésif depuis un substrat plan, à vitesse imposée. Grâce à une caméra rapide montée sur un microscope, nous pouvons observer soit le front de pelage, soit le profil du ruban, tout en enregistrant simultanément les émissions acoustiques. Dans une certaine gamme de vitesse, le pelage présente une dynamique instable multi-échelles, avec deux échelles spatio-temporelles très différentes. L'instabilité à plus grande échelle correspond au stick-slip traditionnellement observé. Celle à plus petite échelle, que nous appelons micro stick-slip, est liée au relâchement de l'énergie de courbure dans le ruban adhésif, concentrée à proximité du front de pelage. Nous montrons que ce micro stick-slip correspond à la propagation de fractures transverses le long de la largeur du ruban, comme cela a été observé récemment [1, 2]*

## Abstract :

*We study the stick-slip instability when peeling an adhesive tape from a flat substrate at an imposed driving velocity. Using a high-speed camera mounted on a microscope, we image either the detachment front, or the ribbon profile at microscopic scale, while simultaneously recording acoustic emissions. In a given range of driving velocity, the peeling displays a multi-scale unstable dynamics, with two well-separated spatio-temporal scales, which corresponds to microscopic and macroscopic dynamical stick-slip instabilities. We show that the microscopic stick-slip dynamics – which presents very different characteristics than the well-known macroscopic instability – is related to a high-frequency periodic release of the elastic bending energy of the adhesive ribbon concentrated at the vicinity of the peeling front. Moreover, we also show that it corresponds to the recently observed [1, 2] periodic propagation of fast transverse fractures across the tape width in the ultrasonic range.*

## Mots clefs : Stick-Slip ; peeling ; adhesive

When peeling an adhesive tape at fixed velocity, in a typical range of driving velocity, even though the velocity is imposed on one end of the tape, the detachment front can oscillate between a fast and slow motion. Even though such unstable stick-slip dynamics has been studied extensively [3–11], it is still not fully understood and remains nowadays an industrial concern.

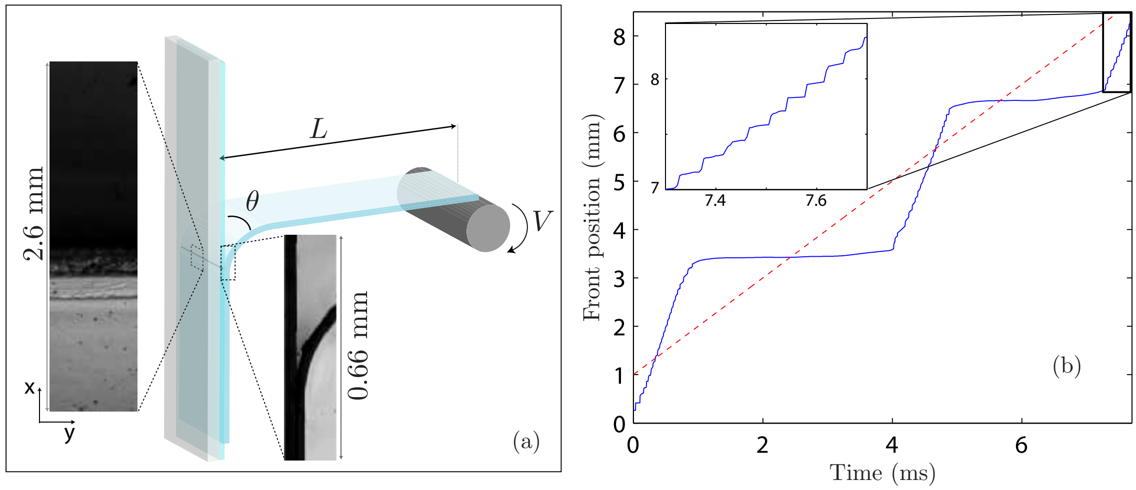


FIGURE 1 – (a) Microscopic observations of the detachment front and ribbon profile, when peeling an adhesive tape from a flat surface, imposing a velocity $V$ at a distance $L$. (b) Peeling front position as a function of time for $L = 80$ cm, $\theta = 90°$ and $V = 1$ m s$^{-1}$ (continuous line). Two stick-slip cycles are shown. The slope of the dashed line is the peeling velocity $V$. The inset is a zoom on a slip event.

Here, we present an experimental study, where we directly observe the peeling dynamics at very high spatial and temporal scales. We peel an adhesive tape (3M Scotch® 600) from a microscope transparent plate by winding its extremity at a constant velocity $V$, using a brushless motor. The substrate is a microscope glass plate covered with a first layer of the studied adhesive. The winding cylinder is placed at a distance $L$ from the substrate and the peeling angle is set to $\theta \approx 90°$, as shown in figure 1(a). The peeling angle $\theta$ and the peeled length $L$ can be considered constant since they vary less than 4% and 0.2% respectively, during an experiment.

Using a high-speed camera (PHOTRON SA5) mounted on a microscope (Zeiss), we image either the detachment front, or the ribbon profile at microscopic scale, while simultaneously recording acoustic emissions during the peeling experiments.

First, we report measurements based on the observation of the peeling front (see left picture in figure 1(a)). Depending on the imposed peeling velocity $V$, frame rate and image size are varied between 300 000 fps for $256 \times 64$ px images and 525 000 fps for $192 \times 32$ px images, for a fixed spatial resolution of 9.5 $\mu$m/px. From the gray-scale images, we extract the longitudinal position of the detachment front $x(y_0, t)$ at a given transverse position $y_0$. Figure 1(b) provides a typical example of such local front position time series for a peeling experiment at $L = 80$ cm, $\theta = 90°$ and $V = 1$ m s$^{-1}$. We observe that the front advances by steps, characteristic of a stick-slip unstable dynamics. In those experimental conditions, the duration of the stick-slip events is about 3 ms, and their amplitude 3 mm, which corresponds to previous results for this adhesive [12]. In the insert, we zoom into a slip event. We observe again a regular step-like dynamics at much shorter spatial and temporal scales, with periods of about 40 $\mu$s and jumps of about 140 $\mu$m. Increasing the acquisition frame rate of the camera up to 700 000 fps, we could observe that these micro-stick-slip events correspond to the periodic propagation of a transverse fracture across the tape width in the adhesive, as reported in [1].

Simultaneously to the direct observation of the detachment front, we measure also the acoustic signal emitted during the peeling, using a microphone (Bruel & Kjaer, 4190) placed at 6 cm from the peeling front, with a sampling frequency 500 kHz. On figure 2(a), we show the evolution of the acoustic emission during an experiment with $L = 100$ cm and $V = 0.5$ m s$^{-1}$. The acoustic signal is composed of a series of bursts, separated by quiescent periods with almost no emissions. On figure 2(b) we zoom in on a portion of the experiment for which we measure simultaneously the front position, and thus its velocity (see figure 2(c)). We observe that the acoustic bursts correspond to the macro slip events, while no acoustic emission are registered during a macro stick event.

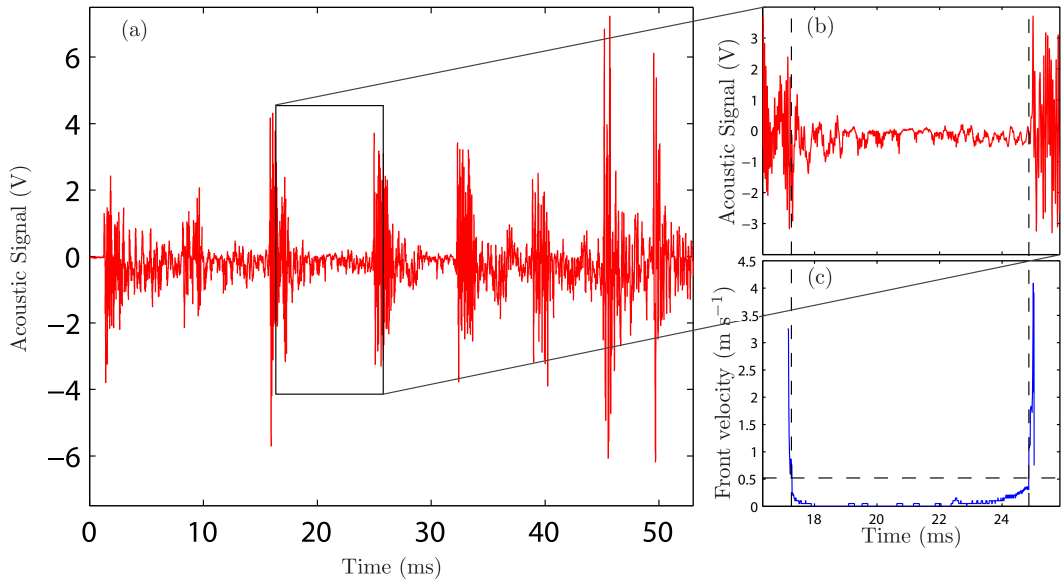


FIGURE 2 – (a-b) Acoustic signal as a function of time. (c) Front velocity $v_f$ as a fonction a time. The horizontal dashed line represents $v_f = V$. The vertical dashed lines correspond to the beginning and the end of a macro stick event (when $v_f = V$). Experiment with $L = 100$ cm and $V = 0.5$ m s$^{-1}$.

In figure 3, we show an example of synchronized acquisitions during a macro slip event. We observe that the period of the acoustic emissions is the same as the one of the microscopic stick-slip instability.

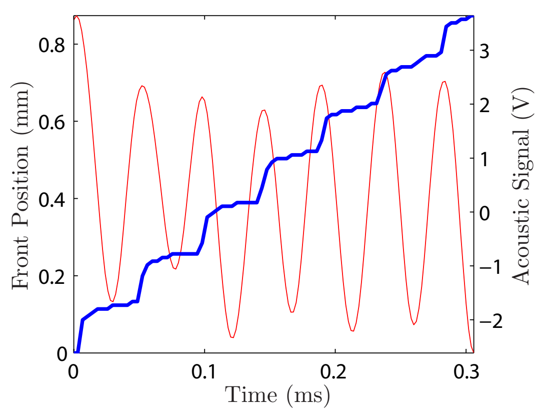


FIGURE 3 – Experiment with $L = 1$ m and $V = 0.5$ m s$^{-1}$. Red : Acoustic emissions. Blue : peeling front position.

Finally, we also observe the peeling dynamics from the side, imaging the tape edge at 150 000 fps and $512 \times 80$ px, with a resolution of 5 $\mu$m/px (right picture on figure 1(a)). From these images, we extract the peeled tape profile evolution as a function of time as reported in figure 4(a) for an experiment at $V = 0.73$ m s$^{-1}$, $L = 1$ m, and $\theta = 90°$. At the beginning of the recording (right side), there is a high density of profiles, typical of a stick phase. Then there are few profiles over a large distance, typical of a slip event. During this slip phase, one can observe sudden jumps of about 100 microns, characteristic of the micro-slips. From the shape of the profiles, using Elastica Theory, we can extract the evolution of the peeling force $F$, as shown in figure 4(b). Each point represents one profile, and the colors correspond to figure 4(a). We can observe that each micro-slip is accompanied by a drop in the peeling force $F$. This drop corresponds to a decrease of the curvature of the peeled tape profile, and thus a release of the bending energy of the ribbon. Assuming that this energy release allows the front to advance of a micro-step, we could obtain an estimation of the associated fracture energy $\Gamma = 13.5 \pm 1.3$ J m$^{-2}$. Interestingly, this value is remarkably close to the macroscopic effective fracture energy $\Gamma = G(V)$ measured at the local minimum of $G(V)$ around 19 m s$^{-1}$ [9].

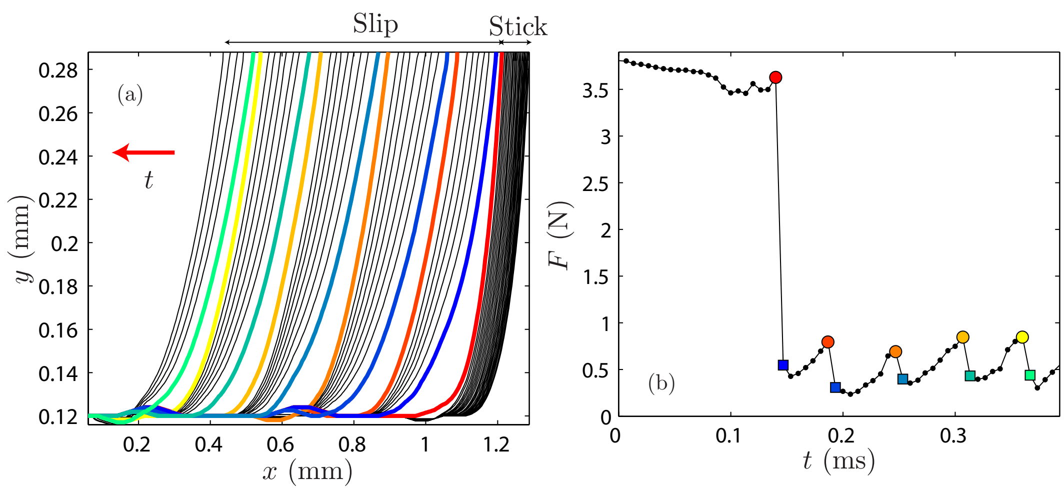


FIGURE 4 – Time evolution of the peeled ribbon profile in the laboratory frame (a) and corresponding force in the straight part of the peeled tape (b), for an experiment at $V = 0.73$ m s$^{-1}$, $L = 1$ m and $\theta = 90°$. Warm colors correspond to profiles just before a micro-slip (circles in (b)) and cold colors to profiles just after a micro-slip (square in (b)).

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