Stick-Slip instability during adhesive tape peeling : from regular to unstable peeling dynamics

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Résumé :

Nous étudions le pelage d'un ruban adhésif depuis un substrat plan à vitesse imposée constante. Grâce à une caméra rapide haute résolution, nous observons et suivons la dynamique du front de détachement, à angle de pelage et longueur de ruban fixés. Nous caractérisons les différentes dynamiques observées, du pelage régulier au pelage saccadé ("Stick-Slip"), en fonction de la vitesse de pelage imposée. En particulier, à la transition entre ces deux régimes, nous avons mis en évidence l'existence d'une nouvelle dynamique de pelage instable, composée d'oscillations quasi-sinusoïdales en vitesse autour de la vitesse imposée. La période de ces oscillations correspond à la durée des cycles de Stick-Slip observés à haute vitesse de pelage, et peut être prédite en prenant en compte l'inertie du ruban.

Abstract :

We study the peeling of an adhesive tape from a flat substrate at a constant imposed velocity. Thanks to a high resolution fast camera, we observe and follow directly the detachment front dynamics, for a peeling angle and length of the ribbon fixed. We characterize the various dynamics of the detachment front observed, from a regular to a Stick-Slip motion, as a function of the imposed peeling velocity. In particular, at the transition between those two regimes, we reveal the existence of a novel unstable dynamics, with quasi-sinusoidal oscillations of the front velocity, around the set-point value. Interestingly, the period of those oscillations corresponds to the duration of the Stick-Slip cycles observed at large peel velocities, which can be predicted by taking into account the ribbon inertia.

Mots clefs : Stick-Slip, instabilité, pelage, ruban adhésif

1 Introduction

When peeling an adhesive tape at a constant velocity, the adhesion energy can become a decreasing function, in a given range of peeling velocities [1]. As a consequence, it costs less energy to the peeling front to propagate faster, and a dynamical instability may occur. In this range of velocity, the detachment front can indeed display periodic alternations of fast and slow phases, usually called "Stick-Slip" [1, 2]. Despite a large number of studies, such dynamical instability remains nowadays an industrial problem, due to the resulting intense acoustic noise and damages produced to the adhesive layer.

Thanks to high resolution fast imaging, recent studies have shown the key role of the peeling angle [3] and the ribbon inertia [4] on such unstable motion, as well as its multi-scale nature [5, 6]. Indeed, the fast "Slip" phases of the Stick-Slip cycles present as well a Stick-Slip dynamics but at microscopic spatio-temporal scales [5, 6].

In the present work, we pursue those experimental studies by investigating the propagation of the detachment front during the peeling of an adhesive tape from a flat surface at a constant imposed velocity. We reveal here the existence of a novel regime of the unstable dynamics occurring at the onset of the Stick-Slip instability, and characterized by quasi-sinusoidal oscillations of the detachment front velocity around the imposed velocity. The period of those oscillations corresponds to the duration of the periodic Stick-Slip cycles observed at large peeling velocities. Taking into account dynamical effects related to the ribbon inertia, a recent model could predict the duration of those Stick-Slip cycles [4]. We argue here that such approach is perfectly adapted to explain the quasi-sinusoidal velocity oscillations of the detachment front observed at the transition between the regular and the Stick-Slip peeling.

2 Experimental set-up

We have developed an experimental set-up - represented on Fig. 1 - dedicated to the characterization of the detachment front dynamics at a high resolution both spatially (μm scale) and temporally (μs scale) for peeling experiments at high velocities.

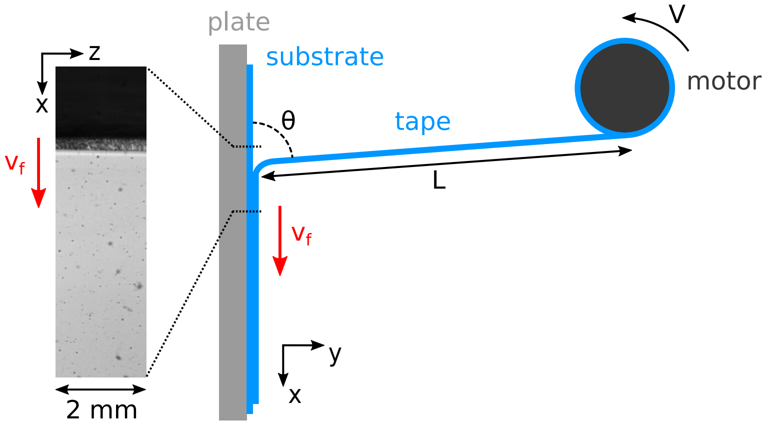

FIGURE 1 – Experimental set-up : the adhesive tape (3M Scotch® 600) is peeled from a flat substrate by a motor at the velocity V and the distance L, with the peeling angle θ. A high resolution fast camera images the detachment front through a transparent substrate (backing of the 3M Scotch® 600 adhesive tape) mounted on a transparent plate.

The adhesive tape is peeled from a transparent flat substrate at a constant velocity V, by a motor placed at a distance L with a peeling angle set to θ. Using a high resolution fast camera (Photron SA5) with a macro lens, we observe and follow directly the detachment dynamics through the transparent substrate mounted on a transparent plate. A typical recorded image is shown on Fig. 1. For each image, we extract the position of the detachment front (black-white interface) and deduce its velocity v_f, computed on a temporal window of 100 μs.

We use 3M Scotch® 600 tape [1, 2, 3, 4, 5, 6] made of a polyolefin blend backing ($e = 34$ μm thick, $b = 19$ mm wide, tensile modulus $E = 1.41$ GPa) coated with a 20 μm layer of a synthetic acrylic adhesive. The preparation of the adhesive-substrate joint is crucial to obtain reproducible results. In practice, for each experiment we extract two layers of such a tape from a roller. We then fix them on a transparent plate and perform the peeling at the interface between those two layers - the backing of the 3M Scotch® 600 tape constitutes the substrate of our peeling experiments.

In the present study, we fix $L \approx 50$ cm and $\theta \approx 90°$. During an experiment, θ and L vary less than 3% and 0.4% respectively, and we can consider them constant. In these conditions, the velocity of the motor V is the unique control parameter of our peeling experiments. We have studied the evolution of the peeling dynamics from $V = 0.01$ m/s to 1.5 m/s.

3 Different regimes of the peeling dynamics

3.1 Regular peeling

At low peeling velocity, $V < 0.18$ m/s, the displacement of the front is linear and regular, its velocity is constant and corresponds to the velocity imposed by the motor. A typical example of such stable peeling dynamics is shown on Fig. 2, with $V = 0.11$ m/s.

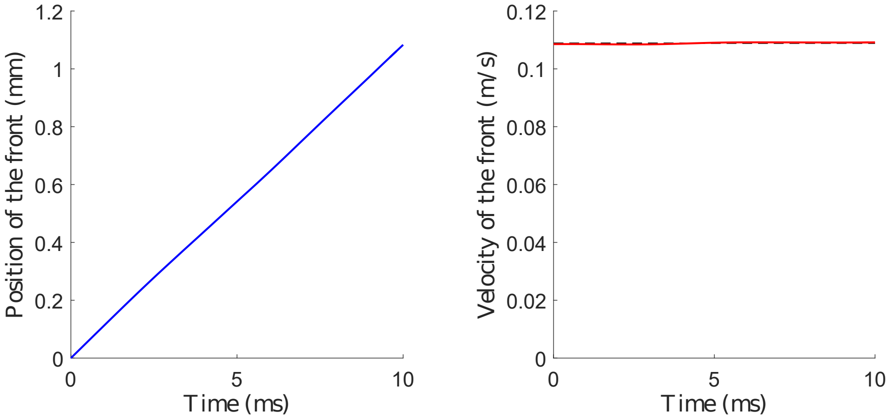

FIGURE 2 – Displacement and velocity of the front for a regular peeling dynamics at $V = 0.11$ m/s. The displacement of the peeling front is linear and its velocity is constant, equal to the one imposed by the motor.

3.2 Oscillations of velocity

In a very short range of peeling velocity, 0.18 m/s $< V <$ 0.20 m/s, we could observe that the displacement of the front displays a succession of acceleration and deceleration, leading to quasi-sinusoidal oscillations of velocity v_f around the imposed velocity V. An example at $V = 0.18$ m/s is represented in Fig. 3.

This novel unstable dynamics is characterized by low amplitude oscillations of periods $T_{osc} \sim 3$ ms. Contrary to the Stick-Slip dynamics, observed at larger peeling velocities and discussed in the following section, in this oscillatory regime the detachment front dynamics does not present any microscopic instability.

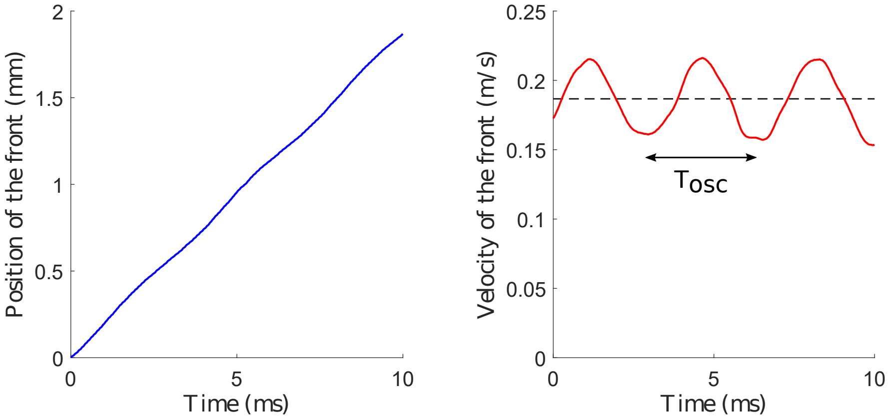

FIGURE 3 – Displacement and velocity of the front for an oscillatory dynamics at $V = 0.18$ m/s. The velocity of the peeling front oscillates around the imposed velocity, with a period $T_{osc} \sim 3$ ms.

3.3 Multi-scale Stick-Slip

For larger peeling velocities, 0.20 m/s $< V <$ 1.5 m/s, the displacement of the front presents a multi-scale Stick-Slip instability [6]. An example at $V = 0.55$ m/s is represented in Fig. 4.

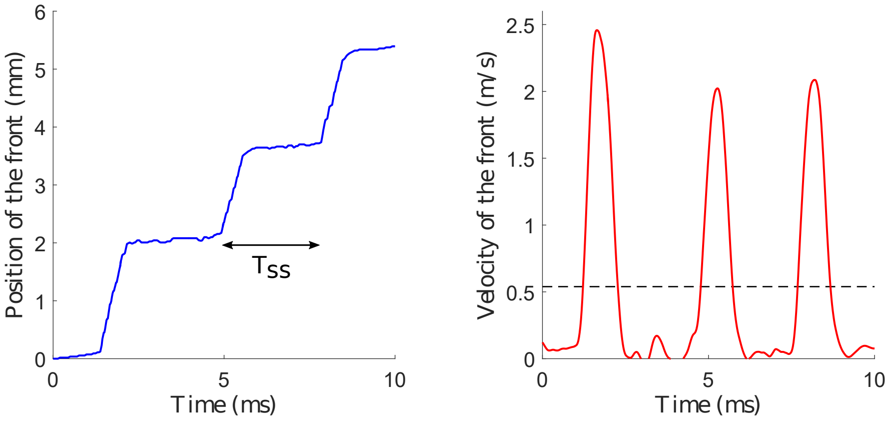

FIGURE 4 – Displacement and velocity of the front for a Stick-Slip dynamics at $V = 0.55$ m/s. The velocity during the fast phases is well above the average velocity, and the front is quasi-stationary during the slow phase.

While the average front velocity over the experiment duration is equal to the driving velocity V (dashed line in Fig. 4), we observe that the peeling front advances by steps, characteristics of a Stick-Slip instability. Indeed, we can observe large fluctuations of the detachment front velocity, with periodic alternations between fast phases (“Slip”) - well above the imposed peeling velocity - and quasi-static phases (“Stick”). The shape of those velocity fluctuations are not sinusoidal, with an amplitude much larger than the one observed in the previous oscillatory regime. We can measure the period T_{SS} of those Stick-Slip cycles of a few ms, which evolve with the imposed velocity V as reported in [3].

Moreover, during the rapid Slip phase, we can observe on Fig. 5 a step-like dynamics at a much shorter spatio-temporal scales, corresponding to a micro-Stick-Slip instability [6]. In the zoom, we can indeed observe a succession of regular jumps of the detachment front of around ~ 200 μm [5, 6], separated by periods of rest of few tenth of μs, much smaller than the duration of the macro-Stick, and therefore than the duration of the macro-Stick-Slip cycles.

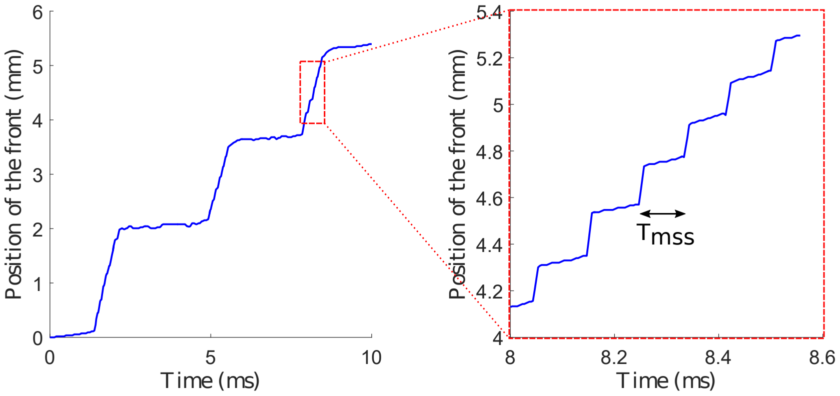

FIGURE 5 – Illustration of the multi-scale Stick-Slip dynamics of the detachment front, obtained during a peeling experiment at $V = 0.55$ m/s. The regular jumps in the zoom correspond to the micro-Stick-Slip instability.

In the present study, we wanted to investigate the transition from regular to unstable Stick-Slip peeling dynamics. Therefore, we did not perform experiments at very large peeling velocities above 1.5 m/s. However, previous studies have shown that the peeling dynamics become regular again at high velocity [1], with a disappearance of the micro-instability [6].

4 Evolution of the period of the macro-instability

We have performed up to 10 different experiments at a given constant imposed peeling velocity V. We could then detect up to a few tenth of either oscillations or Stick-Slips events, depending on the range of imposed peeling velocity. On Fig. 6, we report the averaged value of the duration of those unstable events as a function of the peeling velocity.

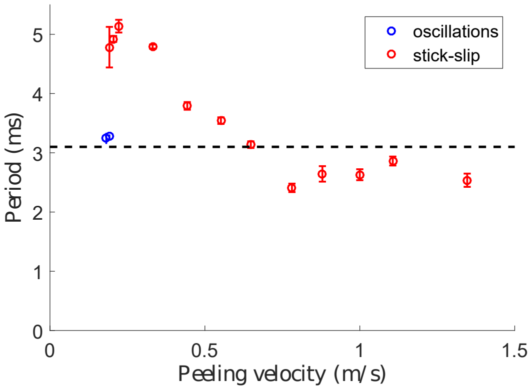

FIGURE 6 – Evolution of the period of the macro-instability with the imposed velocity V. The prediction of the constant value by the inertial model [4] is represented in dashed line.

As already discussed in the previous section, the oscillatory dynamics detected at the transition between a regular peeling and the Stick-Slip motion of the front is present in a very narrow range of imposed velocity. Nevertheless, for those experiments, the period of the oscillations is really robust around $T_{osc} \approx 3.2$ ms, and independent of the velocity (in contrast to their amplitude, which seems to increase with V).

Strikingly, for slightly larger peeling velocity, in the regime of the multi-scale Stick-Slip instability, the periods of the macro-instability jumps to a much larger value (almost a factor 2). Then, this period decreases with V, towards a constant value around 2.6 ms for peeling velocities $V > 0.6$ m/s, in agreement with previous experimental results [3, 4].

Barquins, Maugis and co-workers in [1, 2] proposed in the late 80's a quasi-static approach to model the Stick-Slip dynamics, assuming that the detachment front can be described in the Stick phase by a steady state equation giving an equilibrium between the instantaneous energy release rate and the fracture energy Γ. Assuming moreover that the Slip phase duration is negligible, they could predict the duration of the Stick phases and thus the Stick-Slip period, using measurements of the adhesion energy $\Gamma(V)$ at low peeling velocities, below the onset of the instability. In particular, they could predict that the period of the Stick-Slip instability evolves as the inverse of the imposed peeling velocity :

$$T_{SS} \sim T_{Stick} \propto 1/V.$$

As we can observe on Fig. 6, and in agreement with previous experiments [4], such a model seems to be valid at low peeling velocity 0.2 m/s $< V <$ 0.8 m/s. However, it fails to reproduce the large constant Stick-Slip periods measured at larger peeling velocities.

Therefore, in order to understand this regime at large peeling velocity, a novel model that took into account the inertia of the peeled ribbon has been proposed recently [4]. This approach predicts quasi-sinusoidal oscillations of the peeling front velocity with a period independent of the peeling velocity :

$$T_{SS}^{(i)} = \frac{2\pi L}{c\sqrt{1-\cos\theta}} \approx 3.1 \text{ ms}$$

with c the celerity of the dilatation wave in the ribbon ($c \approx 1.0\;10^3$ m/s for the 3M Scotch$^{\circledR}$ 600 adhesive tape [4]).

Interestingly, one can notice that such behavior corresponds quantitatively to our measurements characterizing the oscillatory dynamics, which appears at the onset of the multi-scale Stick-Slip instability. It is important to remark that the assumptions required to develop this model are perfectly valid in this range of velocity. In this approach, an important assumption was to consider that the variation of the fracture energy Γ with the velocity V is negligible. This is indeed the case, since Dalbe *et al.* [4] reported a plateau behavior for $\Gamma(V)$ in the range of velocity for which we observe the oscillatory front dynamics.

5 Conclusion

We have performed an experimental study of the detachment front dynamics of an adhesive tape peeled at a constant imposed velocity from a flat substrate. We could observe and characterize various unstable regimes of the peeling front dynamics. In particular, we could unveil a novel unstable dynamics with sinusoidal oscillations of the peeling front velocity, that occurs at the transition between a regular and multi-scale Stick-Slip motion. The period of those oscillations seems to be independent of the imposed peeling velocity. They can be understood thanks to a model originally developed to describe the Stick-Slip dynamics observed at large peeling velocities, which considered the kinetic energy cost to accelerate and decelerate the peeled ribbon. We are currently studying how the peeling angle θ affects this novel unstable dynamics of the detachment front, in particular at large peeling angles.

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