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Stick-slip peeling of a roller adhesive tape at a constant velocity

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Résumé :

Nous étudions expérimentalement la dynamique de pelage à vitesse imposée d'un rouleau de ruban adhésif, et en particulier son régime dit de stick-slip qui consiste en des oscillations à haute fréquence entre des phases lentes et rapides du pelage. Grâce à l'analyse d'images de caméra rapide, nous mesurons les caractéristiques de l'instabilité (durée et amplitude) pendant ces phases lentes et rapides lors du régime de pelage stationnaire. Nous montrons que leurs dépendances avec la vitesse de pelage et la longueur de bande pelée sont radicalement différentes de celles présentées dans des études antérieures.

Abstract :

We study experimentally the peeling dynamics at an imposed velocity of a roller adhesive tape, focusing on the so-called stick-slip regime which consists in high frequency oscillations between phases of slow and rapid peeling. Thanks to an analysis of high speed camera images, we measure the statistics of the stick and slip phases characteristics. We show that their dependences on peeling velocity is radically different compared to previously reported results.

Mots clefs : Stick-Slip ; Peeling ; Adhesive

1 Introduction

Everyday examples of adhesive peeling are found in applications such as labels, postage stamps, tape rollers, self-adhesive envelopes or post-it notes. During the peeling of those adhesives, a dynamic instability of the fracture process corresponding to a jerky advance of the peeling front and so called “Stick-Slip” instability may occur and damage the adhesive.

From a fundamental perspective, it is the non-monotonous dependence of the fracture energy with the peeling velocity (typical of confined adhesive material), coupled with the compliance of the peeling system which is expected to trigger such unstable crack growth within a specific velocity range. Although stick-slip peeling of adhesives has been an industrial concern since the 1950's, it is still a limiting factor for industrial productivity due to noise pollution, chattering damage on some assembly lines and finally to the low reliability of the technical solutions applied trying to suppress it. Quantitative experimental information concerning the stick-slip dynamics itself, except the velocity onset of the instability, is rather scarce. Indeed, stick-slip dynamics has been characterized, for a long time, only through indirect measurements of the periodic marks left on the tape [1, 2, 3], the peeling force oscillations [3, 4, 5, 6], the emitted acoustic sounds [6, 7], and occasionally the emitted X-rays [8]. It is only very recently that the first direct observation of the peeling point motion during the stick and slip phases of a roller tape pulled either at constant force or constant velocity has been fulfilled by our group [9, 10].

In this paper, we present a study of the stick-slip motion obtained using a time-resolved imaging technique that we recently developed [9]. The stick-slip motion is observed in stationary conditions, i.e.

at constant applied peeling velocity. We analyze the stick-slip characteristics –duration and amplitude of stick and slip– as function of the peeling velocity V and peeled length L . Surprisingly, we show that the stick-slip characteristics have a dependence on those control parameters V and L , which is radically different compared to results previously reported [2, 4].

2 Experimental setup and extraction of the peeling point dynamics

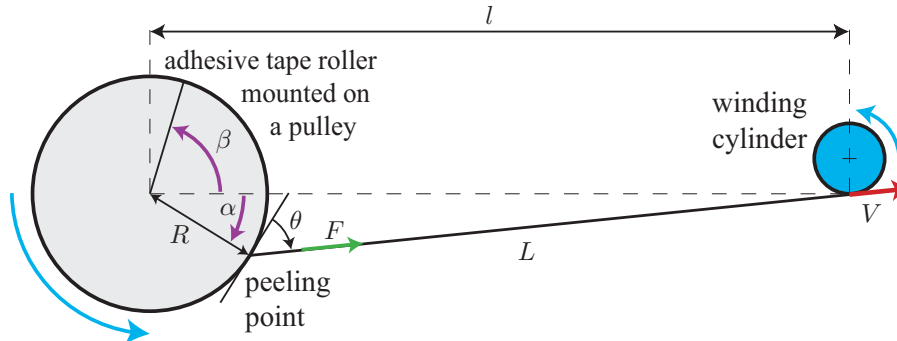


FIGURE 1 – Schematic view of the experimental setup. The angles α and β are algebraic and oriented clockwise and counter-clockwise, respectively. Roller diameter : $40 \text{ mm} < 2R < 58 \text{ mm}$, roller and tape width : 19.5 mm , tape thickness : $50 \mu\text{m}$.

We peel a roller adhesive tape, mounted on a freely rotating pulley, by winding up the peeled ribbon extremity on a cylinder at a constant linear velocity V using a servo-controlled brushless motor (see Fig. 1). The adhesive tape used —3M Scotch[®] 600— is of the same kind as in previous works [9, 11]. Each experiment consists in increasing the winding velocity from 0 up to the target velocity V at a rate of 1 m s^{-2} . Once the peeling velocity V is reached, it is maintained constant during two seconds before decelerating the velocity back to zero. When stick-slip is present the peeling is stationary only in a statistical sense and the 2 seconds stationary regime of the adhesive tape peeling are long enough to get excellent statistics for the stick-slip events. We have varied the distance between the pulley and the winding cylinder from $\ell = 10 \text{ cm}$ up to $\ell = 2.5 \text{ m}$, and the peeling forcing velocity from 0.15 to 2.5 m s^{-1} in order to cover the whole range where stick-slip is observed for the considered adhesive. The actual peeled tape length L (Fig. 1) is submitted to fluctuations due to the stick-slip which are negligible compared to its mean value.

The local dynamics of the peeling point is imaged using a high speed camera (Photron FASTCAM SA4) at a rate of 20000 fps. The recording of each movie is triggered once the peeling has reached a constant average velocity V ensuring the stationary regime for the stick-slip only is characterized. Through image processing, the movies finally allow us to access : the curvilinear position of the peeling point $\ell_\gamma = \ell_\beta + \ell_\alpha$ in the roller reference, from the curvilinear position of the peeling point $\ell_\alpha = R\alpha$, in the laboratory reference frame (with α the angular position of the peeling point and R the roller diameter), and the curvilinear position of the adhesive roller $\ell_\beta = R\beta$, in the laboratory reference frame (where β is the unwrapped angular position of the roller). In Fig. 2, we show a typical example of the extracted curvilinear position of the peeling point $\ell_\gamma(t)$ in the roller reference frame as a function of time for an average peeling velocity $V = 0.74 \text{ m s}^{-1}$. One can actually see alternate phases of slow –stick phase– and fast –slip phase– peeling. Differentiating the position $\ell_\gamma(t)$ of the peeling point in the roller reference frame, it is easy to compute the instantaneous peeling velocity $v_{pp} = d\ell_\gamma/dt$. The observed large and saw-tooth shaped velocity fluctuations on Fig. 2 are the signature of the stick-slip motion. One can actually see that the stick-slip fluctuations of the velocity are constituted of oscillations that are quite regular in duration and amplitude at least at the considered peeling velocity $V = 0.74 \text{ m s}^{-1}$. From the signal of instantaneous peeling velocity $v_{pp}(t)$, we define the mean stick velocity v_{stick} and mean slip velocity v_{slip} per stick-slip cycle as follows : for each stick-slip cycle, we compute the average value of the velocity during the phases where $v_{pp}(t) < V$ (stick) and $v_{pp}(t) > V$ (slip) with V the average imposed peeling velocity. These stick and slip velocities are

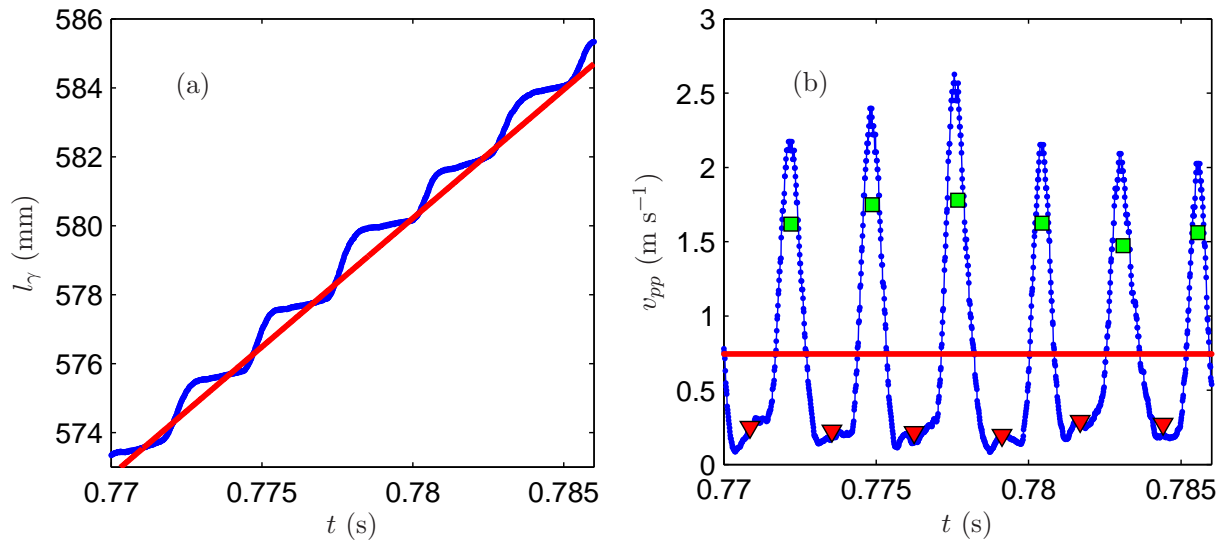


FIGURE 2 – (a) Peeling point curvilinear position $l_\gamma(t)$ in the roller reference frame for an experiment performed at $V = 0.74 \text{ m s}^{-1}$ and $\ell = 0.55 \text{ m}$ (see Fig. 1). The red line represents $l_\gamma = Vt$. (b) Corresponding peeling point velocity $v_{pp}(t)$ in the roller reference frame. The horizontal red line shows the average peeling velocity V . Red triangles and green squares respectively show the averaged stick v_{stick} and slip v_{slip} velocities for each stick-slip cycle.

plotted respectively with red triangles and green squares. We see that the stick and slip velocities are slightly fluctuating in time during a peeling experiment at constant velocity and therefore stick-slip appears to be stationary only from a statistical point of view.

3 Pendular oscillations

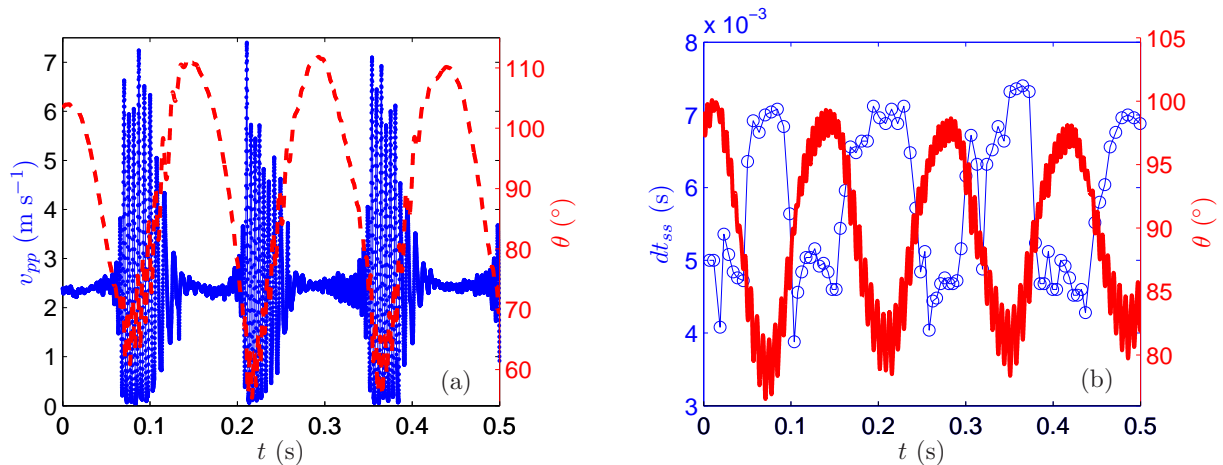


FIGURE 3 – (a) Full line : peeling velocity as a function of time. Dashed line : corresponding oscillations of the peeling angle. The slow oscillations correspond to the pendulum-like motion. The fast oscillations correspond to Stick Slip events. (b) Circles : Stick Slip durations. Full line : oscillation of the angle. The two evolutions seem correlated.

As we have shown recently in [10], when the average peeling velocity V is increased, the stick-slip dynamics may become intermittent alternating between periods of time with fully-developed stick-slip and periods of time without or at least strongly attenuated stick-slip cycles. A typical example of such intermitencies is shown in Fig. 3(a), where we can observe clearly that the intermittent stick-slip behaviour is very-well correlated with the low frequency pendular oscillations of the peeling point

angle $\theta(t)$ (the high frequency variations of the angle are directly correlated to individual stick-slip events). The origin of these oscillations is due to the interplay between the inertia of the roller and the moment applied to the roller by the peeling force [9]. In addition, we show here on Fig. 3(b) that the durations of the stick-slip cycles dt_{ss} display as well a strong correlation with the low frequency pendular oscillation of the peeling point. Therefore, we clearly show that the characteristics of the stick-slip dynamics are affected by the peeling angle which is unfortunately not controlled in this set-up.

4 The stick-slip duration and amplitude

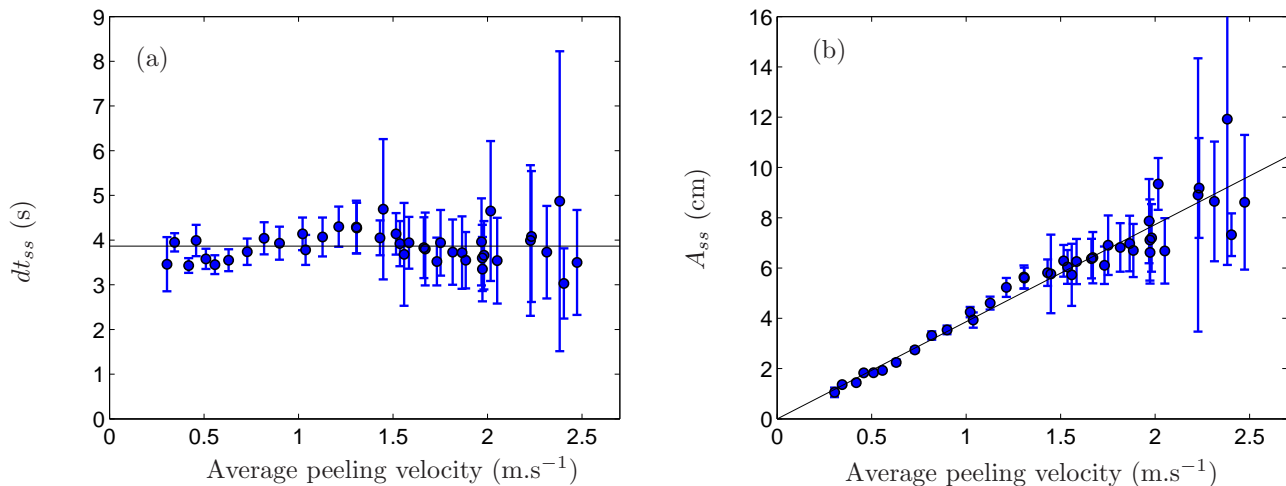


FIGURE 4 – Average stick-slip cycle duration (a) and amplitude (b) as a function of the average peeling point velocity, for $\ell = 1$ m. Each data point corresponds to an average and the error bar to the variance over a single experiment. In (a), the horizontal line shows the mean stick-slip duration $\langle dt_{ss} \rangle$ over all the experiments. In (b), the line traces $A_{ss} = \langle dt_{ss} \rangle V$.

In Fig. 4(a), we observe that the mean durations of the stick-slip cycles is almost constant for a given ℓ , $dt_{ss} = 3.86 \pm 0.3$ ms, as a function of the average peeling velocity. The dispersion inside each experiment is represented through error bars. As previously observed and described in [10], the dispersion increases with the imposed peeling velocity V , in relation with the increase of the amplitude of the slow pendular oscillation. As a consequence of the constancy of the mean stick-slip cycles duration dt_{ss} , the mean amplitude A_{ss} of the stick-slip increases almost proportionally with the average peeling velocity V (Fig. 4(b)). Using the measured mean value for the cycles durations $\langle dt_{ss} \rangle = 3.86$ ms, we can describe fairly well the evolution of the amplitude of the stick-slip with $A_{ss} = \langle dt_{ss} \rangle V$. Again, the dispersion of the stick-slip amplitude inside a given experiment, represented through error bars, is increasing dramatically with the average velocity in relation with the stick-slip intermittencies. It is important to notice that our measurements of the evolution of the stick-slip duration dt_{ss} and amplitude A_{ss} with the imposed peeling velocity V appear in contradiction with the results obtained from indirect observations reported in the literature [2, 4].

We then plot the durations of stick-slip, stick and slip as a function of ℓ for a given velocity $V = 0.74$ $\text{m}\cdot\text{s}^{-1}$ (Fig. 5 (a)). We see that the evolution with ℓ seems non linear, which is again in contradiction with previous work [2]. Besides we also observe that the durations of stick and slip are of the same order of magnitude and seem to follow the same evolution with ℓ .

On Fig. 5(b), we plot the durations of stick-slip as a function of ℓ for different velocities. As observed previously, the durations do not depend a lot on V , and their statistical fluctuations, represented by the error bars, increases with V , and are especially large for $V = 2$ $\text{m}\cdot\text{s}^{-1}$. The data seem to follow a line in the log-log diagram. Fitting this line we obtain a relation $dt_{ss} = \alpha \ell^{0.78}$, which is different from previous work [2], where a linear relation was proposed. This non linear evolution may be due to the intermittencies in the stick-slip.

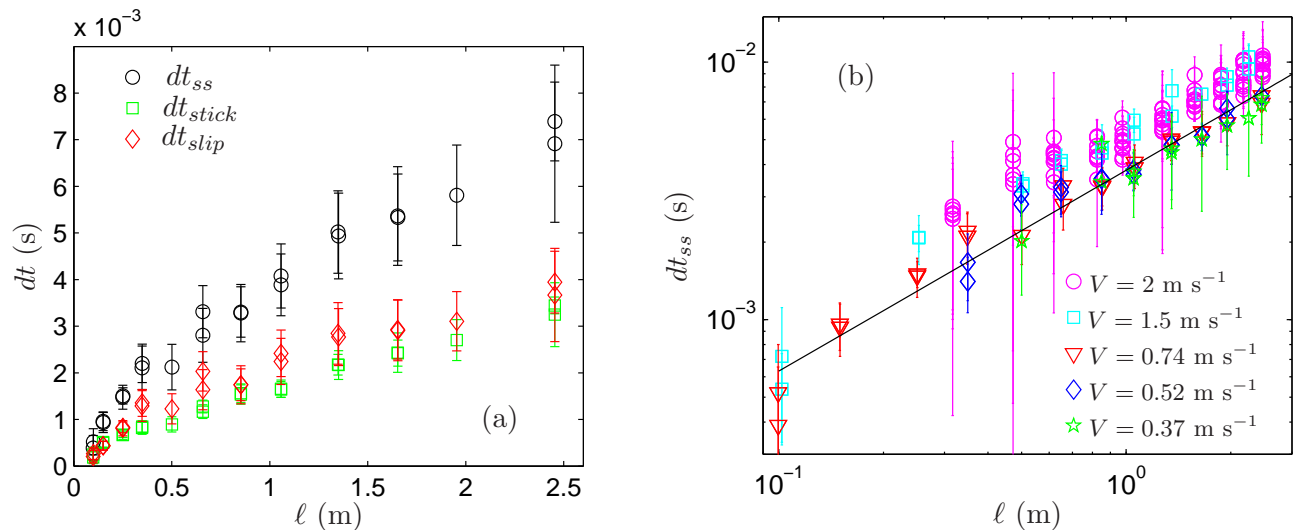


FIGURE 5 – (a) Stick-slip, stick and slip durations as a function of l , for $V = 0.74 \text{ m s}^{-1}$. (b) Stick-slip durations as a function of l for different V . The line represent a fit, giving $dt_{ss} \propto l^{0.78}$. Error bars represent the fluctuations during an experiment.

5 Discussion and Conclusion

The characteristics of stick-slip motion from direct imaging appear to be significantly different from the one presented in previous studies using indirect characterizations. First, we find that the stick and slip phases are generally of comparable durations as already mentioned in [9]. Second, although post-mortem observations suggest that the stick-slip amplitude remains constant as the peeling velocity increases and acoustic measurements find that the stick-slip frequency increases almost proportionally with velocity [2, 4], our direct characterization of stick-slip kinematics shows exactly the opposite behaviour. Moreover, despite its practical interest, the tape roll geometry adds complications to the problem such as the effect of rolling inertia and uncontrolled peeling angle [10]. Stick-slip experiments at large peeling velocities on a flat substrate are inexistent in the research literature, although such tests are commonly performed in the industry to effectively test whether stick-slip is present. Furthermore, existing set-ups that are able to vary the peeling angle are limited to low velocities. Therefore, we have just designed a new experimental set-up, in order to peel at large velocities from a flat substrate that will make possible to peel at an imposed constant peeling angle between 0° and 180° . We are currently performing such experiments, that will provide keystone results for improving constitutive equations of peeling by uncovering the adequate dependency of the adhesive failure energy on the peeling angle. Indeed, analytical modeling of the stick-slip dynamics has been attempted by several authors, mostly during the last decade, following the steps of Maugis [12, 13, 14, 15, 16, 17, 18, 19]. However, the lack of precise experimental data on the stick-slip dynamics is a major limitation which prevents reliable tests of models and further improvements.

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