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On the kinetics of peeling of an adhesive tape under a constant imposed load

M. Barquins and M. Ciccotti
École Supérieure de Physique et de Chimie Industrielles de la Ville de Paris, Laboratoire de Mécanique et de Physique des Milieux Hétérogènes, URA CNRS no. 857, 10 rue Vauquelin, 75231 Paris Cedex 05, France
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The peeling of an adhesive tape is studied when a constant applied load is clamped to its extremity. Three different regimes are observed, as in the peeling at constant speed, previously studied (Maugis, D. and Barquins, M. in 'Adhesion 12' (Ed. K.W. Allen) Elsevier Applied Science, London, 1988, pp. 205–222). If applied loads are small, the peeling is stable and it increases at increasing load so that the strain energy release rate varies as a power function of the peeling speed, as already found (Barquins, M., Khandani, B. and Maugis, D. *C.R. Acad. Sci. Paris.* 1986, **303,** 1517). When the applied load reaches a critical value, a velocity jump is observed whereas the peeling becomes jerky with emission of a characteristic noise. This phenomenon of self sustained oscillations (stick–slip) is well-known. When applied loads are high, the peeling regime is stable again, and the speed increases slowly at increasing load. The new phenomenon which is exhibited in this study is that during the jerky mode of peeling, the mean value of the peeling speed remains constant whatever the applied load in a large range. Moreover, the stick–slip is characterized by simultaneous light-wave and acoustic emissions which have been recorded.

(Keywords: destructive testing by peel; pressure-sensitive tape; fracture mechanics)

INTRODUCTION

In previous works[1–3] recently reported by Hong and Yue[4], the peeling of an adhesive tape (Scotch® 3M, crystal 602) has been studied if a crosshead velocity was imposed. In those experiments, an adhesive roller tape of radius R was unwound at a given linear velocity V (up to $20\,m.s^{-1}$) by a couplemeter motor allowing the peel force P to be measured. In a modified version, the winding roller was mounted on an elastic plate whose deflection gave directly the peel force.

Three modes of peeling were exhibited following the applied velocity: at slow speeds, the tape was peeled regularly and the peeling force increased at increasing speed so that it was shown that the strain energy release rate G varied as a power function of the crack propagation speed V, as in a classical peeling test. The same phenomenon was found at high speeds with an important increasing in the force at increasing velocity. Between these two modes, a phenomenon of self sustained oscillations (stick–slip) already described by Aubrey and Sherriff[5] was observed, the peeling of the tape being jerky with the emission of a characteristic noise.

The aim of the present study is to describe the particular behaviour observed if the adhesive tape is peeled at constant force using a simple apparatus in which the peeling is provoked by the drop of a weight clamped to the free extremity of the adhesive roller tape. New results concern the transient behaviour observed when the peeling of the adhesive tape is jerky.

PEELING OF AN ADHESIVE ROLLER TAPE UNDER A CONSTANT APPLIED LOAD

Experiments were carried out using a simple apparatus schematically shown on *Figure 1a*. A common adhesive roller tape (Scotch® 3M, transparent number 600, total diameter $D = 52\,mm$, total thickness of adhesive turns $e = 26\,mm$, width $d = 19\,mm$, 33 m long and the mass per unit length $p = 1\,g\,m^{-1}$) whose central core is equipped with ball-bearings in order to cancel an inopportune friction. This system is fixed to a horizontal heavy support. A similar device holds a pulley, made of plexiglas® (radius $r = 15\,mm$, 25 mm wide), whose rotation is caused by the motion of the adhesive tape back when a load is clamped to the free extremity of the ribbon (*Figure 1a*). The hooking of the weight is realized with a simple and light (mass $m = 3.1\,g$) triangular system, which allows the uniform pulling of the tape during peeling experiments (*Figure 1b*). The peeling speed is measured with the help of a speedometer, adapted to the pulley, essentially composed from a photoelectric cell coupled with a numerical oscilloscope and an associated plotter. This

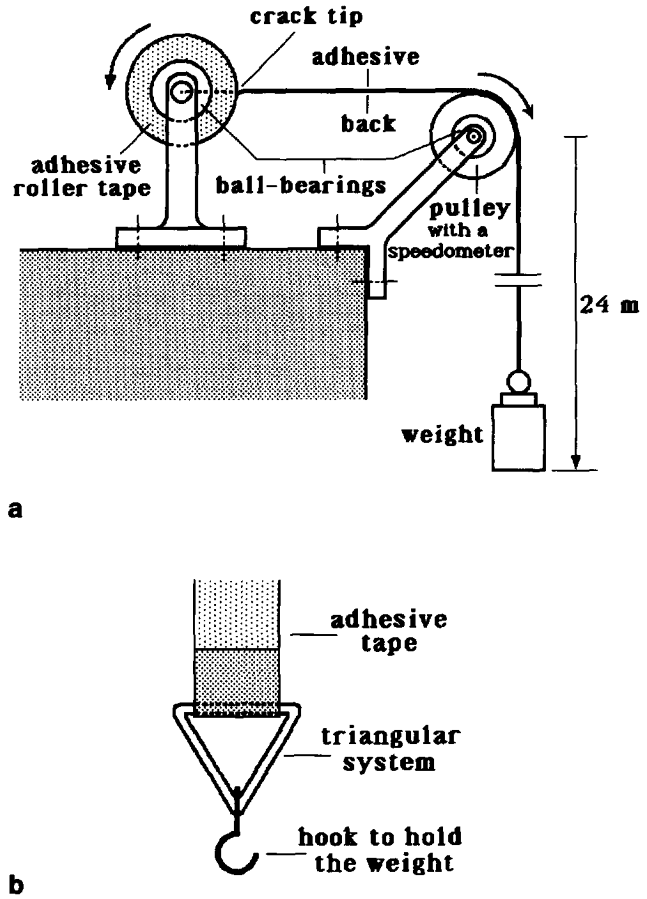

Figure 1 (a) Schematic view of the apparatus used to study the peeling of an adhesive tape when a constant load is applied; (b) detail showing the simple triangular system to hook different masses

system provides the mean value of the linear speed of peeling deduced from the angular velocity of the rotary motion. Due to the duration of the numerous experiments occurred, ambient conditions have varied in the limit values: temperature $23 \pm 2°C$ and relative humidity $65 \pm 5\%$.

For slow peeling speeds, the apparatus was placed near the edge of a table in the laboratory whereas for middle and high speeds, it was placed near the balcony of a building so that a maximal length $h_{max} = 24$ m of ribbon could be unwound. A balcony overhanging a small interior court was chosen in order to remove the intervention of inopportune air currents.

Masses hooked to the free extremity of the adhesive tape varied from $M = 40$–1000 g. In the case of a small set of experiments, the apparatus and especially the support of the adhesive roller tape was covered with the help of an opaque hood, holed by a fine slit for the ribbon crossing, under which were placed a microphone and a photomultiplier in order to record the acoustic emission, characteristic of the jerky mode of peeling and the eventual associated light-waves emission, already seen.

For the different masses used, the recorded peeling velocities are shown on *Figure 2*. As in the previous study at imposed crosshead velocity[2], three regimes can be exhibited. Nevertheless, a different behaviour must be pointed out, taking into account the positions of experimental points in the diagram *M versus V*.

When the mass is smaller than $M_{min} = 40$ g, the experiment shows that the speed of detachment (peeling velocity) is very slow and it is not stable, which can be easily proved by a simple keeping the time. The corresponding data are not shown on *Figure 2*. From $M_{min} = 40$ g to $M_{max} = 160$ g, when the mass is carefully hooked, without inopportune shocks, the peeling velocity, that corresponds to the crack propagation in opening mode I, is stable for every mass tested and slowly increases at increasing imposed force $F = (M + m)g$, g being the acceleration due to gravity (branch A on *Figure 2*). The corresponding strain energy release rate G, for peeling at an angle of $\pi/2$, is given by the simple and well-known formula:

$$G = F/d = (M + m)g/d \tag{1}$$

d being the width of the ribbon ($d = 19$ mm), and $m = 3.1$ g being the triangular hook mass (*Figure 1b*), which cannot be neglected with regard to the smallest masses M tested. For this stable regime of peeling, also called the subcritical crack growth mode, G increases from $G_{min} = 22.3\,J\,m^{-2}$ to $G_{max} = 84.2\,J\,m^{-2}$, the concomitant peeling velocity increasing from $V_{min} = 10\,\mu m\,s^{-1}$ to $V_{max} = 9\,cm\,s^{-1}$, with a quasi-constant slope n in log–log coordinates, so that the strain energy release rate G varies as a n power function of the peeling velocity V, as already seen[2], with $n = 0.146$:

$$G = kV^{0.146} \tag{2}$$

If the mass is greater than $M_{max} = 160$ g, in spite of the good care taken to hook the load, the peeling becomes jerky accompanied by the associated characteristic noisy acoustic emission. Moreover, it can be pointed out that the mean value of the peeling velocity, assessed with the help of the speedometer coupled to the pulley, remains near V_c varying from 3 to $4\,m\,s^{-1}$ (branch B on *Figure 2*) whatever the hooked load such as $M = 200$, 250, 300, 350, 400 and 450 g. Weights seem to drop with the same mean linear

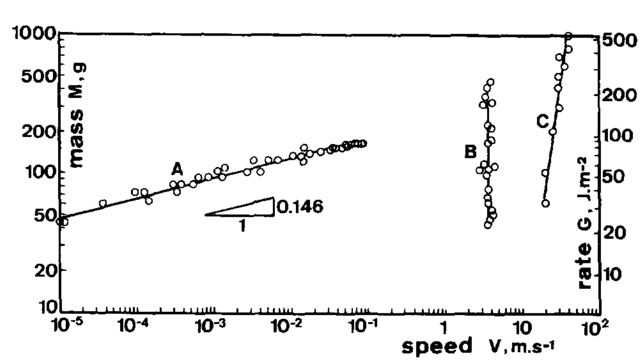

Figure 2 Applied load M (and corresponding strain energy release rate G) as a function of the average value V of the measured peeling speed. Particularly, if the mass M is varied from 40 to 160 g, three peeling speeds can be observed: a slow and stable peeling (branch A), a quick and stable peeling (branch C) and between them, a jerky mode of peeling with an apparent constant mean value of the velocity V (branch B)

velocity. This is a new phenomenon. Nevertheless, the fact that the jerky mode of peeling is associated with forces greater than those corresponding to G_{max} (i.e. corresponding to $M_{max} = 160$ g) had already been observed[1,5].

If the mass is greater than $M = 500$ g, the jerky mode of peeling and the associated acoustic emission disappear, and the peeling velocity becomes abruptly ten times the previous value (branch C on *Figure 2*), and varies from 30 to 40 m s^{-1}, these values are inaccurate because the available drop height is too small ($h_{max} = 24$ m) in order to make easy measurements. This regime of peeling at high velocity is consistent with the previous observations[2].

So, the new result concerns the transient behaviour, for which self-sustained oscillations (stick–slip) appear, the mean value V_c of the peeling velocity remaining constant. Moreover, this phenomenon can be observed for masses smaller than $M_c = 160$ g. Indeed, in the hypothesis where $40 < M < 160$ g, it is possible to trigger off the stick–slip motion if the ribbon is abruptly pulled down vertically, using a fatty towel in order to avoid a sticking with the adhesive tape, and a velocity jump to V_c varying from 3 to 4 m s^{-1} at constant mass M (from branch A to branch B on *Figure 2*) is observed, the peeling mode, previously stable, becoming jerky.

It is in the conditions of stick–slip mode of peeling under small masses ($40 < M < 160$ g) that recordings of acoustic and light-wave emissions were realized, using a tape recorder and a photomultiplier coupled to a numerical oscilloscope. The simultaneous signals recorded are shown in *Figure 3*. The upper signal (A) is provided by the photomultiplier whereas the lower signal (B) is given by the tape recorder. It can be seen that the four acoustic peaks, that correspond to sonorous emissions, are perfectly superimposed on those corresponding to light-wave emissions. It is true that the electronic emission was already known but the coincidence with the noisy signal provides an interesting result.

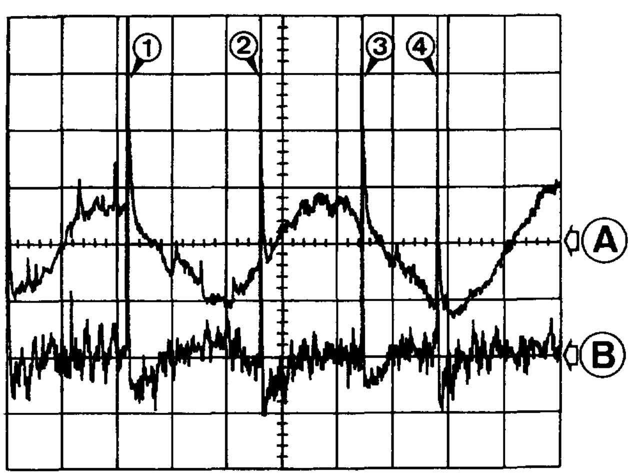

Figure 3 Light-wave (A) and acoustic (B) responses recorded during the stick–slip regime of peeling. (Applied load $M = 100$ g)

In order to verify if the peeling can be observed at very high speeds when the peeling force is small, as in previous peeling experiments at constant crosshead velocity[2,5], another type of experiment has been performed. A system, in which the total mass is greater than $M = 500$ g, is composed of two masses linked together by a thread made of nylon®, 10 m long, and it is hooked to the free extremity of the adhesive tape. In a first set of experiments, a mass $M_1 = 50$ g hooked near the extremity of the ribbon was linked to a mass $M_2 = 500$ g through the thread, so that at the beginning, the peeling, after a few acoustic emissions, occurs with a stable and very high speed (branch C on *Figure 2*). Then, when the first mass touches the bottom, the active mass is instantaneously decreased and the stick–slip motion is not observed with the previous mean value V_c, the stable peeling being due solely to the action of the small mass $M_1 = 50$ g with, in addition, the mass $m = 3.1$ g per meter of tape unwound. A similar set of experiments has been performed using 100 + 500 g, 200 + 500 g and 300 + 500 g, the first mass written in these cases being the lone active mass during the second stage of peeling. These experiments have allowed us to explore the second branch, with a positive slope, characteristic of the peeling at very high speeds (branch C on *Figure 2*), previously observed when a constant crosshead velocity was imposed to the free extremity of the ribbon.

In brief, experimental data on *Figure 2* show that a constant imposed load M varied from 40 to 100 g, hooked to the free extremity of an adhesive tape roller, can provoke three regimes of peeling: a slow and stable detachment (branch A); a quick and stable phenomenon (branch C) and between them a jerky mode of peeling characterized by an apparent mean value of the peeling speed (branch B). For $160 < M < 500$ g, the first regime (slow and stable peeling) is not observed, in spite of the care taken to hook the mass M, so the peeling is stable and very speedy or jerky. If the hooked mass M is greater than 500 g, the lone branch C is observed with a very high corresponding peeling speed which is near 40 m s^{-1}.

DISCUSSION AND CONCLUSION

Two branches with positive slopes (branches A and C on *Figure 2*) are observed as if a constant crosshead velocity is imposed on the free extremity of the ribbon[2,5]. When a constant load is imposed, there is between these two branches a transient behaviour characterized by an unstable peeling for which the peeling speed V_c appears as constant (branch B on *Figure 2*). We think that this phenomenon, which is a new result in the study of adhesive tape peeling, is mainly due to numerous and rapid extensions and relaxations in the free adhesive tape resulting from the jerky mode of detachment in the immediate vicinity of the crack tip (*Figure 1*). This means that the mass drops with a mean speed which is quite different from the instantaneous value v of the detachment velocity from the adhesive roller tape. Consequently, the mass which drops corresponds obviously to a mean value of the peeling force that provokes the detachment. Moreover, if the peeling is effectively realized at a constant $\pi/2$ angle for the branches A and C on *Figure 2*, the intermittent movement (stick–slip) mode observed for the branch B allows one to think that the peeling occurs, in this particular case, at various angles around $\pi/2$. So, for this jerky mode of peeling, the strain energy release rate G is not given by the simple equation (1). Moreover, the fact that a mechanical disturbance during the stable conditions of peeling (branch A on *Figure 2*) induces the instantaneous appearance of the jerky mode, instead of the return to the previous stable peeling mode, seems to indicate the intervention of a subcritical Hopf bifurcation which must be studied later.

Taking into account inertial effects[1,3], it has been shown that, in the case where peel angle variations are neglected, the analysis of the system provides the classical Lienard equation for self-sustained oscillations, for which it is well known that limit cycles exist (an example is provided by the closed dashed line in *Figure 4*), when the dissipation function presents a negative slope. Let us consider (*Figure 4*) the function $F(x)$ which is equal to the difference between values taken by the dissipation Φ:

$$F(x) = \Phi(v) - \Phi(V) \quad (3)$$

for the instantaneous value v of the crack propagation tip and for the mean value V of the peeling velocity, with $x = v - V$. In the diagram $F(x)$ *versus* x, the mean speed V remaining constant ($V = V_c$, branch B on *Figure 3*), it is clear that the behaviour is similar to this observed if the constant crosshead velocity V_c is imposed. Here, *Figure 4* undoubtedly shows that three working points exist, for every mass tested, localized on the three branches A, B and C on *Figure 2* (the three open symbols on *Figure 4*).

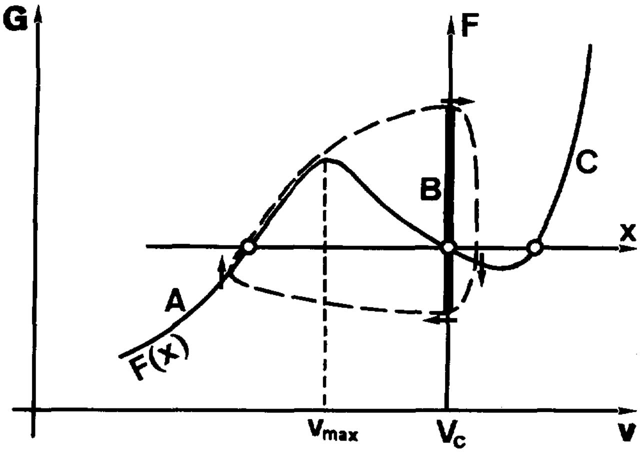

Figure 4 Example of a limit cycle (closed dashed line), superimposed on a schematical view of a curve $G(v)$ with its three different branches A, B and C, showing the evolution of the real crack speed v in a peeling test at constant applied load, during the stick–slip regime for which the mean value of the peeling speed V appears constant whatever the applied load

When the mass applied to the free extremity of the adhesive tape is significant, the peeling observed is stable and it occurs at very high velocities (branch C on *Figure 4*). When the masses applied are small, more often than not it is the unstable branch B on *Figure 2* which is observed. Indeed, if no precautions are taken during hooking the mass, or if the ribbon contains air bubbles (in this case the mass is applied to a smaller width), the strain energy release rate G is abruptly increased so that the jerky mode of peeling becomes the common and ineluctable mode of detachment of the adhesive tape from its roller.

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