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Complex dynamic behavior in adhesive tape peeling*

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Abstract—In this work we analyze dynamic features of the peeling of an adhesive tape from the roll. Two sets of experiments were carried out. In the first, we have measured the unwinding force of an adhesive tape at several constant peel velocities. Analysis of the force–time series, using the Lyapunov exponent and Grassberger–Procaccia dimension, showed that the force oscillations were deterministic. In the second set of experiments, the acoustic emission generated by unwinding at constant peel force was studied. Power spectra analysis of the acoustic emission–time series revealed the existence of two frequency domains: lower frequencies are associated with stick–slip and higher frequencies are related to the massive rupture of adhesive fibrils. The values of the Grassberger–Procaccia dimension for the two sets of experiments were similar, and also comparable to the value reported by Scudiero *et al.*, using electrical current–time series obtained while peeling an adhesive tape from a copper substrate. This agreement indicates that the same dissipation mechanisms are operative in the present case and in the case reported previously by these authors.

Keywords: Peeling; stick–slip; viscoelasticity; chaotic behavior; adhesive tape; deterministic chaos; acoustic emission; force–time series.

1. INTRODUCTION

It is well known that during the peeling of an adhesive tape from a substrate there are different viscoelastic failure stages [1–6], at a given temperature. At low peel velocities, the adhesive behaves as a highly viscous liquid. At intermediate velocities, the adhesive behaves as a rubbery mass. If the velocity is high enough, the adhesive behaves as a glassy solid. For this reason, failure tends to be cohesive at low velocities and interfacial when the velocity is higher. In the transition from one failure stage to another, the adhesion force presents a complex oscillatory profile; this behavior is known as the *stick–slip* effect. Some characteristics of this effect, such as acoustic

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emission and the force oscillation itself, may negatively affect end uses of an adhesive tape. For instance, a large force peak can cause the rupture of the tape backing, which is highly undesirable in actual tape use.

The literature on this subject is very diverse. Some authors have concentrated their analysis on how the peel characteristics vary with the adhesive composition [1, 2, 4, 6, 7], adhesive thickness [6, 8] and peel angle [9]. The effects of temperature and velocity on the peel master curves (according to the WLF theory) were presented in many papers [5, 10, 11–13]. Several authors mention the stick–slip effect while discussing peeling, but a minor effort has been devoted to explain its origin on a deterministic basis. In some cases [8, 14], this effect has been related to nonuniformity of the samples due to random events in the manufacturing of the adhesive tape.

Dickinson and colleagues [15, 16] studied the transient electrical currents generated during peeling an adhesive tape from a copper substrate. These currents are due to charge separation occurring at detachment of the polymer from the metal surface and display fluctuations that are correlated with the micromechanics of peel. Using Grassberger–Procaccia dimensional analysis, a deterministic origin for these fluctuations was revealed. More recent transient current measurements [17, 18] by Scudiero *et al.* with considerable increase in signal-to-noise provided stronger evidence for a fractal ‘strange attractor’ associated with peel dynamics, with a correlational dimension of about 2.3. Lyapunov exponent estimates indicate a fairly large, positive exponent (≈ 100 bits/s). The presence of a positive Lyapunov exponent demonstrated conclusively that the current fluctuations (and thus adhesive detachment) are chaotic. The peel velocities employed in the current fluctuation experiments were all below those required for the occurrence of the stick–slip effect.

Baljon and Robbins [19] have presented a molecular dynamics simulation to study the energy-dissipation mechanisms of the rupture of a thin adhesive bond formed by short chain molecules. They have shown through the simulation how cavities are formed when the adhesive bulk is stressed, and how this mechanism contributes to energy dissipation. Although the strain rates (much higher) and the size of the cavities (much smaller) used in the simulation are very different from the experimental conditions employed in this study, the cavity formation described by the simulation resembles the formation of adhesive fibrils during the peeling of an adhesive tape, which will be discussed further in this paper.

The acoustic emission analysis has not been much employed in the study of polymer systems, although it is a rich information source on the system dynamics. Two examples of the use of acoustic emission analysis in polymer systems are found in recent studies on blend compatibility [20] and on the adhesion of metallized plastics [21].

In this work, we investigate the peel dynamics of an adhesive tape when unwound from its roll, with particular emphasis on the stick–slip effect. According to our proposition, the stick–slip arises from a deterministic rupture transition. It is our goal to characterize the stick–slip as a deterministic, and not as a random, response of the system. The analysis is then directed towards describing the interplay of viscoelasticity and adhesion in this process. We also have conjectured how a theoretical peeling model among those found in the literature [10, 22, 23] could account for a chaotic response of a real system.

Time series were recorded from two different types of peeling experiments: force–time series at constant peel velocity and acoustic emission–time series at constant peel force. These time series are then analyzed in terms of their frequency spectra (Fast Fourier Transform — FFT), their reconstructed attractors [24], their correlational dimensions [25], D_c , and their first Lyapunov exponents [26], λ . This analysis allows us to distinguish the response between a random and a chaotic behavior.

The attractor of a system is the representation of its dynamics, in phase-space. The shape of the attractor reveals if the system is damped, periodic, chaotic or random. In the case of chaotic systems, the attractor orbits never repeat the same path. Nevertheless, they are confined (attracted) to a limited region within the phase-space. According to the delay coordinates method proposed by Takens [24], one can construct a multi-dimensional phase-space from a single observed time series. The method is based on obtaining ‘delayed’ vectors from the original time series, so that the phase-space is defined by the set of vectors given by

$$\{X_0(t_i), X_1(t_i + \tau), X_2(t_i + 2\tau), \dots, X_n(t_i + n\tau)\},$$

where τ is the time delay. The attractors that are so obtained are called ‘reconstructed attractors’.

Following Grassberger and Procaccia [25], the correlational dimension, D_c , is a measure of the density (or dispersion) of the attractor within a D -dimensional phase-space. For random systems, D_c will increase indefinitely with D ; on the other hand, it will reach a constant value when the system is chaotic. In other words, one can say that for random systems, the density of the attractor always increases if one increases its phase-space dimension D . If the system is chaotic, there will be a phase-space dimension D at which the density of the attractor becomes constant (and so does D_c), so that D_c will not increase if D is further increased. According to its definition, the correlational dimension, D_c , provides an estimate of the number of differential equations required to describe the overall system dynamics.

The Lyapunov exponent, λ , is a measure of the rate at which nearby orbits diverge or converge within the attractor. Alternatively, one can say that the Lyapunov exponent provides an indication of how fast we are losing (or not) information while moving along the attractor. A chaotic system will present at least one positive Lyapunov exponent.

2. EXPERIMENTAL

We have studied the peeling of an adhesive tape from its roll. Peeling from the tape roll provides a steady state process involving different failure mechanisms within the test period [11]. The tape is unwound from a rotating dispenser, at a peel angle of approximately 90° . We have used an adhesive tape made by 3M (commercially known as Tartan Tape), which provides a very uniform coating weight and rolling tension, thus minimizing noise generated by irregularities.

This tape is made of a BOPP (bioriented polypropylene) film and a hot-melt pressure sensitive adhesive (PSA) based on a styrene–isoprene–styrene block copolymer (SIS)

Table 1.

Force–time series sampling frequencies

Peel velocity (mm/min)	Sampling rates	
	(Hz)	(points/mm)
5	66.67	800
10	50.00	300
20	125.00	375
50	200.00	240
100	250.00	150
200	500.00	150
500	750.00	90
1000	750.00	45

and a hydrocarbon resin. The tape is 25 μm thick, 25 mm wide and the adhesive coating weight is 15 g/m^2 . The face of the tape without adhesive has a release coating based on polyurethane. The total tape thickness is 40 μm . Therefore, our adhesive joint is made out of a BOPP film at the top, an intermediate layer of adhesive and the polyurethane release coating at the bottom.

In the first set of experiments, the unwinding force was continuously recorded at several constant peel velocities (ranging from 5 to 1000 mm/min) at room temperature on a tensile-testing machine. The force–time series were recorded in a PC through an analog–digital converter board. The sampling rates (in Hz and in points/mm of peeled tape) for each peel velocity are presented in Table 1.

In the second set of experiments, we observed the unwinding of the tape at constant force, provided by a hanging weight. Acoustic emission–time series were recorded from the peel front. The adhesive tape and the rotating dispenser were both the same as used in the force experiments. Pulling by a hanging weight avoids the noise that could be generated by a pulling device. The acoustic emission was recorded in a PC through a conventional sound board with a sampling frequency of 44.1 kHz. A unidirectional microphone was fixed at 45° and 5 cm from the peeling zone. The minimum weight required to initiate the tape peeling was 17 N. The weight was varied from 17 up to 82 N. The peel length in these experiments was 1.5 m, and the measured average peel velocity was 1000 mm/s.

3. RESULTS

3.1. Constant velocity experiments

3.1.1. Force–time series and FFT. Force–time series obtained for peeling at 50, 100, and 1000 mm/min and their respective power spectra are presented in Fig. 1a, b, and c. The oscillations observed here are typical of the stick–slip cycles. One can clearly observe a decrease of the mean force amplitude and an increase in the oscillation instability as the peel velocity increases. Power spectra from these force–time series

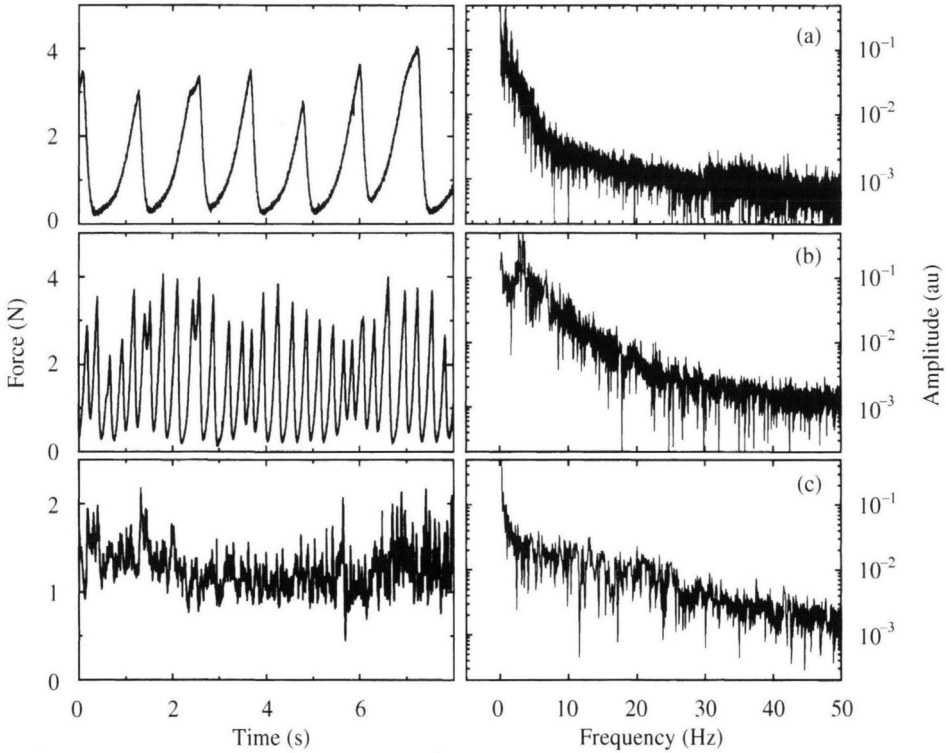


Figure 1. Force–time series (left) and FFT (right) recorded at three different peel velocities: (a) 50, (b) 100, and (c) 1000 mm/min.

are very broad. This behavior is typical of chaotic signals, although at this early point of the analysis we can say only that the time series are neither periodic nor quasi-periodic. Frequencies are presented in Hz on a log–linear plot. At 100 mm/min, the higher frequency band is centered around 4 Hz, while at 1000 mm/min the band is centered around 8 Hz. If we consider the frequencies in terms of cycles per unit of detached tape length, we verify that at 100 mm/min the higher frequency band is around 2 cycles/mm, and at 1000 mm/min this band is around 0.5 cycle/mm. Alternatively, we can express the same results in terms of the stick–slip wavelength, so that at 100 mm/min this length is 0.5 mm, and is 2.0 mm at a 1000 mm/min peel rate. The stick–slip wavelength represents the peeled length of one slip during each stick–slip cycle. It should be borne in mind that the stick–slip wavelength depends on the length of tape already peeled (as will be discussed further), and hence it is changing continuously during the experiment. Also, it is important to note that even during the stick part of the cycle some peeling may still occur.

3.1.2. Average forces. Figure 2 shows a plot of the average force as a function of peel velocity. The average force plot shows a maximum at 10 mm/min. This profile is in accordance with previous results from the literature [1–6], and it reflects a change in the viscoelastic dissipation mechanisms with peel velocity. This peak, as

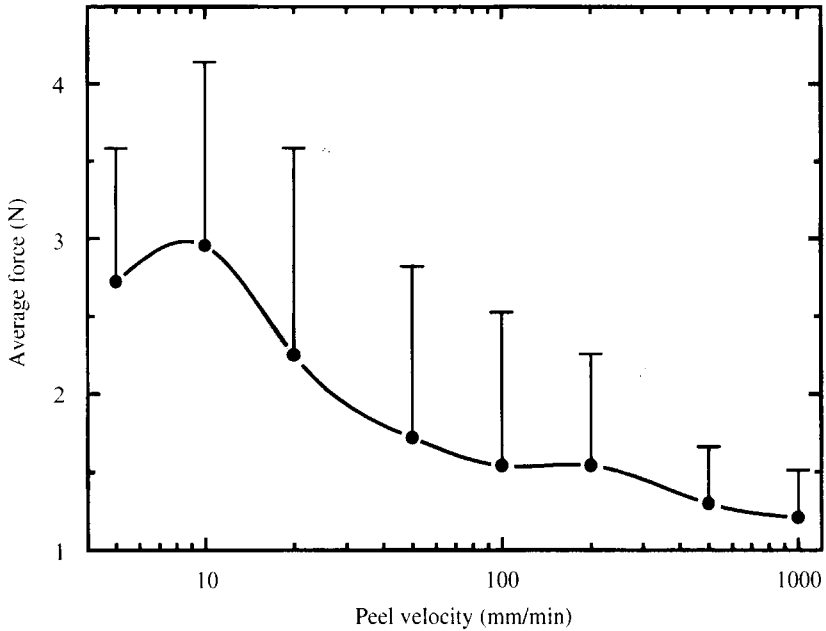


Figure 2. Average force as a function of peel velocity.

will be discussed further, is associated with the transition from a rubbery to a glassy behavior of the adhesive layer. We have observed only interfacial failure between the adhesive layer and the release coating of the tape backing, for all velocities. Cohesive failure of the adhesive would be expected at lower velocities, since in this case the ratio between the perturbation and relaxation times would allow the molecules to slide across the polymer matrix. However, due to the high cohesive strength of the adhesive base elastomer (SIS), as a result of the styrene end-block domains, this type of failure has not occurred.

3.1.3. Reconstructed attractors. Attractors were reconstructed for each peel velocity from single force–time series using the delay coordinates method of Takens [24]. Using our experimental data, the quality of the reconstructed attractor is quite sensitive to the value chosen for the time delay. The attractor quality depends on how well defined the trajectories are within the attractor. There are different criteria in the literature for estimating the optimum time delay. We employed the criterion presented by Fraser and Swinney [27], which corresponds to the time given by the first local minimum of the mutual information function. The mutual information function corresponds to the degree to which one part of a time series contains information on, or resembles, the other parts [28]. It measures the general dependence of two variables, and it provides a better estimate for the choice of time delay than the first zero of the autocorrelation function, another usual criterion for the time delay, which only measures linear dependence. The reconstructed attractor for the force–time series registered at 100 mm/min is presented in Fig. 3. This attractor was reconstructed in

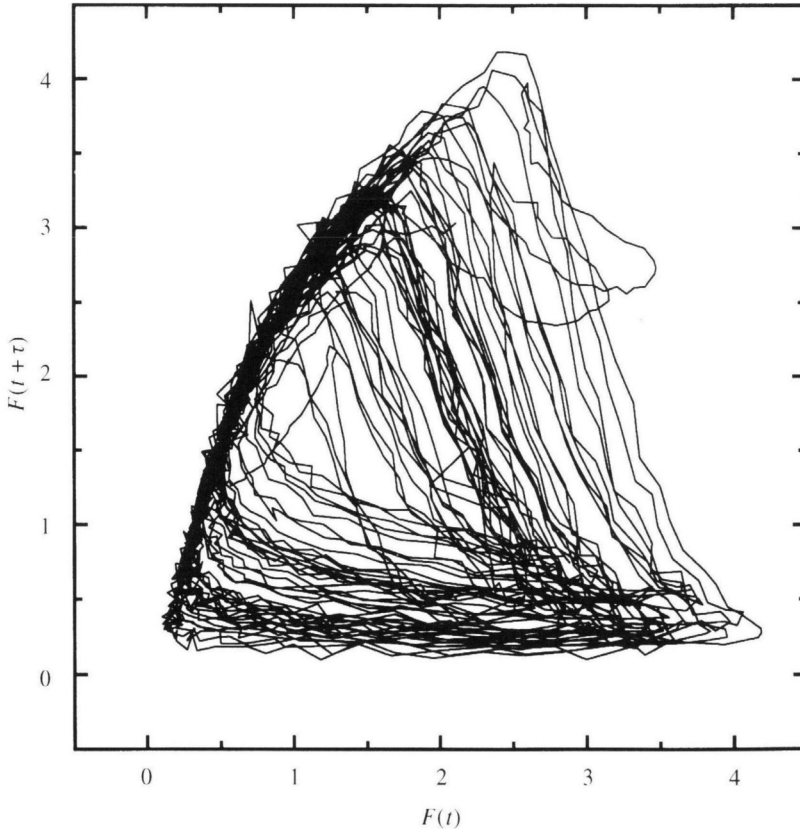


Figure 3. Reconstructed attractor from the force–time series obtained at 100 mm/min.

a two-dimensional space. The embedding dimension, E_D , which is the number of dimensions of the space where the attractor is reconstructed, is thus equal to 2, in this example.

3.1.4. Correlational dimensions. The correct dimension for the attractor reconstruction is not known in advance. We have used the correlational dimension method by Grassberger and Procaccia [25] to define it. The method is based on computing the correlational dimension, D_c , for each subsequent embedding dimension, E_D . This procedure is repeated until E_D becomes equal or smaller than twice D_c , plus unity; i.e. $E_D \leq 2D_c + 1$ [29]. The D_c vs. E_D plot for the peeling at 5 mm/min is presented in Fig. 4. Here, the circle on the correlational dimension curve represents the embedding dimension at which the above defined criterion is met.

3.1.5. First Lyapunov exponent. Another invariant commonly employed to characterize chaotic time series is the first Lyapunov exponent, λ . Systems that present an attractor with non-periodic orbits will have at least one positive Lyapunov exponent. Systems with orbits that decay to a constant value with time present negative

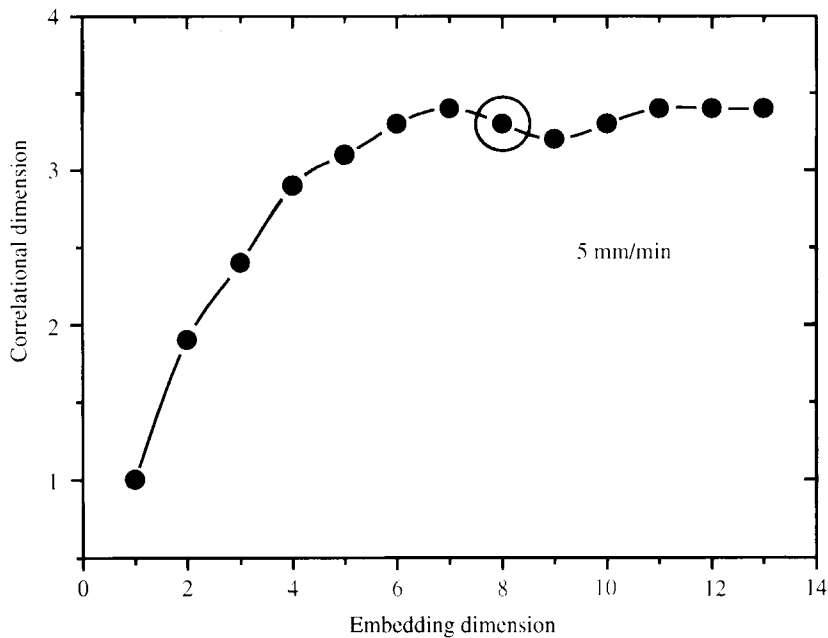


Figure 4. Correlational dimensions for the force–time series obtained at 5 mm/min. The circle represents the embedding dimension where the criterion $E_D \leq 2D_c + 1$ is met.

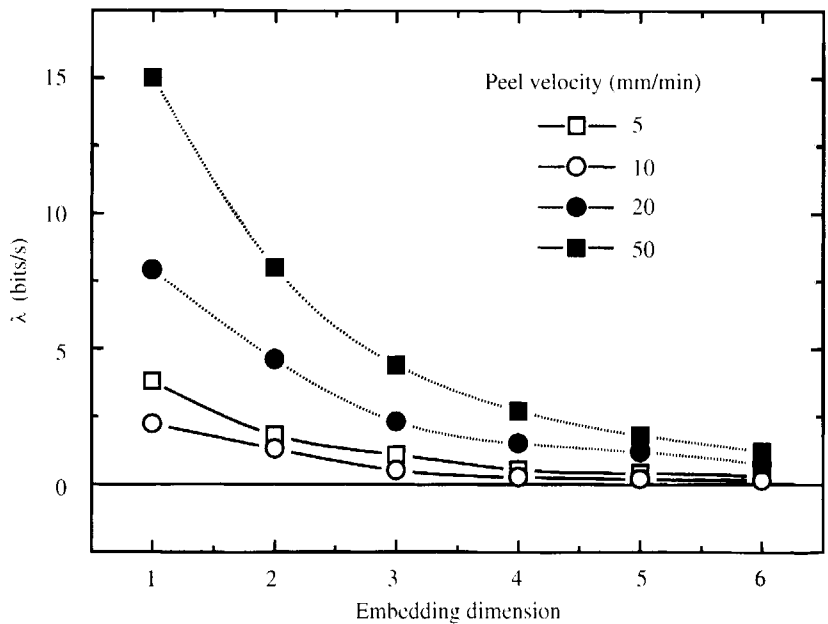


Figure 5. Evolution of the first Lyapunov exponent λ with embedding dimension for constant velocity experiments at 5, 10, 20, and 50 mm/min.

exponents. In the case of periodic orbits, the system will present a null Lyapunov exponent. The value of the first Lyapunov exponent was estimated from the time series data by the method developed by Wolf *et al.* [26]. The evolution of the first Lyapunov exponent with embedding dimension for constant velocity experiments at 5, 10, 20, and 50 mm/min is shown in Fig. 5.

3.2. Constant force experiments

3.2.1. Acoustic emission spectrum. Acoustic emission–time series obtained with different peel forces have shown negligible differences, since the falling average velocities were about the same (*c.* 1000 mm/s); therefore, our analysis will be based on only one of the acoustic emission experiments, i.e. the one obtained with a peel force equal to 23 N. Part of this acoustic emission–time series is presented in Fig. 6a. Also presented here is the time series moving average curve, Fig. 6b, where each point represents an average of its twenty neighboring points (in both directions) in the original time series curve. The oscillations in the moving average curve are representative of the stick–slip cycles.

3.2.2. Fast Fourier Transform. FFT analysis of the acoustic emission–time series revealed the presence of two dominant frequencies, as shown in the power spectrum presented in Fig. 7. There is a low frequency band (160 Hz) of high amplitude, and a higher frequency band (5.7 kHz), of a lower amplitude.

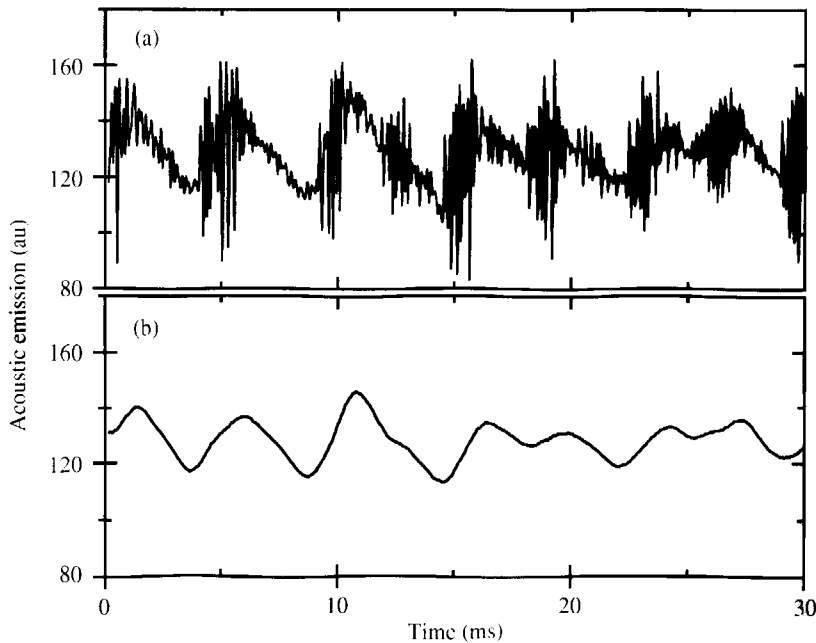


Figure 6. (a) Acoustic emission–time series obtained at constant peel force (23 N); (b) Moving average of the acoustic emission–time series, obtained using twenty neighboring points in both directions.

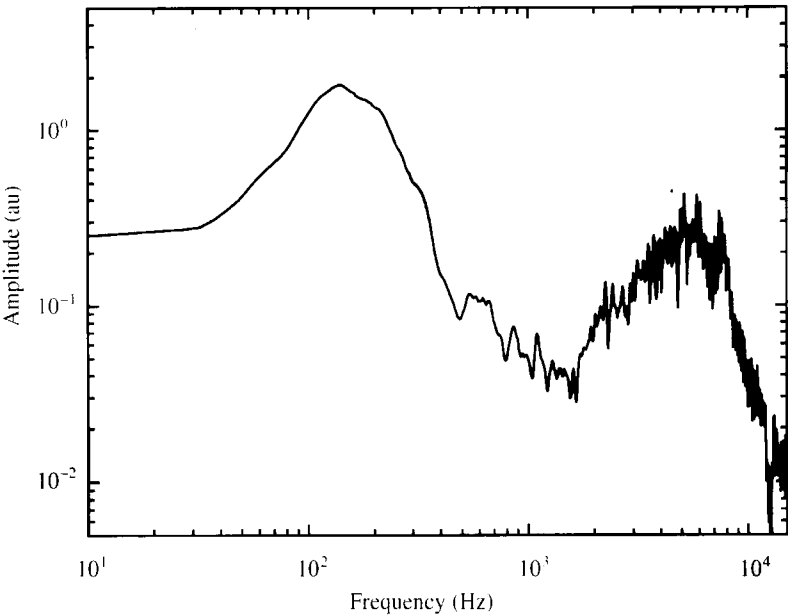


Figure 7. Log-log plot of FFT of the acoustic emission-time series.

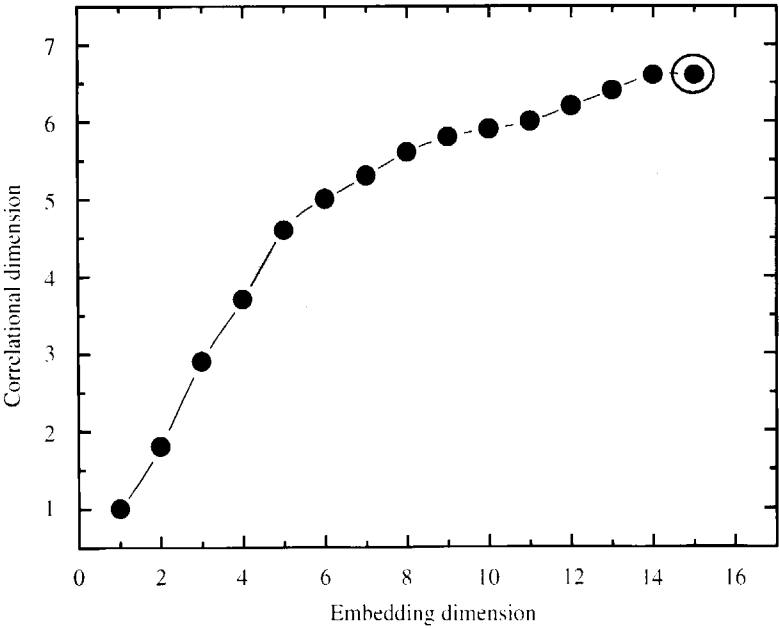


Figure 8. Correlational dimensions of the acoustic emission-time series. The circle represents the embedding dimension where the criterion $E_D \leq 2D_c + 1$ is met.

3.2.3. Correlational dimensions and first Lyapunov exponent. Figure 8 shows the plot of the correlational dimension (Grassberger–Procaccia analysis) for the acoustic emission–time series, which shows a finite dimension equal to 6.6, according to the criterion discussed previously. The first Lyapunov exponent, calculated for $E_D = 6$, presents a value close to 4000 bits/s. This high value for the exponent is due to the high frequency of micromechanic events within one second of peeling. Thus, a lot of information is being lost in each second of peeling, which corresponds to a typical feature of a chaotic signal. In such a case, one can say that predicting the acoustic emission becomes infeasible, even for subsecond time intervals.

4. DISCUSSION

As mentioned previously, the correlational dimension gives an idea of the number of differential equations needed to describe the overall system dynamics, and the first Lyapunov exponent is a measure of the loss of information along the time series. The correlational dimensions and the Lyapunov exponents of the force–time series are presented in Fig. 9a and b, respectively. The values for D_c are those obtained using the criterion $E_D \leq 2D_c + 1$, and the values for the Lyapunov exponents are those calculated for $E_D = 6$. The correlational dimensions (Fig. 9a) are fairly similar for peel velocities smaller than 50 mm/min, but they increase significantly for higher velocities. One can observe the same behavior from the plot of the Lyapunov exponents vs. peel velocity (Fig. 9b). Both plots indicate a marked change in the system dynamics at *c.* 50 mm/min.

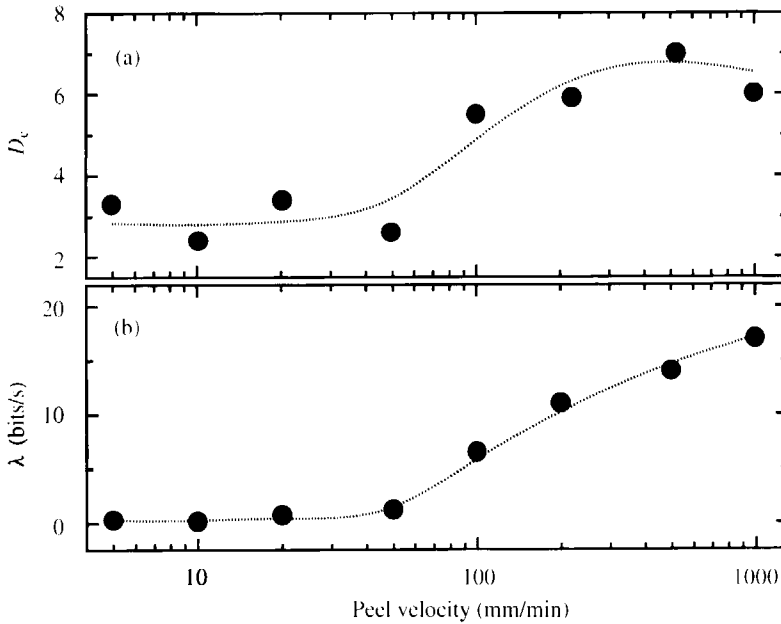


Figure 9. (a) Correlational dimension of the force–time series according to the criterion given by $E_D \leq 2D_c + 1$; (b) Lyapunov exponent of the force–time series for $E_D = 6$.

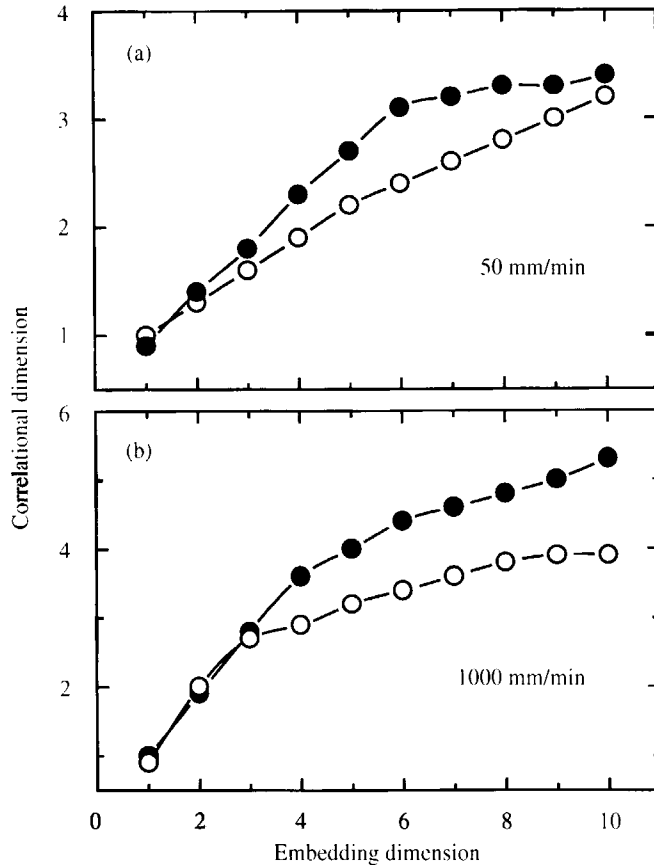


Figure 10. Correlational dimension computed from the first section (one-fifth) (○) and the full (●) peel force–time series at: (a) 50 and (b) 1000 mm/min.

We have computed the correlational dimensions only for the initial section (one-fifth) of the peel force–time series at 50 and 1000 mm/min, and then we have compared these results to those previously obtained, using the full time series. One can see from Fig. 10a that the correlational dimension curves computed from the initial section and from the full time series of the peeling at 50 mm/min are similar. Nevertheless, the same comparison using the 1000 mm/min data (Fig. 10b) reveals that the differences are pronounced. The same observation can be made from an equivalent analysis based on the Lyapunov exponents (comparison between the Lyapunov exponents calculated from the full time series and the exponents obtained from the first section of the time series), as can be seen from Fig. 11a and b.

We associate these differences to the increase of the detached length of the tape for a given time of the experiment, so that this effect is more pronounced in the tests at higher velocities.

The increase of the correlational dimensions and of the Lyapunov exponents with the detached length reflects a change of our system response with time. In other words, we claim that the detached length is a relevant source of complexity in our

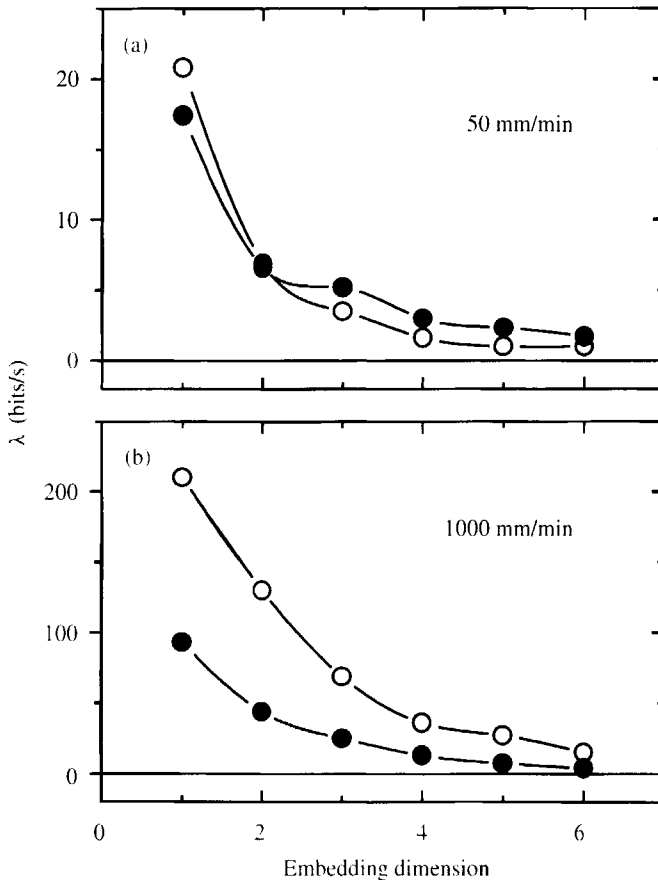


Figure 11. Lyapunov exponent computed from the first section (one-fifth) (○) and the full (●) peel force–time series at: (a) 50 and (b) 1000 mm/min.

system, and that the amplitude of this effect is magnified with time. We could not have observed this influence if we had measured the peel force while keeping a constant detached length.

Other authors [6, 9, 30] have mentioned the influence of the detached portion of the tape on the stick–slip. Aubrey *et al.* [6] found that the stick–slip wavelength depended linearly on the detached length of the tape, with different slopes for different rates. All extrapolated curves passed through the origin showing that with zero length of detached tape, stick–slip could not occur.

One can understand the influence of the detached portion of the tape by observing the peel velocity more closely. Actually, the tape peel velocity is not the velocity of the peel front, which oscillates between velocities higher than the tape peel velocity and zero. If we do not consider any permanent deformation in the detached tape portion, it is correct to say that the tape peel velocity is equal to the average peel front velocity. The detached length of the tape works as a spring, storing elastic energy until this reaches a value greater than the practical work of adhesion. At this

point, the peeling starts and the velocity increases. Due to the viscoelastic properties of the adhesive mass, the adhesion resistance will decrease when the peel velocity increases, so that the peeling will propagate until the velocity is small enough to allow for an adhesion resistance equal to or greater than the peel force. Again, the peel force will start to increase until the rupture point is reached, at which point one stick–slip cycle is then completed. Thus, the stick–slip is caused by the elastic energy stored in the detached portion of the tape, combined with the viscoelastic response of the adhesive.

According to the above mechanism, we can expect a relationship between the energy storage capacity of the detached length of the tape and the stick–slip. Since this capacity increases with the increase of the detached portion, this effect should be more evident for tests at higher velocities, as was pointed out previously.

The FFT analysis of the acoustic emission–time series enables us to identify distinct rupture mechanisms that are not noticeable in the force records. Each of the two dominant frequencies mentioned previously can be associated with one of these mechanisms. The low frequency band (around 160 Hz) reflects the slip steps of the stick–slip cycles. This can be seen from Fig. 12, where the position X_0 represents the stick points and the position X_1 represents the point where the slip steps are initiated. Starting at position X_0 , the tape roll is pulled until reaching X_1 ; during this step there is no actual peeling. At position X_1 peeling really starts. In this step, the peel velocity is greater than the tape roll rotation velocity, so that the peel front reaches again the position X_0 , where it stops, thus completing one stick–slip cycle. These cycles cause the flapping of the tape from X_0 to X_1 at a frequency $c.$ 160 Hz, in our experiment. In addition to this, we can see from Fig. 13 that the high frequency acoustic emission arises predominantly during the slip steps (i.e. when the tape is peeled from X_1 to X_0). As illustrated in this figure, this frequency can be associated with the fast rupture of adhesive fibrils (step d) that are generated when the adhesive mass is stressed

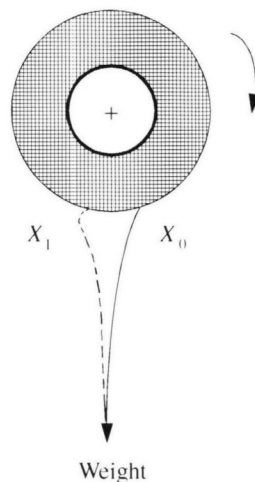


Figure 12. Schematic representation of the tape position at two different stages in the stick–slip cycle. The cyclic transition between position X_0 to X_1 (flapping) is the source of the low frequency acoustic emission.

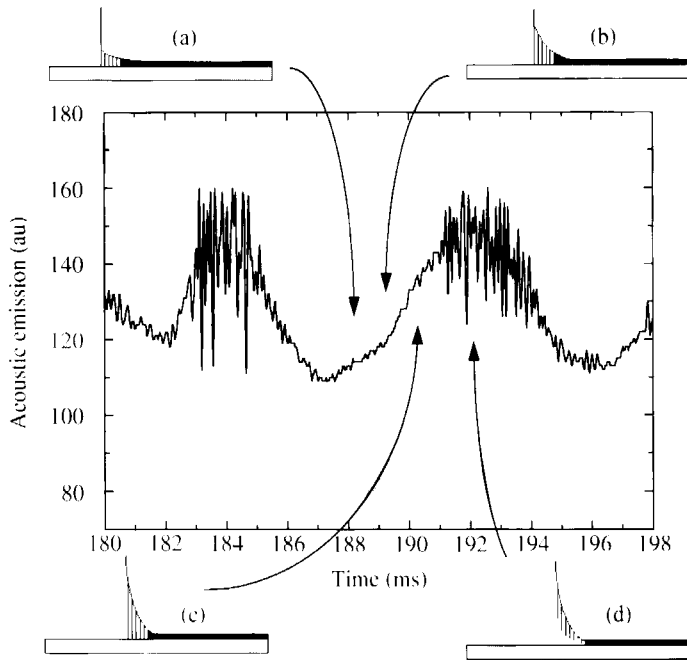


Figure 13. Part of the acoustic emission–time series showing the acoustic events associated with the various steps of adhesive fibril formation (a, b, and c) and rupture (d).

during peeling (steps a, b, and c). From our data, we determine this frequency to be *c.* 5.7 kHz. Scudiero *et al.* [16] have reported how these fibrils are originated. They have shown that, right after the peeling zone, cavities that grow to about 200 μm in diameter are formed due to the menisci of the curved adhesive surfaces above the substrate (also reported by Newby *et al.* [31]). These cavities are then intersected by the peel front, and then the lateral walls of the cavities are transformed into the fibrils that are noticed in the peel front.

Once the average peel velocity is known (1000 mm/s), the stick–slip (160 Hz) and fibril rupture (5.7 kHz) frequencies can be interpreted in terms of their average wavelengths. Stick–slip and fibril wavelengths are thus $(6000 \pm 2000) \mu\text{m}$ and $(200 \pm 80) \mu\text{m}$, respectively. In this case, these wavelengths represent, respectively, the average length between the stick–slip events, and the average length between the fibrils within the slip events. FFT analysis based on different segments of the acoustic emission–time series (‘windowed’ FFT from the time series) showed that the differences between the computed wavelengths along the time series are not pronounced.

Duke [32] has determined a 5000 μm stick–slip wavelength, when the peel rate was 1500 mm/s and the detached length was 500 mm. Despite the differences between the experimental system studied by Duke and ours, Duke’s stick–slip wavelength is very close to the value obtained in the present work. Concerning the fibril wavelength, the value obtained in our work agrees with the cavity diameter value reported by Scudiero *et al.* (200 μm) [16]. This result reinforces our hypothesis that the high frequency is associated with the rupture of these structures.

Although the two experiments we have carried out are different in nature (constant velocity and constant force), it is worthwhile to note that the correlational dimensions calculated from the force and from the acoustic emission experiments are comparable. In the case of constant force, the largest correlational dimension calculated was 7.0, which was obtained from peeling at 500 mm/min; and in the case of acoustic emission, the achieved dimension was 6.6. Scudiero *et al.* [16] have reported a dimension of 5.6 from the electric current fluctuations generated during the peeling of an adhesive tape from a copper substrate. Their more recent measurements yield a dimension of ≈ 2.3 . We note that for their adhesive and range of peel velocities, they are sensing much smaller changes in detachment area (corresponding to just a few fibrils), than in our more 'violent' slip events.

Any attempt to build a theoretical model that could account for the stick-slip deterministic chaos should necessarily take in consideration the difference between peel rate and pull rate. The first rate is related to the actual velocity of peeling (not constant), while the pull rate is related to the velocity of tape traction (constant). The difference between them is the source of the transitions of viscoelastic response (viscous to rubbery, or rubbery to glassy) that results in the stick-slip behavior. The key idea is then to incorporate the difference between these two rates into the viscoelastic model of peeling.

Mizumachi [22] has proposed a model for the rolling friction coefficient of a pressure sensitive adhesive, in the rolling ball test. This test is a measure of the tackiness expressed by the force required to pull a cylinder of defined geometry over a pressure sensitive adhesive surface, at a constant velocity. Despite the fact that the rolling ball and the peel tests are different, both subject the viscoelastic adhesive to similar patterns of deformation. According to Mizumachi's proposal, one can express the rolling friction coefficient in terms of the viscoelastic behavior of the adhesive under stress by the ball movement. Three different criteria for the joint failure (except cohesive failure of the substrate or of the adherend) are adopted when two Maxwell elements in parallel connection are used in the viscoelastic model. In the region where the rate of strain is very low, the failure criterion is given by a critical strain in one of the viscoelastic model dashpots; the failure would be within the adhesive layer, in this case. The second criterion is based on a critical strain in one of the viscoelastic model springs; this type of failure would occur when the rate of strain is moderate, and it would be located also within the adhesive layer. The last criterion is concerned with adhesion itself, and it is relevant at very high strain rates, when the energy stored in the springs of the model reaches a critical value; in this case failure is interfacial. Since all the applied energy is stored in the springs, this last criterion is closely related to the work of adhesion given by surface thermodynamics, which does not consider any permanent deformation (i.e. energy dissipation) in the adhesive mass, but only the surface energy difference between the joint interface and the separated surfaces. From one viscoelastic region to another, we can verify from Mizumachi's work that the rolling friction coefficient varies significantly (the stick-slip, in our case). If we could include accurately the difference between peel rate and pull rate within the peeling model, we believe that the stick-slip would arise deterministically, as a result

of the oscillations due to rate differences combined with the viscoelastic response of the adhesive layer.

5. CONCLUSIONS

From the analysis of both force and acoustic emission–time series, we have concluded that the stick–slip effect derives from a deterministic mechanism. This effect is associated with deviations between the actual velocity of peeling (not constant) and the velocity of tape traction (constant), and these deviations are due to the elastic deformation of the detached tape length, during peeling. The analyses of full acoustic emission–time series and of a section (one-fifth) therefrom, using correlational dimension and Lyapunov exponents, showed the detached length effect on the stick–slip. The correlational dimensions calculated for both experiments (force and acoustic emission) are similar, and they are comparable to the value reported previously by Scudiero *et al.* [16]. This outcome indicates that the same dissipation mechanisms are operative in both cases and, interestingly, this conclusion came out from monitoring distinct responses (force–, acoustic emission– and electrical current–time series) during peeling. It is also demonstrated that fibril wavelength (which is a morphological feature) can be obtained from acoustic emission–time series.

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