# ON THE SIMULATION OF THE COATING FLAKING OFF

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We propose a theoretical and experimental model to explain the phenomenon of coating flaking off. Our model is made of two superimposed rubber strips in adhesive contact: the detachment of a strip in response to instantaneous elongation or constant strain velocity imposed on the other one represents the spontaneous flaking off of a varnish layer, and is analyzed in order to study the variation of the dissipation function versus the crack propagation velocity at the interface.

## INTRODUCTION

Most of the paints, varnishes, and coatings present a flaking off due to ageing. To study this phenomenon, we used an experimental model containing two rubber strips of the same width b. The first strip (Young modulus $E_1$, length $L_1$ and thickness $h_1$) acted as a substrate, and the second strip ($E_2$, $L_2$ and $h_2$) acted as a coating (Fig 1). The contact between the strips was only due to the action of the Van der Waals forces (neither prestress nor additional adhesives were present). The experiments consisted of applying to the substrate an instantaneous or a linearly increasing elongation; a video-camera recorded the evolution of the delamination by taking images of the fracture front observed by transparency. In the experiments, $E_1 = E_2 = 0.89$ MPa, $\nu$ (Poisson ratio) ≈ 0.5 and $T_g$ (glassy transition temperature) = 201 K. The model dimensions are the following : $b = 15$ mm, $L_1 = 12$ cm, $L_2 = 11$ cm, $h_1 = 3$ mm and $h_2 = 2.4$ mm.

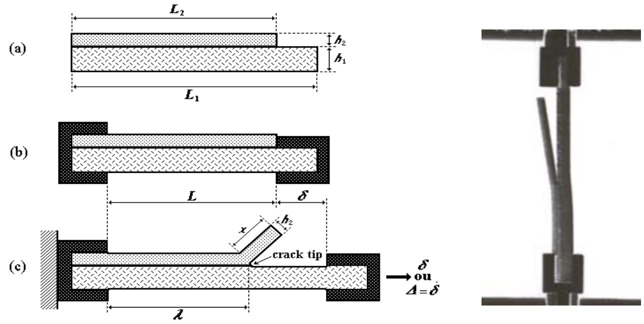


Fig 1 : Experimental model used to study the delamination of a coating from its substrate. (a) : Superimposition of the two rubber strips, the contact only occurring due to the action of Van der Waals forces. (b) : Gluing of the two rubber strips on the left-hand side and of the lower strip on the right- hand side. (c) : Instantaneous elongation $\delta$ or constant cross-head velocity $\Delta$ imposed on the lower strip in order to cause the delamination of the higher one. (d) : View of the sample tested.

The problem of joint delamination under stress has been partially solved by Kendall [1] using energy balances. However, this approach provides information neither on the system stability nor on the kinetics of fracture propagation. It is thus necessary to use fracture mechanics concepts such as the strain energy release rate $G$ to study the system stability, and to analyze the variation of the dissipation function versus the crack propagation velocity at the interface.

## THEORY

The system shown in Fig 1 is assimilated to an assembly of two springs wired in parallel (corresponding to the non-delaminated part of the joint) associated with a third spring (corresponding to the free part of the substrate). For a given elongation $\delta$, the Hooke law gives the force sustained by the system :

$$F = \frac{\delta \cdot E_1 \cdot h_1 \cdot b \cdot (E_1 \cdot h_1 + E_2 \cdot h_2)}{L \cdot E_1 \cdot h_1 + x \cdot E_2 \cdot h_2} \quad (1)$$

where $L$ is the initial length of the joint and $x$ is the delaminated length of the upper strip. From (1), we deduce the following expression for the strain energy release rate :

$$G = \left(\frac{\partial U_E}{\partial A}\right)_\delta = \left(\frac{\partial U_E}{\partial x}\right)_\delta \cdot \left(\frac{dx}{dA}\right) = \frac{\delta^2 \cdot E_1 \cdot h_1 \cdot E_2 \cdot h_2 \cdot (E_1 \cdot h_1 + E_2 \cdot h_2)}{2(L \cdot E_1 \cdot h_1 + x \cdot E_2 \cdot h_2)^2} \quad (2)$$

where $U_E$ is the elastic energy stored by the system ($U_E = ½ \cdot F \cdot \delta$) and $A$ is the contact surface in the case of relaxed conditions [$A = b \cdot (L - x)$].

The equilibrium of the system is reached when $G = w$ (Griffith criterion), $w$ being the Dupré energy of adhesion. The elongation $\delta_{init}$ corresponding to the baiting of the crack at the interface between the two strips is given by $\left(\frac{\partial G}{\partial A}\right)_\delta = 0$ :

$$\delta_{init} = L \cdot \sqrt{\frac{2 \cdot E_1 \cdot h_1 \cdot w}{E_2 \cdot h_2 \cdot (E_1 \cdot h_1 + E_2 \cdot h_2)}} \quad (3)$$

Equation (2) clearly shows that when the crack propagation starts, $x$ increases and consequently $G$ decreases, situation which can leads to a new equilibrium.

Previous work [2] have shown that, in the case of soft vulcanized elastomers, the kinetics of crack propagation are given by : $G - w \equiv w \cdot \Phi(a_T \cdot V)$ (Eq. (4)), where $\Phi$ is the dissipation function (dimensionless) which depends on the temperature through the shift factor $a_T$ of the Williams-Landel-Ferry transformation, and on the propagation velocity $V = dx/dt$. It has been shown that $\Phi$ varies in a large domain of propagation velocities, as a power function of $V$. The viscous losses are supposed to be confined to a very small volume around the crack tip (characterized by the highest strain velocities), displacements in the bulk being assumed to remain purely elastic in order to calculate $G$ with equations of linear elasticity.

The determination of the strains exhibited by the two parts of the substrate (in contact with the higher strip, and free) enables the calculation of the length $x$ of the delaminated strip as a function of the length $\lambda$ (experimentally measured), by the positive root of the equation : $x^2 \cdot E_2 \cdot h_2 + x \cdot [E_1 \cdot h_1 \cdot (L + \delta) - E_2 \cdot h_2 \cdot (L - \lambda) - E_1 \cdot h_1 \cdot L \cdot (L + \delta - \lambda) = 0$ (Eq. (5)), the crack velocity being deduced afterwards in relaxed conditions. This permits us to study the variation of $G$ as a function of $V$, from which we finally deduce the variation of the dissipation function $\Phi$ versus $V$ using equation (4) in which $w = 45$ J/m$^2$ [3].

## RESULTS

We used the experimental device shown in Fig 1. Before the tests, the rubber strips were cleaned with alcohol, dried, and left in ambiant conditions 30 min, out of dust. Their superimposition was made very cautiously in order to avoid prestress and air bubbles, and they were left in contact 15 min in order completely to express the Van der Waals forces [3]. The crack propagation velocity was measured using the video-camera, and the length $\lambda$ (of the non-delaminated part of the joint, Fig 1) was calculated with a precision of 0.5 mm. The experiments were carried out under the following conditions: $T$ (temperature) = 298 K, $RH$ (relative humidity) = 50 %. Fig 2a presents the evolution of length $\lambda$ with time. In the case of an instantaneous elongation (curve $A_5$), the delamination is instantaneous and leads to the total separation of the rubber strips because $\varepsilon_{appl} > \varepsilon_{crit} = 0.871\%$ ($\varepsilon_{crit}$ corresponds to the particular case $G = w$ when $x = L$). In the case of constant cross-head velocities, $\lambda$ increases as long as $\varepsilon_{appl} < \varepsilon_{init} = 0.484\%$, and when $\varepsilon_{appl} > \varepsilon_{init}$, the delamination starts and $\lambda$ decreases to zero. Fig 2b and 2c present respectively the evolution of $G$ and $\Phi$ versus the crack propagation speed $V$. The variation of $\Phi$ as $V^{0.55}$ is found, as in previous experiments [3]. Finally, Fig 2d presents the evolution in the force sustained by the adhesive assembly versus time. In the case of an instantaneous elongation, the force decreases progressively until the total delamination of the joint. In the case of constant cross-head velocities, three phases are evidenced : 1.- when $\varepsilon_{appl} < \varepsilon_{init}$, the force increases linearly, the duration of this phase depending on the applied strain velocity ; 2.- when $\varepsilon_{appl} > \varepsilon_{init,}$ the delamination starts and the force increases more and more slowly as the separation of the strips continues, until the total delamination of the joint, and 3.- after this moment, the force increases linearly with time, corresponding to the effort sustained by the substrate only submitted to a constant strain velocity. The theoretical variations (heavy line) predicted for the force perfectly agree with the experimental values (symbols).

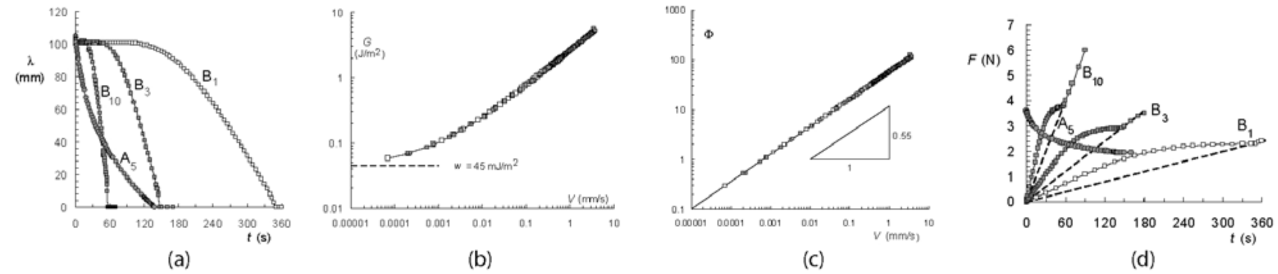


Fig 2 : a): Length λ versus time, when an instantaneous elongation $\delta = 5$ mm (Curve $A_5$) or constant cross-head velocities $\Delta = 1$ mm/min (Curve $B_1$), $\Delta = 3$ mm/min (Curve $B_3$) and $\Delta = 10$ mm/min (Curve $B_{10}$) are imposed on the substrate ; b) : Strain energy release rate $G$ versus crack propagation speed $V$ at the interface of the two superimposed rubber strips for all the experimental data ; c) : Viscous dissipative function $\Phi$ versus crack propagation velocity $V$ ; d) : Force sustained by the adhesive assembly versus time, when an instaneous elongation $\delta = 5$ mm (Curve $A_5$) or a constant cross-head velocities $\Delta = 1$, 3 and 10 mm/min (Curves $B_1$, $B_3$ et $B_{10}$) are imposed.

## CONCLUSION

This study shows that an elementary analysis is sufficient to describe perfectly the kinetics of elastomer spontaneous delamination. The model presented, due to its simplicity and excellent validity, enables the resolution of practical problems such as the ability of paints to adhere to deformable substrates, or to sustain partial/total delamination in response to internal stresses.

## REFERENCES

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