Thermal characterization of adhesive tape peeling: experiments and numerical modelling

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An experimental study of the two-dimensional temperature field evolution during the process of peeling an adhesive tape from a roll is presented. The measurements have been done using a thermographic infrared camera. The aim is to understand the heating process that is produced due to the fracture of the adhesive at different peeling velocities. Experimental data is numerically treated in order to correct the external noise and obtain time dependent temperature profiles along the peeling direction. A model based on the 1D Fourier equation with a moving boundary is proposed and solved numerically. We obtain good quantitative agreement that allows to estimate the heat production at the advancing fracture

I. INTRODUCTION

In recent years the process of peeling adhesive tape has been studied intensively. The simple act of peeling hides something more complicated and still unknown for the scientists. At a microscopic level this process is very similar to a fracture process and shows interesting physical phenomena: instabilities, avalanche behaviour, etc. [1].

Many studies have focused on the mechanical part of this phenomenon [1]. A different point of view will be adopted in this work, that is focused on the thermodynamics of the process.

Infrared-Thermographic Cameras were invented in 1929 by a physicist called Kálman Tihanyi [2]. An infrared camera can capture thermal information without contact with the sample. The equipment measures radiometric thermal frames that contain temperature measurements for each pixel in the frame. With this information one can monitor thermal diffusion and heat sources [3].

Many physical systems show complex, with interacting elements involved. In order to understand them, numerical algorithms have become a useful part of mathematical modelling in physics and many other areas [4,5,6].

II. EXPERIMENTAL SET UP

We have used a commercial roll of adhesive tape (APLI Ref. 11168) with dimensions: width 19 mm, length 33 m, and thickness 28 μm. According to the manufacturer it is made of a plastic film (matt finished) coated with a thin layer of a pressure sensitive adhesive (permanent and noiseless) [7]. Although the exact composition of the plastic is not provided by the manufacturer, similar brands are known to use polyethylene, either low density (LDPE) or high density (HDPE) [8-9]. The physical and thermal properties of these plastic materials are rather similar. Typical values of conductivity and heat capacity can be found in references [10-11].

$$\kappa = 0.46 \frac{\mathrm{J}}{\mathrm{msK}} \; ; \; \mathrm{C_v} = 1'89 \cdot 10^6 \frac{\mathrm{J}}{\mathrm{K\,m^3}}$$

The value of C_v has been obtained from the specific heat $C'_v \sim 2010 \ \mathrm{J\,K^{-1}\,kg^{-1}}$ and from the density $\rho \sim 0.94 \ \mathrm{g\,cm^{-3}}$ [10-11].

The roll of adhesive tape was placed on a tape dispenser that was fixed below the moving crosshead of a Zwick/Roell Z005 testing machine. Special care was taken so that the tape was unrolling as vertical as possible with no twist. The testing machine, controlled using the testXpert III v1.4 software, was imposing a vertical constant unrolling speed that will be varied between v=100 mm/min and v=3000 mm/min. The resolution in displacement is 0.001 mm. Moreover, the machine was simultaneously measuring the force applied to the tape by means of a XforceP 5kN load cell, with a force resolution of 0.01N.

Due to the existence of a gauge in the pivot hole of the rolling support of the dispenser, during a short initial part of the experiments, the tape was not starting to unroll at the desired speed because the roll was lifted up and the tape was elastically strained, until the tension was high enough to start the peeling process.

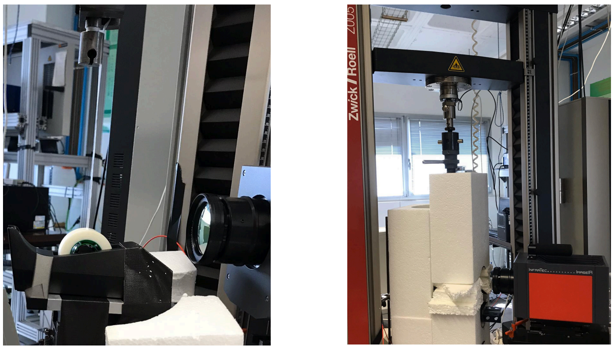

Figure 1. Experimental set up images. In the right image it can be seen the insulating material to avoid reflections of external thermal radiation.

The acquisition of the temperature map of the tape surface was done with an InfraTec ImageIR 8800 thermografic camera (S/N 88173812) with the IRBIS-3.1 software [12]. The camera was recording 540x512 pixel frames every 5 ms. In typical experiments sequences of 3000 frames were taken. The pixel separation was calibrated to be 0.036 mm. The nominal resolution of the camera for the temperature measurements is 0.001 K. Nevertheless, precise temperature measurements with IR cameras are rather cumbersome, since

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one should take into account the difference in emissivity and reflectivity of the monitored surfaces. In order to avoid the influence of external radiation on the tape, the setup was surrounded by a polystyrene cage, which improved the measurement resolution significantly. We estimate that the resolution of our absolute temperature measurements is about 0.5K, but for relative measurements improved up to 0.01K.

III. EXPERIMENTAL RESULTS

Several experiments have been done in this investigation. In order to avoid the already mentioned problem with the gauge in the pivot hole we have followed the following methodology: we start with a first pull of the testing machine at a small velocity of 100 mm/min, in order to ensure that the tape is unrolling under tension. After this first pull, a second pull was performed at different testing velocities: 200, 300, 500, 1000, 2000 and 3000 mm/min.

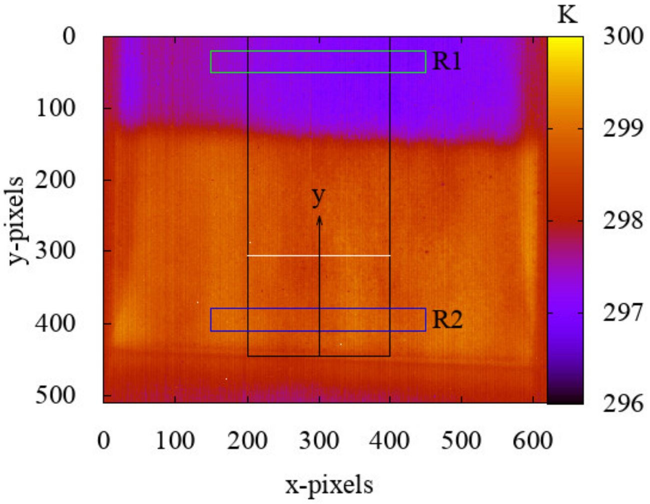

Figure 2. Temperature map obtained by the infrared-thermographic camera. This frame corresponds to frame number 1710 experiment at 3000 mm/min. The areas indicated will be detailed in the text.

Figure 2 show a typical frame recorded by the camera. This temperature map has already been pre-processed in order to correct some defects in the pixel matrix. The slightly tilted line that separates the light red zone (above) and the dark red zone (below), seen in the lower part of the image, corresponds to the place where the tape (above) is unrolling from the roll (below). This line is where peeling takes place. A second line separating the purple region from the light red region corresponds to the peeled front on the tape where the acceleration of the peeling speed occurred, thus leaving a thermal trace that moves up due to the tape advancement while it diffuses. We have measured the average temperatures in the regions R1 and R2 indicated with the small coloured rectangles (green and blue, respectively). The large rectangle in black indicates the region where, after averaging in the horizontal direction, we have obtained the 1D temperature profiles T(y,t), with the vertical y axis starting from the average peeling position at the centre of the rectangle. The horizontal line in white corresponds to a segment, at ~5 mm from the peeling region where the average temperature will be recorded for later comparison with the numerical simulations. The arrow with the y label indicates the direction of the peeling zone propagation and our reference system from now on.

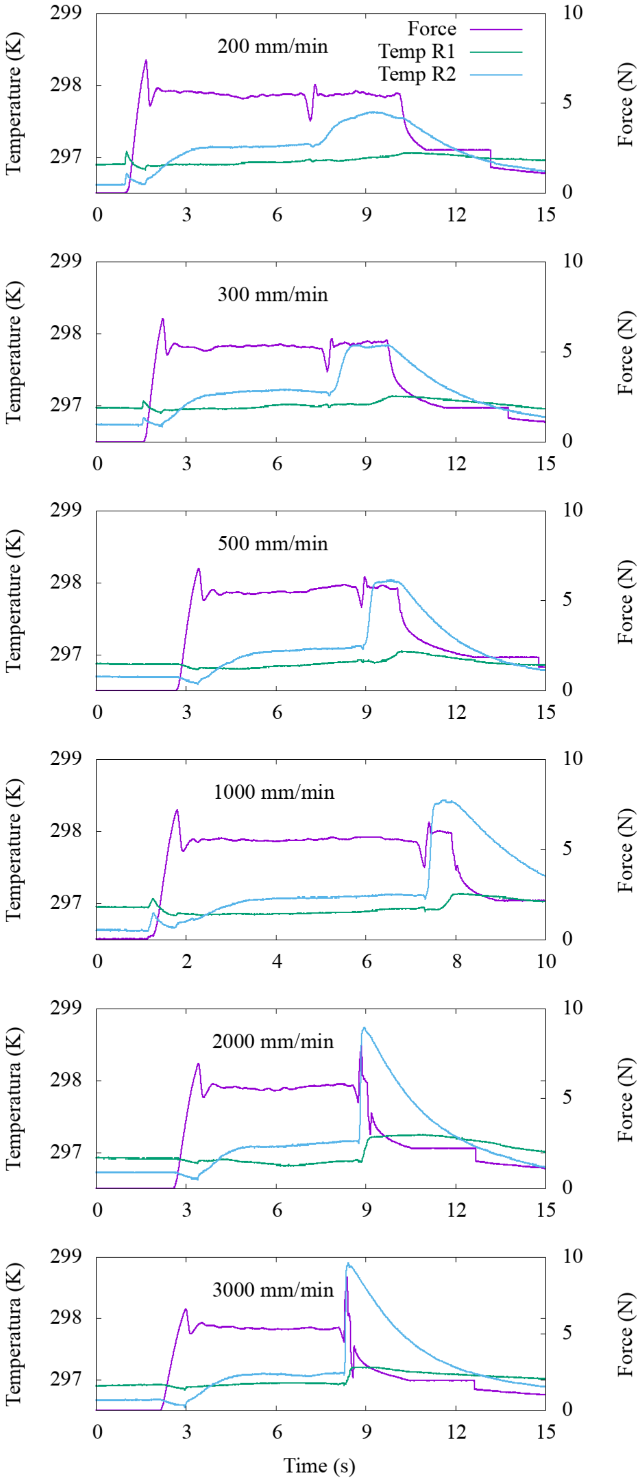

Figure 3. Force and temperature vs time for the different peeling velocities, as indicated by the labels. Average temperatures in regions R1 and R2 are shown with green and blue lines, respectively, and are indicated in the left vertical axes. The corresponding behaviours of the force are indicated with purple lines on the right vertical axes.

Examples of experiments at different constant peeling velocities are shown in Figure 3 that shows the evolution of the temperature in the regions R1 & R2 simultaneously with the behaviour of the force. One can observe that after the initial transient interval in which the roll is lifted up, the force increases linearly indicating an elastic deformation of the tape. When the yield point (maximum value of the force) is reached, the tape starts to peel and the force oscillates until reaching an approximate stationary value. After the displacement of the crosshead has reached 10 mm, the speed is accelerated to a higher value as indicated by the labels on each sub graph. This is revealed by the second increase and oscillation of the force. Note that a new force plateau is then reached (although in some cases is very short). From the observation of the behaviour at 2000 mm/min and 3000 mm/min, one can see that the value of the stationary force is higher, the higher the peeling velocity. One can also observe that after every acceleration, there is a clear increase of the temperature in region R1, close to the peeling line, and after a certain delay, the temperature also increases in region R2, indicating that a thermal front is established and reaches a higher y-position. Thus, it is clear that at the peeling line there is a source of heating that creates the thermal front that propagates vertically, due to the displacement of the tape but also modified by the heat diffusion and the losses to the air.

For the experiment at v=3000 mm/min, the behaviour of the temperature profiles along the tape have been investigated in detail. For this purpose we have performed horizontal averages of the temperature in the rectangular zone indicated in black in Figure 2, and obtained profiles T(y,t). This rectangle has 199 horizontal pixels and 445 vertical pixels corresponding to 7.164 mm and 16.02 mm, respectively. Note that such an average eliminates the temperature fluctuations in the horizontal direction, and transforms the thermal problem in a 1D problem.

In Figure 2, it is interesting to note horizontal fluctuations on the temperature can be observed. These fluctuations could reveal details of the inhomogeneous peeling process, but this phenomenon is averaged out in the present work and will be studied in the future.

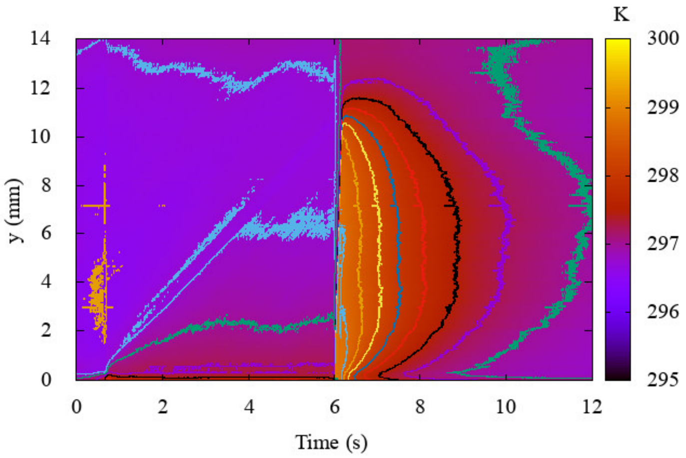

Figure 5. Time evolution of the average experimental temperature profile. The colour shows the temperature in K as indicated with the colour scale.

Figure 5 shows the behaviour of the averaged vertical temperature profile as a function of time for the whole experiment. The coloured lines indicate curves with equal temperature (isotherms). The first ~0.8 s correspond to the time needed to lift the roll and stress the tape. Then, the tape unrolls at 100 mm/min until reaching 6 s. In this process heat is produced at the peeling. Initially the heated temperature front propagates approximately linearly with the advancing tape. But, note that after approximately 4 s of the experiment, the isotherms are flat, indicating a stationary temperature profile, with temperature decreasing with height. At 6 s the speed is instantly accelerated up to 3000 mm/min. Between 6 s and 6.2 s, 10 mm of tape are unrolled, and again the isotherms show an approximately linear increase. The final part of the experiment, from 6.2 s to 12 s corresponds to the thermalization of the tape. Until reaching an almost homogeneous temperature.

IV. MODELLING AND NUMERICAL SOLUTION

The experimental results can be modelled as a heat transport problem that includes losses and a heat production term. Since we are essentially studying the vertical temperature profile T(y,t) we start with the 1D version of the Fourier equation [6]:

$$C_V \frac{\partial T}{\partial t} - \kappa \frac{\partial^2 T}{\partial y^2} + \beta(T - T_0) = \sigma(y,t)\,, \qquad (1)$$

where the first term corresponds to the energy variation per unit time and unit volume, the second term corresponds to the heat diffusions, the third term to Newtonian losses towards the external environment at temperature T_0 and, the term on the right hand side, σ(y,t) to the heat production per unit volume and unit time. C_V is the heat capacity, κ is the thermal conductivity and β is a loss coefficient.

The SI units of the equation terms are J s^{-1} m^{-3} and, therefore, the units of the coefficients are:

$$[C_V] = \frac{J}{Km^3}\,;\, [\kappa] = \frac{J}{msK}\,;$$

$$[\sigma] = \frac{J}{sm^3}\,;\, [\beta] = \frac{J}{m^3sK}\,.$$

Note that this equation is written in a reference frame that is fixed on the tape. Thus the source function σ(y,t) represent a moving boundary towards lower values of y at a speed -v. The free variables in the problem to be determined from the experimental data are the loss β and the value of σ that might depend on the peeling speed. T_0 is the room temperature that has been determined as 296.5 K from the analysis of the frames.

From equation (1) we write:

$$\frac{\partial T}{\partial t} = \frac{\kappa}{C_V} \frac{\partial^2 T}{\partial y^2} - \frac{\beta}{C_V}(T - T_0) + \frac{\sigma(y,t)}{C_V}\,. \qquad (2)$$

In order to solve it numerically we use the Crank-Nicholson explicit method for making time derivative and the space derivatives, discretization of time and space is made with t=kΔt and y=iΔy [6] (k is the frame number, i is the segment position and Δt=0.001 s and Δy=0.1 mm). Thus the following discretization has been considered:

$$\frac{\partial \mathrm{T}}{\partial \mathrm{t}} = \frac{\mathrm{T}_{\mathrm{i,k+1}} - \mathrm{T}_{\mathrm{i,k}}}{\Delta \mathrm{t}},$$
$$\frac{\partial^2 \mathrm{T}}{\partial \mathrm{y}^2} = \frac{\mathrm{T}_{\mathrm{i+1,k}} - 2\mathrm{T}_{\mathrm{i,k}} + \mathrm{T}_{\mathrm{i-1,k}}}{(\Delta \mathrm{y})^2}. \tag{3}$$

Combining relations (3) and (2):

$$\mathrm{T}_{\mathrm{i,k+1}} = \mathrm{T}_{\mathrm{i,k}} + \kappa^*\left(\mathrm{T}_{\mathrm{i+1,k}} - 2\mathrm{T}_{\mathrm{i,k}} + \mathrm{T}_{\mathrm{i-1,k}}\right) - \beta^*(\Delta \mathrm{T}_0) + \sigma^*{}_{i,k}\,,$$

where:

$$\beta^* = \frac{\beta \Delta \mathrm{t}}{C_V}\,;\ \sigma^* = \frac{\sigma_1 \Delta \mathrm{t}}{C_V}\,;\ \kappa^* = \frac{\kappa \Delta \mathrm{t}}{C_V \Delta \mathrm{x}^2}\,.$$

The calculation is done on a grid with i =0,…,350. And the number of frames are k=1,…,12000. T_0 has been established as the initial value for all the points of the grid. For positions i=350 and positions under the source position, $T=T_0$ during all the process.

A moving boundary solution has been implemented in order to execute the simulation: the source $\sigma^*_{i,0}$ is zero everywhere except at the position i=210, where it takes a value $\sigma^*(v)$. At every time step the source is moved downwards according to the simulated speed. For v_1= 100 mm/min we displace σ^*_1 one position down (0.1 mm) every 60 steps (0.06 s). Where as for v_2= 3000 mm/min we displace σ^*_2 one position down (0.1 mm) every 2 steps (0.002 s).

From properties found previously on this text, we are able to determine the value of κ^* for the adhesive tape used in these experiments.

$$\kappa^* = \frac{\kappa \Delta \mathrm{t}}{C'_V \Delta \mathrm{x}^2} = 0.2434 \frac{\mathrm{mm}^2}{\mathrm{s}} \cdot \frac{0.001\ \mathrm{s}}{0.01\ \mathrm{mm}^2} = 0.02434$$

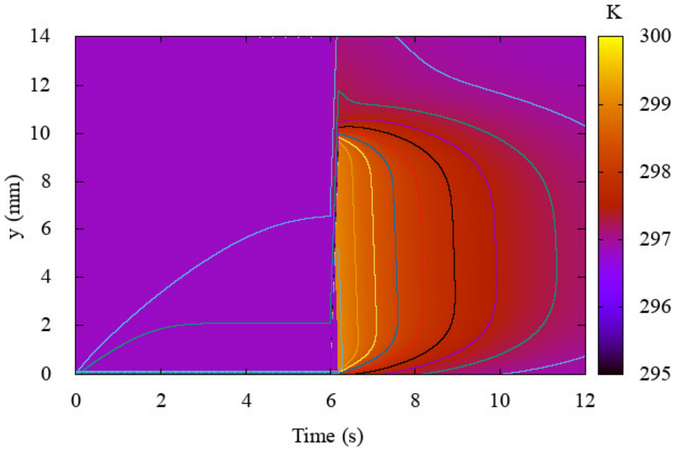

Figure 6. Time evolution of the simulation temperature profile. The colour shows the temperature in K as indicated with the colour scale.

And after trial and error we have we have determined the best parameters that improve the comparison with the experimental behaviour:

$$\beta = \frac{\beta^* C'_V}{\Delta \mathrm{t}} = 5.86 \cdot 10^5 \frac{J}{\mathrm{sKm}^3}\,,$$

$$\sigma_1 = \frac{\sigma_1{}^* C'_V}{\Delta \mathrm{t}} = 4.73 \cdot 10^7 \frac{J}{\mathrm{sm}^3}\,,$$

$$\sigma_2 = \frac{\sigma_2{}^* C'_V}{\Delta \mathrm{t}} = 2.17 \cdot 10^9 \frac{J}{\mathrm{sm}^3}\,,$$

where σ_1 corresponds to the first velocity of 100 mm/min and σ_2 corresponds to the second velocity of 3000 mm/min.

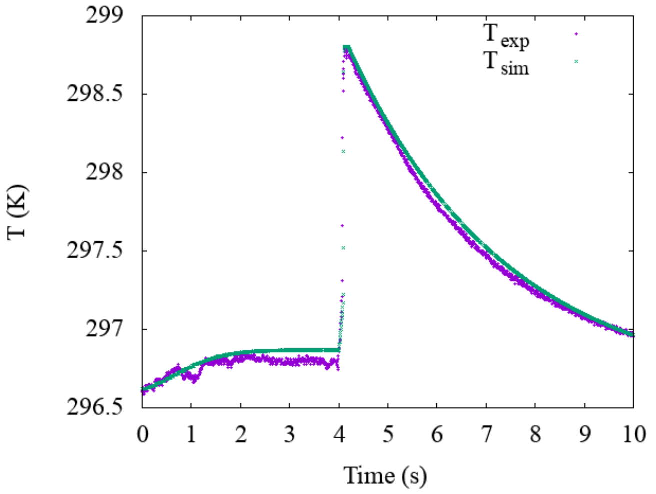

Figure 7. Experimental and Simulation temperature vs time at a 5 mm distance from the peeling zone.

Finally in figure 7 an example of a quantitative comparison between experiments and the numerical modelling is done. The average error is less than 0.1 Kelvin.

V. DISCUSSION AND CONCLUSIONS

Our experimental methodology, combined with the numerical simulation, has allowed us to estimate the heat production at the peeling front σ for different values of the peeling speed. From the values determined in the previous section, it can be observed that σ_2/σ_1~45 is not equal to v_2/v_1 ~30, thus indicating a non linear dependence of the heat production with the peeling velocity.

It is worth noting that such a non linear dependence has been proposed by other authors using mechanical techniques [13] . The authors find that the adhesive energy increases in a non linear way with the speed of the peeling front. In fact, in agreement with our results, they find that the increase in adhesive energy is larger than the expected from a linear hypothesis.

In conclusion we have proposed and tested an experimental method that combined with the numerical solution of the Fourier heat equation, allows us to determine the heat production at the peeling front due to the fracture of the adhesive substance when an adhesive tape is peeled from a roll at constant velocity. In particular for the APLI Ref 11168 tape we have found that heat production is $4.73 \cdot 10^{7}$ J s^{-1} m^{-3} for v=100 mm/min and $2.17 \cdot 10^{9}$ J s^{-1} m^{-3} for v = 3000 mm/min.

Possible lines for further studies in the future will be to systematically study more peeling velocities in order to propose a functional dependence $\sigma(v)$ as well as to analyse the observed temperature fluctuations in the horizontal direction that could be associated to instabilities in the fracture of the adhesive substance.

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