Tearing as a test for mechanical characterization of thin adhesive films[1]

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Thin adhesive films have become increasingly important in applications involving packaging, coating or for advertising. Once a film is adhered to a substrate, flaps can be detached by tearing and peeling, but they narrow and collapse in pointy shapes. Similar geometries are observed when peeling ultrathin films grown or deposited on a solid substrate, or skinning the natural protective cover of a ripe fruit. Here, we show that the detached flaps have perfect triangular shapes with a well-defined vertex angle; this is a signature of the conversion of bending energy into surface energy of fracture and adhesion. In particular, this triangular shape of the tear encodes the mechanical parameters related to these three forms of energy and could form the basis of a quantitative assay for the mechanical characterization of thin adhesive films, nanofilms deposited on substrates or fruit skin.

Torn Posters or Wallpaper

Peeling a Tomato

Photo / Donna Coveney

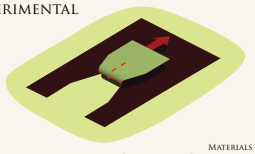
Biomechanics and anatomy of fruit wall peels

Mechanical characterization of thin film electronic devices

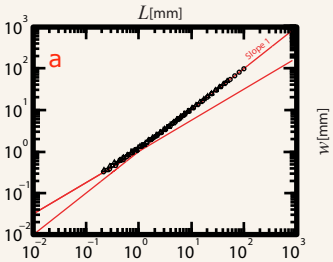
Epiretinal Membrane Peeling (Membranectomy)

Epiretinal membrane (ERM), also known as macular pucker, is a condition characterized by growth of a membrane across the macula, or central retina of the eye. This condition may be thought of as the growth of scar tissue across the macula, thus interfering with central vision. The ERM typically contracts, causing distortion of the central retina, thus producing distortion of vision. The treatment of ERM is vitrectomy and membrane peeling. The ERM peeling procedure begins with a vitrectomy (a procedure that accomplishes removal of the vitreous humor of the eye). The vitreo-retinal surgeon then uses an extremely fine forceps, under high magnification, to grasp and gently peel away the membrane from the retina. This procedure may very well be the most delicate operation ever performed on the eye!

Schematic representation of the experimental set-up



Materials used: Polyester and Polypropylene films



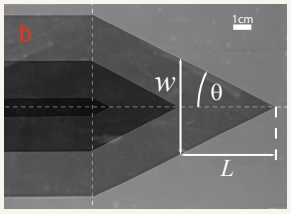


Figure 1 Three rectangular flaps of adhesive film cut and pulled at the same constant speed. a, Width versus length in millimetres on a log–log plot for the flaps with initial widths of 10 (open circles), 50 (times symbols) and 100 (plus symbols) μm. Solid red lines have been included for comparison. b, Tear shapes obtained in the experiment, shown overlapped. L: distance from a given point along the axis of symmetry (horizontal dashed line) to the tip. w (width): distance between the two sides of the tear along the perpendicular line to the axis of symmetry.

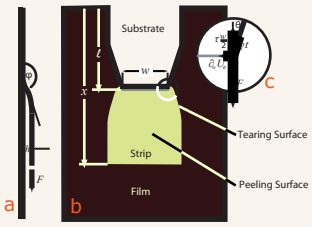


Figure 2 Schematic diagram showing the side and top views of the experiment and the geometrical parameters involved to describe the shape of the tear. a, Side view of the flap. The distance h gives the 'height' of the fold. b, Top view of the experiment. c, The close up shows a view of the tear at the position of the crack tip. The fracture propagation can be interpreted as the balance of four vectorial forces: two of them due to adhesion and fracture force, and the other two due to the pulling force and the inward force $\partial_x U_e$.

Acknowledgments

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Analytical Model

- Total Energy $U = U_e + 2\gamma t s + \tau A$
- Static equilibrium $\delta U = 0$

  and
- Minimal Force $(\partial_\theta F)_{\ell,w} = 0$ *equiv.* $\partial_\theta(\delta U/\delta s) = 0$

leads to

$$F = \tau \frac{w}{2} + \gamma t \cos\theta \quad (1)$$

$$(\partial_w U_e)_{x,\ell} = \gamma t \sin\theta \quad (2)$$

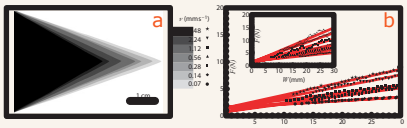

Figure 3 Experimental check of Eq. (1). Film was adhered to a substrate and then a 4-cm-wide flap was pulled at seven different speeds (legend). a, Overlapped tears. b, Force versus width. Inset: same experiment when film was adhered to a substrate with a stronger adhesive affinity, leading to a larger force necessary to detach the tear for a given pulling speed, while the intercept remains the same.

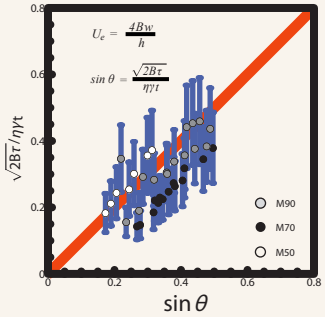

Figure 4 Angle of tearing versus $(2B\tau)^{1/2}/\eta\gamma t$ for experiments with three different materials: *M50* ($B = (3.0\pm0.1)\times10^{-3}$ Nm, $\gamma t = 0.6\pm0.1$ N), *M70* ($B = (5.5\pm0.1)\times10^{-3}$ Nm, $\gamma t = 1.5\pm0.1$ N) and *M90* ($B = (1.5\pm0.1)\times10^{-4}$ Nm, $\gamma t = 1.9\pm0.1$ N). The variation of the angle is produced by changing the substrate and varying the pulling speed. Red line shows the theoretical prediction given by the Elastica (Inset equations). Error bars show the uncertainty obtained from the estimated error of each parameter.

Conclusions

- We developed a formalism for investigating mechanical properties of thin adhesive films.
- As thickness is reduced owing to new technologies, traditional methods giving mechanical properties of a material in bulk form are not applicable due to stress localization[2] and wrinkling[3].
- Coupling between elasticity, adhesion and fracture, imprinted in a tear shape via the apex angle, provide the potential for new methods of material properties characterization[4].
- Mechanical properties of more complex systems: fruit wall[5] and epiretinal membrane.

Bibliography

1. Hamm, E., Reis, P., LeBlanc, M., ROman, B. and Cerda, E. Nature Mater. **7**, 386–390 (2008)
2. Witten, T. A. Stress focusing in elastic sheets. Rev. Mod. Phys. **79**, 643–675 (2007)
3. Cerda, E. & Mahadevan, L. Geometry and physics of wrinkling. Phys. Rev. Lett. **90**, 074302 (2003)
4. Groenewold, J., An angle on sticky films, Nature Mater. **7**, 348–349 (2008)
5. Matas, A. et al. Biomechanics and anatomy of Lycopersicon esculentum fruit peels and enzyme-treated 125 samples. Am. J. Bot. **91**, 352–360 (2004)