Thin-film peeling — the elastic term

K Kendall
ICI Corporate Laboratory, PO Box 11, The Heath, Runcorn, Cheshire

Abstract. An energy balance shows that the force required to peel an elastic film from a rigid substrate depends not only on the adhesive surface energy but also on an elastic deformation term. This elastic term, tending to reduce the adhesion force, can only be significant in two instances: for materials which can support stresses approaching the elastic modulus without fracturing, and for very small peel angles. Experiments using rubber peeling from glass over a range of peel angles support the theory.

1. Introduction

When the energy theory of fracture is applied to an elastic film peeling from a rigid substrate, the resulting equation for the peel force includes a term depending on the elastic modulus and thickness of the film material (Lindley 1971, Kendall 1971). This elastic term, tending to decrease the peel force, is usually negligible. However, under certain circumstances, this term may become very significant, particularly as the peel angle approaches zero. This note investigates theoretically the conditions under which the elastic term is important and presents supporting evidence from experiments on rubber peeling from glass.

2. Theory

Imagine an elastic film of thickness d and Young's modulus E peeling at an angle θ from a rigid substrate under a constant force F (figure 1). Consider the energy changes involved as a length Δc of film peels between the points A and B. There are three contributions to the energy change: a surface energy term $-bR\Delta c$ due to the creation of new surfaces (R being the adhesive energy, that is the experimental energy required to fracture unit area of interface), a potential energy term $F(1-\cos\theta)\,\Delta c$ due to the movement of the
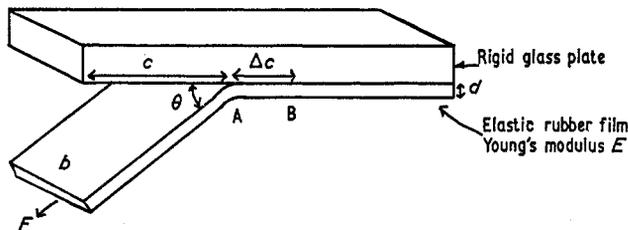

Figure 1. Elastic film peeling from a rigid substrate.

applied force (considering the film to be inextensible), and an elastic term due to exten-sion of the film in the direction of the applied force.

This elastic term, which is the result of the region AB being stressed, has two compo-nents: a component $F^2\Delta c/bdE$ which is the work done at constant force in stretching the region AB, and a component $-F^2\Delta c/2bdE$ which is the amount of recoverable strain energy stored in the stretched element. The material is assumed to undergo small, linear elastic strains in this instance.

Adding up all these energy changes and assuming energy conservation gives

$$-bR\Delta c+F(1-\cos\theta)\Delta c+\frac{F^2\Delta c}{2bdE}=0.\tag{1}$$

Therefore

$$\left(\frac{F}{b}\right)^2\frac{1}{2dE}+\left(\frac{F}{b}\right)(1-\cos\theta)-R=0.\tag{2}$$

This equation, quadratic in F/b, shows how the three terms, elastic, potential and surface, interact. Ordinarily the first, elastic, term may be neglected because the stress F/bd is usually very much smaller than E. In fact, most materials fracture at stresses of $E/100$ or less (Gordon 1968). Only in two situations can the elastic term become signi-ficant: (*a*) for an elastomer where the stress may rise typically to $10E$ before breakage, and (*b*) when the potential term in equation (2) goes to zero as θ becomes small. This latter case was investigated experimentally.

3. Experimental details

In these experiments a sheet of ethylene propylene rubber (Enjay 404) was used, cross-linked with 0·32% sulphur and 2·7% dicumyl peroxide against a glass plate at 160 °C for 1 h. When this sheet was removed from the glass after cooling, a very smooth rubber surface was revealed and this could be readhered to the glass to give reproducible adhesion.

In the present tests the rubber was readhered for a contact time of 1 h before carrying out the peeling. The rubber thickness d was 0·75 mm and its Young's modulus E meas-ured in tensile tests was $1·21\times10^6$ N m^{-2}.

It was first necessary to find the value of R, the adhesive energy for the glass–rubber interface. This was achieved using the peel test at an angle of $\theta=\pi/2$. At this angle the elastic term in equation (2) was only about 1% of the other terms and was therefore neglected, giving the result

$$\left(\frac{F}{b}\right)_{\pi/2}=R.\tag{3}$$

The adhesive energy R in this equation is not a constant but increases with increasing crack speed $\dot c$, as shown by the measurements of figure 2 (Gent and Kinloch 1971). We may therefore write

$$\frac{F}{b}=R(\dot c)\tag{4}$$

where $R(\dot c)$ is an empirically determined function which enables the adhesive energy to be calculated from a measurement of crack speed $\dot c$.
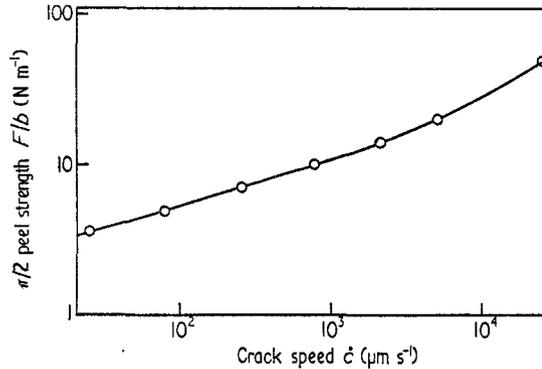
Figure 2. Variation of $\pi/2$ peel strength (equal to adhesive energy R) with crack speed $\dot{c}$.

It should be emphasized that R is not to be equated with the thermodynamic quantities, surface energy or work of adhesion. These are unlikely to be so large as R or to vary with crack speed. Instead, R should be treated as a fracture energy, which has the same units as surface energy but results from irreversible as well as reversible processes.

4. Verification of equation (2)

Once the adhesive energy R had been determined, verification of equation (2) was achieved in the following manner. A force F was applied to the peeling film and the resulting crack speed was determined. The angle θ was then adjusted until the crack speed was 80 μm s^{-1}, corresponding from figure 2 to an adhesive energy of 5 N m^{-1}. The angle θ was measured and the process repeated for a number of different peeling forces. The strain in the peeling film did not exceed 10%—the assumption of linear elasticity was therefore reasonable.

Figure 3 shows the results obtained in this way and compares the values of peel strength F/b with the theoretical predictions calculated from equation (2) using measured
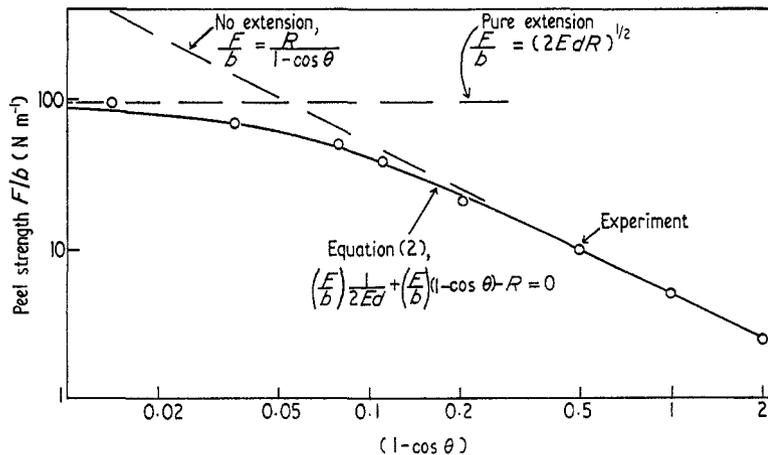

Figure 3. Dependence of peel strength on peel angle for a constant crack speed of 80 μm s^{-1}, i.e. a constant adhesive energy R of 5 N m^{-1}.

values of E, b, d, θ and R. Agreement between theory and experiment was found to be reasonable.

For high values of peel angle θ, the peel strength F/b was given closely by the equation

$$\frac{F}{b} = \frac{R}{(1 - \cos\theta)} \tag{5}$$

which showed that the elastic term was essentially negligible under these conditions. However, as the peel angle decreased, the elastic term became more noticeable until, at angles near 0·1 rad, the peel strength approximated to

$$\frac{F}{b} = (2EdR)^{1/2}. \tag{6}$$

In this case the elastic term was dominant. At such small angles of peel the failure corresponded more nearly to that of a lap shear joint. For a lap joint it has been demonstrated that the failure criterion is (Kendall 1975)

$$\frac{F}{b} = \left(2R \frac{E_2 d_2}{E_1 d_1} (E_1 d_1 + E_2 d_2) \right)^{1/2} \tag{7}$$

where E_1, E_2 and d_1, d_2 are the respective moduli and thicknesses of the lapped members. It is interesting to note that, when this formula is applied to our geometry, the d_1 member is of infinite modulus and the equation becomes equivalent to equation (6).

Acknowledgment

References

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