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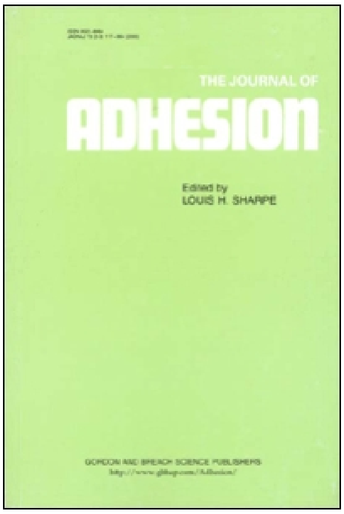

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Wave Phenomena in Low Angle Peeling

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The angular dependence of peeling has been investigated over a wide range of peel angles for a rubber strip peeled from glass. At low peel angles the peel front becomes "V"-shaped, wave phenomena are often observed and the peel energy can increase by an order of magnitude or more. A tentative theory, which appears to give the correct magnitude in a worked example, is advanced to account for the energy increase. The influence of factors such as electrostatic charge, deformation and rate on the observed phenomena are discussed.

INTRODUCTION

Peel tests have proved a popular means of assessing adhesive strength, particularly when at least one of the adhering members is readily flexible. Such tests are commonly carried out at a peel angle of 90° or 180° but one advantage of the method is that the results can be analysed for any angle in terms of the work or energy of adhesion. Thus a check on the validity of an energetics approach is available. Rivlin,[1] Hata[2] and Deryagin and Krotova[3] appear to have been the first to consider this, while Kaelble[4,5] investigated various adhesive systems for peel angles ranging from about 10° to 180°. Subsequently Hata *et al.*,[6] Kendall[7,8] and Lindley[9] have extended the analysis to take account of extension of the peeled leg and found good agreement between theory and experiment. However, in a later paper, Kendall[10] reported the occurrence of "dislocations" during peeling of rubber from glass at angles below about 10° and found increases in peel energy up to two-fold when these occurred.

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During the sliding of rubber over rigid surfaces, Schallamach[11] observed "waves of detachment" to pass across the contact region; indeed, often the relative motion was entirely attributable to the passage of these waves. Schallamach ascribed the wave formation to elastic instability produced by tangential compressive stresses set up in the rubber.

The present paper describes further investigations of the peeling of vulcanising rubbers from glass. It is shown that at low, fixed angles, peeling is often accompanied by the occurrence of waves of detachment and re-attachment. Correspondingly, there can be very large increases in peel energy—more than an order of magnitude. The effects of various factors on the low-angle behaviour are investigated and some tentative theoretical explanations are discussed.

EXPERIMENTAL PROCEDURE

The basic experimental method is illustrated schematically in Figure 1. A strip of rubber, about 2.5 or 5 cm wide and 1 mm thick, was carefully adhered to a glass plate mounted at a fixed angle θ to the vertical and left in contact for a period of 30 seconds. A constant force, F per unit width (referred to the unstrained state), was then applied to the lower end of the strip as illustrated and the rate of peel was measured.

Various rubbers have been examined but nearly all the results reported in the present paper were obtained with natural rubber vulcanized by $2\frac{1}{4}$ parts

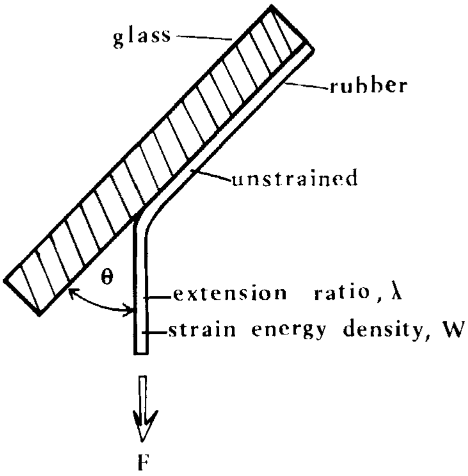

FIGURE 1 Experimental arrangement.

per hundred rubber by weight of di-cumyl peroxide for 120 minutes at 150°C. The rubber surface on which the adhesion was measured was moulded against glass. The glass plate used for adhesion measurement was either normal plate glass, with a measured resistance between point contacts 1 cm apart on the surface of $>2\times10^7$ ohms, or a specially-coated "conducting" glass (kindly supplied by Pilkington Glass Ltd) with a corresponding resistance of about 200 ohms. In either case the glass was cleaned with solvent prior to each experiment. Most experiments were carried out without a backing strip when the extension of the peeled rubber leg could be large but for certain experiments a polyester backing strip was used, which essentially prevented extension of the leg.

In most experiments the peel rate was determined by timing the peel front movement with a stopwatch, but in some experiments a high-speed camera was used.

THEORY

Energy considerations

For the case illustrated in Figure 1, where the adhered rubber is in the undeformed state and the peeled rubber (away from the vicinity of the peel front) is subject to a uniform extension ratio λ, it can readily be shown[9] that the energy available for peeling unit area of surface is given by

$$P = F(\lambda-\cos\theta)-Wt \tag{1}$$

where W is the strain energy density in the peeled leg and t is the unstrained thickness of the strip. If the stress–strain behaviour of the material is linear, Eq. (1) reduces to[6]

$$P = F\left(\frac{\lambda+1}{2}-\cos\theta\right). \tag{2}$$

The peel energy is often found to be dependent on the peel rate, r. In some of the present experiments, this dependence can be approximated by a relationship of the form

$$r = AP^{\alpha} \tag{3}$$

where A and α are constants.

Peeling by waves

Consider a peel front consisting of a system of waves of breadth b and spacing s propagating with velocity v at an angle ϕ to the test piece edge (see Figure 2a). If the front advances by a distance b/m perpendicular to the

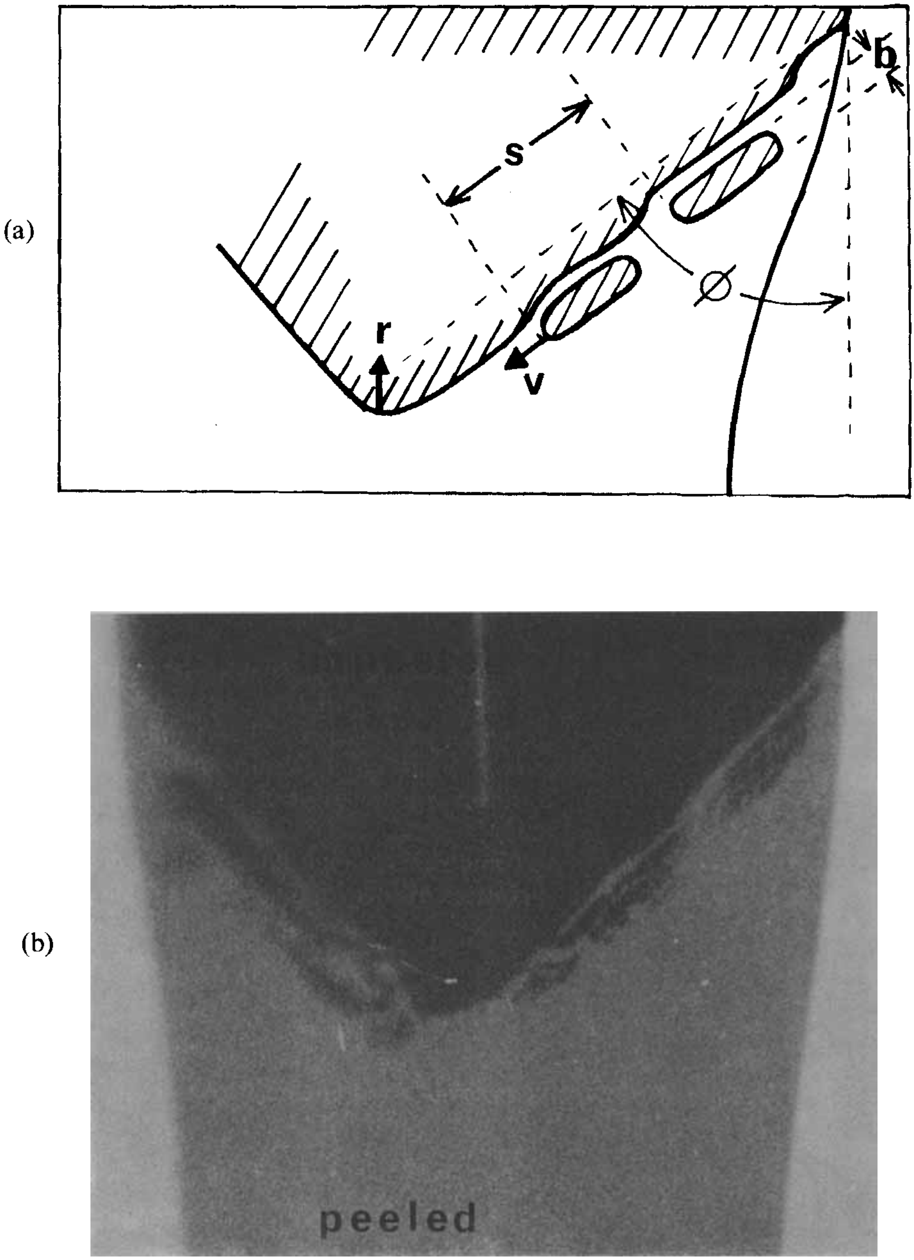

FIGURE 2 (a) Schematic view of the propagation of waves with velocity v.
(b) Photograph of peel front with waves.

direction of wave propagation with the passage of each wave (where m is a numerical factor $\geqslant 1$) and if peeling occurs solely due to the propagation of such waves, then the rate of peel r is given by:

$$r = vb/(ms \sin \phi). \tag{4}$$

Each element of rubber will then be detached m times on passing through the wave front region before it is finally separated from the substrate. If the energy of detachment is much greater than that regained on re-attachment then, similarly to the approach of Roberts and Thomas[12] for Schallamach waves, the total energy, P, required to peel unit area will be given by:

$$P = mP_w \tag{5}$$

where P_w is the energy required on the passage of a single wave. This ignores possible differences[10] in the energy of detachment for material adhered in the strained and unstrained states.

If the rate-dependence is governed by the *local* rate of detachment when waves occur, then from Eq. (3) it follows that $v = AP_w^\alpha$ whereas in the absence of waves, the corresponding relation is $r_0 = AP_0^\alpha$. Thus

$$P_w = (v/r_0)^{1/\alpha} P_0 \tag{6}$$

and from Eq. (5) the total peel energy becomes

$$P = m(v/r_0)^{1/\alpha} P_0\,. \tag{7}$$

On substituting for m from Eq. (4) this becomes

$$P = \{b/(s \sin \phi)\}(v/r_0)^{\frac{\alpha+1}{\alpha}} P_0\,. \tag{8}$$

RESULTS AND DISCUSSION

Peel front angle

When a rubber strip is peeled with little or no extension in the detached leg, the peel front is essentially transverse (*i.e.* $\phi = 90°$ in Figure 2a) and no waves are observed. However, when the extension is high, the peel front takes up the "V" shape illustrated in Figure 2b, with contained angle, or peel front angle, equal to 2ϕ. The results shown in Figure 3 indicate that 2ϕ decreases with increasing λ, independent of either test piece width or peel angle, θ.

Wave phenomena

At low peel angles ($\theta \leqslant 5°$), waves of detachment and re-attachment are often observed at the peel front. The detailed form taken by these waves can vary markedly according to the type of rubber and the conditions employed. Figure 2b shows a photograph of one example of wave formation on which the simplified schematic diagram in Figure 2a is based. The waves were observed to initiate at the test piece edges and run towards the centre, *i.e.* to propagate in the manner assumed in the preceding theoretical section.

Electrostatic effects

It was at first thought that electrostatic charging might contribute to wave formation, since on peeling unfilled rubber from glass appreciable charge could readily be detected on either surface with a simple electroscope. However, when the conductivity of the glass surface was increased more than 10^5 times, charge was detectable only on the rubber and not on the glass after peeling. Neither the rate-energy relation nor the occurrence of waves appeared to be affected by this. Further, if the conductivity of the rubber was increased by a similar amount, no charge was detectable on either surface but copious wave formation was *still* observed. Thus the formation of waves appears to be substantially independent of electrostatic effects.

Deformation effects

In every case where waves were observed, there were substantial lateral deformations in the rubber strip. In a supplementary set of experiments these deformations were prevented by means of a polyester backing strip adhered to the rubber. This suppressed both the occurrence of waves and the reduction in front angle to less than 180°.

The above result suggests that an important condition for the occurrence of waves during peeling is the presence of a sizeable overall deformation in the detached material. The situation in the peel front region is somewhat analogous to that set up when uniaxial tension is applied to an elastic strip clamped along one straight edge. The latter problem has been studied theoretically by Adkins[13] and his solution predicts that above an angle of 45° between a free edge and the clamped boundary, large stress concentrations will occur at the corner. This has been found to hold for rubbers up to 100% strain by Lindley.[14] It follows that with a transverse peel front (*i.e.* $\phi = 90^\circ$) there will be large stress concentrations at the corners if the extension of the peeled material is significant. Hence local peeling is likely to occur readily in these regions. It is believed that the characteristic V-shaped peel front and the tendency for waves to run in from the outside corners may be consequences of this. It also appears that local elastic instabilities, arising from the complex deformations, probably contribute to wave formation just as in the Schallamach wave case.

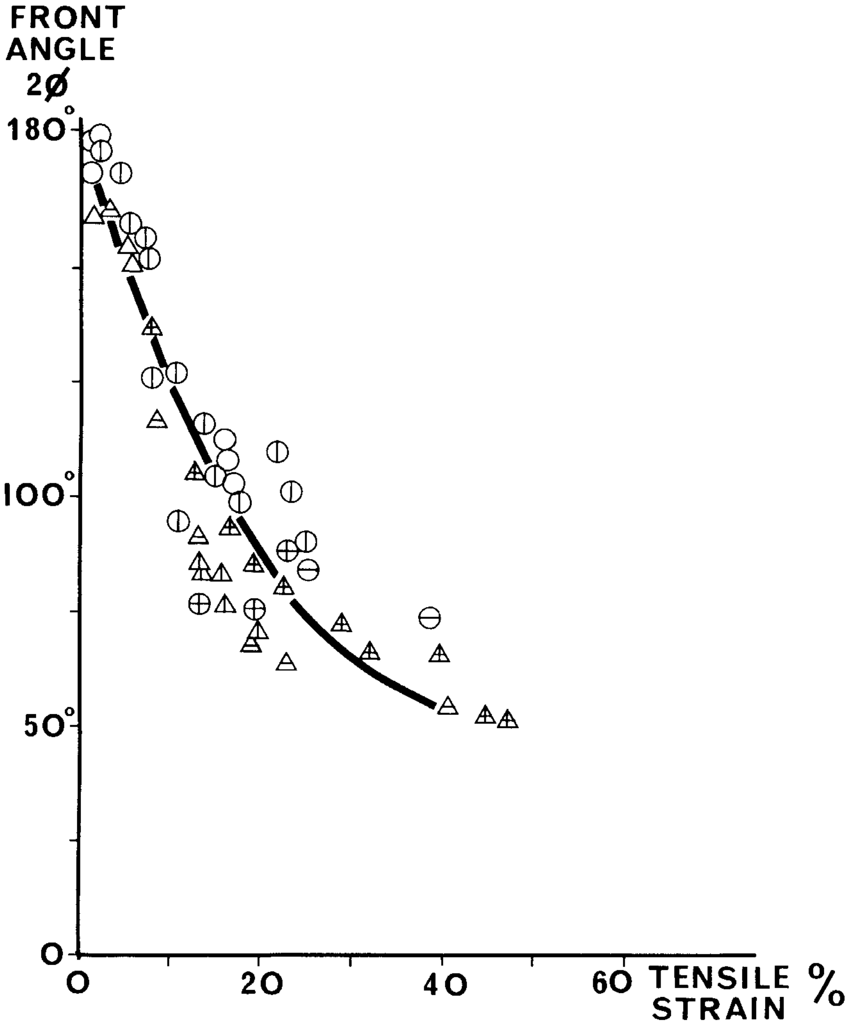

FIGURE 3 Peel front angle *vs.* tensile strain.

KEY For 5 cm wide strips ⊕, ⊖, ○, ⫰, ○— and —○ represent peel angles of 1°, 2°, 5°, 12°, 50° and 80° respectively. Angles of 1°, 2°, 5° and 12° are represented for 2½ cm wide strips by △, △, △ and △ respectively.

Rate effects

The wave phenomenon was not observed at peel rates above 10–15 cm/s, although higher peel rates up to 1 m/s were measured. The peel rate is, of course, the movement of the peel front as a whole. Movement of individual waves along the peel front was typically an order of magnitude faster than the overall peel rate, which implies a maximum wave velocity, v, of 1–2 m/s. This is still significantly slower than the elastic wave velocity in the material which at $\lambda = 1.4$ may be calculated as 57 m/s for the natural rubber vulcanizate used. The limitation in rate may therefore be due more to the need for a finite time for re-adhesion to occur in a wave of attachment than to the elastic wave velocity.

Energy effects

The peel energy, P, was calculated from Eq. (2) or, where departures from linearity were significant, from Eq. (1) using the value of W obtained directly from the stress–strain curve for the rubber. Figure 4 shows results for the peroxide-cured natural rubber vulcanizate plotted against peel rate. At a peel angle of 12° or more the results for all angles fall on the same line which is independent of strip width. This line represents Eq. (3) with $A = 4.5 \times 10^{-3}$ cm $s^{-1}/J^4 m^{-8}$ and $\alpha = 4$. At peel angles of 5° or less this simple picture breaks down, there is a substantial shift to higher energies and waves are observed. This apparent breakdown in the usual energy balance at low peel angles can be at least partly understood in terms of the model for wave formation described earlier.

For example, in one experiment where waves occurred at a peel angle $\theta = 5°$, the peel rate was 2.8 cm/s for an energy, P of 53 J/m^2. The waves (observed by means of high-speed photography) were in this case of average spacing s about 5 mm, height h about 2 mm and travelled towards the centre with a velocity v of 24 cm/s at an angle ϕ of about 45°. Substitution in Eq. (8) yields

$$P_0 = \frac{53 \times 5 \sin 45°}{2} \times \left(\frac{2.8}{24}\right)^{5/4} \mathrm{J/m^2} = 6\ \mathrm{J/m^2}$$

taking $\alpha = 4$, as above, and for the same rate of peel (*i.e.* $r_0 = r$). This estimate of P_0 is within experimental error of the value obtained from "high" angle peel results (*c.* 5.5 J/m^2—see Figure 4). Thus it appears, at least for the vulcanisate presently examined, that the theory developed earlier may account adequately for the large energy changes accompanying wave formation.

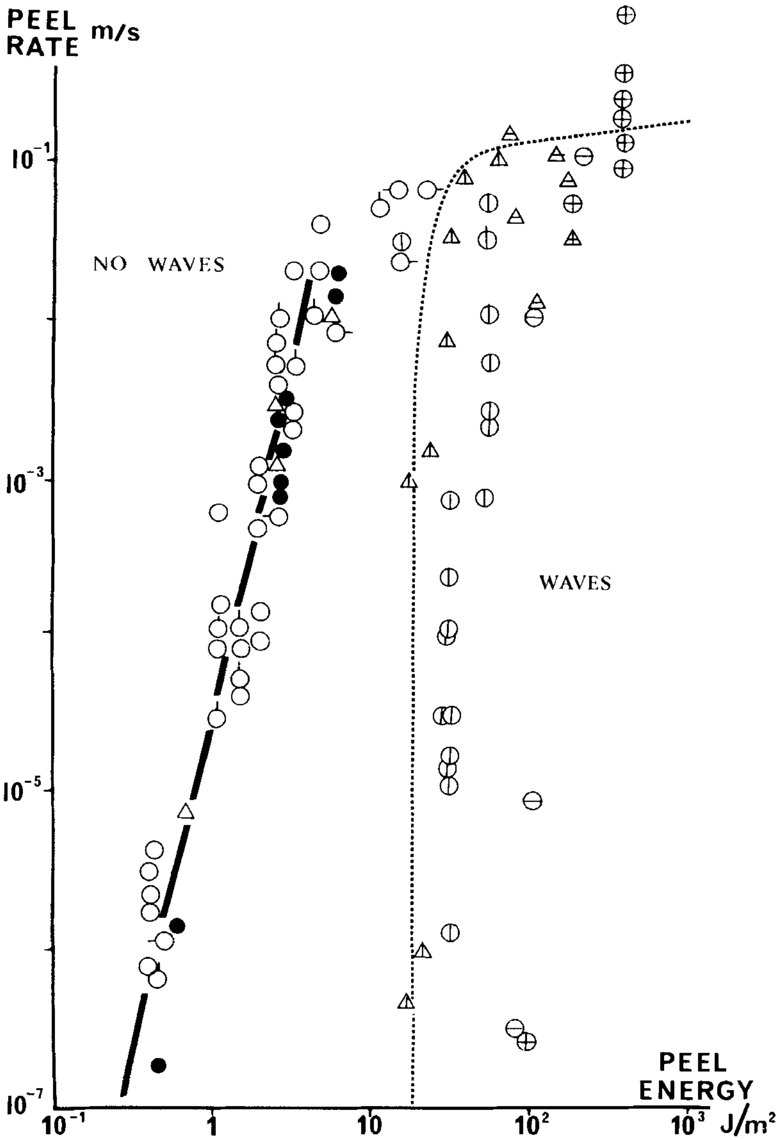

FIGURE 4 Peel energy *vs.* peel rate (peroxide cured NR vulcanizate). The area to the right of the broken line indicates the region where waves are observed. See Figure 3 for key to symbols; in addition, results for 5 cm wide strips with a polyester film backing are represented for peel angles of 1°, 5°, 20°, 50° and 80° by ●.

CONCLUSIONS

Large increases in peel energy, associated with waves of detachment and re-attachment have been observed when a strip of rubber is peeled from a glass surface at low peel angles. The formation of waves is not significantly affected by electrostatic charging but is connected with appreciable deformations in the detached rubber strip. Under some circumstances at least, peeling is solely due to the passage of the waves and it appears that the increase in energy may be attributable to the multiple detachments and re-attachments that occur as an element of rubber passes through the peel front region.

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