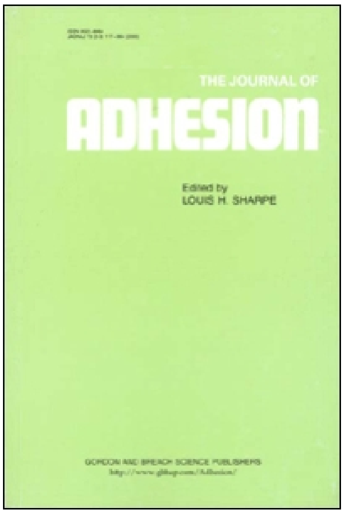

The Journal of Adhesion
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453635

Adhesion of a Rigid Punch to a Thin Elastic Layer

J. F. Ganghoffer[a]; A. N. Gent[a]
[a] C. N. R. S. Centre de Recherche sur la Physico-Chimie des Surfaces Solides, Mulhouse, France

To cite this Article Ganghoffer, J. F. and Gent, A. N.(1995) 'Adhesion of a Rigid Punch to a Thin Elastic Layer', The Journal of Adhesion, 48: 1, 75 — 84
To link to this Article: DOI: 10.1080/00218469508028155
URL: http://dx.doi.org/10.1080/00218469508028155

J. Adhesion, 1995, Vol. 48, pp. 75–84
Reprints available directly from the publisher
Photocopying permitted by license only

Adhesion of a Rigid Punch to a Thin Elastic Layer

J.-F. GANGHOFFER and A. N. GENT*

C. N. R. S. Centre de Recherche sur la Physico-Chimie des Surfaces Solides, 24 av. du President Kennedy, 68200 Mulhouse, France

(Received January 29, 1994; in final form May 18, 1994)

Adhesion between a rigid flat cylindrical punch and an elastic layer has been investigated. FE analysis was employed to determine the layer stiffness. Linear elastic fracture mechanics was then used to determine the energy release rate, G_a, per unit of bonded area for a circular debond propagating inwards from the edge of the punch. The calculations showed a strong effect of Poisson's ratio for thin layers, small departures from complete incompressibility causing large reductions in stiffness and hence in detachment force. Experiments were performed with an aluminum punch adhered to a rubber layer using a rubber-based adhesive. The ratio of punch radius to layer thickness was varied over the range 0.07 to 3.3. Detachment forces were measured and compared with calculated values. Reasonable agreement was obtained for thick layers but not for thin ones, possibly because of a change in the mode of failure.

KEY WORDS Adhesion of a punch; debonding; detachment; fracture mechanics; probe test; pull-off; tack test; tensile failure.

INTRODUCTION

Adhesive properties are often assessed by pressing a rigid flat-ended cylindrical punch ("probe") into contact with an adhesive surface and measuring the force, F_a, required to pull the punch away. The mean failure stress, σ_a, given by $F_a/\pi a^2$ where a is the radius of the punch, gives a measure of the strength of adhesion. We attempt here to determine the relationship between F_a or σ_a and a more fundamental measure of strength—the fracture energy, G_a, per unit area of bonded surface-assuming that the adhesive layer is isotropic and linearly elastic, *i.e.*, using linear elastic fracture mechanics. The resulting relations are then compared with some preliminary experimental data.

The problem was first treated theoretically by Kendall.[1] He evaluated the loss in strain energy, W, in an elastic layer as a circular ring becomes detached at the edge of the flat surface of the punch and spreads inwards. The criterion for spreading was obtained from Griffith's fracture criterion

$$\left.\frac{-\partial W}{\partial A}\right|_d \geqslant G_a \tag{1}$$

* Visiting Scientist, January–June, 1993. Permanent address: Institute of Polymer Engineering, The University of Akron, Akron, Ohio, 44325-0301, U.S.A.

where A is the area debonded ($A = \pi(a^2 - r^2)$ when a central circular region of radius r is still adhering) and the derivative is taken at constant deflection, d. For a punch of small radius, and hence with a small remaining radius r still attached, relative to the thickness and width of the elastic layer, the relation between applied force, F, and displacement, d, is[2]

$$F = \frac{2Erd}{(1 - v^2)} \tag{2}$$

where E is the tensile (Young) modulus and v is Poisson's ratio for the elastic material. For an incompressible material, $v = 1/2$, and Equation (2) becomes

$$F = \frac{8Erd}{3} \tag{3}$$

From Equation 2 the strain energy W is

$$W = \frac{Erd^2}{(1 - v^2)} \tag{4}$$

and hence from Equation (1) the force, F_a, required to initiate detachment is

$$F_a^2 = \frac{8\pi E G_a a^3}{(1 - v^2)} \tag{5}$$

In terms of a mean failure stress, σ_a:

$$\sigma_a^2 = \frac{8EG_a}{\pi(1 - v^2)a} \tag{6}$$

Kendall considered two extreme cases: when the punch radius a is small with respect to the layer dimensions, resulting in Equations (5) and (6); and when the layer is very thin in comparison with the punch radius and is sandwiched between it and a flat rigid base. The relevant elastic property of the layer in the latter case is the modulus, K, of bulk compression, and Equation (6) is replaced by[1]

$$\sigma_a^2 = \frac{2KG_a}{h} \tag{7}$$

We now consider intermediate cases when the thickness, h, of the elastic layer is comparable with or smaller than the punch radius, a, but the material is soft and relatively incompressible. Many commercial tapes probably fall into this category, when tested for "adhesion" using rigid probes of small diameter. First, the effective elastic modulus, E_e, is evaluated for confined elastic layers by means of a simple finite element program.[3] Then, using a general relation for detachment stress in terms of the effective elastic modulus, E_e, predicted detachment stresses are obtained for a wide range of layer thicknesses and punch radii. Finally, some experimental measurements of detachment forces are described and compared with the theoretical predictions.

THEORETICAL CONSIDERATIONS

Approximate Treatment

As a first approximation the effect of material lying outside the contact area is neglected. In other words, the elastic layer is treated as a cylinder having the same radius as the punch and bonded on its base to a rigid plane. The material is also assumed to be completely incompressible. The force-displacement relation is then[4,5]

$$F = \frac{\pi r^2 E d}{h}\left(1 + \frac{r^2}{2h^2}\right) \tag{8}$$

where h is the layer (cylinder) thickness. Using Equation (1) in the same way as before, the detachment stress is obtained as

$$\sigma_a^2 = \frac{2\,EG_a}{h}\left[\frac{1 + (a^2/2h^2)}{1 + (a^2/h^2)}\right] \tag{9}$$

Two extreme cases are: (i) if the layer (cylinder) is thick in comparison with the punch radius, then

$$\sigma_a^2 = \frac{2EG_a}{h} \tag{10}$$

and (ii) if the layer (cylinder) is much thinner than the punch radius, then

$$\sigma_a^2 = \frac{EG_a a^2}{h^3} \tag{11}$$

General Solution

The general relation between load, F, and deflection, d, can be expressed as:

$$\frac{F}{d} = \frac{A}{h}E_e = \frac{AEf(r,h)}{h} \tag{12}$$

where E_e is the effective value of tensile modulus, given by $Ef(r, h)$ where E is the actual modulus of the layer material and f is a function of the radius, r, of the circle of contact and the layer thickness, h. The corresponding relation for compliance $C(= d/F)$ is

$$C = \frac{h}{[\pi r^2 E f(r,h)]} \tag{13}$$

We now invoke a relation equivalent to Equation (1) for linearly-elastic systems[6] in order to calculate the detachment force, F_a, directly:

$$F_a^2 = -\frac{2G_a}{(\partial C/\partial A)} = \frac{-4\pi r G_a}{(\partial C/\partial r)} \tag{14}$$

On substituting from Equations (12) and (13), the average detachment stress, σ_a, is obtained as

$$\sigma_a^2 = \frac{2E_e G_a}{h[1 + (rf'(r,h)/2f(r,h))]} \tag{15}$$

where f' denotes $\partial f/\partial r$. Equations (6), (7) and (9) can be readily obtained as special cases of Equation (15).

EFFECTIVE MODULUS E_e OF CONFINED ELASTIC LAYERS

Numerical Calculations

Calculations of effective modulus, E_e, for layers of a wide range of thickness, compressed by punches of various radii, have been carried out using a simple finite-element program for linearly-elastic materials.[3] A cylindrically-symmetrical grid was employed; an example is shown in Figure 1. Eight-noded quadrilateral elements were used, adjusted in width and thickness to give a greater density of elements in the regions near the edges of the punch. The outer radius of the elastic layer was chosen to be at least three times the radius of the punch. Points on the outer curved surface and on the lower flat surface of the elastic layer were prevented from any displacement, radially or axially.

The radius of the punch and the thickness of the elastic layer were varied over wide ranges, the ratio a/h being varied from 0.02 up to 5. A value of 1 MPa, representative of soft rubbery materials and compounds, was assigned to the elastic modulus, E, of the layer, and several values of Poisson's ratio, ν, were employed, ranging from 0.48 to 0.4999. These represent extremes for normal rubbery materials, for which ν is usually about 0.495. For the punch itself, represented by a thin, flat-ended cylindrical disk, it was found necessary to assign high values of elastic modulus, as high as 10^8 MPa, in order to avoid significant bending deformations. This suggests that, even for the thick punches used in practice, deflections of the punch and/or base may give major contributions to the total strain energy, as Kendall[1] recognized.

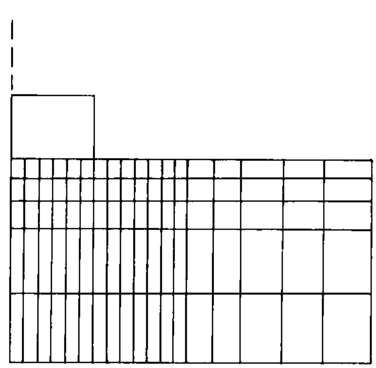

FIGURE 1 Sketch of representative finite element mesh.

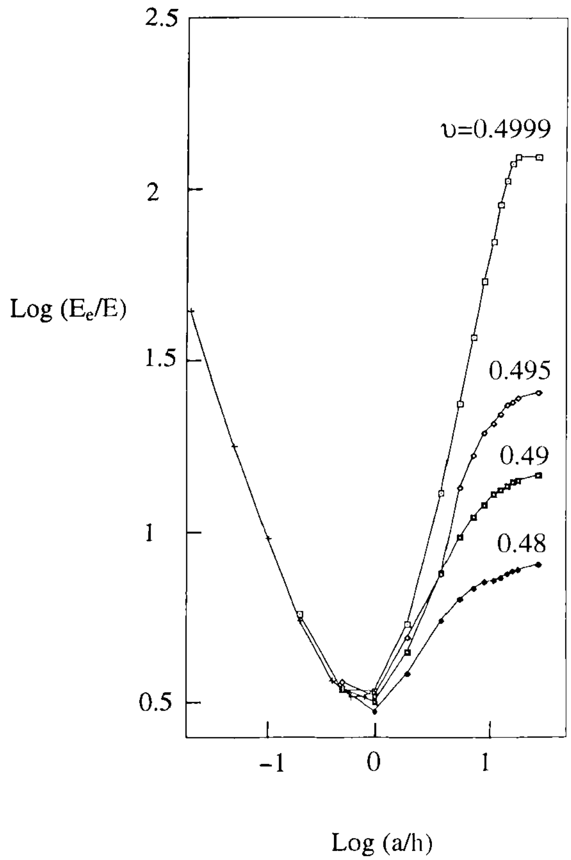

FIGURE 2 Effective modulus, E_e, *vs.* ratio of punch radius, *a*, to block thickness, *h*, for various values of Poisson's ratio. *E* denotes the tensile (Young's) modulus of the rubber.

A plot of effective modulus *versus* aspect ratio, a/h, of punch radius to layer thickness is given in Figure 2 using logarithmic scales for both axes. Three regions can be distinguished. When the ratio a/h is large, there is a strong positive effect on the effective modulus, which increases strongly to reach an asymptotic value for an extremely thin layer. The limiting value is governed by Poisson's ratio, ν, and the modulus, K, of bulk compression. As Poisson's ratio approaches one-half and the modulus of bulk compression approaches infinity, the asymptotic value of effective modulus also approaches infinity. Thus, small departures from absolute incompressibility have a strong effect for thin layers; in the limit, the modulus increases indefinitely as the layer thickness is decreased, but for slightly compressible materials it approaches a finite value dependent on the exact degree of compressibility.

On the other hand, when the aspect ratio a/h is small, the effective modulus decreases as the thickness decreases. In this region, there is hardly any dependence of the effective modulus on Poisson's ratio for values of ν close to one-half. And there is a pronounced intermediate range, when a/h lies between about 0.2 and 2, where the aspect ratio has little effect.

EXPERIMENTAL MEASUREMENTS

Sheets of a soft natural rubber compound were obtained from the Compagnie du Caoutchouc Industriel, Mulhouse. Young's modulus, E, was determined by measuring the tensile stress-strain relations at small strains (less than 5%), resulting in $E \approx 1$ MPa. Sheet thicknesses were 3, 4 and 5 mm. Circular disks were cut from them and firmly adhered to a steel base plate using a cyanoacrylate-based adhesive (Loctite Company). In order to obtain cylindrical blocks with a thickness up to 30 mm, different sheets were glued together with an elastomeric adhesive (Bostik 292). This adhesive dried to form an elastomeric solid with a hardness comparable with that of the rubber sheets. Measurements of indentation stiffness of the thicker composite blocks, using a small-radius indentor, were found to be consistent with the value of Young's modulus of the rubber sheets themselves, using Equation (3). It is concluded that the intervening layers of adhesive did not affect the elastic properties of the rubber disk significantly. Moreover, adhesion of the sheets was sufficiently strong to prevent delamination during detachment of the punch when it was adhered to the upper surface by a thin layer of Bostik 292.

The punch was an aluminum cylinder with a flat contact surface. Its radius varied from 2.5 to 10 mm and the thickness of the rubber block varied from 3 to 35 mm; thus, the ratio of punch radius, a, to rubber thickness, h, varied over the range: 0.07 to 3.33. The external radius of the rubber block was chosen to be always much larger than the punch radius, a, at least $5a$, so that the rubber block could be considered as being infinitely large in this direction.

Before use, the contact surface of the punch was treated with a sulfochromic dip at 100°C for 1 h. The surface of the rubber block was cleaned with acetone before each test. A thin layer of Bostik adhesive was then applied to the punch surface using a metal spreading blade to give a thin homogeneous coating. No adhesive was applied to the rubber surface. After about 10 minutes, both surfaces were brought into contact for 5 minutes under a light pressure of about 1 MPa. The steel base plate was firmly clamped and the punch was raised at a constant speed of 10 mm/min until detachment from the rubber occurred. The corresponding tensile force was recorded continuously during detachment; the maximum value was taken as the detachment force, F_a.

Each experiment lasted about 3 seconds from the start of tension until the force had fallen to zero after complete detachment. From the initial rate of decrease of force after the maximum, the initial rate of crack propagation was deduced to be about 200 mm/min, much faster than the rate of stretching the sample. Several experiments were performed for each aspect ratio, a/h, taking great care each time to reproduce the same preparation conditions.

In other experiments the energy, G_a, required to detach rubber from aluminum coated with Bostik 292 was measured by peeling a thin strip of rubber, 3 mm thick and 5 mm wide, away from the flat surface of an aluminum punch at 90 degrees. Various speeds of peeling were used, from 10 to 200 mm/min. Values of detachment energy were calculated using the relation $G = F/w$; they increased from about 200 to about 500 J/m^2 over this range of speed. A representative value of 300 J/m^2 is used in the following section for calculating detachment forces for a rigid punch.

COMPARISON BETWEEN EXPERIMENTAL RESULTS AND THEORY

Three modes of failure were observed: apparently interfacial at the rubber surface, apparently interfacial at the aluminum surface, or mixed failure, with adhesive remaining on both surfaces. Even when care was taken to reproduce the test conditions closely, all three modes of failure were sometimes observed for the same punch-and-rubber-layer combination. Since interfacial failure at the rubber surface always occurred at a much lower force, these results have been discarded and attention focussed on those cases where the adhesive remained principally on the rubber and detached from the aluminum punch. In all cases, fine threads of adhesive were observed to join the two surfaces together after detachment was otherwise complete. However, their contribution to the measured force seemed to be negligibly small.

Considering extreme cases, when the ratio of punch radius to rubber thickness is either much smaller or much larger than unity, the relevant rupture variable is $h\sigma_a^2$, which depends only on the ratio a/h, Equations (10) and (11). Figure 3 shows a comparison between experimental results for this reduced failure stress as a function of a/h and a theoretical relation, using logarithmic scales for both axes. The theoretical

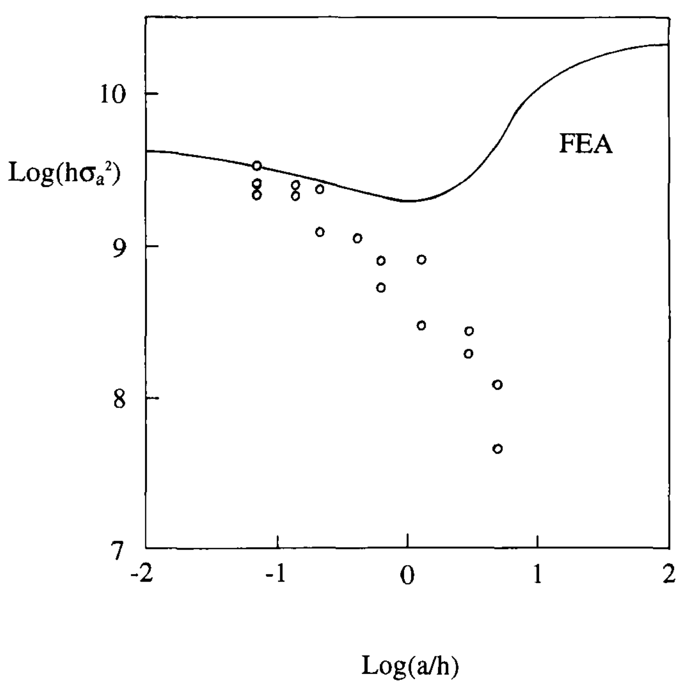

FIGURE 3 Comparison between measured and calculated values of reduced failure stress, σ_a. Full curve: calculated values with $G_a = 300$ J/m^2, $\nu = 0.495$. Circles: experimental measurements.

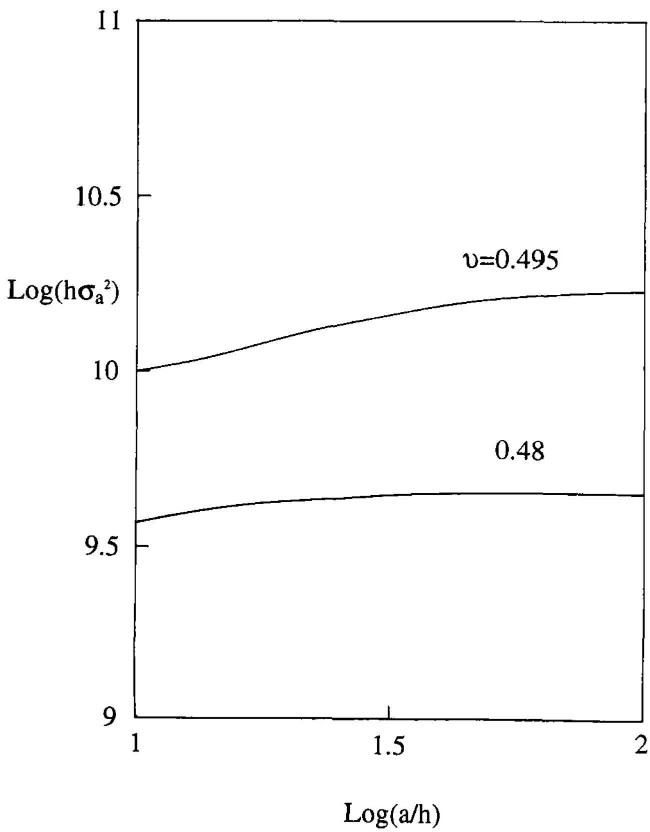

FIGURE 4 Effect of Poisson's ratio, ν, on predicted values of reduced failure stress, σ_a ($G_a = 300\,\mathrm{J/m^2}$).

relation was obtained from Equation (15), using a fourth-order polynomial relation for $f(r,h)$ curve-fitted to values of E_e calculated by FEA, shown in Figure 2.

The numerical solution appears to give the correct order of magnitude for the detachment forces, *i.e.*, similar to experimentally-measured values, when the punch radius, a, is relatively small compared with the thickness, h, of the rubber block, but it seriously over-estimates rupture forces for large values of a/h.

In limiting cases, corresponding to a ratio a/h much larger or much smaller than unity, the simple theory predicts linear relations with slopes of 0 and 2, respectively (Equations (10) and (11). However, at large a/h, because the effective modulus tends to a constant value given by the bulk modulus, K, the final slope can be deduced from Equation (7) to return to zero. This is shown in the numerical predictions of rupture force at large a/h ratios, Figure 4. Since the maximum value of a/h employed in the experiments was only about 5, this aspect of the theory was not examined.

Measurements at relatively large values of a/h, greater than about 1, showed considerable scatter and fell far below the theoretical predictions. Possible reasons for this are mentioned below.

DISCUSSION

When preparing samples, many factors can affect the strength of adhesion and the locus of failure. Two critical steps are: application of adhesive to the aluminum surface, and bringing the adhesive-coated aluminum probe into contact with the rubber layer. Spreading of adhesive was done manually, using a metal blade as a scraper in order to get a thin and homogeneous layer on the punch surface. It seems important also to avoid forming a bulge of excess adhesive around the punch edge, which could affect the failure mechanism. However, care was taken when applying the adhesive so that no visible bulge was formed.

The thickness of the adhesive layer and its homogeneity are also important parameters. In addition, the degree of drying of the adhesive before contacting the rubber surface is probably a critical factor. The optimum drying time will presumably depend on the thickness of the adhesive layer. If the adhesive is quite dry before contact, adhesion will be negligibly small. On the other hand, if the adhesive does not have time to dry after contact but before detachment, then we expect weaker adhesion also. In some peeling experiments using long, wide rubber strips, a drying time of about 45 min was found to be suitable. Accurate control of these parameters should ensure that the mode of failure remains the same and that failure forces are reproducible. Maintaining a constant contact pressure also appears to be important; indeed, fracture forces were found to increase with increasing contact pressure.

Apart from the aforementioned parameters, some other chemical and mechanical factors may have had an influence on the measurements:

—cleanliness of the aluminum and rubber surfaces
—residual acetone
—humidity
—changes in the adhesive before use
—failure occurring unsymmetrically around the edge of the punch
—failure of the adhesive layer itself, by cavitation[7]

It is thought that use of a soft adhesive layer on the elastic layer was the principal source of experimental difficulties in these studies and led to the pronounced discrepancies found between theory and experiment at large values of a/h, Figure 3. They are thought to reflect internal failure, probably by cavitation, of the soft adhesive layer itself under tensile stresses comparable with its elastic modulus.[7] In these circumstances the basic theoretical assumption of the mode of failure, by an inwards spreading of a ring of detachment on the surface of a homogeneous elastic layer, becomes invalid. Instead, the adhesive layer fails internally, probably in a relatively uniform way, and becomes much softer before detaching.

It would be advisable to avoid altogether the difficulties associated with applying a soft adhesive layer to an elastic substrate. Two possibilities are: molding rubber directly in contact with the punch surface, and developing adhesion by contact with an intrinsically-adhesive elastic layer. The latter would be closer to the aim of the present investigation—to model the mechanics of tack measurements using a rigid probe on a simple elastic adhesive layer.

When the ratio a/h is large (above ten), compressibility has a strong effect on the effective stiffness of the rubber layer and hence on the mechanics of fracture. A change of Poisson's ratio from 0.495 to 0.48-which is still representative of rubbery materials-causes a reduction of the rupture force by a factor of about 5 (Figure 4, based on Equation (15)). This effect points to a need for accurate values of compressibility when interpreting probe measurements of adhesion.

CONCLUSIONS

1. Values have been computed of the effective elastic modulus, E_e, of a thin layer sandwiched between, and bonded to, a flat-ended rigid cylindrical punch and a flat rigid substrate. As the radius, a, of the punch is increased relative to the layer thickness, h, E_e decreases, to reach a minimum value of about $3E$ when $a = h$. When a is greater than this, E_e rises sharply to approach an asymptotic value that depends on the compressibility of the material, being infinitely high for a totally-incompressible layer.
2. Values of pull-off force and mean failure stress have been calculated from the computed stiffnesses for a wide range of a/h, in terms of the fracture energy, G_a, of the interface between punch and layer.
3. Measured pull-off forces for an aluminum punch adhered to a soft rubber layer by means of a rubbery adhesive were in good agreement with theory when the punch radius, a, was small. (The fracture energy, G_a, was measured independently; it was about 300 J/m^2.) However, when the ratio a/h was about 1 or greater the mean failure stresses were found to be much lower than theoretical predictions, Figure 3. This discrepancy is tentatively attributed to onset of a failure mechanism different from that considered in the theory—detachment of the adhering layer starting at the outer edge of the punch. Instead, internal failure (cavitation) of the soft adhesive film is hypothesized to occur when the mean tensile stress at the interface becomes comparable with the elastic modulus of the adhesive.[7]

References

1. K. Kendall, *J. Phys. D: Appl. Phys.* **4**, 1186 (1971).
2. S. P. Timoshenko and J. N. Goodier, *Theory of Elasticity*, 3rd. ed. (McGraw-Hill, New York, 1970) p. 408.
3. "TEXPAC-LPC. Structural Analysis of Elastomers. User Manual," (HLA Engineers, Inc., Dallas, Texas, 1993).
4. A. N. Gent and P. B. Lindley, *Proc. Inst. Mech. Engrs.* **173**, 111 (1959).
5. A. N. Gent and E. A. Meinecke, *Polym. Engng Sci.* **10**, 48 (1970).
6. J. G. Williams, *Fracture Mechanics of Polymers* (Wiley, New York, 1984), p. 30.
7. A. N. Gent, *Rubber Chem. Technol.* **63**, G49–G53 (1990).