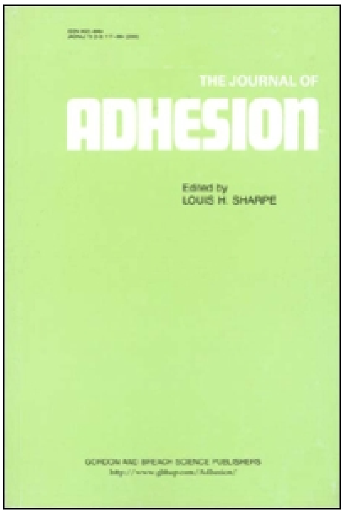

The Journal of Adhesion
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453635

The Mechanics of the Wedge Test

J. Cognard[a]
[a] Asulab S.A., neucha, Switzerland

To cite this Article Cognard, J.(1986) 'The Mechanics of the Wedge Test', The Journal of Adhesion, 20: 1, 1 — 13
To link to this Article: DOI: 10.1080/00218468608073236
URL: http://dx.doi.org/10.1080/00218468608073236

J. Adhesion, 1986, Vol. 20, pp. 1–13
0021-8464/86/2001-0001 $18.50/0

The Mechanics of the Wedge Test

J. COGNARD

Asulab S.A., Passage Max Meuron 6, CH-2001 Neuchatel, Switzerland

(Received October 3, 1985; in final form December 6, 1985)

The wedge test is increasingly used to characterize adhesive joints. It is a simple way to estimate the ageing of joints. In micromechanical and microelectronic applications standard ASTM tests do not give useful information about the behavior of small joints. This led to the use of small-scale assemblies and a comparison of the results with those from other investigators who have also analysed the statics of adhesive joints under wedge deformation. The results are compared to those from standard tests and show good agreement for epoxy resins. The calculated adhesive fracture energy, W_s, values for stainless steel and gold are also in good agreement with results found in the literature. Finally, the behavior of joints in various atmospheres is as expected from surface thermodynamics.

KEY WORDS Adhesive fracture energy; gold joints; mechanics; small joints; stainless steel joints; wedge test.

INTRODUCTION

An unsatisfactory property of an adhesive bond is that it may debond without warning upon exposure to an hostile environment. Among the various ways to test a glued joint, none gives information on its possible ageing. Some adhesive joints have a high initial resistance which will decrease with time. This loss of resistance is often studied by measuring from time to time the mechanical strength of joints exposed to a liquid. This information shows that joints weaken but is hardly useful in the evaluation of the long term behaviour of an assembly.

Joints debond when their elastic strain energy release rate $G = dU_e/dA$ is higher than the adhesive fracture energy W_s where

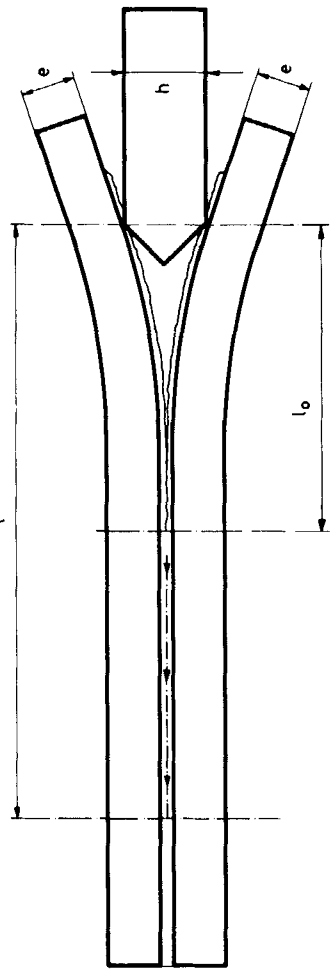

FIGURE 1 Schematic drawing of the wedge-test assembly. The initial length of the crack gives the peel strength P and the adhesive fracture energy, W_S. In an aggressive environment the crack grows to length l_t. The adhesive fracture energy in this environment is $(W_S)_t$.

$W_s = 2\gamma_E A$; where U_E is the mechanical energy of the system, A is the surface of the joint and γ_E is the effective fracture surface energy.[1]

An adhesive joint is, generally, under stress. These stresses may be due to different dilatation coefficients, retraction of the adhesive during curing, or introduced in the adherend during fabrication and so on; in general they are unknown. Upon ageing γ_E decreases either as the adhesive oxidizes and so changes its viscoelastic properties or as γ_E is lowered by a mechanism of environmental attack at the interphase which is not well understood. A very simple test[2] simulates these conditions by introducing a known tension in an adhesive joint. The stress is produced by elastic deformation of two adherend metal plates through the introduction of a wedge (Figure 1). The length of the crack at equilibrium gives both the effective fracture surface energy and the peel strength of the adhesive assuming no plastic yielding in either the wedge test or the peel test.

DESCRIPTION OF THE WEDGE TEST ASSEMBLY

For D3672 of ASTM two rectangular (17.8 × 21.5 cm) metal plates, 1.5 mm thick, are put together with the adhesive under study and cut into seven test pieces. The adhesive thickness is controlled by a Teflon spacer, 1.5 mm thick and 50 mm wide. After removal of the spacer, an aperture remains which allows the introduction of the wedge (1 × 20 × 30 mm) (Figure 2a).

Other geometries have also been used but sometimes dimensions are omitted, rendering any comparison impossible. In this laboratory small joints are used to study the bonding of expensive substrates. It is often difficult to correlate the information obtained from large specimens with the properties of smaller configurations. Also, when adhesion to gold is studied,[3] large specimens would be prohibitively expensive. In this work the geometry of the wedge test has been scaled to the dimension shown in Figure 2b. In order to keep the deformation of the plates in the elastic domain, stainless steel AISI 301 "hard" is used with the following dimension:

Length	$L = 40$ mm (instead of ASTM 165 mm)
Width	$w = 10$ mm (instead of ASTM 25 mm)

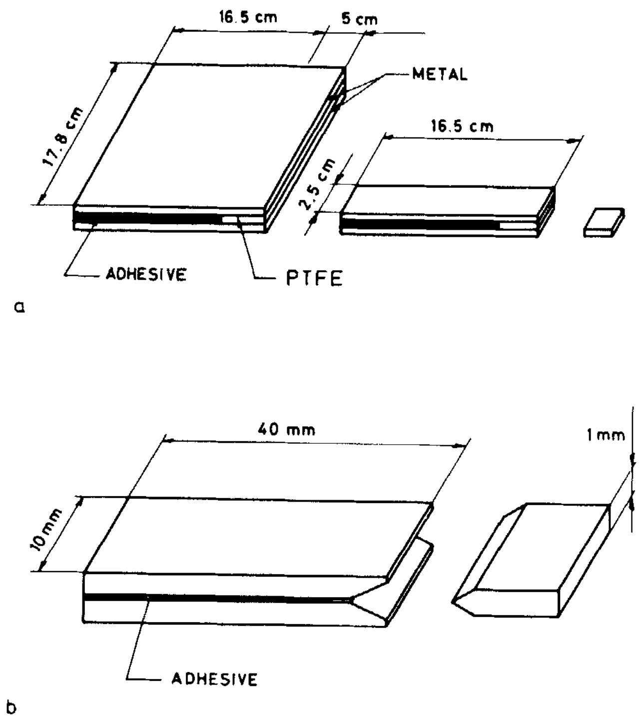

FIGURE 2 Geometry of the wedge-test. (a) As recommended by ASTM. (b) As used in this work.

Thickness $e = 0.5$ mm (instead of ASTM 3.12 mm)
Wedge height $h = 1$ mm (instead of ASTM 3.12 mm)

The stainless steel plates are stamped out and the edges filed to remove any residual asperities. One extremity of each plate is angled to make an opening in order to introduce the wedge. The rugosity of the surface measured on a Talysurf is $Ra = 0.35\ \mu m$ and Young's modulus, E, is $215\ GNm^{-2}$. Very thin glue lines (below $20\ \mu m$) are used and it seems that adhesive thickness does not play a rôle. In the first experiments the wedge was introduced by gentle knocking with a wooden mallet but later experiments used a bench with a micrometric screw. The total thickness was measured with a micrometer which was slid along the bonded parts. The aperture of the micrometer was then widened by 0.1 mm and the fracture tip taken as the point where the micrometer touches the assembly.

FRACTURE MECHANICS OF THE WEDGE TEST

Elastic energy due to the deformation of the metal plates

The elastic energy, U_E, stored in the adherend beam is

$$U_E = \int_0^L \frac{M^2(x)}{2EI}\,dx + \chi \frac{\tau^2(x)}{2\mu S}\,dx \tag{1}$$

where $M(x)$ and $\tau(x)$ are the bending moment and the curvature moment respectively, at a point along the beam:

E is Young's modulus

I is the inertia moment $I = (w \cdot e^3)/12$

χ is the shear factor ($\chi = \frac{6}{5}$ for a rectangular beam)

μ is the shear modulus related to E through Poisson's Coefficient ν by $\mu = E/2(1+\nu)$

S the beam section is $w \times e$.

Under the action of force F $M(x) = -Fx$ and $\tau(x) = F$ (Figure 3).

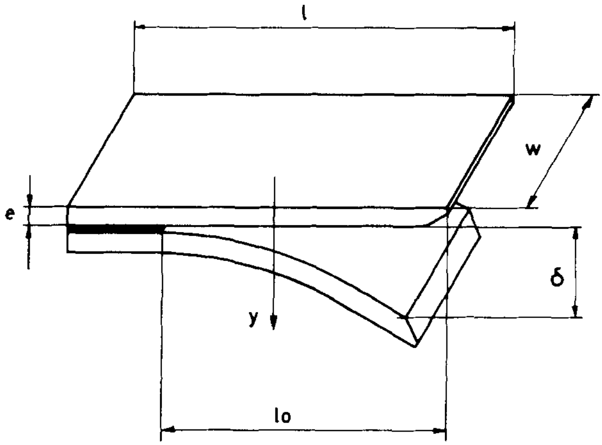

FIGURE 3 Bending of a beam.

Integration of (1) gives

$$U_E = 2F^2L(5L^2 + 3(1+\nu)e^2]/(5Ee^3w) \qquad (2)$$

and the deflection δ is obtained by $\delta = \partial U_E/\partial P$, giving

$$\delta = 4FL[5L^2 + 3(1+\nu)e^2]/(5Ee^3w) \qquad (3)$$

using (3), the elastic energy U_E of Eq. (2) is obtained as:

$$U_E = \frac{5Ewe^3\delta^2}{8L[5L^2 + 3(1+\nu)e^2]} \qquad (4)$$

When the beam thickness is small compared to its length, as it is generally the case, expression (4) simplifies to

$$U_E = Ewe^3\delta^2/8L^3 \qquad (5)$$

with

$$\delta = 4FL^3/Ewe^3 \qquad (6)$$

The wedge test is equivalent to two beams and the elastic energy stored is doubled

$$U_E = Ewe^3\delta^2/4L^3 \qquad (7)$$

As the adhesive joint is thin the elastic energy stored in the adhesive is negligible.

Fracture equilibrium

Upon introduction of the wedge between the two beams a crack forms and propagates over length l_0. During the extension of that crack part of the elastic energy, U_E, stored in the beams releases while two new surfaces are created. Let U_S be the energy necessary to create two surfaces each of area A.

The crack propagation will stop when the release rate of the elastic energy, G,

$G = \partial U_E/\partial A$ is equal to the energy

$W_S = \partial U_S/\partial A$ necessary to create a surface of unit dimension.[4]

That is

$$G = W_S \text{ (Griffith's criterion)} \qquad (8)$$

If G is higher than W_S cracks proceed, while it will recede if $G < 2W_S$. In the case of two bodies of surface energy γ_1 and γ_2 in contact, the Dupre's thermodynamic work of adhesion, W_a, is given by:

$$W_a = \gamma_1 + \gamma_2 - \gamma_{12} \tag{9}$$

and the relationship between W_S and W_a is discussed later.

In the case of the wedge test the calculation of the elastic energy release rate G is relatively simple. The elastic energy is given by (7) and

$$G = \left(\frac{\partial U_E}{\partial A}\right)_\delta = \frac{l}{w}\left(\frac{\partial U_E}{\partial L}\right)_\delta = 3El^3\delta^2/4l_0^4 \tag{10}$$

(as $dA = -w\,dL$).

If h is the wedge thickness $h = \delta/2$ and

$$G = 3E\frac{e^3h^2}{16l_0^4} \tag{11}$$

The stability of the system is given by the sign of $\partial G/\partial A$. If $\partial G/\partial A$ is negative the system is unstable, the crack will propagate with an ever increasing speed until the assembly separates. If $\partial G/\partial A$ is positive the system is in equilibrium. Any modification of the strain will move the crack toward a new equilibrium position.

In the wedge test, derivation of Eq. (4) gives

$$\left(\frac{\partial G}{\partial A}\right)_h = \frac{l}{w}\left(\frac{\partial G}{\partial L}\right)_h = \frac{3Ee^2h^2}{el_0^5} \tag{12}$$

which is always positive.

From both Eqs. (8) and (11) the crack length at equilibrium, l_0, is obtained as

$$l_0 = (3Eh^2e^3/16W_S)^{1/4} \tag{13}$$

The initial length of the crack is a function of the thickness e, the material from which the plates are made through its modulus E, the thickness of the wedge h and the adhesive/fracture energy, W_S.

In practice equilibrium is approached in 24 hours in a desiccator.

Relation between the initial crack and peel strength

The wedge deformation is equivalent to a cleavage, peel strength may be obtained *via* the adhesive fracture energy, W_s. The peel strength P at low speed of peeling is related to W_S through the equation,[5]

$$P = W_S/w \tag{14}$$

Equation (1) relates W_S to l_0 thus from (14) the peel strength P is obtained:

$$P = \frac{l}{w} \cdot \frac{3E}{16} \frac{h^2 e^3}{l_0^4} \tag{15}$$

The peel strength is a function of the speed of peeling[5,6] and tends to a lower limit, P_0, at low speed.

The value is obtained by Eq. (15) should be P_0.

The normalised DIN E53289 procedure measures P at $15\,\text{mm} \cdot \text{mm}^{-1}$ which is a rather high speed and the comparison between experimental values deduced from the wedge experiments and commercial specifications are generally not possible.

APPLICATION TO STAINLESS STEEL EPOXY JOINTS

Glueing stainless steel would bring economical advantages as welding is expensive. However, there is not much confidence in the reliability of adhesive joints in tropical conditions; thus it is a good subject for applied research.

Time necessary to reach equilibrium

Upon the introduction of the wedge an unstable situation is created and equilibrium is approached following an exponential law. This requires infinite time for completion as the speed of propagation reaches a very low value. In practical terms equilibrium is attained after 24 h. In order to avoid any variations due to atmospheric conditions, during equilibrium, wedge-test specimens are kept in a desiccator at the constant temperature of the laboratory.

Adhesive fracture energy

Equation (13) gives relation that exists between the crack length, l_0, and the adhesive fracture energy, W_S. With the dimensions of the test specimens used, $W_S = 5.04 \times 10^{-6}/l_0^4$ (J m^{-2}). A typical value of l_0 for modified epoxies is 10 mm which gives $W_S = 504$ J m^{-2} a value very similar to that obtained by other workers.[7,8] This value is much higher than the Dupré work of adhesion, W_a, as calculated from the contact angle, θ, of a drop of epoxy resin ($\gamma_L = 45$)[3] (before it cures) on stainless steel. Using a measured $\theta = 39°$ gives $W_a = 80$ mJ m^{-2}. It seems generally accepted that W_S is proportional to W_a,[9] $W_S = gW_a$ giving in that case a factor $g = 6000$ which is common[10] in the case of epoxy resins.

Peel strength

Equation (15) gives the relation between the peel strength P and the initial strength, l_0, of the crack. For the above epoxy adhesive (ASU 613), $l = 10$ mm and $P = 5.04$ N for $W = 10$ mm or $P = 0.5$ Nmm^{-1}.

In order to compare the peel strength value obtained from the wedge-test initial crack length l_0 and a classical peel test, the force necessary to peel a thin band of stainless steel AISI 304 bound with a modified epoxy adhesive has been peeled from a rigid bar of steel. Peel strength values were the following:

Peel rate:	(ms^{-1})	1.67×10^{-5}	8.3×10^{-5}	16.7×10^{-5}	83×10^{-5}	830×10^{-5}
Peel strength:	(Nmm^{-1})	1.2	2.2	2.2	3.2	3.6

showing the influence of the peeling rate over the peel strength of epoxy adhesives. This adhesive gives the small scale test an initial crack length l_0 of 8 mm which corresponds to a peel force $P = 9.65$ N for 10 mm width or 0.96 Nmm^{-1} in agreement with the experimental result measured at low speed.

USE OF THE WEDGE TEST TO CHARACTERISE THE RESISTANCE TO ENVIRONMENTAL FACTORS

The case of epoxy–stainless steel joints in tropical atmosphere

40°C, 90% relative humidity (R.H.) is typical of tropical climates, and is used in accelerated testing.[11] In common practice, a hundred lap shear specimens are prepared which will be pulled apart from time to time indicating the loss in shear strength resistance (Figure

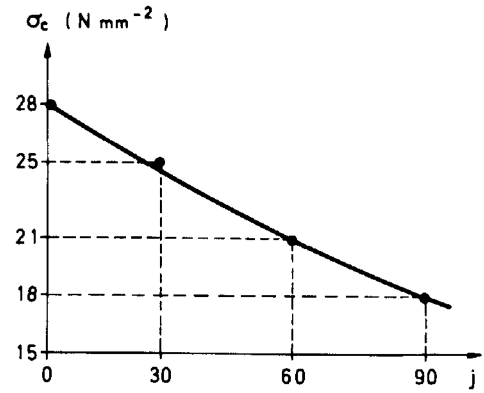

FIGURE 4 Loss in shear strength resistance, σ_c, of adhesive joint exposed to tropical climate.

4). The procedure is often pursued over 90 days. Extrapolation of this procedure to longer times is hazardous. The same information is provided by a wedge test in 24 h which also gives the equilibrium work of adhesion under these conditions. Putting the wedge-test assembly into a tropical atmosphere causes a crack propagation over 24 h (Figure 5) which then remains stable. In one case the fracture remained stable over 3 years, and that equilibrium is reached in 24 h has also been found by others.[12]

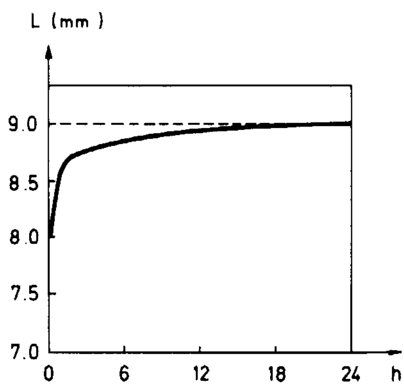

FIGURE 5 Progression of the crack of the wedge-test in a tropical atmosphere. Equilibrium is nearly reached in 24 hours.

The length of the crack after 24 h in tropical conditions, l_{24}, thus gives the adhesive fracture energy at equilibrium in those conditions. From Eq. (4),

$$(l_0/l_{24})^4 = (W_S)_{H_2O}/W_S$$

For instance, $l_0 = 10$ mm, $l_{24} = 12$ mm, indicates a loss of one half of the adhesive fracture energy of adhesion from its initial value. Schultz[13] has shown that variations in W_S are essentially those in W_a (equal to l/gW_S).

From Eq. (6) the ratio of the peel force P_{24} in tropical atmosphere to its initial value P_0 has also diminished as (l_0/l_{24}).[4]

The wedge test can also give indications on adhesive joints weakening in polluted atmosphere of solvent vapours.

Resistance of stainless steel epoxy joints to "synthetic sweat" (salted water)

In this experiment the influence of human sweat on an adhesive joint by the test ISO 3160/2 was simulated.

The synthetic sweat has the composition:

Sodium chloride	20 g/l
Ammonium chloride	17.5 g/l
Urea	5 g/l
Acetic acid	2.5 g/l
Lactic acid	15 g/l
NaOH	to pH 4.7

The wedge-test assembly is sprayed with the mixture and placed over a felt impregnated with the synthetic sweat. The sensitivity to sweat is measured by the progress of the initial crack after 24 hours.

The results surprisingly confirm those of Ref. 14, showing that epoxy joints have less sensitivity to salted water than to high humidity; for example, ASU 613 gives a crack of length of 9 to 11 mm (4 samples) instead of 11 to 13.5 mm (4 samples) in high ambient humidity.

INFLUENCE OF THE SILANATION OF STAINLESS STEEL

The benefit of silane treatment of metal surfaces is not clearly proven. It does not seem that mechanical strength is increased although resistance to humidity may improve.[15,16] Clean stainless steel plates have been treated with aminopropyl triethoxysilane (AMEO) following the procedure of Pluedemann.[17] Comparison of fracture between treated and untreated samples shows first, that the initial crack length is the same, proving that silane treatment has no influence on the strength, but, secondly, that crack propagation is reduced on the silane treated plates showing the positive influence of aminosilane on the water resistance. The adhesive fracture energy was lowered by a factor 0.5 in absence of treatment but only by 0.8 after silanation.

EPOXY JOINT TO GOLD

Surfaces coated with cobalt–gold alloys and a 24 ct gold finish have also been studied. With the same adhesive used for stainless steel (ASU 613), joints formed with gold show the same initial properties ($l_0 = 10$ mm), but exposure to humidity increases the crack length to $l_{24} = 15$ mm which indicates a 75% loss of bond strength.

Epoxy joints to gold are much more sensitive to humidity than those to stainless steel. The silane treatment shown above gives little improvement. In the case of stainless steel blades, gold plated with Au–Co 18 ct, adhesive thickness ~20 μm, the following figures were obtained:

Surface	Test	l_0 mm	l_{24} mm	l_0/l_{24}
Gold	1	9.0	11.5	0.78
	2	8.0	11.0	0.72
	3	8.5	11.5	0.73
	4	8.0	11.0	0.72
Gold + AMEO	5	9.5	12	0.79
	6	10.5	11.5	0.91
	7	10.5	12	0.87
	8	9.5	11.5	0.82
	9	10	11.5	0.85

The initial fracture is $l_0 \sim 8.5$ mm ($P = 5.1$ Nmm^{-1}) while AMEO silane treated blades have $l_0 \sim 11$ mm ($P = 2.35$ Nmm^{-1}).

Fracture length after 24 hours at 40°C 95% RH over gold is $l_{24} \sim 11.5$ mm the same as for AMEO treated gold.

CONCLUSIONS

The wedge-test is a very simple test which can provide much information upon the behaviour of adhesive joints under stresses and scaling down provides a cheaper experiment. In one test the adhesive fracture energy is obtained, together with an estimate of the peel strength at low speed. Furthermore, long term behaviour in a given environment can be compared for various adhesives.

It has been shown for epoxy resins that the quantitative values compare with those of the literature; also the positive influence of silane treatment on the adhesion of one epoxy resin to stainless steel has been demonstrated.

Acknowledgements

I thank Dr Barquins for his help in deriving Eq. (4) and Drs G. P. Anderson and J. Comyn for their critical reading of the manuscript. Most measurements are due to F. Chabloz.

References

1. R. G. Linford, *Solid State Surface Science*, Vol. 2 (Dekker, New York, 1973) pp. 1–152.
2. J. A. Marceau, Y. Hogi and J. C. MacMillan, *Adhesives Age*, **10** (10), 28–34 (1977).
3. J. Cognard and C. Boichard, *Adhesion 8*, Ed., K. W. Allen (Appl. Sci. Publ., London, 1983) pp. 169–193.
4. D. Maugis and M. Barquins, *Adhesion and Adsorption of Polymers*, part A, Ed., L.-H. Lee (Plenum, New York, 1980) pp. 203–247.
5. A. Ahagon and A. N. Gent, *J. Polym. Sci. (Polym. Phys.)* **13**, 1285–1300 (1975).
6. M. Barquins and D. Maugis, *J. Adhesion* **13**, 53–65 (1981).
7. W. D. Bascom, *Proc. Army Mat. Technol. Conf. Adv., Joining, Tech.* **4**, 265–301 (1976).
8. E. H. Andrews, He Pingsheng and C. Vlachos, *Proc. Roy. Soc. Lond.* **A 381**, 360 (1982).
9. J. Schultz and A. Gent, *J. Chem. Phys.* **70**, 708 (1983).
10. L.-H. Lee, *Adhesive Joints*, Ed., K. L. Mittal (Plenum, New York, 1984) pp. 739–53.
11. W. Brockman, Private communication.
12. R. J. Moulds and T. R. Baldwin, *Int. J. Adh. Adhesives* **3**, 203–207 (1983).
13. J. Schultz and A. Carre, *J. Appl. Polym. Sci. Appl. Polym. Symp.* **40**, (1984).
14. J. P. Sargent, *J. Phys. D. Appl. Phys.* **14**, 1933–1938 (1981).
15. A. J. Kinloch, *Adhesion 6*, Ed., K. W. Allen (Appl. Sci. Publ., London, 1982) pp. 95–100.
16. F. J. Boerio and J. W. Williams, *Appl. Surf. Sci.* **7**, 19–31 (1981).
17. E. Plueddemann, *Silane Coupling Agents* (Plenum, New York, 1982).
18. J. Cognard, *Gold Bulletin* **17**, 131–139 (1984).