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Use of the Double Torsion Method to Study Crack Propagation in an Adhesive Layer

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ABSTRACT: The double torsion technique offers a simple method of studying crack propagation in adhesive layers. The method has been applied successfully to obtain crack-velocity versus crack-extension-force curves for fracture in bonds constructed from an epoxy and a nylon-impregnated adhesive. The thickness of the adhesive layer is found to have a significant effect on the fracture behavior.

KEY WORDS: adhesives, fractures (materials), crack propagation, composites

The fracture mechanics approach is being increasingly used in the characterization of failure in adhesive joints (see ASTM Test for Fracture Strength in Cleavage of Adhesives in Bonded Joints [D 3433-75]). The properties being measured are the critical crack extension force for mode I and mode II fracture [*1,2*] and the crack propagation velocity at subcritical values of the crack extension force [*3*]. Among the most common testing methods being employed are the compact tension test and the simple and the tapered double-cantilever beam test.

In this paper we describe a new technique for obtaining fracture mechanics data for metal-polymer-metal adhesive joints. The technique was used by Outwater and Murphy [*4*] to study crack propagation in a composite consisting of glass bristles cast in epoxy resin. It has also been applied to study fracture in glass [*5*] and in bulk polymers [*6,7*]. This study is, however, the first attempt to apply the method to study crack propagation in adhesive joints. The main advantage of this method is that at any time during the test the crack length can be estimated by measuring the instantaneous load and the displacement applied to the specimen; also, the crack extension force applied to the crack tip depends only on the load, which is easily measured, and is independent of the length of the crack.

In this paper we shall report the results of a systematic study of crack propagation in two adhesives: a simply epoxy EC-2186, one part, 100% solids, thermosetting liquid adhesive manufactured by the 3M Co., and an impregnated nylon epoxy FM-1000, which is an elastomeric structural adhesive film manufactured by the American Cyanamid Co. The other variables in this study are the thickness of the adhesive joints and the two types of metal adherends.

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Double Torsion Technique

The details of this method have been described by Williams and Evans [*8*]. The shape of the specimens and the loading jig are shown in Fig. 1. The specimen (Fig. 1*a*) is loaded essentially in four-point loading, the load being applied at one end of the specimen. The position of the plane of loading is denoted by the line marked "load points" in Fig. 1*a*. The loading jig is shown in Fig. 1*b*. The thickness of the loading jig (25.4 mm) is much less than the length L of the specimen (152.4 mm); as such, the specimen is supported only at one end during the test. The crack length a is measured from the loading position to the crack tip, as shown in Fig. 1*a*. The specimen is loaded by applying a vertical downward displacement y (Fig. 1*b*) by means of an Instron machine. The corresponding force is measured by a compression load cell. To obtain information on a and crack velocity $\dot{a}$, it is necessary to know how the compliance of the specimen varies with a. If the deformation is elastic, then

$$y/P = Ba + C \qquad (1)$$

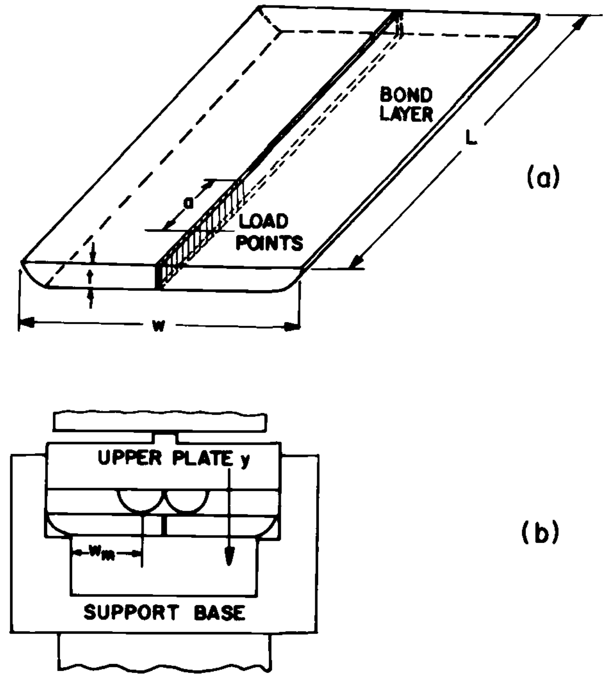

FIG. 1—*The specimen geometry* (a) *and the loading jig* (b) *used in the double torsion test. The dimensions were as follows:* $W = 73$ *mm,* $w_m = 25.4$ *mm,* $t = 2.54$ *mm, and* $L = 152.4$ *mm.*

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where P is the load and B and C are constants, C being the compliance of the specimen when $a = 0$. For sufficiently long cracks, $Ba \gg C$, an approximate formula can be derived for B [8]:

$$B = 3w_m{}^2/Wt^3G \tag{2}$$

where G is the shear modulus of the adherends and w_m, W, and t are as shown in Fig. 1. It is possible, of course, to measure the actual value for B and to compare it with the value calculated from Eq 2. As we shall report later, we find that they agree to within 10% error. This justifies the assumption that local crack tip plasticity does not significantly affect the compliance, particularly in our test since all the plasticity is confined to the adhesive layer, which is much thinner than the width of the specimen.

Differentiating and rearranging terms in Eq 1 leads to an expression for the crack velocity in a constant displacement test ($\dot{y} = 0$):

$$\dot{a} = -(\dot{P}y/P^2B) \tag{3}$$

The relationship between a, P, and the stress intensity factor K can be obtained semiempirically. There are some unanswered questions as to the mode of fracture in this type of test, although it has been shown that the crack moves approximately perpendicular to its front and that the fracture is primarily mode I [8]. This is particularly true when the crack is moving in the midsection of the specimen. An exact analysis for K_I for this geometry has not been carried out but the following approximate formula has been shown to provide a valid value for K_I in many systems [8]:

$$K_I = AP$$

$$A = w_m \left(\frac{3\,(1+\nu)}{Wt^4}\right)^{1/2} \tag{4}$$

where ν is the Poisson's ratio. Note that K_I depends only on P and the specimen geometry; it is independent of a.

In the study of adhesives it is more appropriate to describe the crack propagation behavior in terms of the crack extension force $\mathcal{G}_I$ since $\mathcal{G}_I$ is independent of the elastic constants of the adherend while K_I is not. For crack propagation in mode I, plane strain, they are related as follows [9,10]:

$$\mathcal{G}_I = (1-\nu^2)K_I{}^2/E \tag{5}$$

where E is Young's modulus.

For sufficiently thin layers of the adhesive, $\mathcal{G}_I$ will be nearly independent of the elastic properties of the adhesive because it is a measure of the change in the potential and elastic energy when the crack propagates. Since only a small fraction of the total elastic energy is stored in the adhesive layer, the influence of the elastic properties of the adhesive on $\mathcal{G}_I$ will be small.

The actual tests were performed by applying a displacement to the specimen as rapidly as possible and then holding that displacement fixed. As the crack propagates, the compliance increases and the load decreases. The values of a, $\dot{a}$, and $\mathcal{G}_I$ at any instant during the test may be calculated by means of Eqs 1, 3, 4, and 5.

Experiments

Specimen Preparation

The specimens were prepared from two types of alloys, 2024 aluminum alloy and stainless steel, and from two types of adhesives, EC-2186 and FM-1000. The thickness of the adhesive joints in the specimens was controlled by inserting shims at the ends of the specimens. The adhesive joints ranged from 25 to 250 μm in thickness, which was measured optically at four locations along the glue line. It did not vary by more than 10%.

The surfaces to be glued were ground flat to a textured finish. The plates were then cleaned with a commercial detergent, degreased in carbon tetrachloride solution for 10 min at 50°C, and etched.[2] They were then rinsed in water and methanol and blow-dried. Both adhesives were cured at 182 ± 10°C for 1 h and then cooled to room temperature. The samples were brought up to the cure temperature in less than 45 min. During the curing process a constant pressure of 172 kPa (25 psi) was applied by means of a spring-loaded alignment jig. After preparation, the specimens were stored in a vacuum of 1.33 Pa (0.01 torr).

The aluminum specimens, in most cases, fractured cohesively with the crack propagating near the center of the adhesive layer. The few cases when it did not were not included in the test results reported here. Considerable difficulty, however, was experienced with the preparation of the stainless steel specimens. The fracture always propagated very near one of the interfaces even though it occurred within the adhesive. The results from these tests are therefore considered to be anomalous; they are described briefly in the Appendix, and Figs. 2 and 3 show the fracture surfaces of the aluminum and stainless steel specimens.

Determination of the Constant B *in Eq 1*

We prepared six specimens which did not contain a bonded layer but which had had cracks of different lengths machined into them. The compliance of these specimens was measured and plotted against a, as shown in Fig. 4. The measured value of B compared favorably with the value calculated from Eq 2, as is also shown in Fig. 4. The measured values for B were 5.45×10^{-4} kg^{-1} for the aluminum specimens. The values used for the elastic constants for aluminum were $E = 71.8$ GPa, $\nu = 0.33$, and $G = 26.2$ GPa [11].

Testing

The tests were carried out within an environmental chamber maintained at a constant temperature of 308 K and 9% humidity. The specimens were subjected to cyclic loading to sharpen the crack and propagate it a short distance forward. The sample was then loaded rapidly to a load of 294 to 588 N (30 to 60 kgf) at a rate of 0.3 mm/s and then the *displacement* was held constant and a load relaxation curve was obtained. The procedure was repeated until the crack had propagated through the entire length of the specimen.

The data analysis consisted of recording the net crosshead displacement and measuring the slope of the load-time curve and

[2]The etchant for aluminum was 30 parts distilled water, 10 parts sulfuric acid, and 1 part sodium dichromate. Plates were etched for 10 min at 70°C with agitation. The etchant used for stainless steel was 3 parts hydrochloric acid and 1 part nitric acid for 10 min with agitation.

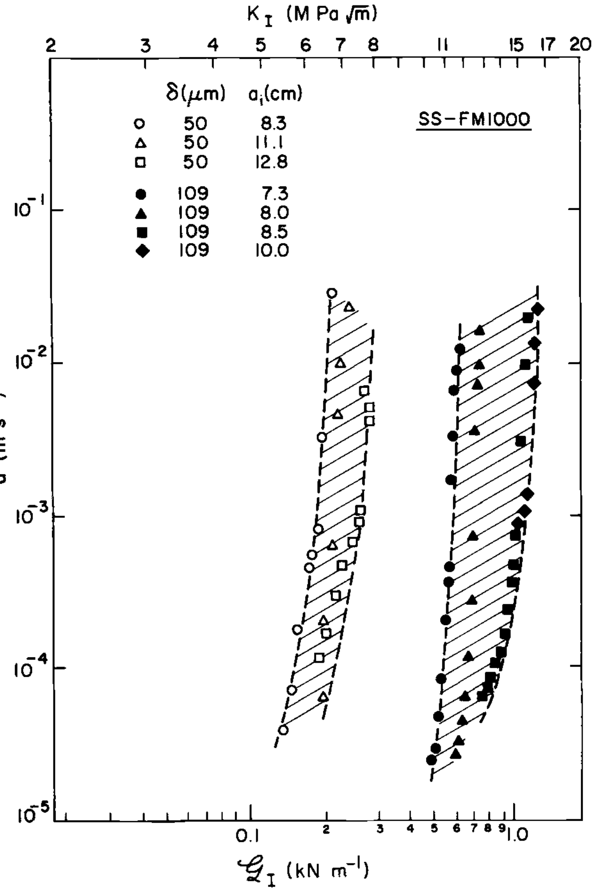

FIG. 2—*The effect of adhesive layer thickness on fracture for stainless steel specimens bonded by FM-1000 adhesive.*

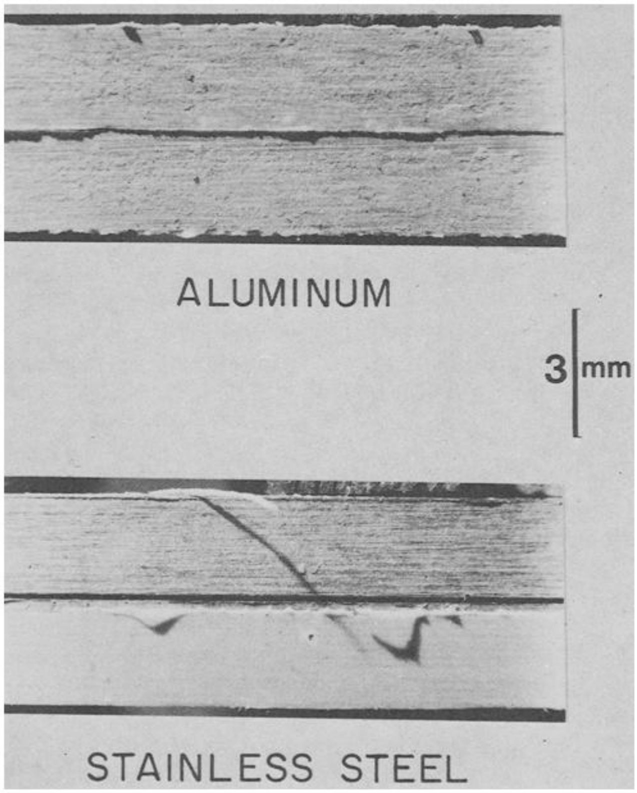

FIG. 3—*A comparison of the fracture surfaces for aluminum and stainless steel specimens. In stainless steel specimens fracture occurred very close to the metal-adhesive interface. The thickness of the adhesive in both cases was approximately 50 μm.*

the instantaneous load at several points along the relaxation curve. Also, the initial and the final crack lengths at the start and the end of each relaxation were calculated as a check on the velocity values calculated from Eq 3.

To minimize the error resulting from machine relaxation the specimens were preloaded to a small load (98 to 196 N [10 to 20 kgf]) for 3 min. In spite of this procedure, it remained likely that some error was still occurring. To estimate this error, relaxation curves for the machine were obtained at loads and time intervals comparable to tests carried out with the specimens. These relaxations were subtracted from the relaxations from the specimens and the $\dot{a}(\mathcal{G}_I)$ curves obtained from corrected relaxation were compared with those from the original relaxation. The correction was less than the scatter in the experimental data.

Measurement of the Amount of Crack Propagation During Each Relaxation

To ascertain whether or not the crack velocities were being measured accurately during the load relaxation experiment the following test was carried out: the increase in the length of the crack during a load relaxation was estimated by the measurement of the compliance of the specimen at the start and at the end of the load relaxation; it was then compared to the increase in crack length computed independently from the integration of the velocity versus time curve obtained from the relaxation. The velocity was

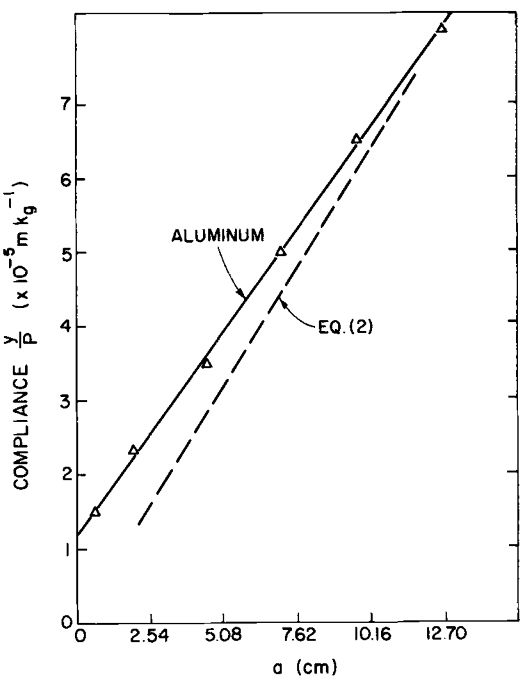

FIG. 4—*Measured and calculated values for the constant* B *in Eq 1 for aluminum.*

calculated from the instantaneous values of $\dot{P}$ and P at various time intervals by use of Eq 3. A typical velocity-time curve is shown in Fig. 5. The total crack advance is equal to the area beneath the curve. In this example it is equal to an increase in crack length of 8.5 mm. The value calculated from the change in compliance was 11 mm. In another test the values were 6.7 and 8.0 mm, respectively. It is reasonable that the compliance value is larger than the value obtained from the velocity-time integral since the latter does not include the crack growth at times longer than 12 s (a typical relaxation test lasted for 3 min). Bearing this in mind, we can consider the agreement to be good.

Results

In this section the $\dot{a}(\mathcal{G}_I)$ curves for crack propagation in EC-2186 and FM-1000 are presented. The primary structural parameter in these tests was the thickness of the adhesive layer. The results for aluminum specimens are summarized in Figs. 6 and 7 (those for stainless steel specimens are described in the Appendix). A typical load relaxation curve for which the $\dot{a}(\mathcal{G}_I)$ curves were obtained is shown in Fig. 8. The slopes of the crack propagation curves were very large, and the stress intensity exponent n in the relationship $\dot{a} = \beta \mathcal{G}_I{}^n$, where β is a material parameter, was in the range of 10 to 50. The slope and the shape of the curves are in agreement with the measurements of Beaumont and Young [6] and Hodkinson and Nadeau [7] on bulk polymeric materials. The main difference between fracture in adhesive joints and fracture in bulk polymers is that in the former the deformation of the polymer is confined to a narrow layer. If the plastic zone size in the polymer at the crack tip is larger than the thickness of the adhesive layer, then fracture would become sensitive to this thickness. The results presented below show that the crack propagation behavior is indeed sensitive to the thickness of the adhesive layer.

Since the slope of the $\dot{a}(\mathcal{G}_I)$ curves is large, we shall characterize the fracture behavior by specifying the range of the crack extension force $\mathcal{G}_{min}$ to $\mathcal{G}_{max}$, in which crack propagation was observed. The crack propagation velocity was measured in the range 10^{-5} to 10^{-1} m/s.

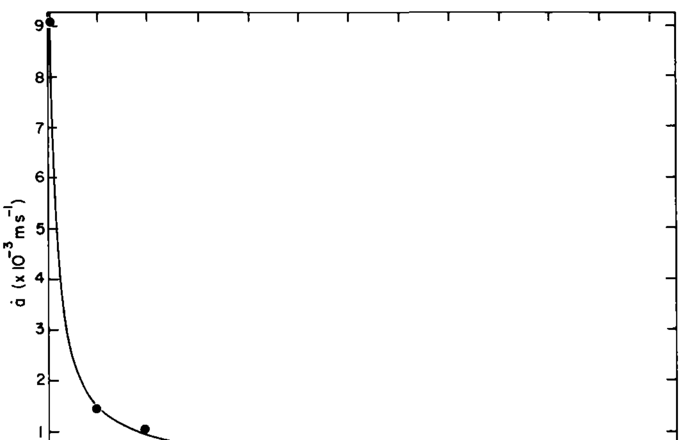

FIG. 5—*Change of crack velocity with time as obtained from a load relaxation curve. The net increase in the length of the crack (equal to the area under the curve) was 8.5 mm.*

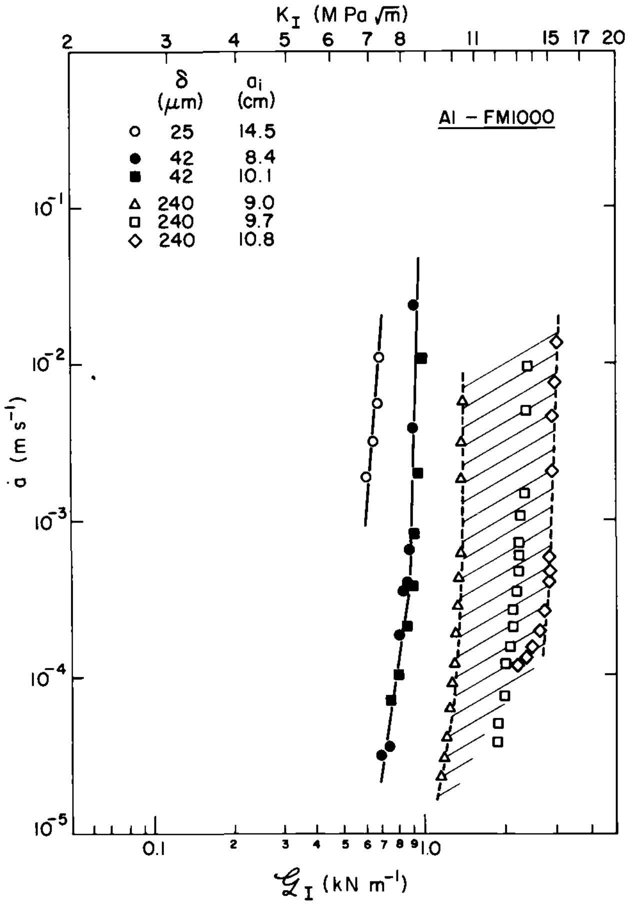

FIG. 6—*The effect of adhesive layer thickness δ on fracture for aluminum specimens bonded by FM-1000 adhesive.*

Effect of Bond Thickness

In all cases the fracture resistance was sensitive to the thickness of the adhesive layer. For example, as shown in Fig. 7 for the FM-1000 adhesive, the range of $\mathcal{G}_I$ values in which fracture was observed was 0.61 to 0.68 kN/m for a 25-μm-thick adhesive layer, 0.70 to 0.96 kN/m for a thickness of 42 μm, and 1.17 to 3.02 kN/m for a thickness of 240 μm. In the case of the 240-μm-thick adhesive, the fracture behavior was also sensitive to the length of the crack. For example, as a increased from 90 to 108 mm, the $\mathcal{G}_I$ for propagation increased by a factor of nearly 2.5. The sensitivity to a may be attributed in part to the fact that the shape of the crack front changes with crack length, as shown in Fig. 9. However, since this effect was observed only for thick bonds on the order of 240 μm, plasticity in the adhesive layer may be an explanation. In the double torsion technique, the applied displacement is accommodated by elastic deformation of the metal plates and by plastic bending in the adhesive. For accurate $\mathcal{G}_I$ measurements most of the deformation should be stored in the plates. As the adhesive layer becomes thicker, however, the plastic bending component increases, which increases the error in estimating $\mathcal{G}_I$. As shown in Fig. 9, the crack shape occupies a larger area in the adhesive as it grows longer; therefore, if plasticity in the adhesive is important, the apparent $\mathcal{G}_I$ will increase as a increases.

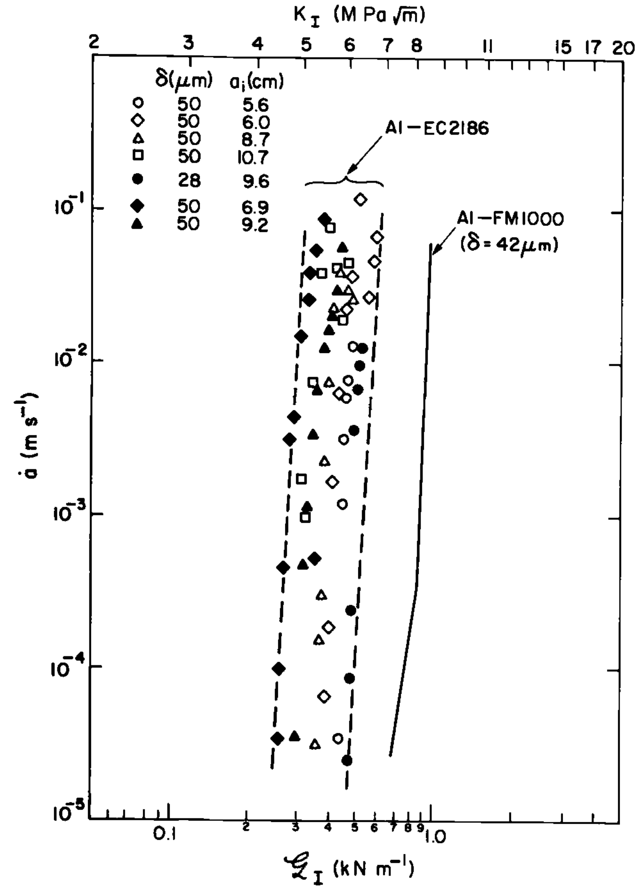

FIG. 7—*A comparison of the fracture properties of two types of adhesives for aluminum specimens.*

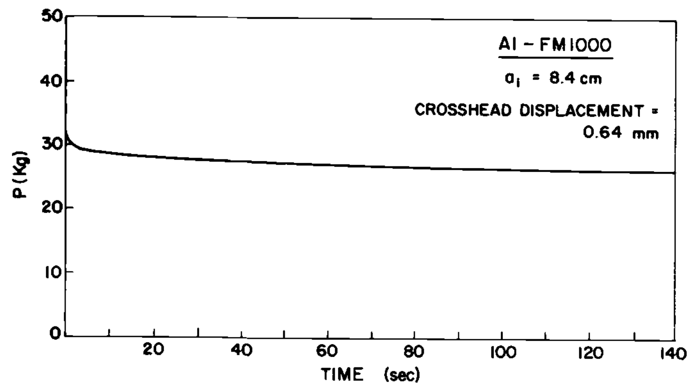

FIG. 8—*A typical load relaxation curve for a constant displacement test.*

Results for Two Different Adhesives

A comparison of the results for fracture in the adhesive layer between aluminum plates for the adhesive EC-2186 and FM-1000 are shown in Fig. 7. The EC-2186 is a lower toughness material than the FM-1000. Furthermore, the spread in the data was greater for EC-2186 than for FM-1000. This spread, we believe, represents the variability in the bond during fabrication. The FM-1000 is a film-type adhesive; therefore, provided the surfaces are well prepared, it is possible to prepare a bond that is free

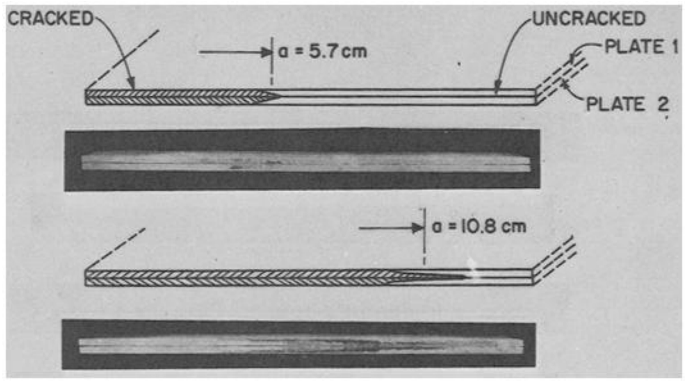

FIG. 9—*The crack front changes with the length of the crack in the double torsion experiment. The pictures of the front were obtained by propagating the crack to some distance and then spraying it with a die penetrant. The dark areas are the fractured parts of the adhesive layer.*

from such defects as air bubbles. The EC-2186, on the other hand, is a paste, and it is likely that air bubbles get trapped in the adhesive layer during fabrication. Such defects can be expected to lower the fracture strength of the adhesive layer [12].

Discussion

The double torsion technique has been used to study crack propagation in adhesive joints. The equation normally used to describe $\dot{a}(\mathcal{G}_I)$ behavior is

$$\dot{a} = \beta \mathcal{G}_I^{\,n} \tag{6}$$

where β and n are material parameters, and n is normally temperature-independent. In our experiments we have found that n changes from a range of 10 to 15 for crack velocities less than 10^{-4} m/s to a range of 35 to 50 for crack velocities higher than about 10^{-3} m/s. These values for n are in agreement with the measurements of crack growth in bulk polymers reported in the literature [6,7]. We did not observe the three distinct stages of crack growth normally associated with time-dependent crack propagation, which is also in agreement with these measurements. The evidence, then, is that only stage III crack growth is observed in polymers, that is, time-dependent crack growth is observed only at $\mathcal{G}_I$ values slightly less than $\mathcal{G}_{Ic}$, and that the crack velocity varies very rapidly with $\mathcal{G}_I$.

We now compare our measurements of $\mathcal{G}_I$ for crack propagation in adhesive joints with other measurements in adhesive joints and bulk polymeric materials. For the aluminum specimens the $\mathcal{G}_{Ic}$ values (defined as the crack extension force required to propagate the crack at a rate of 0.1 m/s) were 0.90 kN/m for 42-μm-thick adhesive joints and 3.02 kN/m for 240-μm-thick adhesive joints, for the FM-1000 adhesive; the value for the EC-2186 adhesive was 0.57 kN/m for a joint thickness of 50 μm. In an earlier study [13] the $\mathcal{G}_I$ for fracture in these adhesives was measured by using compact tension specimens. The specimens were machined in two halves from aluminum to standard specifications for external dimensions [14]. The two halves were bonded by placing the adhesive between the two halves, holding with a C clamp, and curing at 180°C for 1.5 h. The specimens were tested in an Instron machine at a displacement rate of 0.05 to 1.3 mm/min. The average $\mathcal{G}_I$ measured for EC-2186 was 0.82 kN/m and for FM-1000 was 3.71 kN/m. Unfortunately, the thickness of the joints was not carefully controlled in these experiments [*13*], and therefore these results are not directly comparable with the measurements reported in this paper. Nevertheless, these values are within 20% of the $\mathcal{G}_I$ values measured by us. Given the variability in the fabrication procedure, the agreement is fairly good.

Mostovoy et al [*15,16*] have performed tapered double-cantilever beam experiments on DER-332 resin using curing, bond thickness, and hardener as variables. Their results indicated critical $\mathcal{G}_I$ levels from 0.06 to 0.24 kN/m. These are about half as large as the $\mathcal{G}_I$ values measured by us for EC-2186. Beaumont and Young [*6*] have reported $\mathcal{G}_I$ levels of 0.04 to 0.06 kN/m for fracture in bulk silica-filled epoxy. The conclusion to be drawn is that from a fracture toughness point of view these materials are inferior to EC-2186 and FM-1000.

Our measurements indicate that $\mathcal{G}_I$ for crack propagation is sensitive to the bond thickness. Since in the aluminum samples fracture occurred cohesively and near the center of the adhesive layer, the preparation of the bond should not have been a factor in these results. One approach to explain these results is to consider the joint as a composite material where the thickness of the adhesive layer is thin as compared to the metal and where the elastic modulus of the adhesive is lower than that of the metal. The sensitivity of $\mathcal{G}_I$ to the thickness of the adhesive layer δ and to E/E' (where E and E' are the Young's moduli for the metal and the polymer, respectively) can then be calculated if all deformation is assumed to be elastic. In elastic deformation the stress singularity at the crack tip is maintained and $\mathcal{G}_I$ is a true crack extension force. Two procedures have been used to calculate $\mathcal{G}_I$ for crack propagation in the adhesive. In one, a crack contained in a slender strip that represents the adhesive layer is considered [*17-19*]. The stress analysis is carried out for different sets of boundary conditions at the strip boundaries. These calculations are necessarily approximate since the boundary conditions should be determined by the tractions and displacements at the metal-adhesive interface that occur as a result of the deformation of the composite as a whole rather than by the deformation of the adhesive layer by itself. It is preferable to consider the coupling of the deformation in the metal and the adhesive. This has been carried out recently by Wang et al [*20*]. They have analyzed the double-cantilever beam configuration of the specimen, but results pertaining to the effect of δ on $\mathcal{G}_I$ should have general applicability. A plot of $\mathcal{G}_I$ normalized with respect to the value for the monolithic case $\bar{\mathcal{G}}_I$, as a function of δ, was obtained from the calculations of Wang et al [*20*] by using the following procedure. For the monolithic case $\bar{K}_I^2 = (12\ Pa/hb^3)/(1-\nu^2)$, where P is the load applied to the double-cantilever beam specimen, a is the crack length, b is the thickness of the beam in the plane of the crack, and h is the height of the beam normal to the plane of the crack [*21*]. Substituting K_I into Eq 5 yields the expression for $\bar{\mathcal{G}}_I$. The actual $\mathcal{G}_I$ as calculated by Wang et al for the case of the composite was related to an apparent K_I^{app} according to the equation[3] $\mathcal{G}_I = (K_I^{app})^2/E'$, which leads to the equation:

$$\frac{\mathcal{G}_I}{\bar{\mathcal{G}}_I} = \frac{1}{12}\cdot\frac{(K_I^{app})^2}{Pa/hb^3}\cdot\frac{E}{E'} \tag{7}$$

The right-hand side of Eq 7 has been calculated in Ref *20* as a function of δ. The results in terms of $\mathcal{G}$ are given in Fig. 10. The influence of the thickness of the adhesive layer on $\mathcal{G}_I$ is small. The relative elastic modulus of the adherend and the adhesive has a much stronger influence, but the effect is nonlinear: at small ratios of E/E' the effect is stronger than for larger values E/E'. The influence of δ as measured by us (Fig. 7) is much stronger than the curves in Fig. 10 and hence cannot be explained by considerations of linear elastic fracture mechanics.

It has been shown, however, that concepts from linear elastic fracture mechanics can be applied even when the crack tip is blunted by local yielding and the stress singularity is no longer present. A simple model to consider is the rigid-plastic strip model [*9*] that has been analyzed by Rice [*22*]. The thin strip is assumed to be rigid below a critical stress σ_y, above which it yields without strain hardening. Yielding occurs locally near the crack tip. One measure of the extent of yielding is the crack tip opening displacement ϕ, which is given by [*22*]

$$\phi = \mathcal{G}_I/(1-\nu^2)\sigma_y \tag{8}$$

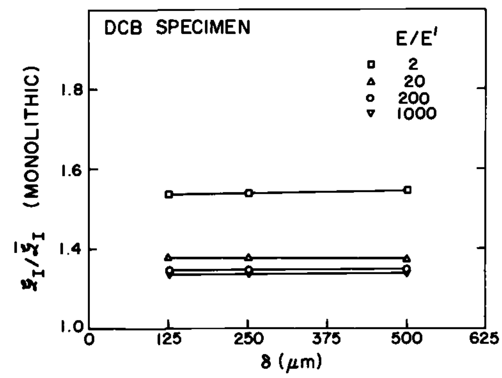

FIG. 10—*The influence of the adhesive layer thickness and the relative Young's modulus of the metal and the adhesive on $\mathcal{G}_I$ (Eq 7).*

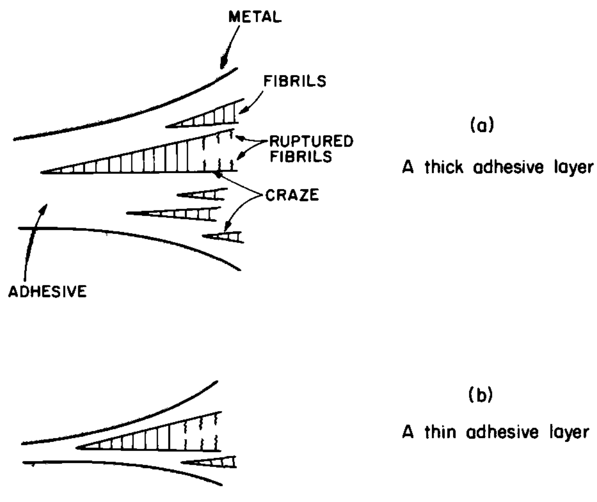

FIG. 11—*A speculative model of crack propagation in an adhesive layer bonded between two metal plates.*

[3] In Ref *20* the results are expressed in terms of K_I (apparent) rather than $\mathcal{G}_I$. The two are related by Eq 5. An ambiguity arises in the value of K_I depending on whether the elastic constants for the adhesive material or for the metal are inserted into Eq 5. But $\mathcal{G}_I$ is an unambigously defined quantity and hence is used here to avoid misinterpretation of results.

for plane strain loading. Note that here $\mathcal{G}_I$ is not a true extension force but an apparent quantity calculated with the assumption of elastic deformation. Equation 8 by itself does not invoke a crack propagation criterion since the crack is not supposed to have moved in its calculation. However, if some microstructure-dependent criterion is invoked, such as that the crack propagates when a critical amount of strain ϵ_c is accumulated in the adhesive layer in the immediate vicinity of the crack tip, then Eq 8 may be used to define an apparent critical value for $\mathcal{G}_I$. We would then use the following fracture criterion:

$$\epsilon \geq \epsilon_c$$

where

$$\epsilon_c = \phi_c/\delta = \mathcal{G}_I/(1 - \nu^2)\sigma_y\delta \quad (9)$$

Qualitatively this criterion would explain why $\mathcal{G}_I$ increases with δ, but it must be noted that the derivation of Eqs 8 and 9 was based on the assumption that the adhesive yields uniformly across the entire thickness. This is clearly an approximation since preferential yielding near the crack tip should lead to a nonuniform distribution of strain in the thickness direction in the adhesive.

Polymers are known to craze before they fracture. The micromechanics of the formation of the craze and then the propagation of a crack into a craze is complex. The criteria for air-crazing have been reviewed extensively [*23-25*], and the breaking of craze fibrils to advance a crack has also been studied [*26-27*]. A discussion of these topics in the context of crack propagation in a polymer in the form of an adhesive in a composite material is outside the scope of this paper. But some qualitative ideas that may explain the influence of δ on $\mathcal{G}_I$ are illustrated in Fig. 11. When δ is large, several crazes may form before one of them fractures. As a result, a large displacement at crack tip opening displacement will be required to attain fracture (Fig. 11*a*). On the other hand, if δ is small, fewer crazes may form and smaller crack opening displacement may be required (Fig. 11*b*). Clearly the micromechanics of craze deformation must be studied independently before such models can be applied. A current review of such studies is available [*28*].

Summary

The double torsion technique offers a simple method of studying crack propagation in adhesive layers. The technique has been used successfully to obtain curves for crack velocity versus crack extension force. The critical $\mathcal{G}_I$ levels measured by this method for two adhesives EC-2186 and FM-1000 are in good agreement with the values obtained from compact tension specimens. The fracture toughness of the nylon-impregnated FM-1000 adhesive was more than 1.5 times the toughness of the simply epoxy EC-2186 adhesive.

We have also considered the effect of the joint thickness on $\mathcal{G}_I$ for crack propagation. As joint thickness increases, $\mathcal{G}_I$ increases. These results imply that the microscopic process of fracture at the crack tip in the adhesive layer needs to be studied. The indication is that the adhesive does not fracture in brittle manner; instead, it yields at the crack tip. It is suggested that crazes form in the adhesive layer near the crack tip and that the breaking of the fibrils in the craze leads to crack propagation.

Acknowledgment

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APPENDIX

Test Results for Stainless Steel Specimens

The purpose of these experiments was to determine whether or not crack propagation in adhesive layers is not $\mathcal{G}_I$ controlled. Strictly speaking, $\mathcal{G}_I$ is a true crack extension force only if the stress singularity at the crack tip is not removed by yielding. But Eq 9 indicates that, even if the polymer yields, a quantity such as a critical amount of strain in the adhesive layer near the crack tip may be used as a failure criterion, which is still related to $\mathcal{G}_I$. Since $\mathcal{G}_I$ is independent of the elastic constants of the adherend metal, the study of fracture using adherend metal of different elastic constants (for example, aluminum and stainless steel) should yield the same value for $\mathcal{G}_I$ for fracture. As shown in Fig. 2 the critical $\mathcal{G}_I$ values for stainless steel specimens were consistently less than those for the aluminum samples, the thickness of the adhesive layer remaining constant (compare Fig. 2 with Fig. 5). Unfortunately, these results more clearly reflect a difference in the quality of the bond in aluminum and stainless steel samples rather than a change in the intrinsic mechanism of fracture in the adhesive layer. The fracture surfaces from the two types of specimens are shown in Fig. 3. Although in both cases fracture is cohesive, in stainless steel specimens fracture occurs very close to one of the metal-adhesive interfaces. These results, therefore, only serve to show that $\mathcal{G}_I$ for fracture is fairly sensitive to the quality of the bond.

The following values for the elastic constants for stainless steel were used: $E = 200.1$ GPa, $G = 73.1$ GPa, and $\nu = 0.30$ [*11*].

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