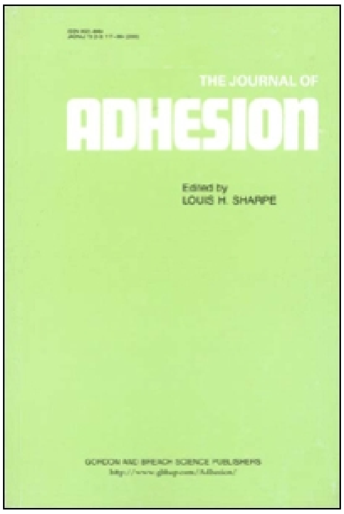

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Measurements of Stress Intensity Factors of an Interface Crack Under Mixed Mode Loading*

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The optical method of caustics has been utilised to measure both the stress intensity factor for a crack lying along the interface of an aluminium/epoxy bimaterial specimen, and the mode mixity arising from the difference in the elastic properties across the interface. Measurements were carried out by using a novel modification to the method whereby caustics are produced and measured from both sides of the specimen, so compensating automatically for the distortion induced in the specimen due to misaligned loading fixtures. A flat reflective surface across the interface was obtained by adhering a reflective coating to the specimen. Verification that this coating does not affect measurement accuracy was obtained by comparing stress intensity factors measured from coated and uncoated monolithic aluminium specimens where good agreement was found to exist between both measurements.

KEY WORDS: Caustics; interface crack; adhesive; stress intensity factor; mixed mode; experimental mechanics.

INTRODUCTION

The study of strength and fracture resistance of interfaces has a great bearing on the development of bimetallics, composites, adhesive joints, etc. The problem has, of late, received a considerable amount of attention. The stress intensity factor concept has provided a very successful basis for the study of the fracture of homogeneous materials and this success has motivated the development of a similar approach for interface crack problems.[1,2] Cracks in homogeneous, isotropic materials tend to propagate under mode I conditions. The fracture mode on an interface of dissimilar materials, however, is usually mixed: differences between elastic properties across an interface will generally disrupt symmetry even when the geometry and loading are otherwise symmetric with respect to the crack. That is, nominally mode I loading produces a mixed mode (I, II) condition at the crack tip.

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The optical method of caustics is potentially a valuable tool for the study of interfaces. However, very few researchers have investigated its applicability to this type of problem.[3–7] Theocaris *et al.*[3–5] used the optical method of caustics to study the stress intensity factors, as well as the nature of the elastic stress singularity, at the tip of a crack lying along the interface of two bonded homogeneous, isotropic and elastic half planes. Much of this work was conducted at the interface between materials of very similar elastic properties and with the method of caustics used in its transmission mode, although Theocaris has also applied the reflected caustic technique to interfaces between a steel wedge and a PMMA plate.[8,9] Additionally, Herrmann *et al.*[6,7] have analysed quasistatic and dynamic interface crack extension problems for the application of caustics, but their work is purely theoretical.

This paper reports initial results of the experimental application of the optical method of caustics to study the problem of a crack lying along the interface between epoxy and aluminium, materials of greatly different elastic properties. Both the static mixed mode stress intensity factor and the mode mixity for such interfacial cracks have been measured with CTS (compact tension-shear) specimens loaded in pure mode I, mixed mode (I, II) (an angle of 45° between the crack and the loading axis), and pure mode II. The method of caustics has been found to be susceptible to specimen distortion arising from even minimal misalignment of the loading fixture.[10] For this reason, the split-beam caustic modification as used by Wallhead and Edwards[10] was adopted whereby caustics were produced and measured from both sides of the specimen simultaneously.

The method of caustics applied to opaque materials requires the specimen to exhibit an optically flat mirror surface. In order to achieve this across the bimaterial interface a "coating adhesion" technique was developed. The effects of this coating layer on caustic measurements were explored by measuring caustics from coated and uncoated aluminium CTS specimens.

INTERFACE CRACK TIP FIELDS

At an interface between dissimilar materials, the difference in elastic properties of the two materials causes a change in the crack tip stress intensity relative to the case for a homogeneous material. Whereas the stress field associated with conventional LEFM approaches, which predicts a decrease in stress from the crack tip dependent on $r^{-0.5}$ (where r is the distance from the crack tip), the near-tip stresses and displacements are found to oscillate as the crack tip is approached.[11]

The stresses are found to vary as:

$$\sigma \sim r^{-0.5}(\sin, \cos)(\varepsilon \log r) \tag{1}$$

where

$$\varepsilon = \frac{1}{2\pi} \ln\left(\frac{1-\beta}{1+\beta}\right) \tag{2}$$

β is one of Dundurs' parameters,[12] which are composite parameters based on the mechanical properties of each material:

$$\alpha = \frac{G_2(\kappa_1 + 1) - G_1(\kappa_2 + 1)}{G_2(\kappa_1 + 1) + G_1(\kappa_2 + 1)} \tag{3}$$

$$\beta = \frac{G_2(\kappa_1 - 1) - G_1(\kappa_2 + 1)}{G_2(\kappa_1 + 1) + G_1(\kappa_2 + 1)} \tag{4}$$

G_1 and G_2 are the shear moduli of each material at the interface; $\kappa = 3 - 4\nu$ for plane strain and $\kappa = (3 - \nu)(1 + \nu)$ for plane stress; where ν is the Poisson's ratio of the material. For the epoxy/aluminium combination studied here, $\alpha = -0.91$, whereas $\beta = -0.21$ in plane strain and -0.29 in plane stress. α and β are zero for an interface between two identical materials.

The definition of an interface stress intensity is therefore problematic, and hence the characterisation of interface cracks has often been treated using energy balance methods based on G.[13,14] Although this allows for comparisons to be made between different bonding treatments, for example, it does not have direct applicability to geometries other than those used for the particular experiments. It is, therefore, necessary to attempt to define an interface stress intensity that is related to the applied loading and the conditions existing near the crack tip.

If the far-field applied complex stress intensity is written as:[15]

$$K^{\infty} = K_{\mathrm{I}} + \mathrm{i}K_{\mathrm{II}} \tag{5}$$

then the interface stress intensity K_{in} is given by:[15]

$$K_{\mathrm{in}} h^{i\varepsilon} = p K^{\infty} \mathrm{e}^{i\omega} \tag{6}$$

or

$$K_{\mathrm{in,I}} + \mathrm{i}K_{\mathrm{in,II}} = p(K_{\mathrm{I}}^{\infty} + \mathrm{i}K_{\mathrm{II}}^{\infty}) h^{-i\varepsilon} \mathrm{e}^{i\omega} \tag{7}$$

where ω is the real function of α and β, and is tabulated elsewhere;[15] and p is given by:

$$p = \left(\frac{1 - \alpha}{1 - \beta^2}\right)^{1/2} \tag{8}$$

A problem with this approach is that it is not entirely clear what length scale is applicable as h for a bimaterial interface. Suo and Hutchinson[15] and Cannon *et al.*[16] use the layer thickness for a dissimilar material at an interface between two larger blocks, which is effectively a sandwich structure. This is clearly not valid for the problem studied here.

However, it has been suggested[1] that this variable could simply be taken to be 1 μm for all material combinations, so that it is invariant for different crack lengths or other changes in geometric factors. Alternatively, it could be approximated that $\beta = 0$,[15] giving $\varepsilon = 0$ and thereby removing the contribution of h. The factor $h^{-i\varepsilon}$ has, therefore, been neglected in this analysis.

A simple interpretation of the interface stress intensity factor has been given by Suo and Hutchinson,[15] who showed that the interface stress intensity factor combination,

$K_{in}h^{i\varepsilon}$, is related to the far-field stress intensity factor, K^{∞}, by the factor p:

$$|K_{in}| = p|K^{\infty}| \tag{9}$$

and is phase-shifted by ω, although this shift is generally not large ($\sim 10°$ for the material combination studied here).

For experimental characterisation of crack growth at bimaterial interfaces, it is therefore possible to use either the far-field stress intensity range, $\Delta|K^{\infty}|$, as calculated from the crack length and sample geometry, or the interface stress intensity factor, $p\Delta|K^{\infty}|$.

The application of the caustics technique allows the interface stress intensities at the crack tip to be measured directly.[4–6,17] Since this optical technique relies on reflections obtained from each material at the interface, the caustic obtained from each side of the interface is interpreted as giving the stress intensity in *each* material. Using subscripts 1 and 2 for each material:

$$K_1 = K_{1,I} + K_{1,II} \tag{10}$$

$$K_2 = K_{2,I} + K_{2,II} \tag{11}$$

The relationship between the stress intensities in the two materials is given by:[5,18]

$$K_2 = \left(\frac{1+\beta}{1-\beta}\right) K_1 \tag{12}$$

where the factor $(1+\beta)/(1-\beta)$ is commonly given the symbol g.

If it is assumed that the magnitude of the crack tip stress intensity is related to the interface mode I and mode II components, and the stress intensity in each material by:

$$K_{in} = \sqrt{K_I^2 + K_{II}^2} = \sqrt{K_{in,1}^2 + K_{in,2}^2} \tag{13}$$

then it is possible to calculate the interface stress intensities in each material arising from the applied loading, as follows.

The caustic measurements will supply K_1 and K_2, the stress intensities in each material. It is also possible to determine the mode mixity, Ψ, from the caustics. Since this mode mixity corresponds to the mode mixity at the interface, it is therefore possible to calculate the mode I and mode II interface stress intensities which result from the applied loading: the interface stress intensity is related to the far-field applied stress intensity by the factor p, and the mode mixity is known.

The optically-measured stress intensities from the caustics can, therefore, be compared with the calculated applied values from the far-field applied loading.

In this study a Compact Tension Shear (CTS) specimen geometry was used, as shown in Figure 1. The stress intensity factor for a homogeneous CTS specimen (determined from mechanical parameters such as applied load and crack length) is given in Reference[19] in terms of the crack length to the specimen width ratio, a/W, and the angle, φ, between the applied load and the perpendicular axis of the crack as:

$$K_{mech,I} = Y_I\sigma(\pi a)^{1/2}\cos\varphi \tag{14}$$

$$K_{mech,II} = Y_{II}\sigma(\pi a)^{1/2}\sin\varphi \tag{15}$$

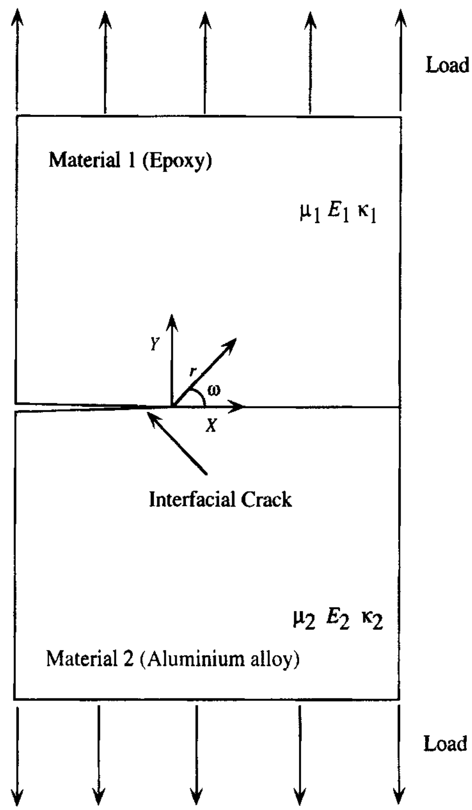


FIGURE 1 Crack along a bimaterial interface.

where the subscript *mech* is used to indicate that these values are calculated simply from the applied mechanical loading and the geometry of the samples.

$$Y_{\mathrm{I}} = \frac{1}{1-\dfrac{a}{W}}\left(\frac{0.26+2.65\dfrac{a}{W-a}}{1+0.55\dfrac{a}{W-a}-0.08\left(\dfrac{a}{W-a}\right)^2}\right)^{1/2} \tag{16}$$

and

$$Y_{\mathrm{II}} = \frac{1}{1-\dfrac{a}{W}}\left(\frac{-0.23+1.40\dfrac{a}{W-a}}{1-0.67\dfrac{a}{W-a}+2.08\left(\dfrac{a}{W-a}\right)^2}\right)^{1/2} \tag{17}$$

The stress intensity factor K_{in} can be measured using this specimen over a wide range of mode mixity, Ψ, by continuously varying the angle of the applied load to the crack, φ.

The interface stress intensities are given by combining Equations (14) and (15) with Equation (9), and accounting for the phase shift of ω introduced by the difference in materials properties across the interface:

$$K_{\text{in,I}} = \left(\frac{1-\alpha}{1-\beta^2}\right)^{1/2} Y_{\text{I}}\sigma(\pi a)^{1/2}\cos(\varphi+\omega) \tag{18}$$

$$K_{\text{in,II}} = \left(\frac{1-\alpha}{1-\beta^2}\right)^{1/2} Y_{\text{II}}\sigma(\pi a)^{1/2}\sin(\varphi+\omega) \tag{19}$$

THE EQUATIONS OF OPTICAL CAUSTICS

The principles of caustics from reflective homogeneous materials have been described in detail by many authors.[20,21] The mapping equation for the caustics from reflective homogeneous materials is given by:[20,21]

$$V = z + 4C\,\overline{\Phi'(z)} \tag{20}$$

where z is the complex variable ($z = x + \mathrm{i}y$) on the specimen referred to the Cartesian co-ordinate system oxy (Fig. 2), V is the complex variable ($V = X + \mathrm{i}Y$) on the screen referred to another Cartesian co-ordinate system OXY, $\overline{\Phi'(z)}$ denotes the complex conjugate of the first derivative, $\Phi'(z)$, of the complex stress potential, $\Phi(z)$, of Muskhelishvili, and C is the caustic coefficient, which depends on the material properties, ν/E, the thickness, d, of the plate and the distance, z_0, between the plate and the screen. This factor is given by $C = (\nu d z_0/E)$. Therefore, Equation (20) establishes the correspondence between point z of the specimen and the corresponding point V of the screen. Moreover, the locus of all points z on the specimen surface satisfy the equation

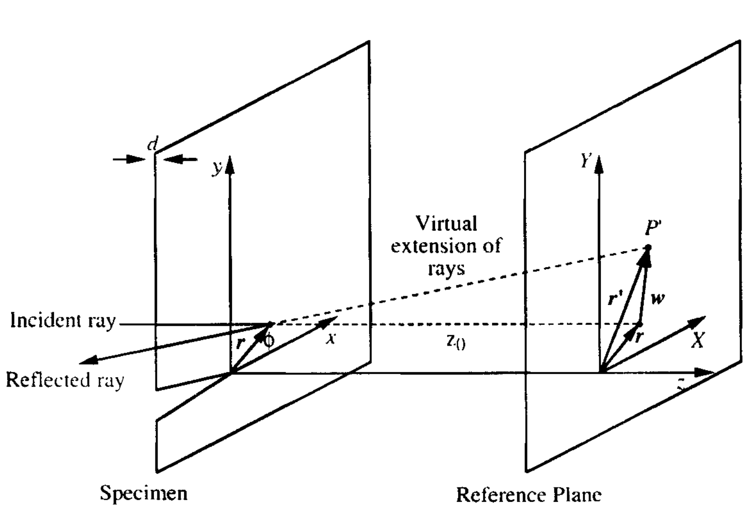


FIGURE 2 Geometry of the formation of a caustic from a cracked specimen.

of the initial curve of the caustic on the screen:[20,21]

$$|C\Phi''(z)| = 1 \tag{21}$$

Therefore, Equations (20) and (21) allow the complete determination of the shape of the caustic on the screen.

Theocaris and Stassinakis[3] proposed that the complex stress potential, $\Phi(z)$, of Muskhelishvili for homogeneous materials takes the form of $\Phi_j(z)$ for the interface crack problem where $j = 1, 2$ for the two materials and is expressed as:

$$\Phi_j(z) = K_j z^{(-1/2 - i\varepsilon)} \tag{22}$$

where K_j plays the role of a generalised stress intensity factor at the interfacial crack tip. By differentiating Equation (22) twice with respect to z, and inserting it in Equation (21), the equation for the initial curve of the caustic can be written as:

$$\left| C_j\left(\frac{3}{2} + i\varepsilon\right)\left(\frac{1}{2} + i\varepsilon\right) K_j z^{(-5/2 - i\varepsilon)} \right| = 1 \tag{23}$$

If r is the polar radius about the origin, o, in Figure 2, that is $z = x + iy = r\theta$,[20] then the radius $r_{0_{1,2}}$ of the initial curve in the above equation is given by:[3]

$$r_{0_{1,2}} = (K_j(1 + 4\varepsilon^2)^{1/2} 2C_j H)^{2/5} \exp\left(\frac{2}{5}\varepsilon\theta\right) \tag{24}$$

where subscript 1 (denoting material 1) corresponds to angles θ in the interval $0 \leq \theta \leq \pi$, and subscript 2 corresponds to angles θ given by $0 \geq \theta > -\pi$.

From Equation (24), it can be derived that the initial curve of the caustic does not form the locus of a circle, as is the case for isotropic elastic media, but presents curves which are no longer connected to each other due to the discontinuity in material properties across the interface.

Substituting the first derivation of Equation (22) in Equation (20), the equation of the caustic can be written as:

$$V_{1,2} = r_{0_{1,2}}\left(\exp(i\theta) + \frac{1}{H}\exp\left[i(\varepsilon \ln(r_{0_{1,2}})) + \frac{3}{2}\theta - \omega + \eta\right]\right) \tag{25}$$

where

$$H = \sqrt{2.25 + \varepsilon^2} \tag{26}$$

That is, Equation (25) describes the locus of the bimaterial caustic on the screen generated from the locus r_0 on the specimen.

Wallhead and Edwards[10] have modified the optical method of caustics by producing and measuring caustics from both sides of an opaque homogeneous specimen to compensate for distortion induced in the specimen due to loading. The modification can be described briefly as follows. The value of the opening mode stress intensity factors, K_I, can be determined using a collimated beam by measuring the caustic diameter, D, at a given reference plane, z_0.[20,21] Wallhead and Edwards[10] found that specimens distort in a cylindrical cross-section to a varying degree when loaded and that the caustics can be analysed as if a non-collimated beam has been used on a plane specimen. The mode I stress intensity factor for opaque homogeneous materials was measured from both sides of the specimen as:

$$K_{\mathrm{I}} = \frac{E}{10.71 z_0 d v}\left(\frac{D_c^{5/3} + D_v^{5/3}}{2}\right)^{3/2} \tag{27}$$

where D_v is the virtual caustic diameter as measured from the convex surface of the specimen and D_c is the virtual caustic diameter as measured from the concave surface of the specimen. The use of Equation (27) has been found to compensate for load-induced distortion, and so maximise the accuracy of the caustic technique.

For an interface crack lying between two dissimilar materials, the optical stress intensity factors, $K_{1\mathrm{opt}}$ and $K_{2\mathrm{opt}}$, for each half of the specimen can be obtained from Equation (24) as:

$$K_j = \frac{R_j^{5/2}}{17.956(1+4\varepsilon^2)^{1/2} 2C_j H\left(\exp\left(\frac{2}{5}\varepsilon\theta\right)\right)^{5/2}} \tag{28}$$

Using the Wallhead and Edwards[10] modified caustic Equation (27) for homogeneous materials in terms of the measured caustics radii from both surfaces of the specimen, Equation (28) can be rewritten as follows:

$$K_j = \left(\frac{R_{jc}^{5/3} + R_{jv}^{5/3}}{2}\right)^{3/2} \frac{1}{17.956(1+4\varepsilon^2)^{1/2} 2C_j H\left(\exp\left(\frac{2}{5}\varepsilon\theta\right)\right)^{5/2}} \tag{29}$$

where R_{jc} is the virtual caustic radius as measured from the concave surface of the specimen and R_{jv} is the virtual caustic radius as measured from the convex surface of the specimen. Thus, by measuring the caustic radii from each half of the specimen (see Fig. 3) and each side of the specimen it is possible to determine experimentally the stress intensity factors in each material. The mode mixity can then be determined from the ratio of the stress intensity factors according to $\Psi = \tan^{-1}(K_2/K_1)$, using the caustic curves from each material as illustrated in Figure 3. This way of measuring the stress intensity factor and the mode mixity for interface crack is similar to that used by Theocaris[20] and Kalthoff[21] to measure the stress intensity factor and the mode mixity for homogeneous materials.

From Equations (12) and (13) it can be seen that the interface stress intensity, K_{in}, can be calculated from the measured stress intensities in each material from the caustics by:

$$K_{\mathrm{in}} = K_{1\mathrm{opt}}\sqrt{1+g^2} \tag{30}$$

or

$$K_{\mathrm{in}} = \frac{K_{2\mathrm{opt}}\sqrt{1+g^2}}{g} \tag{31}$$

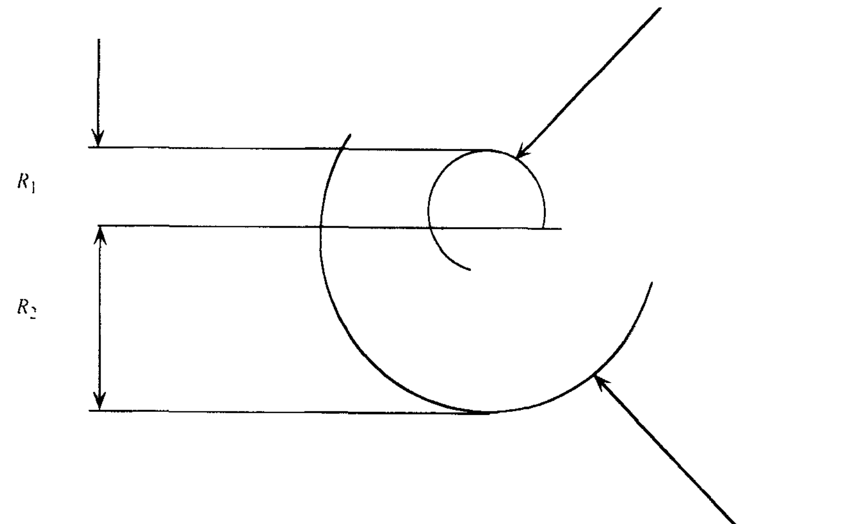


FIGURE 3 *Schematic caustics image from an interface crack.*

EXPERIMENTAL DETAILS

A bimaterial (Aluminium-Epoxy) 5 mm thick CTS specimen was used in this work to enable imposed crack tip stress conditions to be changed from pure tension (mode I) *via* both tension and shear (mixed mode) to pure in-plane shear (mode II).[19] The materials used were 6082 aluminium alloy, and a rubber-toughened epoxy adhesive, the mechanical properties of which are as follows:

Material	Epoxy	Aluminium
Young's modulus E (GPa)	3	70
Poisson's ratio v	0.39	0.3
Shear modulus (GPa)	1.07	25

The optical bench used in this work comprised a 1 mw spatially filtered Helium-Neon laser, a series of lenses ranging in focal length from 300–750 mm, a high quality beamsplitter, three flat mirrors and a CCD camera interfaced to a computer. The precise experimental arrangement is shown schematically in Figure 4 which is that adopted by Wallhead and Edwards.[10] It allows the production of caustic images from both surfaces and which can be explained briefly as follows.

An adjustable laser beam expander is used to obtain the parallel beam which then enters a beamsplitter. The emergent beams are directed by a series of fold mirrors to the

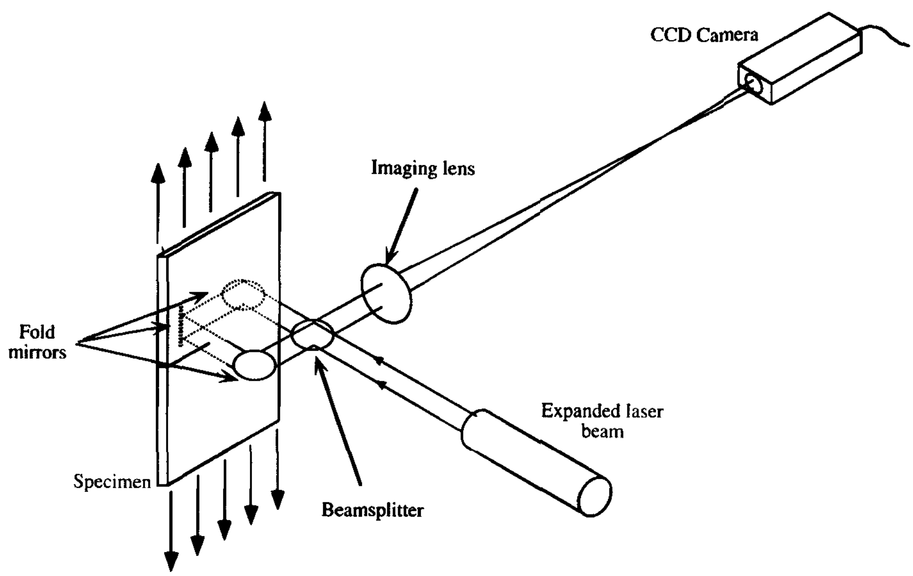


FIGURE 4 Schematic of the arrangement to produce split beam caustics.

tip of the crack on either side of the specimen from where they retroreflect back to the beamsplitter. A lens placed in the reflected optical path is then used to image the virtual caustic on to a CCD camera in front of the specimen in the real image plane. A small tilt is introduced to one of the fold mirrors to separate the images in the camera. The caustic images are then relayed *via* a frame grabbing board to a computer complete with image processing software to facilitate measurement of the caustic diameter.

Due to the significantly different reflectivity of aluminium and epoxy a "coating adhesion" technique[22] was developed in order to obtain a flat, reflective surface across the interface. In this technique an optically flat glass plate is coated with a metallic film which is subsequently adhered to the specimen using a thin layer ($\sim 20\,\mu$m) of Dow Chemical epoxy resin DER324 with 10% curing agent DEH24. After curing, the glass substrate can be removed leaving the coating adhered to the specimen so providing an optically flat mirror surface. The effects of the coating adhesion layer on the caustic measurements have been explored in this work and are discussed in the next section.

In addition, prior to conducting the tests, it was necessary to determine the initial curve radii which correspond to plane stress conditions and so facilitate valid caustic measurements. Several researchers (see, for example, Meletis *et al.*[23], and Rosakis and Ravi-Chandar[24]) have analysed this criterion for homogeneous specimens and concluded that caustic measurements should be taken at initial curves greater than half the specimen thickness; the upper and lower bounds of validity for the measurements have also been determined by Theocaris and Petrou.[25] A similar analysis has not previously been performed on a bimaterial specimen.

The main series of tests were carried out at loads corresponding to stress intensity factors between 0.25 MPa/m$^{1/2}$ and 1.4 MPa/m$^{1/2}$. Three loading angles, φ, between the applied load and the axis of the crack were used: 0° (mode I), 45° mixed mode (I, II) and 90° (mode II). The theoretical interfacial stress intensity factor, K_{in}, was determined using Equations (13)–(15) and compared with the experimental stress intensity factor given by Equations (27) and (9).

RESULTS AND DISCUSSION

Figure 5 shows the results of the test examining the effects of the adhesive coating layer on caustic measurements. Here the optical stress intensity factors, K_{opt}, measured from the coated and uncoated aluminium specimens, are plotted against the respective applied stress intensity factors. The coated specimen is observed to yield marginally higher stress intensity factors (within the range 2.5–7%) throughout the range of applied K. This value, however, is only marginally higher than the measurement accuracy of the technique, which has been given as 2–3%[10] and 5%[26] by different studies. A similar test on a monolithic epoxy specimen was not performed due to the difficulty in producing a specular reflection from the uncoated epoxy with which to compare a coated specimen. However, since the coating adhesive exhibits mechanical

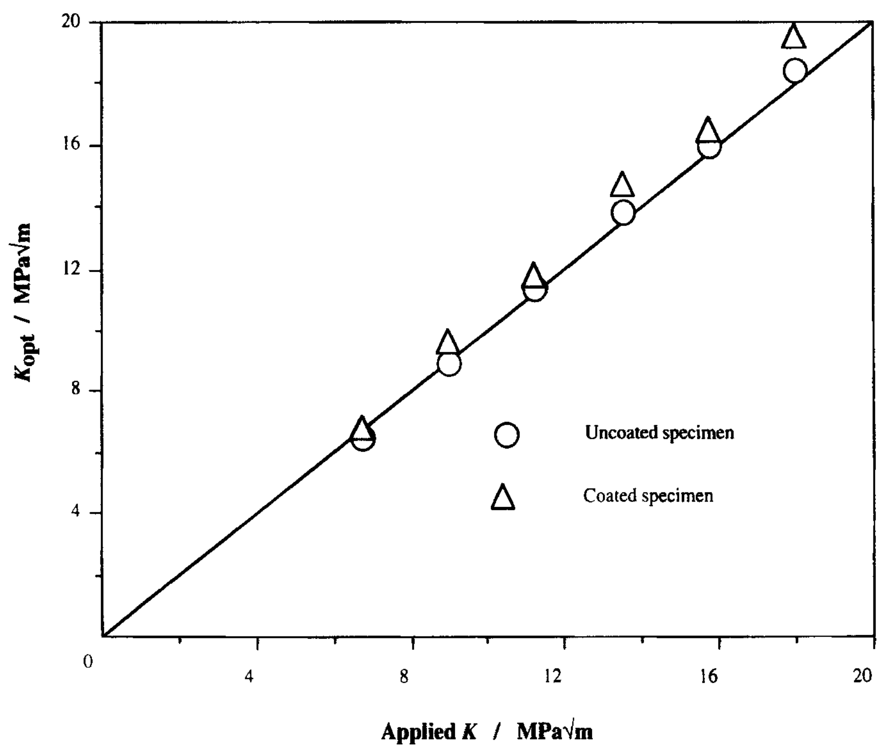


FIGURE 5 Stress intensity measurements from coated and uncoated Al specimens.

properties similar to the epoxy substrate the effects of the coating on the epoxy are expected to be considerably lower than those for aluminium.

Figure 6 presents the results of the test to determine the initial curve radii required for valid measurements on a bimaterial specimen. In Figure 6 the measured interface stress intensity factor, normalised by the applied stress intensity factor (fixed for this test), is plotted against the ratio of the initial curves and the specimen thickness (*i.e.* r_0/d) for a range of loading angles. In contrast to homogeneous specimens, however, the initial curve for a bimaterial caustic is not a fixed radius. For the purpose of this analysis the initial curve used was the mean of the two initial curves from each half of the specimen. The data in Figure 6 show that the ratio K_{opt}/K_{mech} reaches a plateau at $(r_{01} + r_{02})/2d > 0.5$. For smaller initial curves the triaxial stress state around the crack tip affects the Poisson contraction and, accordingly, the caustic diameter. This result is in agreement with the findings of Meletis *et al.*[23] and Rosakis and Ravi-Chandar[24] for homogeneous isotropic media.

Using this result, all measurements in the main study over the range of stress intensity factors were taken from plane stress conditions corresponding to the plateau region of Figure 6. The results from these experiments are plotted in Figures 7 to 9.

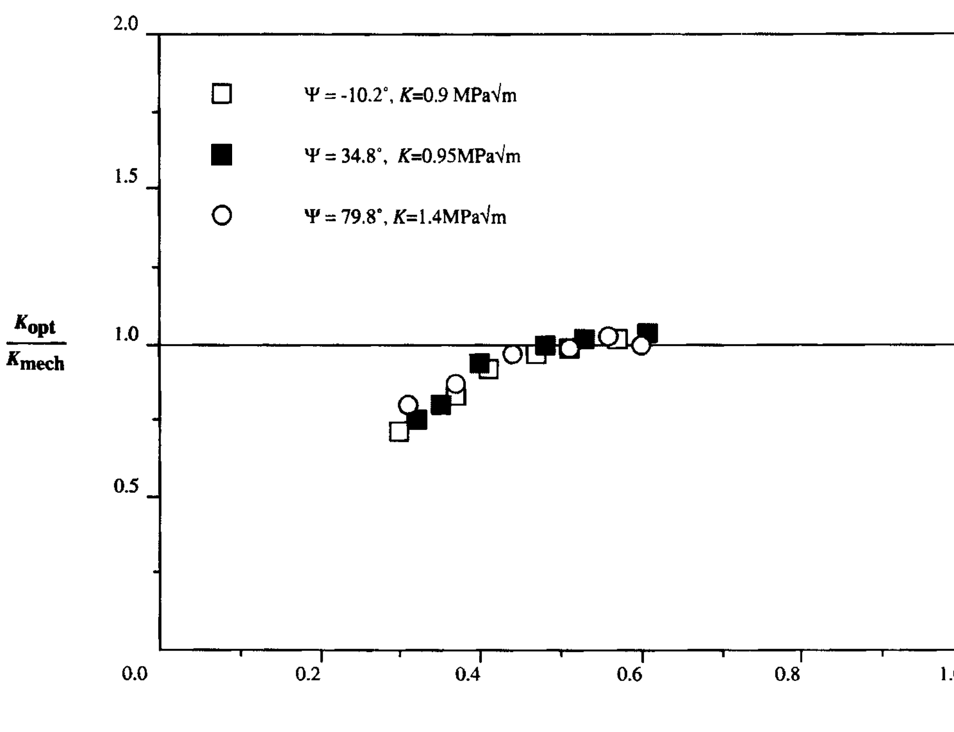


FIGURE 6 K_{opt}/K_{mech} *vs.* $(r_{0_1} + r_{0_2})/2d$ from bimaterial CTS specimen loaded over a range of angles.

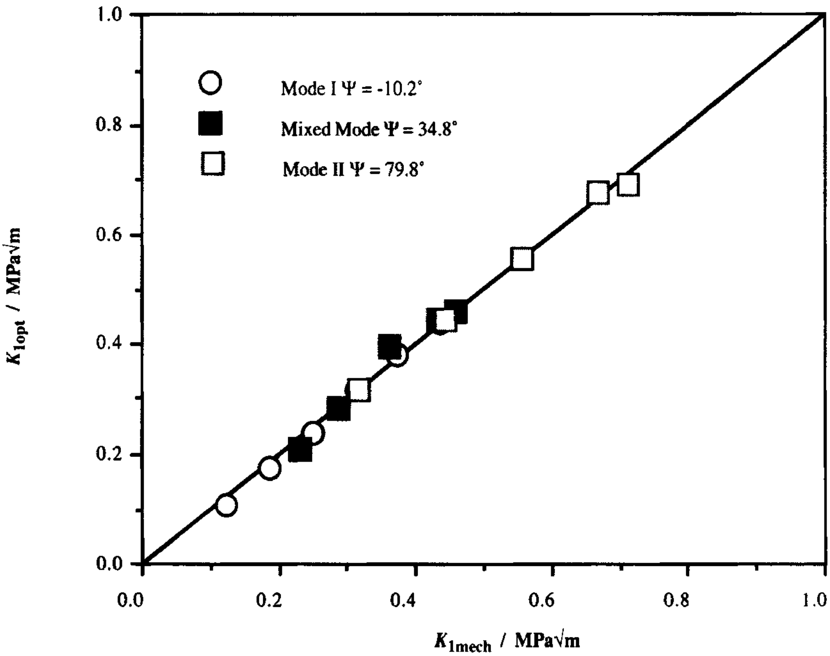


FIGURE 7 K_{1opt}/K_{1mech} from epoxy half of a bimaterial CTS specimen.

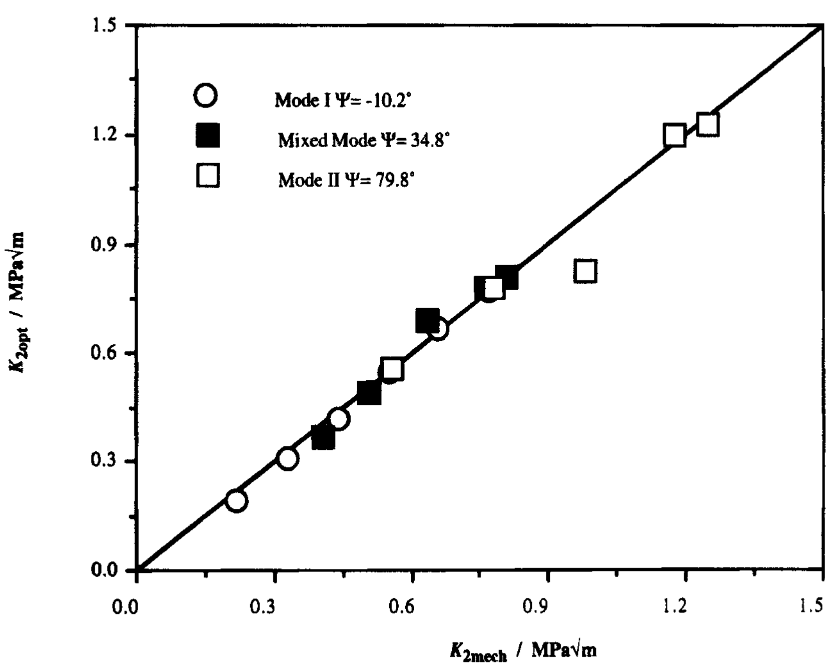


FIGURE 8 K_{2opt}/K_{2mech} from Al half of a bimaterial CTS specimen.

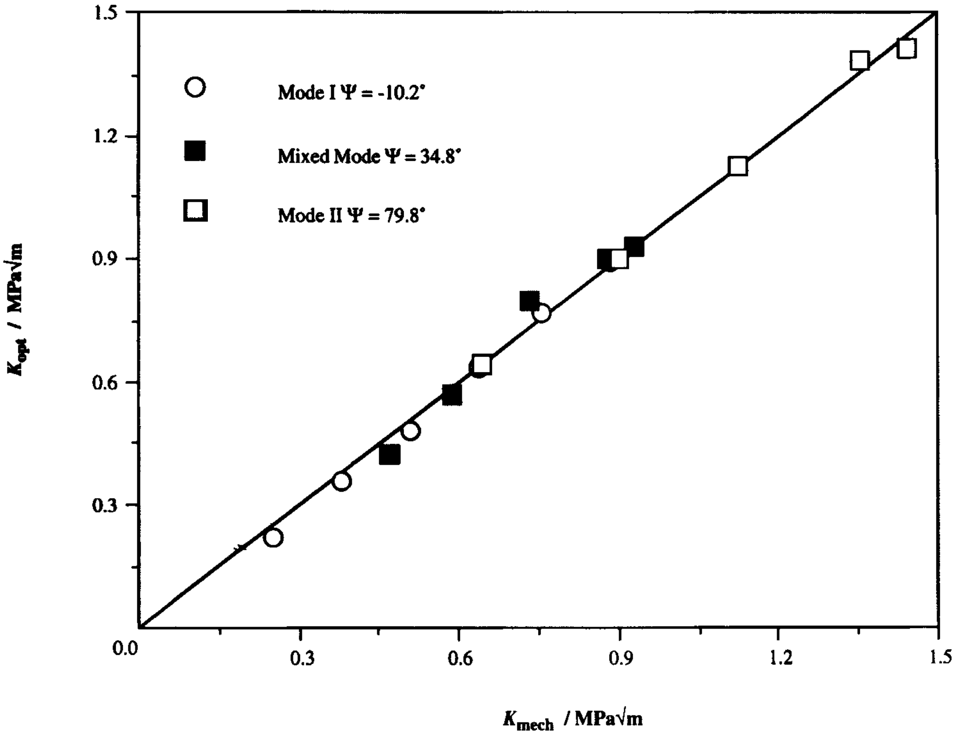
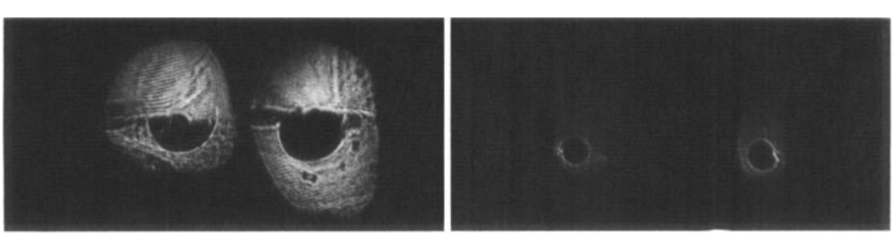


FIGURE 9 Total K_{opt} *vs.* K_{mech} from a bimaterial CTS specimen.

Figure 10 shows an example of a pair of bimaterial caustics together with a pair of monolithic aluminium caustics (after Wallhead and Edwards[10]) for comparison.

Figure 7 presents the measured stress intensity factors taken from the epoxy half of the specimen only. Over the three loading angles the measured stress intensity factors are in good agreement with the theoretical Ks from Equations 30 and 31, especially for mode I loading where the overall mode mixity is lowest.



a) b)

FIGURE 10 Example caustics from the front and rear surfaces of a) aluminium/epoxy bimaterial specimen (the aluminium is the upper material, the epoxy is the lower material: note that a larger caustic radius is obtained in the epoxy); and b) a monolithic aluminium specimen (after Wallhead and Edwards[10]).

Figure 8 shows the corresponding curve for the aluminium half of the specimen. Again, the agreement with theory from Equations 30 and 31 is good. It is interesting to note, as Figures 7 and 8 show, the difference in stress intensity factors between the two materials under the same loading conditions. For nominally mode I, mode II and 45° loading the epoxy experiences a lower K than the aluminium, as predicted by Equation (12).

Figure 9 shows the generalised stress intensity factor determined from caustics compared with that analytically determined over a stress intensity factor range from 0–1.5 MPa/m$^{1/2}$ and for the three loading angles. Good agreement is observed between the experimental and analytical results over the whole loading range and angles.

Figure 11 shows the measured mode mixity, Ψ_{opt}, obtained from $\Psi = \tan^{-1}(K_{2opt}/K_{1opt})$, normalised by the mode mixity, Ψ_{cal}, calculated from $\Psi = \tan^{-1}(K_{II}/K_{I}) + \omega(\alpha, \beta)$, plotted *versus* the interface stress intensity factor due to the applied loading, K_{in}. Reasonable agreement is observed (within approximately 15%) between the experimental and analytical mode mixities over the whole loading range.

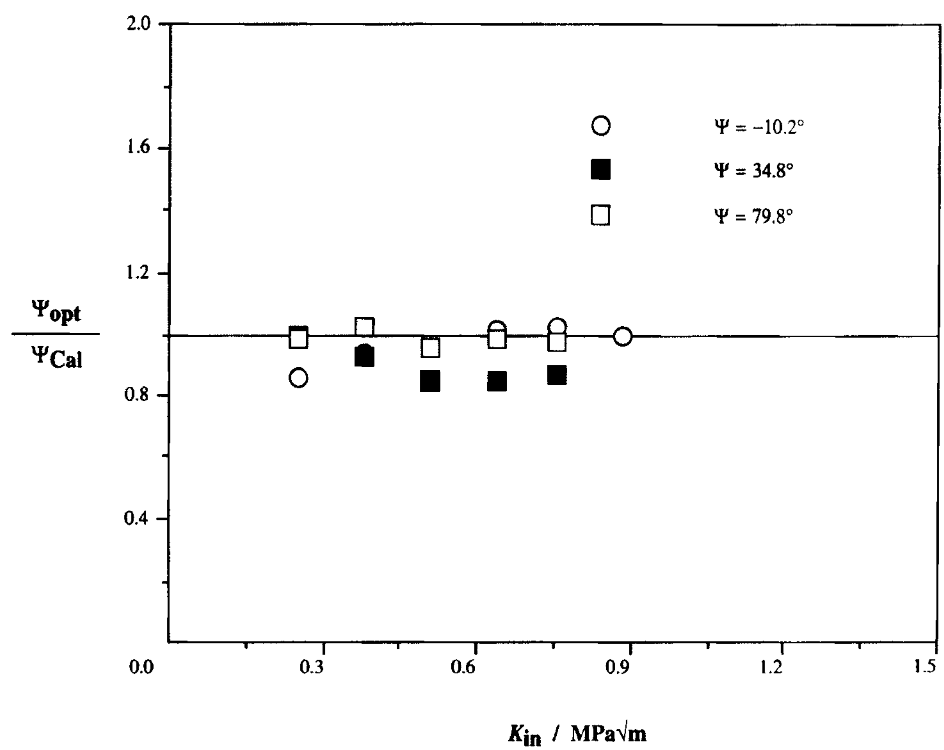


FIGURE 11 Mode mixity *vs.* K_{in} from a bimaterial CTS specimen.

CONCLUSIONS

The optical method of caustics with the "split-beam" modification constitutes an efficient method for the experimental determination of stress intensity factors and mode mixities for cracks along interfaces of dissimilar materials under a range of loading conditions. In general, good agreement is observed between the experimental measurements and analytical calculations using the stress intensity factor approach. As is the case with homogeneous specimens, caustic measurements must be taken from the plane stress region around the crack which is observed to be greater than half the specimen thickness from the crack tip. The metallic coating applied to overcome the problem of obtaining a specular reflection from the epoxy material was observed to have only a slight detrimental effect on the caustic measurements.

The results of this work provide experimental evidence in support of the stress intensity factor approach for the analysis of interface cracks. It also provides a means of investigating interface crack conditions using this approach where no analytical solution exists. This may be particularly useful when attempting to provide damage-tolerance-based life assessments of adhesive joints.

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