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OPENING-MODE DOMINATED CRACK GROWTH ALONG INCLINED INTERFACES: EXPERIMENTAL OBSERVATIONS

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Abstract—This experimental study investigates the dynamic decohesion of inclined interfaces between aluminum and a polymeric material PSM-1. Two lead azide explosive charges are detonated to initiate dynamic loading in a specially designed bimaterial specimen. The dynamic loading results in crack initiation, propagation and arrest in the same experiment. Photoelasticity, in conjunction with high-speed photography, is used to observe the dynamic event. Dynamic complex stress intensity factor and the energy release rate histories are obtained using the available steady-state singular stress field equations. The dependence of the dynamic initiation and arrest toughness on the mixity under dynamic loading is also investigated. Mixity at crack initiation is controlled by the inclination of the interface. The results show that the initiation toughness is higher than the arrest toughness by about 21%. Based on the experimental observations, a dynamic fracture criterion for subsonic crack growth along the bimaterial interfaces is proposed. According to this criterion, the displacement at a point behind the crack tip varies exponentially with the crack-tip velocity ($0 < v < c_s$; where c_s is the shear wave speed of the compliant material). This criterion establishes a generalized relationship between the dynamic energy release rate and the instantaneous crack-tip velocity. © 1998 Elsevier Science Ltd. All rights reserved.

INTRODUCTION

Interfacial failure plays an important role in limiting the overall performance of multiphase materials. This has propelled a large body of work in the area of interfacial fracture in recent years. The earliest study of interfacial fracture mechanics was by Williams (1959), who employed the eigen function expansion technique to obtain the stress field near the crack tip located at the interface of two perfectly bonded elastic half spaces. He showed that the interfacial crack tip exhibits an oscillatory stress singularity. Shih and Rice (1964) and Rice and Shih (1965) provided explicit expressions for the near-tip stress fields and related them to the remote stress fields. Nonetheless, the concept of stress intensity factor to completely characterize the stress field surrounding the crack tip was unavailable for many years. Recently, Rice (1988) has introduced the notion of complex stress intensity factor as a crack-tip characterizing parameter. The predicted stress and displacement fields exhibited abnormal crack-face contact.

Considerable experimental effort has gone into investigating the fracture of bimaterial interfaces. However, a majority of these studies have been quasistatic in nature. Liechti and Knauss (1982a, b), using optical interferometric measurements, observed that the quasistatic crack growth along a polymer/glass bimaterial interface was governed by the vectorial crack-face displacement. Liechti and Chai (1992) proposed a criterion for quasistatic interfacial crack initiation. The criterion involves a U-shaped relation between the energy release rate, G, and the mixity, ϕ, for quasistatic crack initiation and growth. Also, it has been shown that interfacial fracture toughness has a very strong dependence on the mixity.

Dynamic studies of interfacial fracture are scarce and have only recently received attention. This is primarily due to the complexity of the problem. The first experimental study on the dynamic interface fracture was by performed Tippur and Rosakis (1991). Their investigation demonstrated the possibility of interfacial crack growth at velocities up

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to 80% of the shear wave velocity of the more compliant material. This experimental study motivated several analytical and numerical investigations of the same problem (Yang *et al.*, 1991; Nakamura, 1991; Deng, 1993; Xu and Needleman, 1995, 1996). A higher order asymptotic stress field equation for dynamic crack propagation along bimaterial interfaces was provided by Liu *et al.* (1993). Lambros and Rosakis (1995a) demonstrated that crack propagation along a bimaterial interface can occur at intersonic velocities. Singh and Shukla (1996b) used dynamic photoelasticity, in conjunction with high-speed photography, to investigate the crack propagation at subsonic and intersonic velocities and showed the existence of a shock front at the crack tip in the intersonic regime. Recently, Lambros and Rosakis (1995b,c) proposed a criterion for dynamic crack growth along a bimaterial interface. According to this criterion, the dynamically growing crack propagates by maintaining a constant crack face profile. Most recently, Kavaturu and Shukla (1998) have proposed interface fracture criteria that relate the dynamic energy release rate to the instantaneous crack-tip velocity. These criteria are based on the premise that the crack-face displacements increase exponentially with the crack-tip velocity in the subsonic regime.

The majority of dynamic interface fracture studies available to date are limited to the specimen configurations which were loaded predominantly in shear. To completely understand the catastrophic nature of the interfacial fracture, a detailed investigation of the dynamic fracture process under opening-mode dominated applied loading, is necessary. Additionally, most of the investigations to date have focussed on the dynamic crack propagation and, to some extent, on the initiation of interfacial cracks. There are no available studies on the arrest of the interface cracks. Most recently, a novel specimen geometry has been developed by Singh *et al.* (1997) to study the complete process of initiation, propagation and arrest of an interface crack subjected to explosively generated tensile wave.

The present study investigates the complete process of initiation, propagation and arrest of an interface crack subjected to a planar tensile stress wave resulting in opening-mode dominated crack growth under different mixities of loading. The mixity at the initiation was controlled by the inclination of the interface. The specimen geometry developed by Singh *et al.* (1997) was used to load the bimaterial interface with plane-fronted tensile stress waves. The interface inclination was varied in a sequence of experiments to study complete process of initiation, propagation and arrest under different mixities of loading. The entire event was observed by dynamic photoelasticity in conjunction with high-speed photography. The isochromatic fringe patterns obtained from the experiments were analyzed to determine various fracture parameters such as the crack-tip velocity, the complex stress intensity factor, the mixity, and the energy release rate. The analysis procedure was based on the steady-state singular stress field equations developed by Yang *et al.* (1991).

EXPERIMENTAL TECHNIQUE

Specimen preparation

A schematic of the bimaterial specimen used in the present study is shown in Fig. 1. The bimaterial specimen consisted of a compliant half bonded to a stiff aluminum half. The compliant half was chosen to be transparent and photoelastic PSM-1 (a birefringent polymer supplied by Measurement Group Inc., NC, U.S.A.). The mechanical properties of the constituent materials are listed in Table 1. The ratio of Young's moduli of the constituents of the bimaterial is approximately 26, providing a significant elastic mismatch across the interface. The two halves of the bimaterial specimen were machined to produce square edges. The aluminum half was sandblasted and the PSM-1 half was sanded to provide better bonding surfaces. Both the surfaces were thoroughly cleaned using methanol prior to bonding. PMC-1 (supplied by Measurement Group Inc., NC, U.S.A.; batch 2), a two component polymer, which has mechanical properties similar to PSM-1 (as claimed by Measurements Group Inc., NC, U.S.A.) was used as the bonding cement on the interface. The adhesive was cured at 70°F for 24 h and then at 100°F for 1 h. A sharp starter pre-crack (25 mm long) was introduced at the bimaterial interface by means of Teflon®

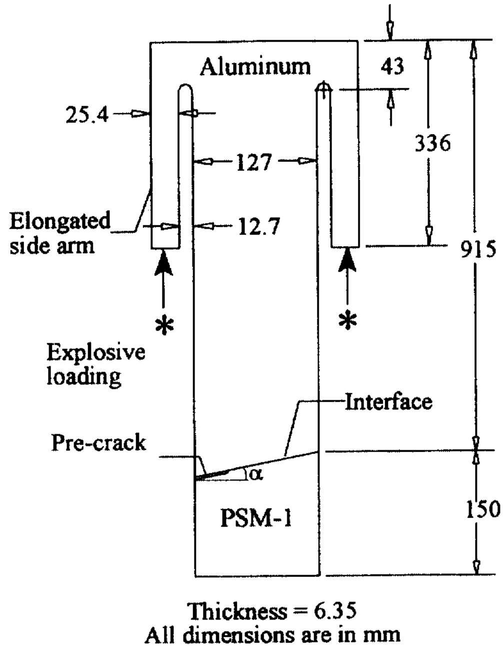


Fig. 1. Schematic of the bimaterial specimen used to study the interface fracture under different mixities of loading.

Table 1. Material properties of the bimaterial interface constituents

Property	PSM-1	6061 Al
Young's Modulus, E (GPa)	2.76	71
Poisson's Ratio, ν	0.38	0.33
Density, ρ (kg/m^3)	1200	2770
P-wave velocity, c_l (m/s)	1640	5430
S-wave velocity, c_s (m/s)	913	3100
Rayleigh velocity, c_R (m/s)	857	2890
Fracture toughness, K_{Ic} ($MPa\sqrt{m}$)	3.1	29
Yield strength, σ_y (MPa)	35	257
Material fringe value, f_σ (kN/m)	6.8	—
Mismatch parameter, ε	0.0936	

tape (50 μm thick) during the bonding procedure. The sharp crack had a root radius of approximately 25 μm in all the experiments.

Experimental procedure

The bimaterial specimen was placed on the optical bench of the Cranz-Schardin high-speed camera, as shown in Fig. 2. Two explosive charges, with 100 mg of lead azide explosive in each, were detonated at the end of each side arm of the aluminum half of the specimen, as shown in Fig. 1. This detonation sets up a compressive wave in the side arms of the bimaterial specimen which reflects off the opposite free surface as a tensile stress wave. A stiff steel spacer was incorporated between the explosive holder and the side arms of the aluminum half of the specimen to further increase the loading rate. The tensile wave propagates down the aluminum half of the specimen and develops a planar front before reaching the interface to load the starter crack. The distortional stress wave generated upon the reflection off the free end was spatially separated from the dilatational wave by the elongated central portion of the aluminum half, so that only the tensile dilatational stress wave loads the interface throughout the observed fracture process. The dynamic behavior of the explosively loaded bimaterial specimen was characterized by using strain gages in a

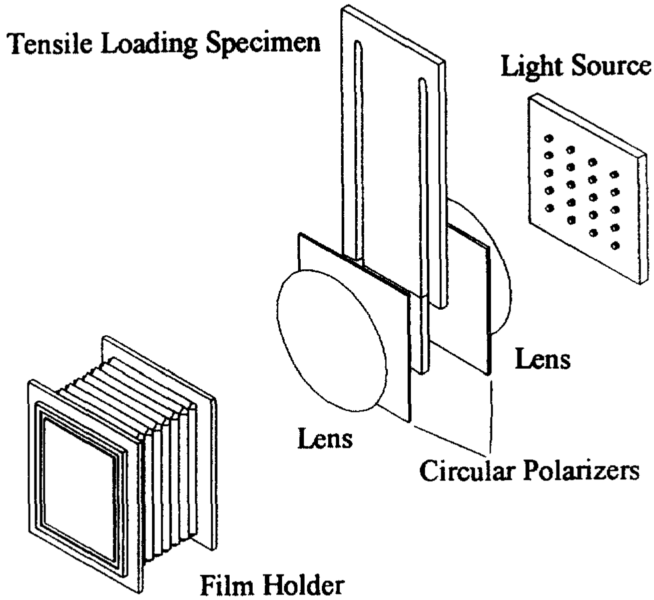


Fig. 2. Schematic of the experimental set-up used for investigating the bimaterial fracture under explosively generated tensile loading.

simple experiment. These experiments verified the planar nature of the tensile dilatational wave. The details of the experiment are given in Singh *et al.* (1997).

The plane-fronted tensile wave loads the starter crack resulting in crack initiation, propagation and arrest. The dynamic event was observed in PSM-1 using dynamic photoelasticity in conjunction with high-speed photography. The Cranz-Schardin high-speed camera provided twenty images at discrete intervals of time. The photographic images obtained from the experiment represent the full-field isochromatic fringe patterns for the stress field surrounding the propagating interface crack. A typical set of the isochromatic fringe patterns for dynamic crack growth along the bimaterial interface inclined at an angle of 10° is shown in Fig. 3. The crack-tip velocity history was determined from the knowledge of crack-tip location as a function of time. In a sequence of experiments, the interface inclination (α) was varied from $-20°$ to $20°$ in steps of $5°$, in order to better understand the interface fracture under different mixities of loading. The interface inclination is denoted to be negative when the crack propagates into the oncoming tensile wave, positive otherwise.

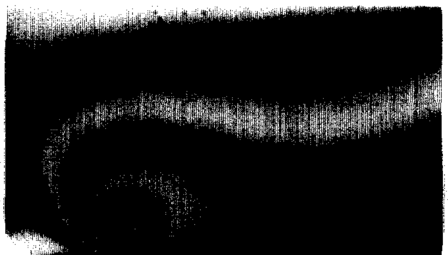
ANALYSIS OF ISOCHROMATICS

The full-field isochromatic fringe patterns obtained from the high-speed camera were analyzed to determine various fracture parameters such as the complex stress intensity factor, the mixity and the energy release rate. This analysis procedure was based on the steady-state singular stress field equations for a crack propagating along a bimaterial interface developed by Yang *et al.* (1991). Liu *et al.* (1993) performed a fully transient higher order asymptotic analysis and observed that the leading term of the transient asymptotic expansion which represents the complex stress intensity factor has the identical spatial structure as the one obtained by Yang *et al.* (1991).

The geometry of the interface crack problem is shown in Fig. 4. The compliant material (material-1) occupies the positive x_2 plane. The generation of isochromatic fringe patterns, which are contours of constant maximum shear stress, is governed by the stress optic law:

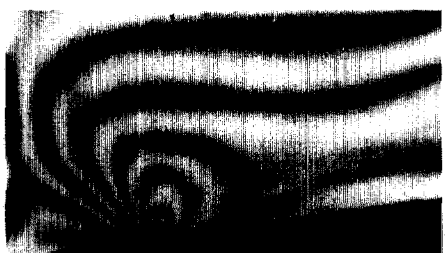
$$\frac{Nf_\sigma}{2h} = \tau_{max} = \frac{\sigma_1 - \sigma_2}{2} = \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^2}, \tag{1}$$

where f_σ is the material fringe value and h is the thickness of the specimen. The stress optic



Frame 3: $t = 24\ \mu s$, $a/w = 0.21$, $v/c_s = 0$
Initiation

Frame 5: $t = 36\ \mu s$, $a/w = 0.23$, $v/c_s = 0.32$



Frame 7: $t = 48.0\ \mu s$, $a/w = 0.27$, $v/c_s = 0.5$

Frame 10: $t = 65.5\ \mu s$, $a/w = 0.34$, $v/c_s = 0.6$

Frame 15: $t = 108\ \mu s$, $a/w = 0.49$, $v/c_s = 0.3$

Frame 18: $t = 124.5$, $a/w = 0.51$, $v/c_s = 0$
Arrest

Fig. 3. Isochromatic fringe patterns for crack growth along a PSM-1/aluminum bimaterial interface inclined at 10°.

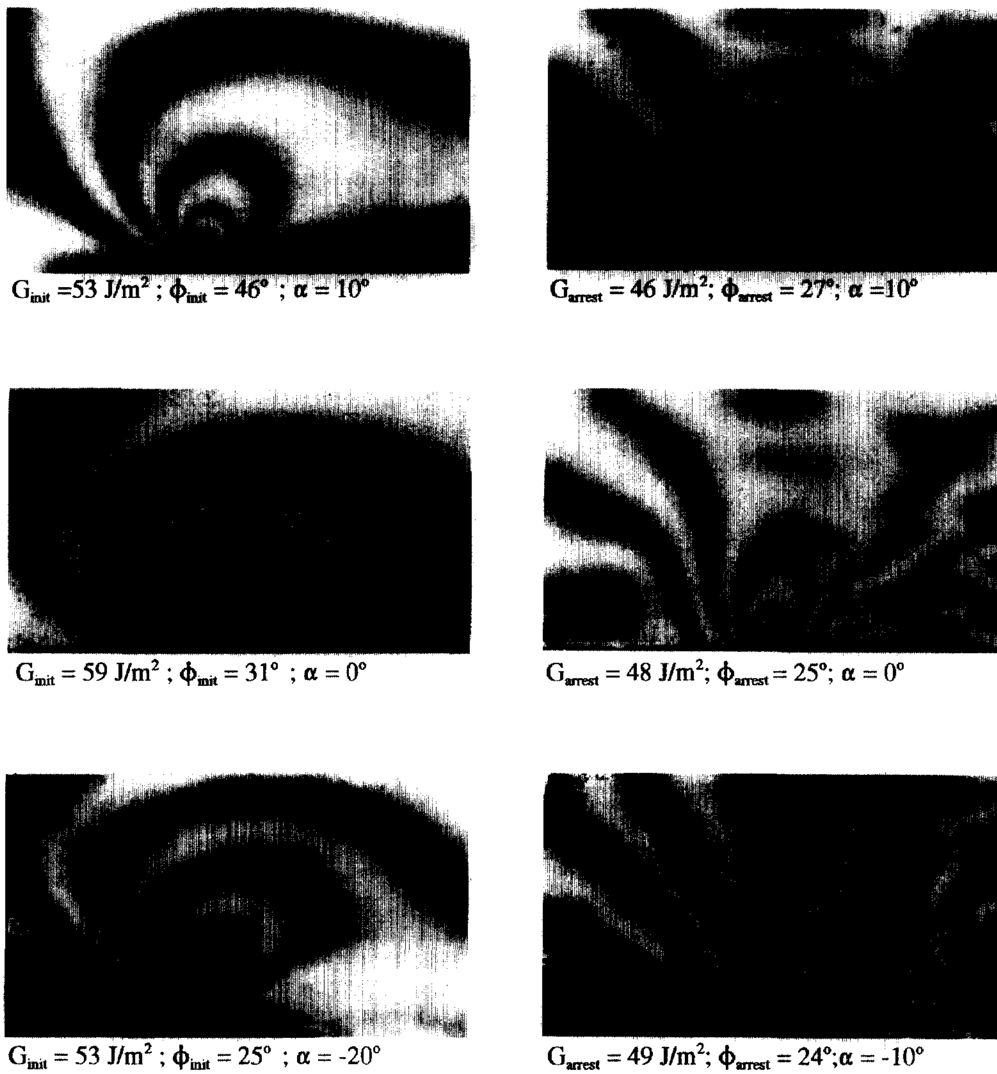


Fig. 11. Isochromatics at crack initiation and arrest as a function of interface inclination.

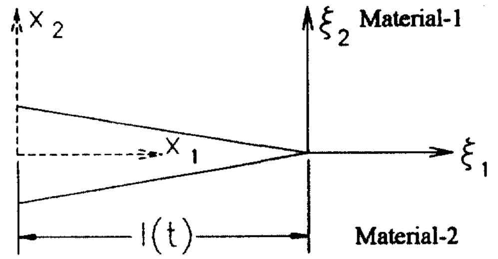


Fig. 4. Coordinate system for crack propagation along a bimaterial interface.

law is coupled with the steady-state stress field to yield the relation that defines isochromatic fringes in the vicinity of a crack-tip propagating dynamically along a bimaterial interface:

$$\left(\frac{Nf_\sigma}{2h}\right)^2 = \mu^2\{[(1+\alpha_1^2)ReF_0''(z_1\,;t)+2\alpha_s ReG_0''(z_s\,;t)]^2$$

$$+[2\alpha_1 ImF_0''(z_1\,;t)+(1+\alpha_s^2)ImG_0''(z_s\,;t)]^2\}, \quad (2)$$

where

$$\alpha_1^2 = 1-\frac{v^2}{c_1^2}, \quad \alpha_s^2 = 1-\frac{v^2}{c_s^2}, \quad (3)$$

with v being the crack-tip velocity, and c_1 and c_s being P- and S-wave velocities, respectively, of PSM-1. The modified coordinates z_1 and z_s are defined as $z_1 = \eta_1+i\alpha_1\eta_2$ and $z_s = \eta_1+i\alpha_s\eta_2$. The functions F_m'' and G_m'' have been defined in terms of the material properties, crack-tip velocity, positional coordinates and the complex stress intensity factor by Liu *et al.* (1993). Equation (2) was used to analyze the experimental isochromatic fringe pattern to determine the various fracture parameters such as the complex stress intensity factor, the energy release rate and the mixity. The analysis procedure employed a non-linear least squares method based on the Newton-Raphson technique. Singh and Shukla (1996a) provide the details and also establish the validity of this analysis procedure.

The fracture parameters extracted using these singular stress field equations are valid only when the experimental data is collected from K^d-dominant zone surrounding the crack-tip. It has been shown that there exists such a zone of K^d-dominance outside the region of three dimensional deformation by Lee and Rosakis (1993). The experimental data was carefully sampled from these K^d-dominant zones for the purpose of analysis.

RESULTS AND DISCUSSION

The history of crack-tip speed obtained in a typical experiment involving the fracture of an interface inclined at an angle -10° is shown in Fig. 5. It can be seen from the figure that the complete process of crack initiation, propagation and arrest has been observed in the same experiment. The crack initiated a finite time, $t_i = 26$ μs, after the tensile wave reached the interface. After initiation, the crack accelerated at the rate of 1.5×10^6 g (g being the acceleration due to gravity) to a maximum velocity of approximately 65% of the shear wave speed of the more compliant material. The crack decelerated after reaching the peak velocity and finally arrested. This phenomenon of *subsonic* crack propagation was observed in all the experiments involving fracture of inclined interfaces. The steady-state singular stress field equations described in the previous section were employed to evaluate the dynamic complex stress intensity factor, $K^d(t)$. It should be pointed out once again that the results presented in this study were from isochromatics in which a K^d-dominant region around the crack tip could be established. The energy release rate, G^d, and the mixity, ϕ,

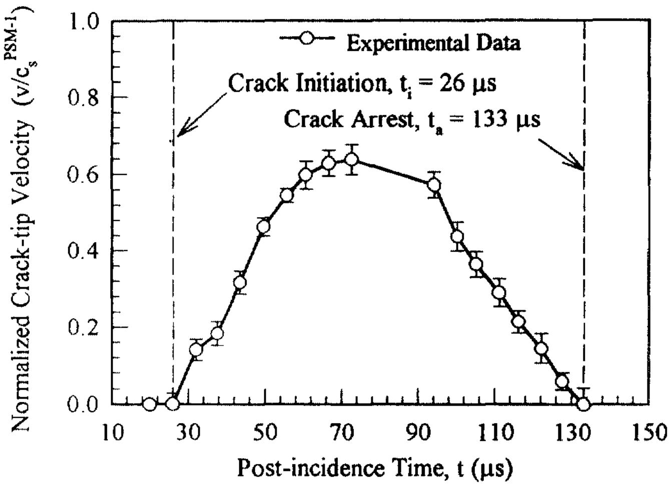


Fig. 5. Crack-tip velocity history for the fracture along a PSM-1/aluminum interface inclined at an angle of $-10°$.

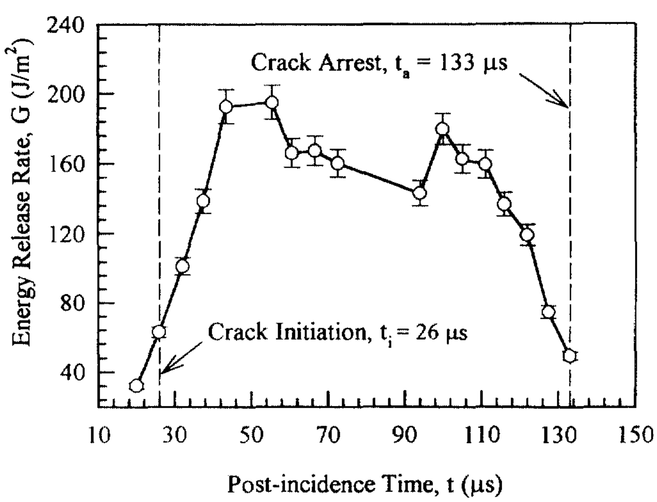


Fig. 6. Time history of the dynamic energy release rate for the crack growth along PSM-1/aluminum interface inclined at $-10°$.

for the case of dynamic interfacial crack growth were related to the complex stress intensity factor by Yang *et al.* (1991) as

$$G^d = F(v)\frac{|K^d|^2}{4\mu_1},$$

$$\phi = \arctan\left(\frac{K_2^d}{K_1^d}\right), \tag{4}$$

where F is a function of the crack-tip velocity and the mechanical properties of the interface constituents and μ_1 is the shear modulus of the compliant material, i.e., PSM-1 and K_1^d and K_2^d are the real and imaginary parts of the dynamic complex stress intensity factor, respectively. The factor F is shown to be finite at the Rayleigh wave speed of the compliant material by Yang *et al.* (1991). In contrast, this factor F is asymptotic to the Rayleigh wave speed for crack growth in homogeneous materials. The mixity is evaluated at a representative length scale of 1 m.

The time histories of the energy release rate, $G^d(t)$, and the mixity, $\phi(t)$, are shown in Figs 6 and 7, respectively. In this typical experiment, the crack initiated at $G_i = 63$ J/m^2

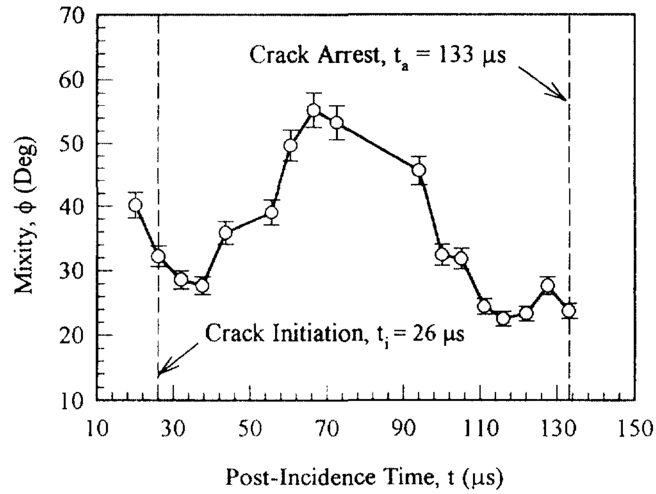


Fig. 7. Time history of the mixity for the fracture of PSM-1/aluminum interface inclined at −10°.

and $\phi_i = 32°$ and the arrest occurred at $G_a = 49$ J/m^2 and $\phi_a = 24°$. It can be seen from Fig. 6 that the energy release rate increases monotonically to a peak value in 55 μs. During this time, the crack tip accelerated to achieve a speed of approximately 55% of shear wave speed of PSM-1 ($c_s^{\text{PSM-1}}$), as is evident from Fig. 5. Thus, it can be concluded that the energy release rate increased monotonically with the crack-tip velocity up to 55% of $c_s^{\text{PSM-1}}$. This increasing trend in the energy release rate with the crack-tip velocity suggests that the crack growth in this velocity range is stable ($dG^d/dv > 0$). The energy release rate after reaching a peak at 55 μs showed a decreasing trend up to about 90 μs. During this time period, 55 μs $< t <$ 90 μs, the crack-tip velocity increased to approximately 65% of $c_s^{\text{PSM-1}}$ as shown in Fig. 5. This decreasing trend in energy release rate with the crack-tip speed is typical of unstable crack growth behavior ($dG^d/dv < 0$). Finally, after 90 μs, the energy release rate dropped monotonically as the crack decelerated indicating stable crack growth ($dG^d/dv > 0$). This interesting phenomenon of transition from stable to unstable and back to stable crack growth was characteristic of all the experiments involving fracture of inclined interfaces in this loading configuration. On the other hand, the mixity, plotted in Fig. 7, increased continuously with crack-tip velocity after initiation and decreased as the crack tip decelerated. This could also be inferred, at least qualitatively, by examining the isochromatic fringe patterns in Fig. 3. It can be seen from the figure that the fringes tilt away from the newly formed crack faces as the velocity increases suggesting an increase in the mixity.

Recently, Lambros and Rosakis (1995b, c) have proposed a criterion for dynamic crack growth along bimaterial interfaces. According to this criterion, the crack growth along an interface occurs by keeping the instantaneous shearing (δ_1) and opening (δ_2) crack-face displacements, at a point behind the crack tip, constant at their initiation values. Figure 8 defines the sliding and the opening displacements. The shearing and the opening displacements, δ_1 and δ_2, are given by (Yang *et al.* 1991)

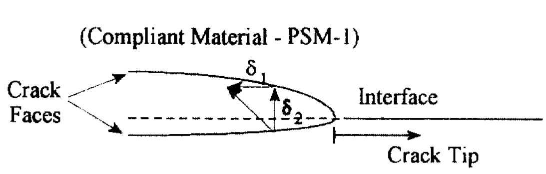


Fig. 8. Schematic definition of the shearing and opening displacements at a point behind the crack-tip.

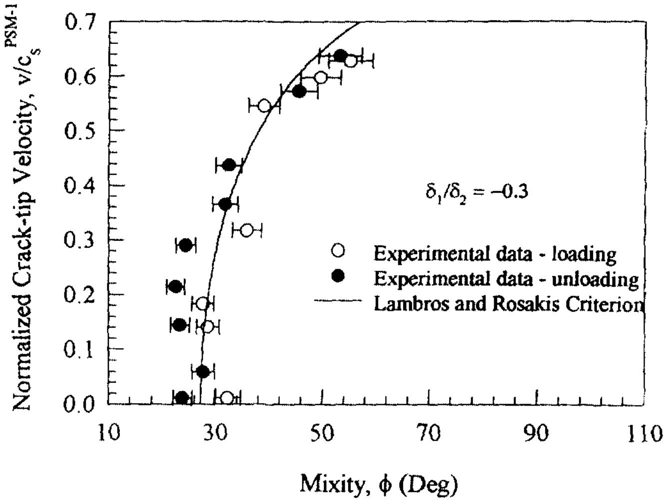


Fig. 9. Fit of eqn (6) with the experimental data from an experiment involving the fracture of PSM-1/aluminum interface inclined at $-10°$.

$$\delta_2 + i\eta\delta_1 = \frac{H_{22}Kr^{i\varepsilon}}{(1+2i\varepsilon)\cosh\pi\varepsilon}\sqrt{\frac{2r}{\pi}}, \tag{5}$$

where $i = \sqrt{-1}$ and the parameters ε, η and H_{22} which are functions of crack-tip speed and bimaterial properties are defined in Yang *et al.* (1991). The Lambros and Rosakis criterion has been proposed in two parts. The first part of the criterion which was based on the assumption that ratio δ_1/δ_2 at a point a behind the crack tip remains constant $(\delta_1/\delta_2|_{r=a} = C_1)$ leads to a relationship between the crack-tip velocity to the instantaneous mixity given by

$$\phi(v) = \arctan(C_1\eta(v)) + \arctan(2\varepsilon(v)) - \varepsilon(v)\ln a. \tag{6}$$

In addition to the constancy of the ratio, δ_1/δ_2, the fracture criterion also requires that the opening displacement, δ_2, at a point behind the crack tip remain constant. This yields a functional relationship between the energy release rate and the crack-tip speed and constitutes the second part of this criterion.

The experimental data for the subsonic fracture of the PSM-1/aluminum bimaterial interface was fitted to the first part of the criterion which leads to the relationship between the crack-tip velocity and the mixity (eqn (6)) as shown in Fig. 9. Recall that this analytical relation between v and ϕ was a result of the assumption that $\delta_1/\delta_2|_{r=a}$ = constant = C_1. It is clear from the figure that the experimental data fits well with the criterion suggesting that the ratio δ_1/δ_2 at a point ($a = 2$ mm) behind the crack tip remained fairly constant. The ratio δ_1/δ_2 for the fracture of an interface inclined at an angle of $10°$ was observed to be -0.3, implying that the crack growth was primarily opening-mode dominated. The crack growth was observed to be opening-mode dominated in this series of experiments involving crack growth along inclined interfaces. This is not surprising, and in fact, is expected since the bimaterial interface was loaded primarily in opening mode by a plane-fronted tensile dilatational wave.

The second part of the Lambros and Rosakis criterion which yields a functional relationship between the energy release rate, G^d, and the crack-tip velocity, v, predicts that the crack propagation is unstable right from crack initiation unlike the trend shown by the experimental data. As discussed earlier, the experimental data showed stable crack propagation up to crack-tip speeds of about 55% of the lower shear wave speed. The

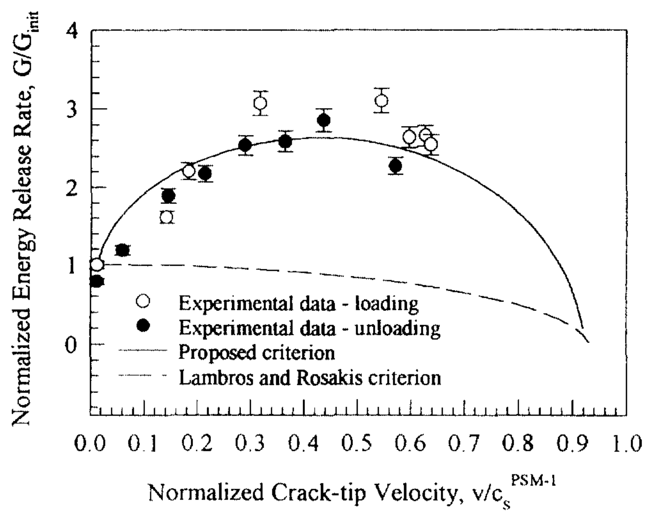


Fig. 10. Variation of the normalized energy release rate with the instantaneous crack-tip velocity for the crack growth along PSM-1/aluminum interface. Fit of the experimental data to the prediction of the proposed and the Lambros and Rosakis criteria.

experimental data along with the Lambros and Rosakis criterion is represented in Fig. 10. It is clear from the figure that there is considerable disagreement between the experimental data and this part of the criterion.

An attempt was made to identify a criterion that relates dynamic release rate to the instantaneous crack-tip velocity for crack growth along the bimaterial interfaces covering the complete range of crack-tip velocities in the subsonic regime. A new criterion that relates the dynamic energy release rate to the instantaneous crack-tip velocity was formulated based on the assumption that the opening-mode displacement at a point behind the crack tip ($r = a$) varies exponentially with the crack-tip velocity (Kavaturu and Shukla, 1998) as

$$\delta_2|_{r=a} = C_2(v/c_s)^n, \tag{7}$$

where C_2 is a proportionality constant and n is a parameter that depends on the bimaterial combination and on the cohesive properties of the bond. The proposed criterion also assumes that the ratio δ_1/δ_2 at a point behind the crack tip is also a constant. This assumption is essentially the same as the first part of the Lambros and Rosakis criterion (eqn (6)).

Using eqn (7) in eqn (5) results in a relationship between the magnitude of the complex stress intensity factor and the crack-tip speed given by

$$|K^d| = C_2(v/c_s)^n \frac{\sqrt{1+4\varepsilon^2}\cosh \pi\varepsilon}{H_{22}\cos(\arctan(C_1\eta))}\sqrt{\frac{\pi}{2a}}. \tag{8}$$

The constant C_2 in eqn (8) can be eliminated by normalizing $|K^d|$ with the corresponding value at initiation. The eqn (8) can be expressed in terms of G^d using eqn (4a).

A fit of the experimental data to the proposed criterion (eqn (8)) is also shown in Fig. 10. The experimental data shows good agreement with the proposed criterion. For the case of crack propagation along PSM-1/aluminum bimaterial interface, the opening-mode displacement at a point 2 mm behind the crack tip was observed to be proportional to $(v/c_s)^{0.15}$. Interestingly enough, the criterion predicts that the crack propagation turns unstable at crack-tip velocities of about 50% of the lower shear wave speed. Also, the criterion predicts that the energy release rate is finite in the limit of Rayleigh wave velocity of the compliant material.

In light of the increasing trend between the energy release rate and the crack-tip velocity similar to homogeneous materials, the fracture surfaces were examined under a

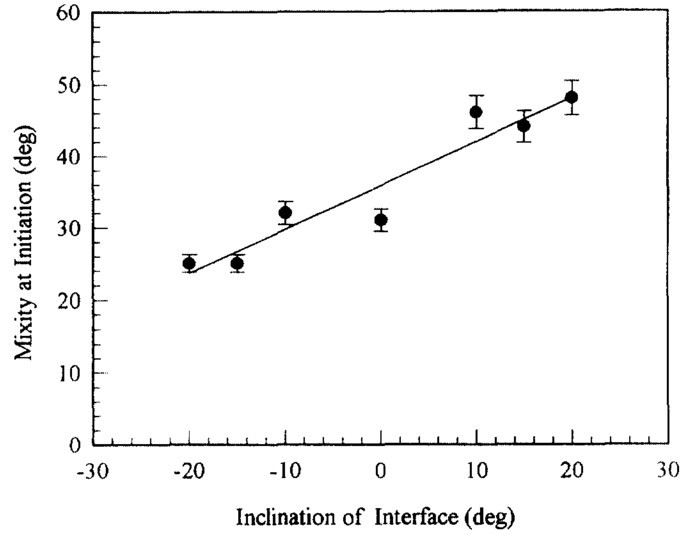


Fig. 12. Effect of the interface inclination on the initiation mixity for fracture along PSM-1/aluminum interface using the specially designed specimen geometry.

Nikon SMZ-U microscope to see if the fracture is truly interfacial and the crack did not branch into adhesive layer. The fracture was indeed observed to be truly interfacial and there was no adhesive layer left behind on the aluminum half, in all the experiments (Singh, Kavaturu and Shukla, 1997).

One of the primary interests of the present study was to investigate the dependence of the dynamic initiation and arrest toughness of the bimaterial at different mixities of loading. As discussed earlier, the interface inclination was varied to control the initiation mixity. A sequence of experiments was conducted by varying the inclination of the interface (α) from -20° to 20° in steps of 5°. A set of isochromatic fringe patterns at initiation and arrest as a function of mixity is shown in Fig. 11. It can be seen from the figure that the fringes at initiation that the fringes tilt away from the crack faces as the mixity increases. The arrest toughness was observed to be less than the initiation toughness in all the experiments. A simple observation of the isochromatic fringes suggests that the arrest toughness would be less than the initiation toughness as the number fringes surrounding the crack tip in the frames corresponding to arrest are less than that of initiation.

The effect of interface inclination on the initiation mixity is shown in Fig. 12. It can be seen that the crack initiation mixity can be varied continuously by controlling the interface inclination. Thus, this specimen geometry is suited for the dynamic crack initiation studies in bimaterials. The initiation mixity was altered by about 100% by varying the interface inclination by only 20°. The dependence of initiation and arrest toughness on the corresponding mixity values is plotted in Fig. 13. The dynamic initiation and arrest toughness remained fairly constant in the range of mixities obtained in this class of experiments. It should be mentioned at this point that the dynamic arrest toughness is measured before any ringing down or dissipation of kinetic energy occurs near the crack tip. Table 2 summarizes the crack initiation and arrest toughness and corresponding mixity values as a function of the interface inclination obtained in this series experiments. The average initiation toughness was 57 $J/m^2 \pm 10\%$ while the average arrest toughness was 47 $J/m^2 \pm 12\%$. The initiation toughness was observed to be higher than the arrest toughness by about 21%. One reason for this is that the dynamic effects are more predominant at the initiation than at arrest. Thus, the experimental data shows similar trend as the initiation criterion for quasistatic crack growth proposed by Liechti and Chai (1992) in the range of mixity values obtained in this series of experiments.

Finally, a series of five experiments was performed on a center cracked tension specimen geometry to get an estimate of the quasistatic initiation toughness for the bimaterial system under study. The analytical equations developed by Rice *et al.* (1990) were employed to

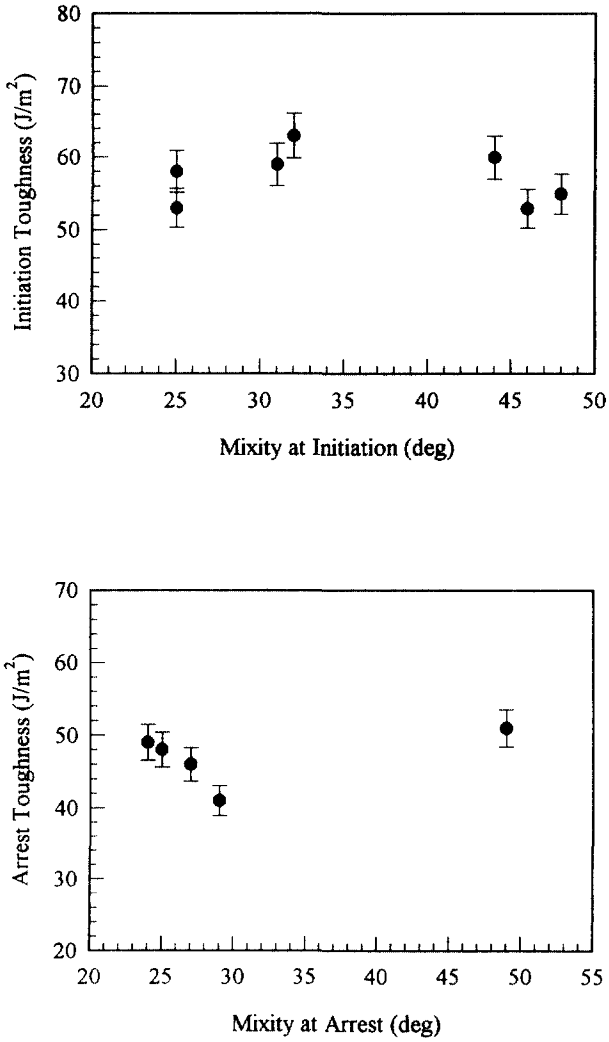


Fig. 13. Dependence of the dynamic initiation and arrest toughness on the mixity for the dynamic fracture of PSM-1/aluminum bimaterial interface.

Table 2. Summary of the experimental results. Initiation and arrest toughness and corresponding mixity values

Interface inclination (°)	Initiation toughness (J/m^2)	Initiation mixity (°)	Arrest toughness (J/m^2)	Arrest mixity (°)
20†	55	48	—	—
15	60	44	41	29
10	53	46	46	27
0	59	31	48	25
−10	63	32	49	24
−15	58	25	51	49
−20†	53	25	—	—

† Shear wave started to interact with the crack-tip during the arrest event.

evaluate the quasistatic fracture toughness. The quasistatic initiation toughness was calculated to be 33 $J/m^2 \pm 10\%$ and the corresponding mixity was found to be 30°. The dynamic initiation toughness was observed to be higher than the static initiation toughness by about 70%. This is not surprising as even in the case of fracture of homogeneous materials the dynamic toughness was observed to be higher than the static initiation toughness (Dally and Barker, 1988). The initiation process is difficult to explain using continuum mechanics models as the fracture process occurs in a small process zone very close to the crack tip by the formation of microcracks. It can be better explained, at least qualitatively, by utilizing micromechanics models. A qualitative explanation for this was provided by Ravi-chander and Knauss (1984). They suggested that there exists an intrinsic rate associated with the nucleation and growth of the microcracks that develop in the process zone. If the applied rate of loading is lower than this rate of the microprocesses, one would obtain the quasistatic results. On the other hand, if the loading rate is higher, the microprocesses are incompletely developed and hence they would sustain higher loads resulting in higher fracture toughness.

CONCLUSIONS

A sequence of experiments was performed on the PSM-1/aluminum bimaterial specimens to study fracture of inclined interfaces under opening-mode dominated loading. A novel specimen geometry was developed to control the mixity at initiation and also to provide crack initiation, propagation and arrest in the same experiment. The dynamic loading was achieved by detonating two explosive charges in the bimaterial specimens. The dynamic fracture event was observed in the polymeric half using dynamic photoelasticity in conjunction with high-speed photography. It was observed that initiation and arrest toughness remained constant in the range of mixities obtained. The results showed that the initiation toughness was higher than the arrest toughness by about 21%. Also, the dynamic initiation toughness values were higher than the quasistatic initiation values by about 70%. Finally, a criterion that establishes a relationship between the dynamic energy release rate and the instantaneous crack-tip velocity for the dynamic interfacial fracture was proposed. According to the criterion, the crack face displacement at a point behind the crack tip increases exponentially with the crack-tip speed. The experimental data fits well with the proposed criterion.

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