FAST FRACTURE OF INCLINED INTERFACES: SUBSONIC REGIME

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ABSTRACT

The present experimental study investigates the initiation, propagation, and arrest of a bimaterial interface crack subjected to controlled stress wave loading. The bimaterial interface crack is dynamically loaded by a plane fronted tensile stress wave generated by detonating lead azide explosive in a specially designed specimen. The specimen is designed such that different mode mixities of loading can be achieved by a simple modification of the specimen geometry. The tensile loading of the bimaterial interface results in crack initiation, acceleration, propagation, deceleration, and arrest, all in the same experiment. The entire event is observed using dynamic photoelasticity in conjunction with high speed photography. The isochromatic fringe patterns obtained from the fast fracture of the inclined interface are analyzed to determine the variation of various fracture parameters such as the crack-tip velocity, the complex stress intensity factor, the mode-mixity, and the energy release rate as a function of crack propagation along the inclined interface.

KEY WORDS

Bimaterial, inclined interface, dynamic photoelasticity, complex stress intensity factor, mode mixity.

INTRODUCTION

Dynamic studies of interfacial fracture are scarce and have only recently received attention. The first experimental study on the dynamic interface fracture was by Tippur and Rosakis (1991). Their investigation demonstrated the possibility of interfacial crack growth at velocities upto 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, Deng, 1992, Nakamura,1991, Singh and Shukla, 1995a,b, Xu and Needleman, 1996). A criterion for quasi-static interfacial crack initiation and growth has been proposed by Liechti and Chai (1991). A higher order asymptotic stress field equation for dynamic crack propagation along bimaterial interfaces was provided by Liu *et al.* (1993). Lambros and Rosakis (1994) demonstrated that crack propagation along a bimaterial interface can occur at intersonic velocities. Singh and Shukla (1995b) used dynamic photoelasticity in conjunction with high speed photography to investigate the crack propagation at subsonic and intersonic velocities.

Present study investigates the complete process of initiation, propagation and arrest of an interface crack subjected to plane fronted tensile stress wave loading. A specimen with geometry similar to that used by Dally and Barker (1988) is used to generate tensile waves by detonating lead azide explosive in the specimen. The mode-mixity of loading is controlled by changing the inclination of the interface. The tensile loading of the bimaterial interface results in crack initiation, propagation, and arrest, all in the same experiment. Entire event is observed by dynamic photoelasticity in conjunction with high speed photography. The isochromatic fringe patterns obtained from the experiments are analyzed to determine various fracture parameters such as the crack-tip velocity, the complex stress intensity factor, the mode-mixity, and the energy release rate. The analysis procedure is based on the transient higher order stress field equations developed by Liu *et al.* (1993).

EXPERIMENTAL PROCEDURE

The experimental setup used to investigate crack propagation along bimaterial interface subjected to plane fronted tensile waves is shown in Fig. 1. The bimaterial specimen consists of a compliant half directly bonded to the stiff half. The compliant half is chosen to be transparent and photoelastic PSM-1 (supplied by Measurement Group, NC, USA), while aluminum is chosen as the stiff half. This combination provides significant mismatch in the mechanical properties of the two materials comprising the bimaterial interface. The mechanical properties of the constituent materials are listed in Table.1. PMC-1 (supplied by Measurement Group, NC, USA) which has the same mechanical properties as PSM-1, is used as the bonding cement on the interface. A starter edge notch of length 25.4 mm is introduced at the bimaterial interface by means of a Teflon tape during the bonding procedure.

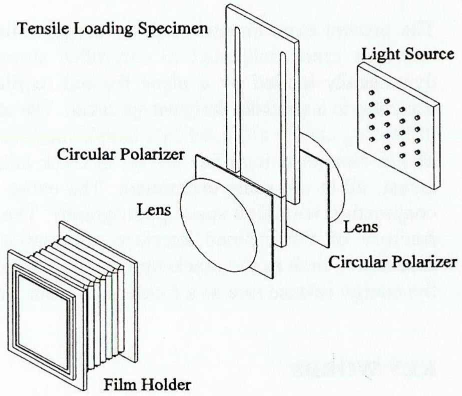


Fig. 1. Schematic of the Experimental set-up.

As shown in Fig. 2, two Lead azide explosive charges are detonated simultaneously at one end of the specimen to generate compressive stress waves which reflect off the opposite free surface as tensile stress waves. These tensile waves propagate down the aluminum half of the specimen and dynamically load the starter crack situated at the bimaterial interface. The dynamic stress field produced by the propagating crack is observed using dynamic photoelasticity. This is made possible by the transparent and photoelastic nature of the compliant half of the bimaterial specimen. These photographic images 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 is shown in the Fig. 3. The isochromatic fringe patterns are analyzed to determine the fracture parameters such as the crack-tip velocity, the complex stress intensity factor, the mode-mixity, and the energy release rate. The inclination of the interface is changed from 0° to 25° in steps of 5°, in a sequence of experiments, to study the interface fracture at varied mode-mixities of loading.

Table. 1. Mechanical properties of the interface constituents.

Property	Al - 6061	PSM-1
Young's Modulus, E, (GPa)	71.0	2.76
Poisson Ratio, ν	0.33	0.38
Density, ρ, (Kg/m³)	2770	1200
Mismatch Parameter, ϵ	0.0936	

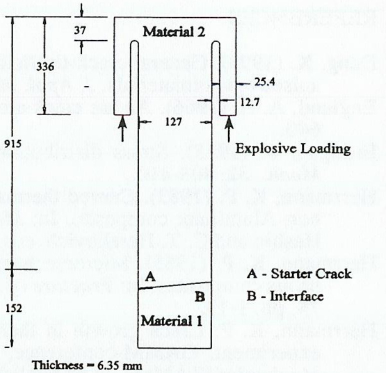
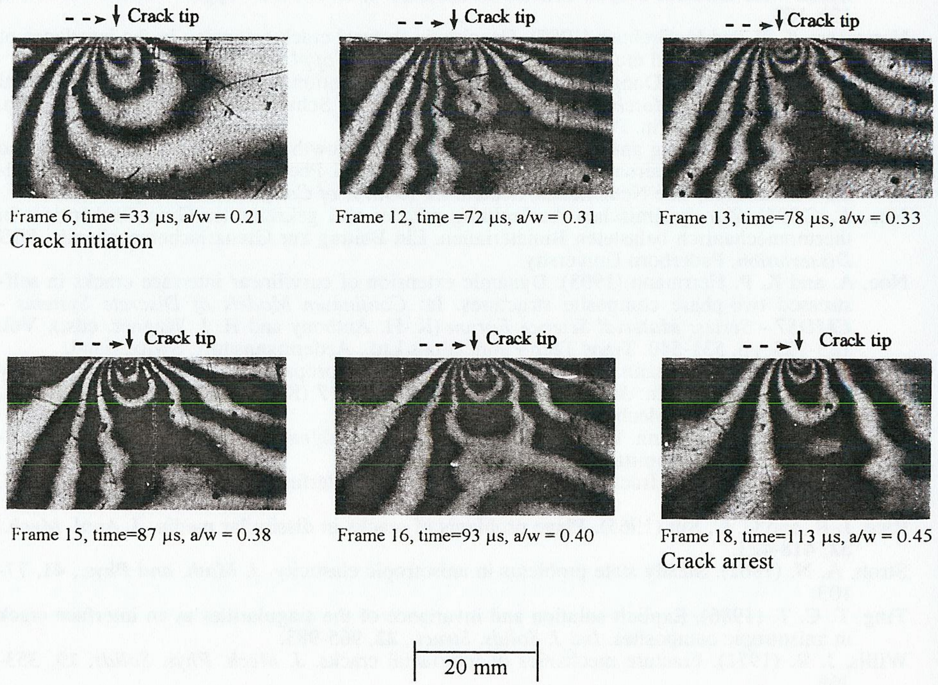


Fig. 2. Schematic of the bimaterial specimen with inclined interface.



Frame 6, time =33 μs, a/w = 0.21
Crack initiation

Frame 12, time =72 μs, a/w = 0.31

Frame 13, time=78 μs, a/w = 0.33

Frame 15, time=87 μs, a/w = 0.38

Frame 16, time=93 μs, a/w = 0.40

Frame 18, time=113 μs, a/w = 0.45
Crack arrest

Fig. 3. A typical sequence of isochromatic fringe patterns for the crack propagation along PSM-1/ aluminum inclined interface.

DYNAMIC PHOTOELASTIC ANALYSIS

The full field isochromatic fringe patterns obtained from the high-speed camera are analyzed to determine various fracture parameters such as the crack-tip velocity, the complex stress intensity factor and the energy release rate. This analysis procedure is based on the transient higher order asymptotic stress field equations for a crack propagation along a bimaterial interface (Liu *et al.*, 1993). Consider a crack propagating along a bimaterial interface as shown in Fig. 4. From the higher order asymptotic analysis of Liu *et al.* (1993) the stress field in vicinity of the crack-tip is given as,

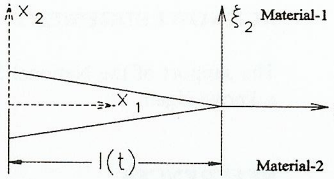


Fig. 4 Schematic of a crack propagating along a bimaterial interface.

$$\sigma_{ij}(\xi_1,\xi_2,t) = \sum_{m=0}^{\infty} \epsilon^{p_m} \sigma_{ij}^{(m)}(\eta_1,\eta_2,t) \tag{1}$$

where $\eta_i = \xi_i/\epsilon$, $i \in \{1, 2\}$, and ϵ is a small arbitrary positive number. This parameter is used to scale a small region around the crack-tip such that the scaled coordinates η_i fill the entire field of observation. Now, $p_0 < p_1 < p_2 < \ldots$, i.e. $\sigma_{ij}^{(0)}$ are the primary terms, $\sigma_{ij}^{(1)}$ are the first order corrections and so on.

The generation of the isochromatic fringe patterns, which are contours of constant maximum shear stress, is governed by the stress optic law,

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

where f_σ is the material fringe value and h is the thickness of the specimen. The stress optic law is coupled with the higher order asymptotic stress field to yield the relation that defines isochromatic fringes in the vicinity of a crack-tip propagating dynamically along a bimaterial interface, as

$$\begin{aligned}\left(\frac{N f_\sigma}{2h}\right)^2 = {} & \mu^2\Big\{\big[(1+\alpha_1^2)\,\mathrm{Re}\,F_0''(z_1;t) + 2\alpha_s\,\mathrm{Re}\,G_0''(z_s;t)\big]^2 \\ & + \big[2\alpha_1\,\mathrm{Im}\,F_0''(z_1;t) + (1+\alpha_s^2)\,\mathrm{Im}\,G_0''(z_s;t)\big]^2\Big\} \\ & = \mu^2\Big\{(1+\alpha_1^2)^2\big[\mathrm{Re}\,F_0''(z_1;t)\big]^2 + 4\alpha_s^2\big[\mathrm{Re}\,G_0''(z_s;t)\big]^2 \\ & + 4\alpha_s(1+\alpha_1^2)\,\mathrm{Re}\,F_0''(z_1;t)\,\mathrm{Re}\,G_1''(z_s;t) + 4\alpha_1^2\big[\mathrm{Im}\,F_0''(z_1;t)\big]^2 \\ & + (1+\alpha_s^2)^2\big[\mathrm{Im}\,G_0''(z_s;t)\big]^2 + 4\alpha_1(1+\alpha_s^2)\,\mathrm{Im}\,F_0''(z_1;t)\,\mathrm{Im}\,G_1''(z_s;t)\Big\}\end{aligned} \tag{3}$$

where,

$$\alpha_1^2 = 1 - \frac{v^2}{c_1^2}, \qquad \alpha_s^2 = 1 - \frac{v^2}{c_s^2} \tag{4}$$

with v being the crack-tip velocity, and c_l and c_s the P- and S-wave velocities, respectively, of material-1. The modified coordinates z_l and z_s are defined as $z_l = \eta_1 + i\alpha_l\eta_2$ and $z_s = \eta_1 + i\alpha_s\eta_2$. The functions F''_m and G''_m have been defined by Liu *et al.*, 1993. Equation (3) is used to analyze the experimental isochromatic fringe pattern to determine the various fracture parameters. The analysis procedure employs a non-linear least squares method based on the Newton-Raphson technique. Singh and Shukla (1995a) provide the details and also establish the validity of this analysis procedure.

RESULTS AND DISCUSSIONS

Two explosive holders, with 100mg of lead azide explosive in each, are detonated in the bimaterial specimen. The tensile dilatational wave generated upon explosion interacted with starter crack resulting in crack initiation, propagation, and subsequent crack arrest. The instantaneous crack-tip velocity history in a typical experiment involving bimaterial fracture along 5° inclined interface is plotted as a function of post-incidence time in Fig. 5. It is evident from the figure that the crack initiated at a certain finite time (t_i = 33 μs) after the tensile wave had impinged on the bimaterial interface. After initiation crack-tip velocity increased rapidly with acceleration of about 2 x 10^6 g (g is the acceleration due to gravity) to about 55% of the shear wave velocity of the more compliant material, c_s^{PSM-1}. Thereafter, the crack-tip velocity stabilized for a short interval of time and then started to decrease as the trailing edge of the tensile wave passed by the bimaterial interface. Finally, the crack-tip velocity decreased to zero and crack arrested (t_a = 113μs).

The higher order asymptotic stress field equations are used to determine various fracture parameters such as the complex stress intensity factor $\mathbf{K}_d$, the mode-mixity, ϕ, and the energy release rate, G. The variation of real and imaginary parts of the complex stress intensity factor for a typical experiment for crack growth along 5° inclined interface is shown in Fig. 6. It can be seen from the Fig. 6 that even under primary mode-1 loading, interface crack growth is characterized by non-zero values for the real and imaginary parts of the complex stress intensity factor K_d. This is due to the coupling of the real and imaginary parts of the complex stress intensity factor arising due to the mismatch across the bimaterial interface. As shown in Fig.7, the energy release rate increased during propagation phase and stabilized at a value of 80 J/m² before it started to decrease as the crack

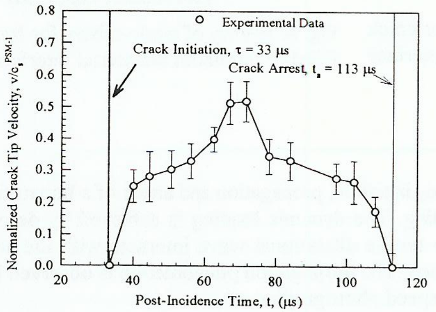


Fig. 5. History of crack-tip velocity for fracture along PSM-1/aluminum inclined (5°) interface.

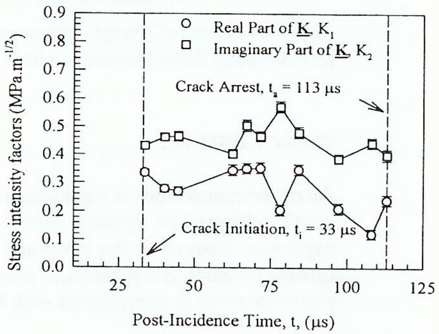


Fig. 6.. Variation of real and imaginary parts of the complex stress intensity factor for fracture along PSM-1/aluminum inclined (5^0) interface

decelerated. The values of the initiation and arrest toughness of the PSM-1/aluminum bimaterial interface can be obtained directly from this figure. The crack initiated at a value of $G_i = 55$ J/m^2, $\phi_i = 52°$ and the crack arrested at a value of $G_a = 37$ J/m^2, $\phi_a = 58°$. The mode-mixity evaluated at a representative length of 1 m for experiments involving dynamic fracture of 5° inclined and straight interfaces is plotted in Fig. 8. It can be seen from the figure that the mode-mixity of the loading can be changed by a simple modification of the specimen geometry.

The experiments discussed above represent the only study conducted so far that investigates dynamic initiation, propagation and arrest of cracks along a bimaterial interface at different mode-mixities subjected to tensile stress wave loading. The study is currently under investigation and the results will be discussed in detail at the conference.

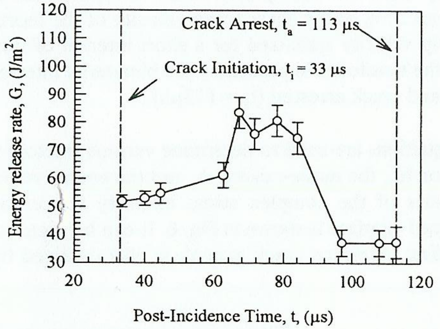


Fig. 7 Variation of energy release rate for crack growth along PSM-1/aluminum inclined interface

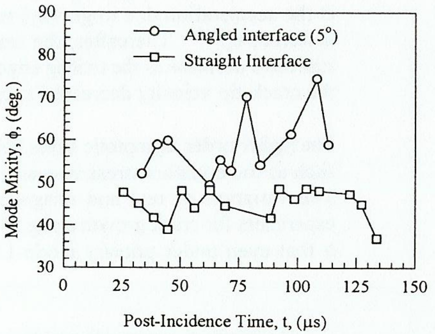


Fig. 8. History of mode-mixity for fracture along PSM-1/aluminum bimaterial interface.

CONCLUSIONS

An experimental study is conducted to study initiation, propagation and arrest of a bimaterial interface crack subjected to dynamic tensile loading. The dynamic loading is achieved by detonating two explosive charges in the specimen. The tensile dilatational wave interacts with the starter crack causing initiation and subsequent propagation. The propagation phenomenon is observed by dynamic photoelasticity in conjunction with high speed photography.

- The crack initiated at a finite time after the wave impinged on the interface. The crack-tip accelerated rapidly with an acceleration of about 2 x 10^6 g (g being the acceleration due to gravity) to a velocity of about 55% of the shear wave velocity of the more compliant material. Thereafter, the velocity started to decrease as the trailing edge of the tensile stress wave cleared the interface. Finally, the crack-tip velocity decreased to zero and crack arrested.
- The real and imaginary parts of the complex stress intensity factor are observed to be non-zero and comparable in value despite the mode-1 loading. The energy release rate increased till initiation and remained constant before it started to decrease as the crack decelerated. The

5° inclined interface crack initiated at a value of $G_i = 55$ J/m^2, $\phi_i = 52°$ and arrested at a value of $G_a = 37$ J/m^2, $\phi_a = 58°$.

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