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Dynamics of crack penetration vs. branching at a weak interface: An experimental study

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ABSTRACT

In this paper, the dynamic crack-interface interactions and the related mechanics of crack penetration vs. branching at a weak interface are studied experimentally. The interface is oriented perpendicular to the incoming mode-I crack in an otherwise homogeneous bilayer. The focus of this investigation is on the effect of interface location and the associated crack-tip parameters within the bilayer on the mechanics of the ensuing fracture behavior based on the optical methodologies laid down in Ref. Sundaram and Tippur (2016). Time-resolved optical measurement of crack-tip deformations, velocity and stress intensity factor histories in different bilayer configurations is performed using Digital Gradient Sensing (DGS) technique in conjunction with high-speed photography. The results show that the crack path selection at the interface and subsequently the second layer are greatly affected by the location of the interface within the geometry. Using optically measured fracture parameters, the mechanics of crack penetration and branching are explained. Counter to the intuition, a dynamically growing mode-I approaching a weak interface at a lower velocity and stress intensity factor penetrates the interface whereas a higher velocity and stress intensity factor counterpart gets trapped by the interface producing branched daughter cracks until they kink out into the next layer. An interesting empirical observation based on measured crack-tip parameters for crack penetration and branching is also made.

1. Introduction

The competition between crack penetration, deflection, and branching behaviors at interfaces govern the fracture mechanics of brittle layered solids and structures. Early work by Cook and Gordon (1964) has suggested the possibility of strength and toughness enhancement of such systems by optimizing the ratio between the adhesive strength of the interface and the cohesive strength of the brittle phase. Several works reported since, most performed under quasi-static conditions (He and Hutchinson, 1989; Gupta et al., 1992; Leguillion et al., 2000; Paramgiani and Thouless, 2006; Xia et al., 2012), have studied various aspects of this problem. The dynamic counterparts of these introduce a host of additional parameters such as crack velocity, inertia, stress-wave interactions, making the problem more challenging.

Most reports on this topic that deal with dynamic interfacial crack growth *along an interface* (Tippur and Rosakis, 1991; Washabagh and Knauss, 1994) have brought to light several previously unknown aspects of fracture mechanics including unusually high crack speeds and the possibility of crack propagation at intersonic speeds (Lambros and Rosakis, 1995;

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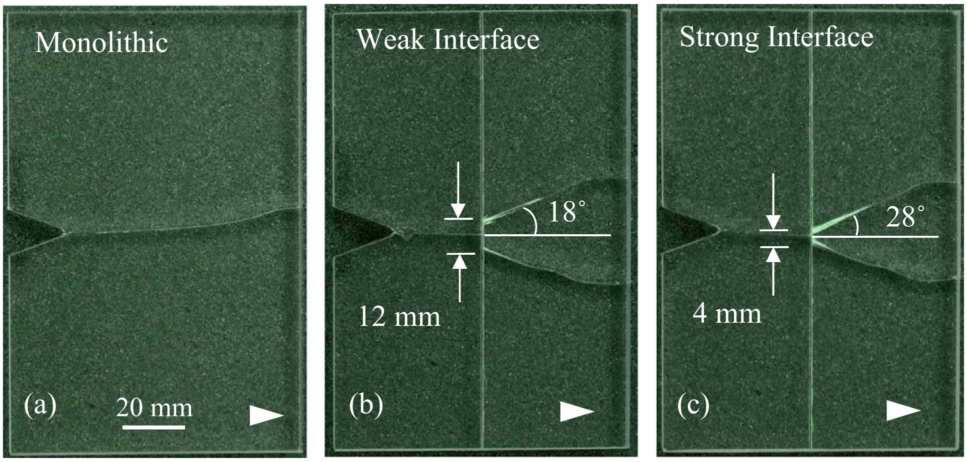

Fig. 1. Photographs of fractured specimens from the previous study showing crack path selection in (a) Monolithic (b) 'Weak' 90° layered configuration (c) 'Strong' 90° layered configuration. Arrowhead indicates crack growth direction (Sundaram and Tippur, 2016).

Rosakis et al., 1998; Coker and Rosakis, 2001). Further, to fully comprehend the dynamic fracture of layered materials, crack growth across interfaces needs to be understood as well. The existing studies on this subject generally deal with interfaces *inclined* to the crack propagation direction where deflection/penetration mechanics of a single crack tip are analyzed. Rosakis and his co-workers (Xu et al., 2003; Chalivendra and Rosakis, 2008) are among the few who have studied in detail interactions between a dynamically growing crack and an inclined interface experimentally. They have used optical methods to visualize crack-tip fields and location during highly transient fracture events. Understanding the mechanics of a dynamically growing crack becoming an interfacial crack when it encounters an interface is addressed in their works. They have observed significant jumps in crack velocity as well as crack deflection at an interface. Xu and Wang (Xu and Wang, 2006) have recently revisited those measurements and suggest that the *T*-stress could also play a significant role in the interfacial debond initiation besides stress intensity factors. Park and Chen (Park and Chen, 2011) have visualized fast-fracture in layered glass using high-speed photography. Specifically, they have examined crack branching and arrest behaviors at an interface as a function of interfacial characteristics such as thickness, strength, and surface finish.

A few numerical investigations using finite element analyses, either in conjunction with stiffness degradation techniques (Timmel et al., 2007) or using cohesive elements (Siegmund et al., 1997), and peridynamic simulations (Hu et al., 2013) have also been reported on crack growth across interfaces. The stiffness degradation or element erosion techniques usually suffer from mesh refinement issues. The analysis based on cohesive elements, on the other hand, are more common; for example, in Siegmund et al. (1997) the role of interface strength on crack penetration vs. deflection at an interface situated perpendicular to the crack growth direction using cohesive elements is examined. Higher strength of the interface is shown to promote crack penetration whereas the weaker one causes the crack to deflect at the interface. In a more recent study, Liu et al. (2011) have studied strain rate effects on growth dynamics of a crack-tip lodged into an interface perpendicular to the crack. The possibilities of crack growth through the interface as well as its bifurcation along the interface before entering the next layer are examined in their work.

In this context, *the research reported here exploits the experimental methodology demonstrated by the authors' in a previous report on dynamic crack growth in PMMA bilayers* (Sundaram and Tippur, 2016). Previously, the feasibility of a relatively new optical technique called Digital Gradient Sensing (DGS) technique for mapping crack-tip deformations when a mode-I crack branches at an interface oriented perpendicular to a growing crack was demonstrated. Unlike its monolithic counterpart where a single crack traversed the entire uncracked ligament *without branching*, in bilayers the dynamically growing mode-I *mother* crack in the first layer transitioned to an interfacial crack at the weak plane before penetrating the next layer as two globally symmetric but locally mixed-mode *daughter* cracks, as shown in Fig. 1. An increased fracture surface area and crack velocity perturbations[2] were caused by the interface situated in the crack path. The effect of two different interface fracture toughness, both weak relative to the parent material (approx. 75% and 50% of the crack initiation toughness of PMMA and identified as 'strong' and 'weak', respectively), were examined. A methodology for evaluating stress intensity factors of mixed-mode cracks using the DGS technique under dynamic conditions was also developed. Thus measured crack driving forces at the branched crack-tips were lower than the monolithic counterpart. Further, the weaker of the two interfaces was found to be a more favorable configuration in terms of energy absorption and crack arrest.

Building upon Sundaram and Tippur (2016), the *focus of this work* is to examine the conditions under which a dynamically propagating mode-I crack in the first layer of the bilayer would penetrate the interface with and without crack branching. The measurement of full-field crack-tip deformations, crack velocities and stress intensity factors (a) when a mode-I crack approaches the interface, and (b) when the crack departs from the interface into the second layer either as a single mode-I crack or multiple

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[2] Crack branching in monolithic materials is known to occur with very little change in crack velocity (Freund, 1998).