International Journal of Solids and Structures 83 (2016) 45–64

Contents lists available at ScienceDirect

International Journal of Solids and Structures

journal homepage: www.elsevier.com/locate/ijsolstr

Mode I fracture along adhesively bonded sinusoidal interfaces

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ARTICLE INFO

Article history:
Received 22 September 2015
Revised 20 December 2015
Available online 7 January 2016

Keywords:
Sinusoidal interfaces
Double cantilever beam
Adhesive joint
Cohesive zone model
Crack propagation
Toughening

ABSTRACT

Fracture along sinusoidally-patterned and flat interfaces in AA7075-T6 double cantilever beam (DCB) adhesive joints was investigated with an experimental/theoretical approach. Sinusoidal profiles of $A/\lambda = 1/4$, 1/3 and 1/2 (A = amplitude, λ = wavelength) were prepared with wire EDM followed by application of a 0.3 mm adhesive layer. Crack propagation from remote mode I loading occurred as the DCBs were separated under displacement control. All tests exhibited crack propagation within the adhesive. Experimental analysis, analytical and finite element models of crack propagation along a cohesive patterned interface provided fundamental insights into the differences between the sinusoidally-patterned and flat DCBs observed in the experiments. For the sinusoidal DCBs, crack propagation is delayed relative to the flat DCBs and the peak load increases with A/λ. The sinusoidal DCBs induce intermittent crack extension that resembles "stick–slip" conditions with slow (stable) crack propagation and fast (unstable) crack propagation. The intermittent crack propagation is facilitated by the release of strain energy though the viscous response of the adhesive in a non-equilibrium "snapback" mechanism which enhances energy dissipation through the crack propagation process. Such release is also associated with a drop in the applied load leading to a serrated load–displacement behavior. The size of the fracture process zone also plays an important when it is comparable with the sinusoidal characteristic length scale. These results demonstrate that patterned adhesive joints can be substantially tougher than joints with no pattern.

1. Introduction

Structural failures via crack nucleation and growth often occur at load-bearing interfaces that have been joined by various means. Experimental studies with non-patterned (Liechti and Chai, 1992; Anderson et al., 1974; Mulville and Vaishnav, 1975; Dauskardt et al., 1998; Charalambides et al., 1989; Charalambides et al., 1990) and patterned interfaces (Ritchie et al., 1988; Reedy, 2008; Kim et al., 2010; Suzuki et al., 2013) have found that interface morphology can effectively increase interfacial fracture resistance thereby maintaining the desired load transfer in a structure. This has significant implications for many technological applications and the ability to join a broader range of materials associated with these applications (Hector et al., 2011; Antico et al., 2012; Marya et al., 2006; John Hart-Smith et al., 2011; Bonanni et al., 2001; Takeichi et al., 1992). Decohesion at joints subjected to protracted load transfer must be delayed or even prevented altogether to avoid catastrophic failure (Atallah, 2000; Hendricks et al., 1991). The geometry of a patterned interface has a high spatial correlation and it is quantified by a minimal set of parameters (e.g. wavelength and crest-to-trough height, aspect ratio). A stochastic description is not required in most cases, as would be the case for an interface that is not intentionally patterned (e.g. the ground finish on an aluminum beverage container which is typically characterized by a Gaussian distribution of roughness heights) (Hector et al., 1996). Representative patterned interfaces from various engineering applications can be found in Hector et al. (2011), Howarth and Hector (2001), Sheu et al. (1998) and Hector and Sheu (1993). Previous studies of crack propagation under impact (Chen, 2008) and mixed mode conditions in single and bimaterial interfaces (Liechti and Chai, 1992; Ritchie et al., 1988; Kim et al., 2010; Swadener and Liechti, 1998; Howe, 1993a, 1993b; Xu et al., 2011) have also shown that increasing surface area, by adding roughness or patterning the interface, results in an improvement in the interfacial toughness with respect to the flat interface. Examples of man-made and naturally-occurring structures with patterned interfaces at specific length scales have also shown surprisingly high interfacial strength and toughness (Barthelat et al., 2007; Espinosa et al., 2009; Ben-artzy et al., 2010; Song et al., 2011). However, only a few computational models have been developed to investigate the mechanics of interfacial fracture along patterned interfaces (Reedy, 2008; Evans and Hutchinson, 1989; Yao and Qu, 2002; Noijen et al., 2012). For example, analytical models such as the kinked crack model by Cotterell and Rice (1980) were successfully employed

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http://dx.doi.org/10.1016/j.ijsolstr.2015.12.028
0020-7683/

to describe material toughening in patterned sinusoidal interfaces (for low asperity aspect ratios) (Zavattieri et al., 2007; Xiaoping and Comninou, 1989). However, more realistic computational models based upon finite element methods were necessary to study interfaces patterns with large aspect ratios (Zavattieri et al., 2007, 2008; Cordisco et al., 2012, 2014) and geometrically complex patterns, as most analytical solutions are unable to capture the correct mechanical behavior of such interfaces (Barthelat et al., 2007; Zavattieri et al., 2007, 2008; Cordisco et al., 2012, 2014; Li et al., 2011; Li, 2012). A combined experimental/computational approach that investigates the relationships between patterned interface length scales, geometric features of the interface, and interface toughening is currently unavailable in the extant literature.

The present study aims to address this need by investigating crack growth along a sinusoidal adhesive interface. We employ a bonded, double cantilever beam (DCB) geometry designed to enable remote mode I loading conditions during crack growth along a sinusoidal interface between the beams. An adhesive layer was applied along the sinusoidal interfaces between the beams in each DCB. The adhesive layer was sufficiently thin so as to supply a resisting force during mechanical testing in which the separation force and crack tip position were measured as the DCB was gradually pulled apart at one end at a displacement rate of 0.1 mm/min. The experimental results with a flat interface were then used to characterize the cohesive traction-separation laws using a finite element model of the DCB experiments. This enabled a computational investigation of the effect of key parameters, such as sinusoidal aspect ratio and material properties, on the crack propagation behavior. Based upon insights from the finite element model results, we propose a simple analytical model that allows us to further understand the toughening mechanism as a function of the main interface characteristics. We expect these results to provide guidelines for the design of fracture resistant patterned interfaces.

2. Experiments

A schematic of the bonded double cantilever beam (DCB) specimens employed in this study is shown in Fig. 1a for a flat interface and Fig. 1b for a sinusoidal interface. Both specimen types have the same overall dimensions (width, B, total length, L, and adhesive thickness, ϕ), and the same initial crack tip position, which is located at a distance, a_0, from the left side of the beams where the load is applied. For the flat DCB, the total thickness is $H = 2h + \phi$, where h is the beam thickness and ϕ is the thickness of the adhesive layer. An opening displacement, $\pm\Delta$, is applied to the left end of each beam to induce remote mode I conditions at the crack tip. The right side of the DCB is free. Details of the sinusoidal interface are shown in Fig. 1c. For both flat and sinusoidally-patterned DCBs, the crack extension can be calculated as the actual distance traveled by the crack front, a_s, from its initial position. Using a Cartesian system with its origin $O(0,0)$ located at the initial crack tip, the sinusoidal interfaces can be described as $y(x) = A\{1 + \sin[2\pi(x - \lambda/4)/\lambda]\}$, where A represents the sinusoidal amplitude, λ is the wavelength, and A/λ is the interface aspect ratio. Assuming that the crack front remains straight and perpendicular to the crack propagation direction, the coordinates of the crack tip can be described as the projection of a_s along the x and y axes, a_x and a_y, respectively. Likewise, a_s can be described as a function of these coordinates, i.e., $a_s = a_s(a_x, a_y)$.

The DCBs were obtained from individual 160 mm $\times$ 25 mm $\times$ 6 mm AA7075-T6 aluminum alloy blocks each of which was cut through the middle of its thickness following either a flat or a sinusoidal path using hot wire electrical discharge machining (WEDM) with a 0.3 mm-diameter copper wire (Hector and Sheu, 1993). Four different aspect ratios, viz. $A/\lambda = 1/2$, 1/3, 1/4 and 0 (or *flat*) were prepared for the experiments. While the sinusoidal interfaces were fabricated with a fixed amplitude $A = 1.00 \pm 0.05$ mm, they were cut with varying wavelength, λ, to achieve the desired A/λ values.

We also note that the WEDM process produces a higher frequency microroughness. Measurements done with non-contact 3D optical metrology (using a Bruker Contour K1 System) revealed an arithmetic mean roughness of $R_a \approx 12$ μm across all the specimens. A representative surface asperity for the $A/\lambda = 1/2$ specimen is shown in Fig. 2a. Red contours denote the crest of the asperities while blue contours denote regions in the vicinity of a trough. Note that this surface microroughness results from the successive formation and disruption of micron-sized crater features in the AA7075-T6 surface from the electrical current and subsequent thermocapillary convection and spark overlap as the specimen was articulated through the spark during WEDM.

Previous studies showed that roughness improves the adhesion of interfaces between materials with very low surface energy (Hector et al., 2011; Antico et al., 2012). While improving the chemical bonding certainly increases the intrinsic adhesive strength of interfaces, high frequency roughness provides sites for mechanical interlocking of the adhesive upon curing, contributing to an additional increase in strength (Adams et al., 2001; Alfano et al., 2011, 2012, 2014). Moreover, a recent study has shown that wettability of epoxy on aluminum is significantly improved with roughness of the order of 10–14 μm (similar to those produced by our WEDM process). By using the same cutting technique for all specimens, we can ensure the same micro-roughness and hence, the same aluminum/adhesive strength and toughness. Moreover, considering that the characteristic length scale of the micro-roughness is much smaller than the other geometrical characteristic length scales (i.e., A, λ, H and ϕ), we expect that the overall effect of the micro-roughness is to enhance cohesive failure instead of interfacial failure.[1]

Once cut, the beams were first cleaned with *acetone* to remove any debris and contaminants, and subsequently with *isopropyl alcohol* to remove the *acetone* and any remaining water on the surfaces. After drying, the beams were bonded with a layer of a commercial, rubber-toughened, one part epoxy-based adhesive (*Dow Betamate 1486*), pre-heated to 40 °C and applied to the two individual beam inner surfaces with a pneumatic caulk gun. Young's modulus and ultimate tensile strength from quasi-static (0.0006–0.01/s reported in Sun et al., 2008a) tensile tests are 0.9 ± 0.2 GPa. 29.9 ± 2.5 MPa, respectively. Sun et al. (2009a, 2009b, 2008a, 2008b) reported a mode I toughness and cohesive strength of 4.2 ± 0.3 kJ/m^2, and 24 ± 3 MPa, respectively, for a adhesively bonded dual-phase steel DCB with a flat interface and adhesive thickness of 0.8 ± 0.2 mm. While we will use information from these previous experiments to make decisions about the general cohesive behavior of the adhesive, we note that the flat DCB experiments performed by Sun et al. on steel are different in the sense that their beams deformed plastically and the adhesive layer was considerably thicker than that used in our test specimens. As such, we will employ the information from our flat DCB to characterize the fracture properties of the DCBs discussed in this study.

To maintain an adhesive film thickness of $\phi = 0.3$ mm, we placed several 0.3 mm-diameter wires on one of the beam surfaces to maintain the distance while both beams were mated. The adhesive layer thickness was determined to fill the gap left by the inevitable material removal caused by the WEDM process. During adhesive curing, the beams were held under low pressure in a convection oven for 50 min at 180 °C. *Teflon* tape was used to avoid adhesion along the initial crack length, a_0, where

[1] Cohesive failure means that the crack will propagate through the adhesive rather than along the metal/adhesive interface.