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Effects of bondline discontinuity during growth of interface cracks including stability and kinetic considerations

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ABSTRACT

The effects of a single discontinuity/void on the mode I interface crack growth under a constant loading rate are investigated experimentally and analytically. To account for a co-existence of the void and the crack tip process zone, a new unit pattern model is derived. The crack growth path is composed from the three distinctive zones: (1) The initially bonded crack front vicinity region––carrying the majority of the loading––is of finite length and modelled as a series of elastic springs. (2) The discontinuity region is modelled as a simple beam not carrying any surface tractions. (3) The far field is of infinite length and represented with elastic springs. In this model, the constant loading rate boundary conditions are fully considered. Subsequently, the kinetic effects associated with the specimen geometry and the presence of the discontinuity are attempted using the generalized Griffith's theory. A very good agreement between the experimental and the analytical results is observed for both the load response and the *R* curves for all void-to-process zone length ratios. A new light and a more profound appraisal of the equilibrium paths are gained.

1. Introduction

For layered materials reliability under mechanical loading constitute an important technical problem. Controlling material properties and structural response through design of their interfaces could be an interesting approach to address the problem and an important step towards fracture metamaterials. For example, in bonded joints and laminated composites structural response could be tuned to a desired behaviour, properties or damage tolerance. This, however, demands introduction of heterogeneities along the crack growth path. Heterogeneities are an inevitable part of layered materials and could be associated with one of the following groups: (1) 'Extrinsic' - associated with the geometry of the joint and materials used, and leading to stress gradients and stress singularities due to the presence of edges and corners (Adams and Peppiatt, 1974; Bogy, 1968; Dundurs, 1969; Goland and Reissner, 1944; Hart-Smith, 1973; Jensen, 2003; Reedy, 1993, 1990; Volkersen, 1938; Weißgraeber et al., 2016; Williams, 1952). (2) 'Intrinsic' - associated with the microscopic features of the materials such as chemical and physical variations in composition of the bondline and the adherends (das Neves et al., 2009; Sancaktar and Kumar, 2000). (3) Interfacial–related to the quality of the surfaces of the materials to be joined, e.g. unwanted technological flaws, remaining by-products, oils, dust or water, but also release films and kissing bonds (Hong and Boerio, 2007; Lengline et al., 2011; Olia and Rossettos, 1996). However, the variation in the surface properties could be introduced 'on demand', e.g. to fine tune properties like the fracture energy (Alfano et al., 2014; Budzik et al., 2013; Cuminatto et al., 2015; Davami et al., 2016; Xia et al., 2012).

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The presence of flaws and heterogeneities, including their location and size, affects the observed strength of the joint and the crack path (Cao and Evans, 1989) with the onset and the evolution of crack propagation being of central importance for assessment of failure and crucial to address reliability issues. A methodology frequently adopted to consider heterogeneities is based on statistical analysis of their effects (Bazant and Pang, 2006; Bresson et al., 2013; Towse et al., 1999). To extract the effective properties of a material containing flaws, a representative volume element modelling or homogenization and rules-of-mixtures techniques are used (Budzik et al., 2013; Eshelby, 1957; Gao and Rice, 1989; Mori and Tanaka, 1973). On the crack front scale, analyses based on perturbation theory as proposed by Rice (Gao and Rice, 1989) are used to explore crack front trapping phenomena (Mower and Argon, 1995). In the direct approach, the local crack front morphology is assessed (Budzik and Jensen, 2014; Chopin et al., 2011; Patinet et al., 2011; Patinet et al., 2014). Provided that the crack front morphology is known, through an inversed method, estimation of the resultant fracture toughness is possible (Dalmas et al., 2009). Considering the problem as an out-of-the-plane i.e. the plane perpendicular to the crack growth plane (or simply, as seen from the side of the fracture specimen), crack growth paths are deduced (Akisanya and Fleck, 1992).

The effect of locally varying surface adhesion has been analysed experimentally, analytically and numerically (Cuminatto et al., 2015; Jumel, 2017; Razavi et al., 2017). Recently, two closed-form analytical solutions were proposed, both using unit pattern models (Cuminatto et al., 2015; Heide-Jørgensen and Budzik, 2017). The strain energy release rate (ERR, $\mathcal{G}$) was elucidated for a joint containing a single and multiple discontinuities. The local variation in the surface energy along the crack growth path must affect the kinetics of the crack growth process. Effects of the induced unstable or non-smooth crack growth processes were not addressed arising some concerns. From one side, the bondline materials are frequently polymer based. A rate-dependence analysis of such materials shows that the stress at failure $\sigma \propto \dot{\varepsilon}^{1/n}$, where $\dot{\varepsilon}$ is the deformation rate and n is the hardening exponent (Arruda et al., 1995). In Landis et al. (2000) a competition between the strain rate hardening and the rate strengthening within the fracture process zone, arising from the increased crack velocity, was identified. In Blackman et al. (2012) the authors confirmed, experimentally and numerically, the dependence between $\mathcal{G}$, σ and $\dot{\varepsilon}$. The effects of material rate dependence could be negligible under quasi-static conditions and are not expected unless $\dot{\varepsilon}$ varies across few orders of magnitude. More importantly for the present study, according to the generalized Griffith's theory (Davidson and Waas, 2012; Griffith, 1921), the crack growth and the observed material resistance are governed by the critical fracture stress ('static' component) and a ratio between the loading and crack growth rates ('kinetic' part). The ERR is an outcome of these and as such the non-constant (rising or falling) R curve behaviour could be explained without taking into account the rate dependence of the materials. An efficient interface design tool can clearly benefit from taking the crack front and the loading kinetics into consideration.

In the present work, the effects of a single discontinuity/void introduced along the crack growth path during the mode I fracture experiment are analysed analytically and experimentally. The size of the discontinuity is systematically varied across different void-to-(crack front) process zone size ratios. It is found that the presence of the discontinuity, including the size and the position within the process zone, is manifested by undulations in the load response and the resistance curves. The otherwise steady-state crack growth is altered. This work aims to identify the phenomena and the length scales involved. The paper is structured as follows. At first, the experimental details including materials and methods are provided followed by a steady-state analysis of the fracture experiment. To gain a phenomenological and a quantitative insight, a new unit pattern model is proposed for analysis. Contrary to the previous work of the authors (Heide-Jørgensen and Budzik, 2017), using a reconstituted unit pattern model, the effect of the finite length of the bonded/contact zones and behaviour of the crack front in the vicinity of the void are studied in details. This enables a correct representation of the effects introduced by the constant displacement rate and the constant displacement boundary conditions including the snap-down behaviour in the load response curve. Fracture results are summarized and discussed within the framework of static analysis. For full comprehension, the double cantilever beam (DCB) test is further revised using the generalized Griffith's fracture theory to capture the effects of the loading and the crack growth rates. The accent is on the effects of a single void on the loading curve and the R curve for which a detailed theoretical discussion is proposed. Finally, remarks and conclusions are listed.

2. Materials and methods

The major part of the experimental work is performed under fracture mode I loading conditions. Displacement controlled experiments are conducted on adhesively bonded DCB specimens, half of the specimen being schematically shown in Fig. 1, to investigate the load response and the phenomena associated with interactions between the crack front and the vicinity of discontinuity.

2.1. Materials and preparation of specimens

Two transparent brittle PMMA (polymethyl methacrylate, supplied by Bayer®, Germany) adherends of width, $b \cong 25$ mm, thickness, $h \cong 8$ mm and Young's modulus, E, of 3.2 ± 0.3 GPa (estimated from a series of three point bending experiments) were bonded using a commercial acrylic adhesive (Bostik, Germany). The bondline material (Young's modulus E_a of ca. 0.5 MPa) was checked, by hysteresis loop testing, and found not to expose any significant irreversibility until failure under a tensile loading while maintaining a linear loading path.

Prior to bonding the PMMA adherends were sandblasted (aluminium oxide with average 100 μm diameter), cleaned in an ultrasonic bath (water-isopropyl solution, at 35 kHz for 5 min) and rinsed in ethanol to remove any residues. Ten of the