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Three-dimensional crack observation, quantification and simulation in a quasi-brittle material

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Abstract

To investigate the fracture behaviour of polygranular graphite (a quasi-brittle material), crack propagation in a short bar chevron notched specimen was studied by synchrotron X-ray computed tomography combined with digital volume correlation. Displacements were measured within the loaded test specimen, particularly the three-dimensional (3-D) profile of crack opening displacement. Analysis of the 3-D displacement field confirmed the existence of distributed damage in a fracture process zone, which significantly increased the effective crack length. Finite element simulations affirmed that the measured crack opening profiles could be reproduced using a cohesive zone model, but not with a linear elastic analysis. Comparing the simulation to the experimental results, it was deduced that the critical strain energy release rate varied across the crack front, i.e. the fracture toughness is constraint-dependent. This is proposed to be a general characteristic of quasi-brittle materials.

Keywords: Fracture; Quasi-brittle; X-ray tomography; Digital volume correlation; Cohesive zone model

1. Introduction

The structural integrity of quasi-brittle materials, such as graphite [1–3], ceramic composites [4] and bone and bone replacements [5], is commonly assessed with the conservative assumption of brittle fracture (e.g. [6,7]). Although the nonlinear behaviour of some quasi-brittle materials such as concrete has received much attention in the fracture community (e.g. [8–10]), the inelastic behaviour of many quasi-brittle materials is generally treated as negligible (e.g. for graphite see Refs. [6,11,12]); yet post-initiation tension-softening behaviour can play an important role in the integrity of components that are made of quasi-brittle materials. Understanding and quantifying this effect could improve confidence in the safety margins of their structural integrity assessment.

During the fracture of a partially cracked component that is fabricated from a quasi-brittle material, a fracture process zone develops due to distributed microcracking ahead of the crack tip [2,13]. The extent of the fracture process zone dictates the magnitude of the deviation of the component's deformation and fracture behaviour from that predicted by linear elastic analysis. An analogy may be established between the fracture process zone in quasi-brittle materials and the plastic zone in ductile materials [14]: a larger fracture process zone contributes more redundant inelastic energy to the measured critical energy release rate, resulting in higher fracture resistance. The fracture

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process zone can increase in size with crack propagation [15], leading to the classic *R*-curve behaviour [16]. In-plane constraint (geometric) and out-of-plane constraint (thickness) influence the fracture of elastic–plastic materials [17–19], and it is therefore likely that quasi-brittle materials are similarly affected [20].

In-plane constraint effects have been studied in polygranular graphites through the sensitivity of their *R*-curve to stress state [21] and geometry [22]. Although indications of out-of-plane constraint effects, such as crack tunnelling [23], have been also observed, it has not been investigated fully. An objective of the study reported in this paper is therefore to examine through-thickness variation of the crack propagation behaviour in graphite. Measurements of the three-dimensional (3-D) displacements in a cracked specimen can provide useful information on fracture behaviour, as demonstrated in recent combined X-ray computed tomography (XCT) and digital volume correlation (DVC) studies [21,24], in which full-field displacement measurements were used to map the 3-D crack opening profile. The measurements allow testing of the validity of crack opening profile simulations, obtained by the finite element method for different material models.

It has been well established that there is a fundamental difference between the crack opening profiles obtained by models that consider the strip yield model, and the predictions of linear elastic or elastic–plastic fracture mechanics [25,26] (schematic profiles are compared in Fig. 1a). A recent investigation in polygranular graphite [24] showed that the measured crack opening profile was close to that suggested by strip yield models. Crack propagation in

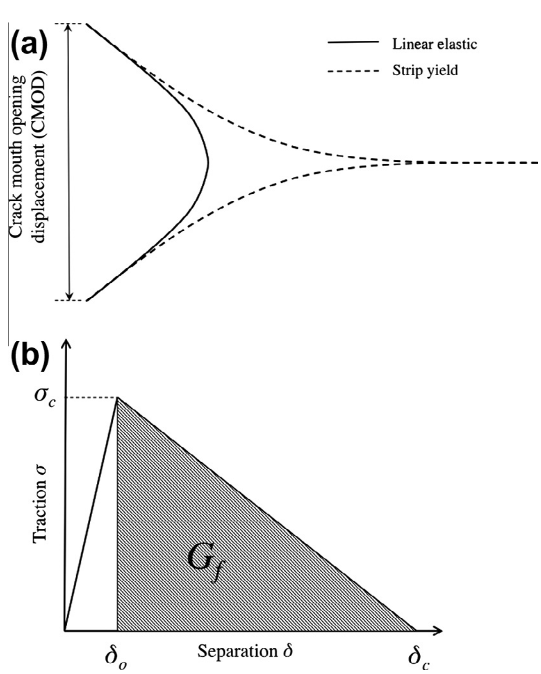

Fig. 1. Cohesive zone model: (a) crack opening profile; (b) traction-separation law.

materials that demonstrate strip yield model behaviour [27] may be simulated by cohesive zone modelling. Proposed by Hillerborg et al. [8] through a traction-separation law (Fig. 1b), cohesive zone models have been applied widely, simulating fracture in concrete (e.g. [9,28–31]), adhesively bonded joints [32,33], ceramic–metal composites [34] and elastic–plastic ductile metals [20,35]. The fracture process in quasi-brittle materials other than concrete, such as bone [36] and graphite [37], has also been simulated by cohesive zone models.

Gilsocarbon is a near-isotropic, heterogeneous artificial graphite used in the UK's advanced gas cooled (AGR) nuclear fission reactors as a moderator and reflector, which are load-bearing components [38] in the form of graphite blocks that are keyed in a structure that forms the reactor core. Dimensional change of the graphite, caused by fast neutron irradiation and thermal strains, develops multiaxial stresses within the structure; these have the potential to initiate fracture in the moderator blocks [39]. Improved understanding and knowledge of the criteria for crack initiation and propagation in graphite under different constraint conditions, both in-plane (i.e. geometry and stress states) and out-of-plane (i.e. through thickness) can support the integrity assessment of the graphite bricks. It has been shown for materials with elastic–plastic behaviour that taking constraint into account can reduce over-conservatism in fracture assessments, allowing the life of components to be safely extended [40]. It is therefore useful to develop an analogous treatment of quasi-brittle materials that can support the assessment of graphite components.

Small samples are extracted from the core of operating reactors to monitor changes in the properties of the graphite. Though not presently used to measure fracture properties, other than flexural strength, the size of such extracted samples may be suitable to fabricate test specimens to study fracture behaviour [41,42]. To investigate the potential of such tests, crack initiation and propagation were examined in this work using a chevron notch specimen fabricated from 'virgin' (un-irradiated) Gilsocarbon graphite. X-ray tomographic images were taken of the specimen in its undamaged condition at the Diamond Light Source synchrotron (beamline I12). A sharp wedge was driven progressively into the specimen's notch to initiate and propagate a crack; tomographic images were taken at each loading stage and subsequently analysed using commercially available digital volume correlation software [43] to obtain full-field 3-D displacements, thereby measuring the crack opening profile. Digital image correlation (DIC) analysis [44,45] has become a routine tool to study the deformation, fatigue and fracture behaviour of materials by analysis of two-dimensional (2-D) images (e.g. see Refs. [46–51]). DVC is based on a similar mathematical concept, extended to three dimensions [52–54].

The improved measurement precision in this work, relative to an earlier low-resolution laboratory tomography study [21,24] allows cohesive zone models and their input parameters to be tested by experimental data. A strip-yield