Engineering Fracture Mechanics 110 (2013) 410–420

Contents lists available at SciVerse ScienceDirect

Engineering Fracture Mechanics

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

# Observation and quantification of three-dimensional crack propagation in poly-granular graphite

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ARTICLE INFO

*Article history:*
Available online 12 January 2013

*Keywords:*
Nuclear graphite
Computed X-ray tomography
Digital volume correlation
Crack propagation
Fracture process zone

ABSTRACT

Observations of fracture are generally restricted to the surface of test specimens; yet the fracture process occurs within the material. X-ray computed tomography (XCT) provides valuable insights into the structures within materials: when XCT is combined with digital volume correlation (DVC) the response to applied loads can be measured with high precision in the form of the three-dimensional displacement field within the material. This paper reports a study of the fracture behaviour of a short-bar chevron notch crack propagation specimen fabricated from polygranular nuclear graphite – a quasi-brittle material. A three-dimensional linear elastic finite element simulation of the specimen obtained the relations between crack length, opening displacement and stress intensity factor along the crack front. Tomographic absorption contrast images were obtained from the specimen before and after crack propagation, whilst loaded. The DVC-measured displacement field was used to measure and map the crack opening displacements in 3D; the experimentally calculated crack opening displacements were consistent with the FE-predicted values. The measurements demonstrate the existence of a cohesive fracture process zone ahead of the crack tip, which is a characteristic of quasi-brittle materials. This suggests that simulation of the fracture of non-irradiated polygranular nuclear graphite requires a material model capable of showing softening behaviour.



## 1. Introduction

Quasi-brittle fracture is an emergent characteristic of inhomogeneous brittle materials. For example, a simple network of individually brittle elements of variable strength will exhibit the characteristic damage tolerant and graceful failure of a quasi-brittle material; as loading progresses, failures of individual elements occur and coalesce to form cracks, while elastic strains are redistributed in the remaining structure. The cracks in the network reduce its stiffness and thereby influence its elastic strain energy. The network's ultimate failure depends on the balance between the release of this stored elastic energy and the energy absorbed by fractures of individual elements. The gracefulness of this failure is affected by the distributions of strength, stiffness and the connectivity of the brittle elements. These are properties of a quasi-brittle material's microstructure, and they have a direct effect on the strength and damage tolerance of structures, so studying the interactions between microstructure, damage and mechanical behaviour in such materials contributes to the improvement of their structural integrity assessment. Many materials show degrees of quasi-brittle behaviour: concrete [1], polygranular graphite [2], rocks

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http://dx.doi.org/10.1016/j.engfracmech.2012.11.023

**Nomenclature**

| | |
|---|---|
| $a$ | crack length |
| $l$ | length of crack front |
| $r$ | radial distance from the crack tip |
| $x$, $y$, $z$ | conventional Cartesian coordinates with origin at the crack tip: $x$ is along the crack propagation direction, $y$ is the out of plane direction and $z$ is along the crack opening direction |
| $\bar{y}$ | normalised crack front length |
| $A$ | area of uncracked ligament |
| CMOD | crack mouth opening displacement |
| COD | crack opening displacement |
| $F$ | applied force on |
| $K_N$ | normalised stress intensity factor |
| $K_{max}$ | maximum stress intensity factor along the crack front |
| $K_{min}$ | minimum stress intensity factor along the crack front |
| $T$ | non-singular term of stress |
| $W$ | ligament length (distance between the tip of the notch to the end of specimen) |
| $\beta$ | biaxiality ratio (normalised $T$-stress) |
| $\sigma$ | nominal stress applied on the specimen |

[3], bone [4] and porous ceramics [5] to name a few. Graphite is an important component in several current and future designs of nuclear fission reactors, and the structural integrity of the graphite moderator is critical to the safe operation of the UK's Advanced Gas Reactors (AGRs); radiolytic oxidation degrades nuclear graphite strength while amongst other effects the fast neutron irradiation causes dimensional changes. Ultimately their combined effect may develop tensile stresses sufficient to cause damage to the reactor core. It is important that structural integrity methods are developed that can take appropriate account of the damage mechanisms in the graphite.

Graphite is generally treated as a linear elastic material and its structural integrity is conservatively assessed using linear elastic fracture mechanics [6–9]. However, non-irradiated graphite may be regarded as a quasi-brittle material; there is clear evidence of the non-linear mechanical behaviour [10], a rising fracture resistance curve ($J$–$R$ curve) [2,11] and also the development of a micro-cracked fracture process zone [12]. The effects of mechanical constraint on the fracture process zone may explain observed behaviours such as crack tunnelling [13] and also the effects of load biaxiality [14] and size [15] of both components and cracks [12] on structural integrity. An improved understanding of its fracture may give improved confidence in safety margins, and will aid the design of small-scale fracture specimens for measurement of the properties of irradiated graphites; irradiation tends to remove the non-linearity of mechanical behaviour [16], and inspection samples are necessarily limited in size.

The two-dimensional digital image correlation (DIC) technique has been used for quantitative in situ studies of damage nucleation and propagation in a range of materials [14,17,18]. Hild and Roux, for example, introduced a direct DIC method to calculate the stress intensity factors associated with a crack from the measured displacement field [19–21]. The measured displacement field can readily be converted into a strain field and, if the material constitutive law is known, the stress field and its associated energy may also be derived as a $J$-integral [22]. DIC is confined to studies of damage nucleation and propagation on the surface of specimens: yet damage propagates within the specimen. Measurements of the full three-dimensional displacement field within the material by the three-dimensional digital volume correlation (DVC) technique [23–25] can provide further useful insights and quantitative measurements of the processes of damage development [26–28].

In this paper, we demonstrate the suitability of combined X-ray computed tomography and digital volume correlation (DVC) to study three-dimensional crack initiation and propagation behaviour. As the main goal is to understand and characterize a 3D crack, the DVC and XCT techniques are explained briefly only; although each is a significant topic. A short bar chevron notched specimen, fabricated from non-irradiated virgin nuclear graphite, was used to propagate a stable crack. The variation of critical stress intensity factor for stable crack propagation along the crack front was obtained via a three-dimensional finite element simulation. The specimen underwent two cycles of loading and unloading, observed with XCT, to explore the effects of irrecoverable deformation. The displacements associated with the crack, in response to load, were measured by analysing the tomographic images with digital image volume correlation.

## 2. Methodology

### 2.1. Experiment

The short-bar chevron notched specimen (Fig. 1) is a specimen geometry utilised in several fracture mechanics standards [29,30]. This study followed the recommendations of the International Society of Rock Mechanics [30] as the material of