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Investigation of fracture toughness for a polycrystalline graphite under combined tensile-tear deformation

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ABSTRACT

In the present contribution, mixed mode I/III fracture toughness of a polycrystalline graphite is studied experimentally, numerically and theoretically using a new designed test specimen. A simple disc shape specimen subjected to three-point bending named herein edge notched disc bend (ENDB), is successfully employed for fracture toughness experiments on graphite. This specimen can introduce full combination of modes I and III including pure mode I, pure mode III and complete intermediate mode mixities. Fracture toughness values (K_{Ic} and K_{IIIc}) of investigated graphite are obtained for six different mode mixities for and the obtained experimental data are compared with theoretical predictions of two conventional mixed mode I/III fracture theories namely: maximum tangential stress (MTS) and maximum tangential strain energy density (MTSED). It has been observed that the fracture toughness results are in good agreement with the mixed mode I/III curve of MTSED criterion. Consequently, the suggested ENDB specimen can be proposed as a suitable specimen for mixed mode I/III fracture toughness study of based on graphite materials.

1. Introduction

Graphite is known as an engineering material not only for its thermal shock resistance, electrical conductivity and good mechanical properties but also for its excellent isotropic homogeneous structure. Therefore, it is widely used in various laboratory studies as brittle model material and also in industrial applications such as carbon brushes, graphite electrodes, molds in continuous casting systems for making steel and glass, lubricant, heating elements, flame retardants, heat shields, conductive suspensions, resistance films, battery systems, coatings, catalysts, crucibles and refractory graphite parts. As an important application, graphite is utilized in high temperature gas-cooled or nuclear fusion reactors as fuel block, moderator, reflector and support or first wall material. Graphite is also used in manufacturing of polymer-graphite composites in many engineering components and applications. For example, the outer parts of space shuttle fuselage or its wings are currently manufactured by polymer-graphite composites or honeycomb sandwich plates containing graphite. New and modern sport devices such as javelin, baseball bat, pole vault, professional bicycle and frame of tennis or badminton racquets are made by polymer-graphite composites to increase the strength-to-weight ratio in such devices. However, in spite of the numerous advantages, reliability of graphite material can be comparatively low due to its brittle behavior particularly in the presence of stress concentrators like cracks, notches and geometrical discontinuities. Indeed, graphite components are vulnerable to brittle fracture and crack growth due to the application of external forces or the influence of thermal shocks or internal mechanical stresses induced by dimensional and material property changes or neutron irradiation. In some applications such as nuclear electrodes or moderators, graphite components are not designed for load bearing purposes; but they are sometimes subjected to mechanical loads transferred from the adjacent components. In some other applications, materials made or reinforced with graphite, should withstand against direct applied loads. Therefore, in order to investigate the integrity of such components it is important to study the mechanical failure behavior of cracked or flawed graphite material.

Tensile type fracture or mode I cracking is the common mode of failure in cracked graphite components and a large number of research works have been done in the past for understanding the mode I fracture behavior in materials. Accordingly, extensive data are available in the literature for mode I fracture toughness (K_{Ic}) of different grades of graphite as a characteristic resistance value against tensile or opening mode fracture [1–10]. Different test

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Nomenclature

Abbreviations

ENDB	Edge Notched Disc Bend
MTS	maximum tangential stress
MTSED	maximum tangential strain energy density

List of symbols

a/t	crack depth to thickness ratio
E	elastic modulus
K_I	mode I stress intensity factor
K_{II}	mode II stress intensity factor
K_{III}	mode III stress intensity factor
K_{Ic}	mode I fracture toughness
K_{IIIc}	mode III fracture toughness
$K_{eff(I/III)}$	effective mixed mode I/III stress intensity factor
$K_{eq\text{-}initiation}$	equivalent stress intensity factor at the onset of fracture
$K_{eq\text{-}branched}$	equivalent stress intensity factor for branched crack
M_{13}^{e}	mixity parameter
P	applied load
P_c	critical fracture load
r,θ	crack tip co-ordinate
D	disc diameter
$2S$	distance between the bottom supports in the ENDB specimen
$2S/D$	loading span to radius ratio
t	disc thickness
f_I	mode I geometry factor
f_{III}	mode III geometry factor
Y	parameter showing the location of crack front relative to the mid-section
A_f	section modulus
M_f	bending moment
W	tangential strain energy density

Greek Letters

β	crack inclination angle
$\varepsilon_{\theta\theta}$	strain component in polar system
$\sigma_{\theta\theta}$	stress component in polar system
σ_{nom}	nominal or reference stress
φ	out of plane fracture angle
ν	Poisson's ratio

methods and specimens including rectangular [2,3] or circular shape [1,11,12] samples subjected to tensile or compressive loads have been employed up to now for determining K_{Ic} in graphite materials. Some researchers have also investigated the influence of affecting parameters such as neutron irradiation, microstructure, thermal shock and texture of graphite on R-curve behavior or mode I fracture growth in wide ranges of graphite grades from fine to coarse grained structures [13–15]. In addition to tensile loads, shear loads or sliding deformations can also contribute significantly in the process of graphite cracking; since real graphite components may experience various combinations of tensile and shear deformations. Accordingly, several experimental and theoretical research studies have been performed in the past to figure out mixed mode opening-in plane sliding (i.e. mixed mode I/II) fracture behavior of different of graphite grads. Center cracked Brazilian disc specimen [1,11], semi-circular bend specimen [12], edge cracked four-point bend beam specimen [2,3] and double edge notched compression plate [16] are among the frequently used test configurations for obtaining mixed mode I/II and mode II fracture toughness (K_{Ic} and K_{IIc}) of different grades of graphite such as 7477, SM 1-24, IG-11, IG-110, PCEA and NBG-18. There are also some theoretical investigations for predicting the onset of mixed mode I/II fracture [17–20] or studying the micro and macro mechanisms of crack growth under mixed mode I/II loading [21,13,15] for graphite materials. These criteria are usually derived based on the stress, strain or energy field equations near the crack tip.

Mode III or tearing mode is also another important failure mode of engineering materials such as pure graphite or graphite fiber composites. For example, as mentioned earlier many of modern sport devices such as the frame of tennis or badminton racquets, baseball bat or pole vault are currently manufactured by the graphite-polymer composites which have higher strength and lesser weight in comparison with the older metallic frames. These devices are often subjected to bending and torsion loads simultaneously and hence micro cracks initiated inside them (for example in graphite fibers) would experience mixed mode I/III deformations. Thus, the investigation of mixed mode I/III fracture process is crucial for life extension or estimating the catastrophic failure loads in such components. However, in spite of several mode I, mode II and mixed mode I/II fracture toughness studies available for graphite materials, there are very limited papers for mode III or mixed mode I/III fracture behavior of cracked or notched graphite. In one of the very few related articles published in this subject, Berto et al. [22] studied the fracture of isostatic graphite bars containing V, U and semi-circular notches under pure torsion loads. They determined mode III notch stress intensity factor (NSIF) and critical strain energy density of graphite for different notch root radii. Similarly in other paper, Berto and coworkers [23] tested some V-shaped circumferentially notched bars made of isostatic polycrystalline graphite (with commercial name of EG022A) under combined tension-torsion loads. They investigated the effects of notch opening angle (ranging from 30° to 120°), notch root radius (ranging from 0.3 mm to 2 mm), notch depth and different combinations of tensile/torsion loads on mixed mode I/III notch fracture behavior of EG022A graphite. In another research work, Li et al. [2] obtained mode III fracture toughness (K_{IIIc}) of a graphite/epoxy composite using the edge crack torsion mode III test setup. Torsional buckling and damage tolerance of an un-cracked graphite/epoxy shaft was analyzed by Bauchau et al. [24]. Even these very limited available and related contributions obviously indicate that mixed mode I/III fracture behavior of cracked graphite components have not been understood and investigated well till now and therefore, the main aim of this research is to figure out the fracture toughness of graphite under combined tensile-tear deformation. However, the major problem raised in this regard is the lack of a suitable test configuration for producing different mode I and mode III mixities in graphite. Available mixed mode I/III fracture test specimens such as inclined edge cracked three-point bend beam specimen [25], inclined edge cracked compact-tension specimen [26,27], rod shape specimen containing a circumferential crack/notch and subjected to tension-torsion load [28–31], edge cracked plate loaded by a special pin loading fixture [31], split-shear torsion (SST) and edge crack torsion (ECT) [32,33], have two major drawbacks: (i) most of them cannot produce full combinations of mode I and III mixities (particularly pure or dominantly mode III condition) [25–27] and (ii) most of them have complex geometries and require difficult and time consuming manufacturing process or need complicated loading fixtures and apparatus for testing [28–34]. Moreover, some of the mentioned specimens are loaded by tensile type pin loading fixtures that is not suitable for brittle materials like graphite.

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