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Strain-based criteria for mixed-mode fracture of polycrystalline graphite

M.M. Mirsayar [a], F. Berto [b,c], M.R.M. Aliha [d], P. Park [a,*]

[a] Zachry Department of Civil Engineering, Texas A&M University, College Station, TX 77843-3136, USA
[b] Department of Management and Engineering, University of Padova, Stradella, S. Nicola 3-36100 Vicenza, Italy
[c] NTNU, Department of Engineering Design and Materials, Richard Birkelands vei 2b, 7491 Trondheim, Norway
[d] Welding and Joining Research Center, School of Industrial Engineering, Iran University of Science and Technology, Narmak, 16846-13114 Tehran, Iran

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ABSTRACT

The mixed-mode brittle fracture of two types of commercial graphite is investigated focusing on strain-based fracture criteria. The previously published experiments using centrally-cracked Brazilian disk specimens subjected to mixed-mode loadings are simulated by two strain-based fracture criteria: the traditional maximum tangential strain (MTSN) criterion only considering the singular terms, and the extended maximum tangential strain (EMTSN) criterion, which considers the first nonsingular strain term as well as the singular terms. Numerical simulations on the centrally-cracked Brazilian disk specimen show that the first nonsingular tangential strain term significantly influences the tangential strain distribution around the crack tip. The comparison of the evaluations by the MTSN and EMTSN criteria with the experimental data shows that the EMTSN criterion is more capable of successfully estimating the fracture resistance of graphite materials rather than the traditional MTSN criterion. In addition, when the first nonsingular term is considered, the strain-based fracture criterion provides better predictions for near mode II loadings than the stress-based fracture criterion.

1. Introduction

Graphite materials are extensively used in various specialized applications such as electric discharge machining processes, carbon brushes, and crucibles for the steel industry. During the service life of the components made from graphite, cracks may initiate and develop around the most vulnerable area as a result of external mechanical and thermal loadings, and eventually may lead to failure.

The study on the fracture resistance is one of the primary steps toward understanding of the material failure mechanisms. The fracture resistance of graphite has been studied by previous investigators using various types of specimens [1–7]. Awaji and Sato [1] obtained the fracture toughness of graphite under mixed-mode conditions (mode I and II) using centrally-cracked Brazilian disk specimens. The mixed-mode fracture toughness of graphite materials have also been studied by Yamauchi et al. [3,5] using the Brazilian disk and semi-circular bend (SCB) specimens. Mostafavi et al. [7] measured flexural strength of graphite under different states of stress using four-point bending and ring-on-ring specimens. In composite materials such as graphite/epoxy composites, ultimate strength of the graphite fibers has always been a matter of concern.

* Corresponding author. Tel.: +1 (979) 847 5690.
E-mail address: ppark@civil.tamu.edu (P. Park).

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Nomenclature

a	crack length
B	biaxiality ratio
E	Young's modulus
F	applied force in Brazilian disk
$f_{ij},n(\theta)$	function of θ; $i, j = r, \theta$ and n = fracture mode
K_{eff}	effective stress intensity factor
K_I, K_{II}	mode I and II stress intensity factors
K^*_{IC}	generalized fracture toughness taking into account the effect of the Poisson's ratio
R	radius of Brazilian disk
r, θ	variables in cylindrical coordinate reference system
r_c	critical distance from crack tip
t	thickness of Brazilian disk
T	coefficient of first nonsingular strain term around crack tip
T^*	normalized T-stress
α	normalized critical distance
β	angle between load and crack in Brazilian disk
ε_T	critical strain
$\varepsilon_{\theta\theta}$	tangential strain in cylindrical coordinate reference system
η_I, η_{II}	model I and II normalized stress intensity factors
θ_0	angle of maximum tangential strain
v	Poisson's ratio
σ_T	tensile strength

The study of fracture resistance of these materials has been one of the active fields in composite science and technology [8–10].

The microstructural behavior during the fracture of graphite materials was also studied by many researchers [11–14]. Burchell [13], for instance, proposed a model applying a failure criterion based on both fracture mechanics and microstructural considerations, and employed the model to evaluate the fracture strengths of four types of graphite.

The mixed-mode fracture of polycrystalline graphite was investigated by Li et al. [15] using single-edge notch bending specimens. They pointed out that the maximum tangential stress criterion is capable of predicting the fracture resistance of the polycrystalline graphite. Shi et al. [16] obtained the mode I fracture toughness of a type of graphite used in nuclear industries employing three-point bending sandwiched specimens.

The brittle fracture of notched specimens made from graphite was also studied by many researchers [17–19]. In a work done by Ayatollahi et al. [17], the brittle fracture of polycrystalline graphite was studied using Brazilian disk specimens containing sharp and rounded-tip V-notches subjected to different mixed-mode loading conditions. Berto et al. [18] investigated the brittle fracture of polycrystalline graphite under torsional loadings using axisymmetric specimens containing sharp and rounded-tip V-notches. They were the first investigators who provided data from the notched graphite specimens under torsion. Berto et al. [19] also studied compressive strength of notched prismatic specimens made from graphite.

A quick look through the literature reveals that a number of fracture criteria have been proposed to evaluate fracture resistance of materials. Those fracture criteria can be classified into three basic categories: energy-based [19–22], stress-based [23–27] and strain-based [28–34] criteria. Each category employs a different concept to describe the fracture mechanism, and has intrinsic advantages and disadvantages. For instance, the stress-based fracture criteria are described with a simpler set of equations than the energy-based criteria, and each stress field parameter represents a clear role in estimating the onset of fracture. On the other hand, the energy-based criteria employ more realistic assumptions for examining the crack propagation phenomenon by taking into account the effect of energy dissipation during fracture.

The maximum tangential stress (MTS) criterion is a representative stress-based criterion proposed by Erdogan and Sih [23]. The MTS criterion states that a crack propagates when the tangential stress around crack tip reaches a critical value in a direction perpendicular to the maximum tangential stress. Ayatollahi and Aliha [26] applied the MTS criterion to the experimental data obtained from Brazilian disk specimens by Awaji and Sato [1], and pointed out that the traditional MTS criterion does not properly estimate the fracture resistance of the polycrystalline graphite materials. They concluded that a modified tangential stress-based fracture criterion (Generalized MTS, GMTS), which considers the effect of the first non-singular stress term known as T-stress, provides better evaluations than the MTS criterion in mixed-mode loading conditions. This conclusion is contradictory to the Li et al. [15], who used single-edge notched bending specimens. The discrepancy is caused by the different specimen geometry, which influences on the effect of T-stress.

The strain-based criterion was originally proposed by Chang [33], and has been applied to various materials including human bone [28] and concrete [31]. The maximum tangential strain (MTSN) criterion considers that the maximum