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Determining indentation fracture toughness of ceramics by finite element method using virtual crack closure technique

Liang Sun[a,*], Dejun Ma[a], Lizhi Wang[a], Xinzheng Shi[a], Jialiang Wang[b], Wei Chen[a]

[a] Department of Vehicle Engineering, Academy of Army Armored Forces, Beijing 100072, China
[b] College of Equipment Engineering, Engineering University of Chinese Armed Police Force, Xi'an 710086, China

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ABSTRACT

Based on indentation cracks produced by Vickers indentation tests on Silicon Nitride and Fused Silica, fracture toughness (K_{IC}) of the two materials was determined by a Vickers indentation finite element model using virtual crack closure technique (VCCT). The elastic modulus and yield stress of the materials needed in finite element simulation were determined by using dimensionless expressions specially established for ceramic materials, which revealed the approximate numerical relationship between indentation responses and elastoplastic properties of ceramic materials. Computed K_{IC} was obtained by calculating the stress intensity factor (K_I) at crack tip. Considering that the calculated stress intensity factor (K_I) varied distinctly along an ideal semi-circle crack front, the equi-K_I crack front was acquired through successive simulation and adjustment. By comparison, the computed K_{IC} values of equi-K_I crack fronts were in good consistence with the reference K_{IC} of the two materials, while those of the semi-circle crack fronts presented significant errors. The results indicated that indentation fracture toughness could be well determined by employing finite element method (FEM) and VCCT, and the obtainment of equi-K_I crack front was crucial to the accuracy of computed fracture toughness.

1. Introduction

Fracture toughness (K_{IC}) is an important mechanical property to evaluate the brittleness of ceramic materials. The accurate and convenient measurement of ceramic fracture toughness has long been the focus of researchers. Indentation method [1] is favored because of its convenience. Lawn et al. [2] proposed a Vickers indentation fracture model based on the expanding cavity theory [3], which was frequently used to derive analytical indentation fracture formulae, including the famous experimentally calibrated formula by Anstis et al. [4]. However, the accuracy of existing analytical indentation fracture formulae is under doubt. Quinn and Bradt [5] reported significant errors of tested fracture toughness values from different analytical formulae. Ma et al. [6] revealed that the errors were largely attributed to an overestimation of the volume of residual impression in the model by Lawn et al., which was vital to the solution of crack driving force and crack-tip stress intensity factor (K_I), and proposed a modified Vickers indentation fracture model, yet the precise calculation of stress intensity factor by analytical derivation is still not possible. In recent years, FEM [7–9] is widely used for determining indentation fracture toughness, avoiding the complex mechanical derivation process. A number of numerical methods are employed for calculating crack-tip K_I in FEM, such as J integral [10], extrapolation technique [11], virtual crack extension technique [12] and virtual crack closure technique [13]. Among these, virtual crack closure technique is more suitable to be applied in finite element simulation for fracture toughness, because it requires only one complete analysis with no need

* Corresponding author.
E-mail address: tproud@163.com (L. Sun).

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Nomenclature

a	half-diagonal length of Vickers impression
c	half-diagonal crack length from impression center to crack tip
E	elastic modulus of ceramics
E_i	elastic modulus of diamond indenter
E_r	reduced plane strain elastic modulus
F	nodal force
G	mode I strain energy release rate
h_m	maximum indentation depth
H_n	nominal hardness
K_I	mode I stress intensity factor
K_{IC}	mode I fracture toughness
$K_{IC\text{-}FEM}$	computed fracture toughness
$K_{IC\text{-}REF}$	reference fracture toughness
P_m	maximum indentation load
u	nodal displacement
W_e	elastic reverse deformation work of indention
W_t	total work of indentation
δ	relative error between computed and reference fracture toughness
ΔA, ΔB	virtually closed areas
η	ratio of plane strain reduced elastic moduli
ν	Poisson's ratio of ceramics
ν_i	Poisson's ratio of diamond indenter
σ_y	yield stress of ceramics
FEM	finite element method
HPC	half-penny crack
RC	radial crack
VCCT	virtual crack closure technique

of complicated mathematical calculation or special treatment to the meshing around crack tip. Rybicki and Kanninen [13] first proposed a VCCT method for two-dimensional crack configuration. Shivakumar et al. [14] extended the two-dimensional VCCT by Rybicki and Kanninen to finite element analysis of three-dimensional cracked body. Ma et al. [15] applied VCCT to three-dimensional finite element fracture simulation for radially-propagating indentation cracks induced by Vickers indenter and proposed a numerical indentation method for determining ceramic fracture toughness. In the application of VCCT on indentation fracture simulation, a preset crack front is required, which is generally assumed to be circular half-penny crack (HPC) or radial crack (RC). It has been found that the calculated K_I varies along a circular crack front, against the 'homogenous material' assumption, yet, the impact of such a circular crack shape to the computed fracture toughness has not been experimentally verified.

In this paper, the Vickers indentation fracture models are built on the basis of actual indentation crack lengths from indentation tests on two representative ceramic materials - Silicon Nitride and Fused Silica. VCCT is used to calculate K_I on the crack fronts, i.e. K_{IC} of the tested materials. The computed K_{IC} of both the semi-circle and equi-K_I crack fronts will be compared with the reference K_{IC} values of the two materials. This paper intends to provide an alternative model to determine the indentation fracture toughness of ceramic materials and find out, to what extent, the calculation of fracture toughness can be impacted by the design of crack shape.

2. Vickers instrumented indentation tests

The selected materials – Silicon Nitride (Si_3N_4) and Fused Silica (SiO_2) are standard reference materials prepared by hot isostatic pressing. Si_3N_4 is provided by National Institute of Standards and Technology, Gaithersburg, Maryland, USA, with certified fracture toughness $K_{IC} = 4.572 \pm 0.228\,\text{MPa·m}^{1/2}$. SiO_2 is provided by Baoshan Iron & Steel Co., Ltd, Shanghai, China, with certified elastic modulus $E = 72.3$ GPa and its reference K_{IC} is taken as $0.798 \pm 0.023\,\text{MPa·m}^{1/2}$ from Ref. [16].

The indentation tests were performed on a self-developed instrumented indentation tester [17]. A diamond Vickers indenter was equipped, of which the elastic modulus E_i is 1141GPa and Poisson's ratio ν_i is 0.07. Besides the surface crack length, work ratio W_e/W_t and nominal hardness H_n were also extracted by using the indentation loading and unloading force-displacement data from the tests. W_e and W_t were the unloading and loading work of indenter, and H_n was defined as $H_n = P_m/24.5{h_m}^2$, where P_m was the maximum indentation load and h_m was the maximum indentation depth. W_e/W_t and H_n were to be used for determining elastic modulus E and yield stress σ_y of the materials. Each indentation test was repeated 10 times and the value of indentation responses was the average over the 10 tests. The peak indentation loads P_m for Si_3N_4 were 10, 50 and 100 N. For SiO_2, W_e/W_t and H_n were measured with a peak load of 0.25 N to avoid the influence of possible lateral cracks on the calculation of indentation work and measurable diagonal cracks were obtained at load of 2 N without the presence of severe chipping around impression. The cracks were immediately measured using an optical microscope to minimize the influence of slow crack growth. Crack length c was the distance straight from the center of Vickers impression to crack tip.

The indentation responses are shown in Table 1. The ratio c/h_m was adopted instead of commonly used c/a (a was the impression half-diagonal length) for the simplicity in the establishment of finite element fracture model. The morphologies of the obtained

Table 1
Averaged indentation responses of Vickers instrumented indentation tests on two ceramic materials.

Materials	P_m(N)	W_e/W_t	H_n(GPa)	c(μm)	c/h_m
Si_3N_4	100	0.485	12.91	123.1	6.93
	50	0.497	13.10	78.2	6.13
	10	0.503	13.23	27.1	4.69
SiO_2	2	0.689	4.88	18.2	4.05