Computational Materials Science 77 (2013) 236–244

Contents lists available at SciVerse ScienceDirect

Computational Materials Science

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

# Extended finite element modeling of crack propagation in ceramic tool materials by considering the microstructural features

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ARTICLE INFO

*Article history:*
Received 4 December 2012
Received in revised form 17 March 2013
Accepted 18 April 2013
Available online 24 May 2013

*Keywords:*
Ceramic
Microstructure
Crack propagation
X-FEM

ABSTRACT

A microstructure model is established to study failure of ceramic materials. The model is based on the Voronoi Tessellation in which random functions are employed to take into account the secondary phase volume fraction, the grain centroid distribution, the grain diameter distribution, and the grain boundary volume distribution of the materials. Extended Finite Element Method (X-FEM) is utilized to simulate the crack propagation considering the influence of microstructure of ceramic, which can obtain high accuracy without the need for re-meshing compared with the standard finite element method. The influences of grain diameter, secondary phase volume fraction and grain boundary volume fraction on the fracture toughness of ceramic materials have been systematic studied. The results presented in this article are useful to improve toughness and failure resistance of ceramic materials.



## 1. Introduction

Being naturally brittle, ceramic tool materials possess many excellent performances, including great wear resistance, high hardness, good chemical stability and heat resistance [1,2]. The ceramic tool materials which have irreplaceable advantage in the field of high-speed machining and cutting of difficult to cut materials compared with other tool materials are widely used in the high-speed cutting, dry cutting and hard cutting. However, there are some limitations for further extensive application of the ceramic tool materials because ceramic possesses low fracture toughness and strength [3].

Microstructure plays an important role in determining the fracture toughness of ceramic tool materials [4]. The fracture patterns would be affected by grain diameter and distribution, grain shape, constituent phases and interfacial properties [5–7]. It is difficult to quantify the correlation between microstructure and materials properties due to the complexity of ceramic microstructure. Recently many numerical and theoretical models have been developed to reveal this correlation [8–15]. Sukumar and Srolovitz simulated the crack propagation of polycrystalline materials by the means of X-FEM [8]. Xu and Needleman [10] used the cohesive element method to investigate the crack propagation in the brittle solids. The simulation of crack propagation in microstructure of ceramic was presented by Zhou et al. [12]. The effects of randomness in the distribution of microstructure parameters have been generally neglected or scarcely considered in these simulation models for investigate the crack propagation in polycrystalline materials. To this end, the objective of this paper is to develop a microstructure-level model to simulate the crack propagation in ceramic material. The model is based on the Voronoi Tessellation in which random method are employed by taking into account the secondary phase volume fraction, the grain centroid distribution, the grain diameter distribution, and the grain boundary volume distribution of the materials.

The X-FEM and cohesive element method are commonly used to investigate the fracture propagation in polycrystalline materials. The basic idea of X-FEM is to add the enrichment functions to the conventional displacement approximation [16–19]. The theoretical basis of cohesive element method is to discrete the continuum as buck elements and distributed cohesive elements by releasing the rigid cohesive constraint of standard finite elements [20–22]. Both of them have advantages compared with the standard finite element method, such as accuracy, without remeshing [23]. The cohesive element method were used to simulate the intergranular crack patterns of ceramic materials, which could not been applied to simulate the transgranular crack patterns of materials. However, transgranular fracture is the primary crack mode of the ceramic materials. Intergranular fracture was scarcely found in the fracture surface of ceramic. So the extended finite element method was utilized to simulate the crack propagation of ceramic materials in this paper.

In this paper, a brief review on the basic theory of the extended element method was described in Section 2. Then, a microstructure model was developed by using Voronoi Tessellation and random method, which is better than common models in simulation of the ceramic materials. The detailed construction of microstructure

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http://dx.doi.org/10.1016/j.commatsci.2013.04.045

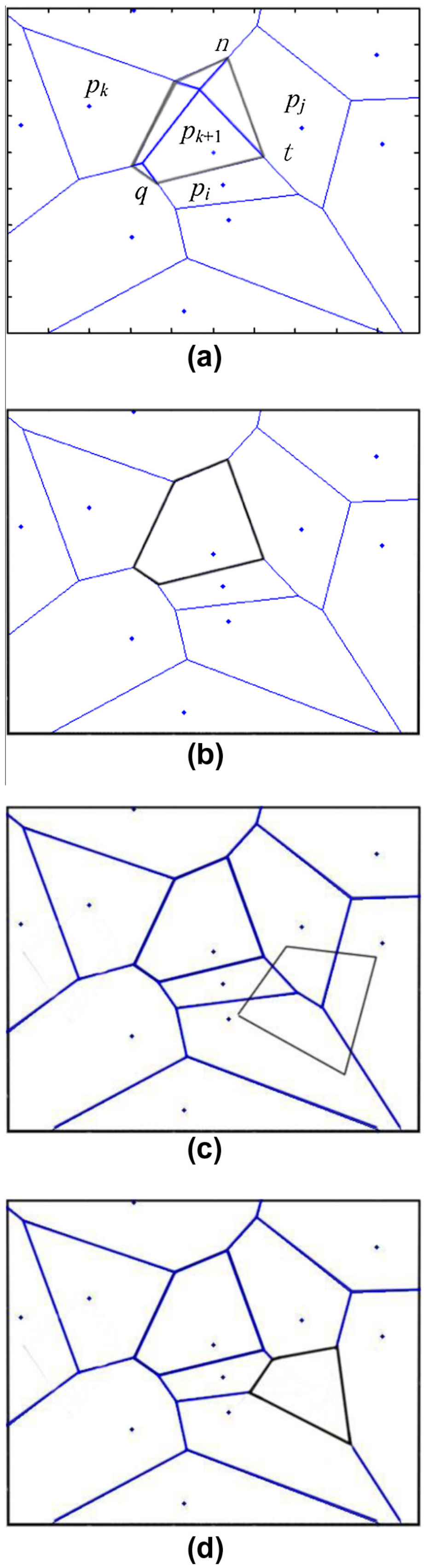


**Fig. 1.** The construction process of VD based on incremental method: (a) location of $p_{k+1}$ and compute of $VR_p$ ($p_{k+1}$); (b) construction of new VD; (c) randomly adding quadrilaterals into matrix; and (d) processing for overlapped area.

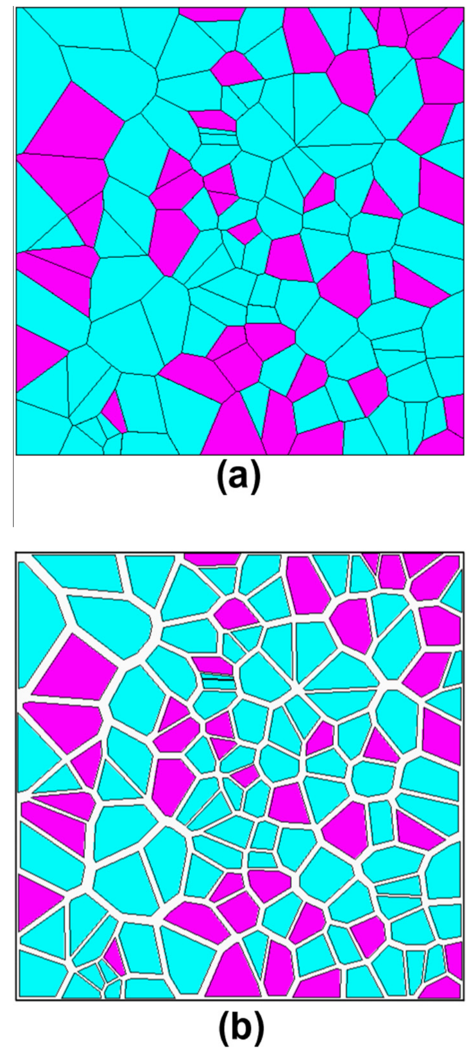


**Fig. 2.** Microstructure of the ceramic: (a) without grain boundary; (b) with grain boundary.

model was presented in Section 3. The simulation procedures and obtained results were presented in Section 4. Eventually, some concluding remarks obtained from this study were given in Section 5.

## 2. Extended finite element method

The finite element method is one of the most effective numerical methods to solve the scientific and engineering problems. Compared with other numerical methods, it can be applied to arbitrary geometry and boundary conditions, and suitable for both material and geometric nonlinearity. However, the FEM has some deficiencies in solving problems with discontinuity such as holes, cracks, and inclusions. In 1999, Belytschko and Black [24] apply the Westergaad asymptotic field function on the crack tip unity for 2D crack propagation. Then, Moës [25] used the Heaviside function as an enriched function to describe the discontinuity of a crack more precisely. After the application of level set method for the geometric description of crack initiation and propagation, the X-FEM was gradually being formed.

In the extended finite element method, the enrichment function is added to the standard displacement approximation. The displacement discontinuity and stress singularity of crack tip field