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Transient thermal shock behavior simulation of porous silicon nitride ceramics

Meng Chen, Hongjie Wang, Haiyun Jin*, Xide Pan**, Zhihao Jin

State Key Laboratory for Mechanical Behavior of Materials, Xi'an Jiaotong University, Xi'an, Shannxi 710049, China

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Abstract

This work presents computational solutions and experimental results on the most important parameters influencing thermal shock behavior. In this paper, the mesoscopic cracks were observed on the surface of the specimen which experimentally confirmed the decay in flexural strength after thermal shock. It has been shown that the crack width decreases with increasing porosity. For higher porosity, it is evident that the crack extended with obvious deflection and bifurcates. The numerical simulations within the framework of damage mechanics considering the coupling between the thermo and mechanical behavior of porous Si_3N_4 on the mesoscopic level of observation can conveniently reproduce the evolution of thermal shock cracks, which is difficult to observe experimentally. The present theoretical-numerical-experimental study has led to an improved under -standing of the formation and evolution of thermal shock crack in porous ceramics.

Keywords: Ceramics; Porous materials; Crack propagation; Thermal shock; Numerical simulation

1. Introduction

Over the past few decades, porous Si_3N_4 ceramics have received wide attentions due to their excellent dielectric properties, good oxidation resistance, high bending strength at room and elevated temperature, and remarkable thermal shock resistance [1–4], which offer porous Si_3N_4 an exciting opportunity for applications in high temperature gas/liquid filters, separation membranes, thermal insulators and catalyst supports [5–9]. In the majority of applications, porous Si_3N_4 ceramics often encounter strong heatflow and/or abrupt temperature shock, which can lead to instantaneous thermal stresses and subsequently to yield ceramics sensitive to crack. Therefore, it is important to make an accurate prediction of thermal shock behavior in order to design a safe and economic structural of this material.

Currently, two of the most important ways to describe the thermal shock behavior of ceramic materials are thermo-elastic analysis [10] and the Hasselman treatment [11]. Unfortunately, it is yet unclear whether a porous ceramic has superior or inferior thermal shock resistance to that of a fully dense ceramic, since the elastic modulus and thermal conductivity of these materials are generally both reduced by presence of porosity [12].

In most cases, the thermal-shock experiments are performed by means of measuring the residual flexural strength in an air atmosphere after quenching heated specimens from successively higher temperatures into a water bath [13–15]. However, only a few studies have examined the interaction of thermal shock induced cracks with the materials microstructure. Thus, understanding such influence mechanism is critical for reliability and optimization of a wide range of porous Si_3N_4 ceramics.

To investigate the influence of porosity and to improve the understanding of material response under thermal loading conditions, the porous Si_3N_4 ceramics with porosities of 32–57% were obtained through die-pressed under different

*Corresponding author. Tel.: +86 29 82663284; fax: +86 29 82668567
**Corresponding author. Tel.: +86 29 82667942; fax: +86 29 82663453
E-mail addresses: hyjin@mail.xjtu.edu.cn (H. Jin), xdpan@mail.xjtu.edu.cn (X. Pan).

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pressures and gelcasting followed by gas-pressure sintering, and then were used to evaluate the thermal shock behavior. Transient responses of the cracked porous Si_3N_4 ceramics under thermal shock were investigated by using a thermo-mechanical model with the finite element analysis. The X-FEM (extended finite element method) model was proposed within the framework of damage mechanics considering the coupling between the thermo and mechanical behavior of porous Si_3N_4 on the mesoscopic level of observation. One of the objectives was to investigate how the porosity affects both the crack initiation and crack propagation after thermal shock. Another objective was to bridge the gap between theoretical predictions of thermo-mechanical behavior and microstructure with the aim of collecting some information on the thermal shock applications of porous Si_3N_4 ceramics.

2. Experimental

The porous Si_3N_4 ceramics fabricated in our previous work were employed as the samples [16]. In this paper, the samples with porosities of 32%, 45% and 57% were used to evaluate the thermal shock behavior. Thermal shock resistance experiments were performed by quenching the specimens (3 mm × 4 mm × 40 mm) from a resistance furnace into 30 °C water bath. The specimens were heated in air atmosphere with a rate of 10 °C/min to a preset temperature and held at this temperature for about 20 min prior to quenching. The specimens were dropped parallel to their long axes into the water. Then, the residual flexural strength of the quenched specimens was measured under the same conditions as those of unquenched specimens. The strength results of specimens in this work were given as the average values of three measurements.

In this paper, the cracking of a finite porous plate subjected to a sudden cooling on its surface was considered. During rapid cooling, the temperature of the surface of the porous plate was much lower than the inside. Thus, the surface of the porous plate tends to shrink. This shrinkage may be constrained inside the porous plate, resulting in a state of tension in the surface. Therefore, modeling of the thermo-mechanical coupling process in porous ceramics was difficult due to the high level of interdependency and nonlinearity. However, some new techniques have been recently developed that allow the simplification of this kind of analysis. One of these techniques was the X-FEM which enriches the finite element approach with special functions that are able to describe the discontinuity and introduce the singular behavior associated with the crack tip, and makes its analysis up to a certain point, independent of the mesh.

In this paper, three numerical examples (porosity: 30%, 50% and 70%) including a horizontal edge-crack in a finite porous plate under a cooling shock were investigated. The X-FEM for modeling crack problems in porous Si_3N_4 ceramics under cooling shock was then described in Section 3. This research work was to numerically study the transient dynamic fracture behaviors of porous Si_3N_4 ceramics subjected to thermal shock.

3. Results and discussion

3.1. Thermal shock behavior

Fig. 1 compares the thermal-shock behaviors of LP-Si_3N_4 (porosity 32%), MP-Si_3N_4 (porosity 45%) and HP-Si_3N_4 (porosity 57%) ceramics. As can be seen from Fig. 1, the flexural strength of the LP-Si_3N_4 and MP-Si_3N_4 degrades abruptly above 700 °C, so the critical temperature differences of thermal shock are above 700 °C, while it is no critical temperature differences of thermal shock for the HP-Si_3N_4 because of gradual degradation of strength. The finding should be associated with Hasselman theory [11,17], samples with higher strength must have more instability in their crack propagation. It can be explained in two ways.

First, MP-Si_3N_4 and HP-Si_3N_4 contain more connected open pores, these pores acting as a stress concentrator in ceramics matrix [15]. In the case of thermal shock, crack probably emerges on the surface because of larger thermal stress. When suffering the same thermal shock severity, a relatively larger number of cracks may initiate and propagate, while the more pores can limit the propagation of each crack, leading to a decrease in crack depth and consequently in strength loss.

Second, the pores can also play the role of crack arresters. As a crack encounters a pore, the crack may be constrained to alter its path or even stop at the pore. In high porosity ceramics, the crack can propagate only over a relatively short distance and then become arrested by the pores, and thus crack propagation occurs in a quasi-static manner and the strength undergoes a gradual decrease.

Fig. 2 shows SEM images of fracture surface after single thermal shock at $\Delta T = 1000$ °C for Si_3N_4 ceramics with samples of LP-Si_3N_4, MP-Si_3N_4, and HP-Si_3N_4. For low porosity (LP-Si_3N_4), the evident cracking phenomenon can be seen due to the propagation of the vertical crack and the propagation of the horizontal crack.

Compare the microstructure of sample of lower porosity (LP-Si_3N_4) with that of higher porosity (MP-Si_3N_4 and HP-Si_3N_4) (see Fig. 2), the difference in crack width of different porosities can be attributed to the presence of pores. It is obvious that the crack width decreases as porosity increases.

Furthermore, for higher porosity, it is evident that the crack extended with obvious deflection (see Fig. 2b) and bifurcates (see Fig. 2c). This fracture characteristic indicated that the

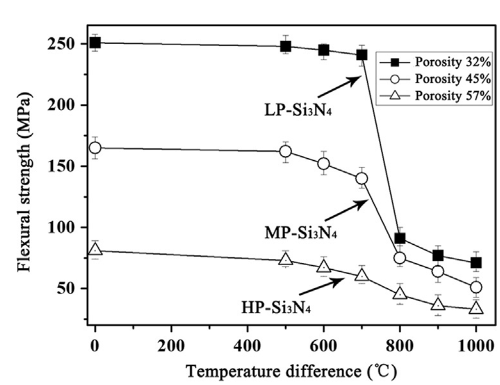

Fig. 1. Flexural strength as a function of quenching-temperature difference.