Available online at www.sciencedirect.com

ScienceDirect

Ceramics International 41 (2015) 1107–1114

CERAMICS INTERNATIONAL

www.elsevier.com/locate/ceramint

Experiments and numerical simulations of thermal shock crack patterns in thin circular ceramic specimens

Yuxing Liu[a], Xiaofeng Wu[b], Qiankun Guo[b], Chiping Jiang[b,c], Fan Song[c,*], Jia Li[d]

[a]*School of Materials Science and Engineering, Beihang University, Beijing 100191, People's Republic of China*
[b]*School of Aeronautic Science and Engineering, Beihang University, Beijing 100191, People's Republic of China*
[c]*State Key Laboratory of Nonlinear Mechanics, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, People's Republic of China*
[d]*LSPM, CNRS UPR 3407, Université Paris XIII, 99 Avenue Jean-Baptiste Clément, Villetaneuse 93430, France*

Received 24 July 2014; received in revised form 6 September 2014; accepted 7 September 2014
Available online 16 September 2014

Abstract

An attempt was made to explore the formation mechanism of thermal shock crack patterns in ceramics and to develop quantitative numerical simulations. A set of experiments on thin circular ceramic specimens yielded two-dimensional readings of thermal shock crack patterns with periodical and hierarchical characteristics. The numerical simulations of the thermal shock crack patterns are based on the minimum potential energy principle, where the convective heat transfer coefficient at high temperatures, which is difficult to measure, was inversely estimated by the crack spacing, which is easy to measure. Numerical simulation results were in good agreement with the experimental data. Several interesting thermal shock crack evolution phenomena were found. Two stability criteria of crack propagation, i.e. the minimum potential energy principle and the fracture mechanics bifurcation theory, were compared. It was found that the two criteria verify and complement each other. The present study leads to an improved understanding of the formation and evolution of thermal shock crack patterns in ceramics and can help engineers to assess the thermal shock failure of practical ceramic components.

Keywords: Ceramics; Thermal shock; Crack patterns; Numerical simulations

1. Introduction

The chemical stability of ceramics above the melting point of metal alloys predestines this class of materials for high temperature applications such as gas turbine engines [1] for aircraft propulsion, marine propulsion, power generation and thermal protection structures in hypersonic vehicle [2,3]. However, thermal shock failure of ceramics is a long-standing problem [4]. It is recognized that a basic understanding of thermal shock failure must be gained to give full play to the potential of ceramic materials at high temperatures [1].

Numerous studies were conducted to explore the mechanism of thermal shock failure of ceramics. Among them, Kingery [5] and Hasselman [6] proposed two theories of thermal shock resistance from the viewpoint of stress and energy, respectively. Soon afterwards, Hasselman [7] developed a unified theory to combine thermal shock fracture initiation with crack propagation in brittle ceramics. Schneider [8] studied thermal shock parameters that depend on crack initiation and arrest criteria for ceramics, and discussed the role of thermal shock experiments. Salvini et al. [9] extended Hasselman's thermal shock theory [7] by considering the crack interaction mechanisms with the refractory microstructure.

Thermal shock resistance of ceramics is commonly evaluated by the degradation of the strength after thermal shock which is caused by the appearance of cracks. Researchers very early noticed that thermal shock cracks exhibit generally regular and elegant patterns, such as periodic and hierarchical characteristics, which are important for a clear understanding of the thermal shock failure mechanism of ceramics. Bažant [10] and Nemat-Nasser et al. [11,12] studied the stability of

---

[*] Corresponding author. Tel.: +86 10 8254 3961; fax: +86 10 8254 3935.
E-mail address: songfan.imech@gmail.com (F. Song).

http://dx.doi.org/10.1016/j.ceramint.2014.09.036
0272-8842/

propagated thermal shock cracks (or drying shrinkage cracks), and theoretically discussed the length hierarchy phenomenon. Bahr et al. [13–15] established a fracture-mechanical model based on the time-dependent energy release rate to explain the thermal shock cracking behaviors. Jenkins [16] used a method based on energy minimization to determine the spacing and penetration of a regular array of cracks in a shrinking slab due to a changing temperature field. Jiang et al. [17] conducted thermal shock experiments of thin rectangular ceramic specimens and developed numerical simulations of thermal shock crack patterns. Li et al. [18] proposed a non-local failure model to simulate the thermal shock crack evolution. Bourdin et al. [19] conducted numerical simulation of reservoir stimulation based on the variational approach. Furthermore, Bourdin et al. [20] and Sicsic et al. [21] studied the morphogenesis, initiation, and propagation of cracks in the thermal shock problem through the variational analysis of the quasi-static evolution of a gradient damage model.

The present work constitutes a continuing study on thermal shock crack patterns in ceramics and the emphasis is on an improved understanding of the formation and evolution mechanism as well as the development of quantitative numerical simulations of thermal shock crack patterns. To eliminate the boundary effects and to yield two-dimensional readings of crack patterns which are convenient to measure quantitatively, a set of thermal shock experiments on thin circular specimens were conducted. Then the crack patterns were numerically simulated based on the minimum potential energy principle. Finally, we made comparison of two stability criteria of crack propagation and comparison with experiments to reveal the evolution and bifurcation mechanism of thermal shock crack patterns.

2. Experimental

99% Al_2O_3 powder (University of Science and Technology Beijing Experimental Factory Co., Beijing, China) was thermoformed into thin circular plates with dimensions of 13 mm diameter and 1 mm thickness. Then the specimens were polished and tightly stacked together in sets of four, with two thick circular ceramic plates on the outside to prevent the temperature distribution from being disturbed by coolant accessing the interior surfaces of the specimens. For the convenient of binding, cross notches were carved on the outside surfaces of the two thick plates. Finally, the stacks of alumina circular specimens were bound with inconel wires, as shown in Fig. 1.

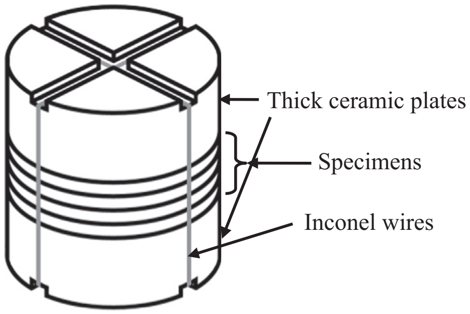

Fig. 1. Bound specimens for thermal shock.

The bound specimens were heated in a furnace at a rate of 10 °C min^{-1} to the preset temperature T_0 and maintained at this temperature for 30 min. The range of T_0 was from 250 °C to 500 °C. The heated specimens were dropped into a water bath at $T_1 = 15$ °C by free fall. The specimens were removed from the water bath 10 min later and dried, then dyed with blue ink to observe the cracks formed. Two sets of specimens (8 specimens in total) were tested at every value of T_0.

The digitally scanned photographs of dyed specimens are shown in Fig. 2. It is observed that the thermal shock cracks are perpendicular to the circle edge and point to the center. In addition, the crack patterns on both sides of the specimen are identical, which shows that the crack geometry is two-dimensional and convenient to observe and measure. Furthermore, it is observed that the crack patterns exhibit elegant periodic and hierarchical characteristics that vary with the thermal shock temperature T_0. The higher the T_0, the more the cracks. The long cracks become longer and the short cracks become shorter as T_0 increases.

The variations in the average crack spacing $\bar{s}_0$ with the thermal shock temperature T_0 are depicted in Fig. 3, where the average crack spacing $\bar{s}_0$ means the arc length on the outer circular circumference between two adjacent cracks. It can be seen that at every value of T_0, the fluctuation in the average crack spacing, $\bar{s}_0$, in eight specimens is small, and the maximum standard deviation from the average value is less than 15%. At the same time the crack spacing $\bar{s}_0$ decreases with the increase of T_0.

In the following sections an attempt is made to quantitatively simulate thermal shock crack patterns as well as to reveal the mechanism of formation and evolution of thermal shock crack patterns, especially the interesting bifurcation mechanism.

3. Numerical simulations

In the study of thermal shock crack patterns, two main approaches are the fracture mechanics bifurcation theory and the energy minimization method. In this section, numerical simulations based on the minimum potential energy principle will be developed. Then in the next section, comparisons will be made with results of fracture mechanics bifurcation theory and experimental data.

3.1. Assumptions

According to the experimental observations, three simplified assumptions are made: (1) The cracks are two-dimensional, and perpendicular to the outer circular circumference of specimens. (2) The crack patterns are periodic and hierarchical, consequently they can be simulated by a periodic unit. (3) From the assumption (1), the temperature field is not disturbed by the cracks, consequently it remains axisymmetric and is easily calculated by Fourier's law of heat conduction.