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Original Article

# Crack propagation speed in ceramic during quenching

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ABSTRACT

The effects of water quenching temperature and specimen size on the propagation speed of thermal shock crack are investigated in real time by water quenching of translucent ceramic and high-speed imaging. The results show that the crack growth rate increases with the increase of quenching temperature difference or specimen size. Within 100 ms, average crack speed is 20.3 mm/s at a temperature difference of 400 °C in 20 mm wide ceramic and is 11.9 mm/s at a temperature difference of 220 °C in 5 mm wide ceramic, respectively. Compare with specimen size, the influence of quenching temperature difference on the crack propagation speed is larger. The calculations based on meso-damage mechanics have similar results to those of experiments. This paper quantitatively studies the thermal-shock crack growth of ceramic in real time and expands the scientific understanding of thermal shock cracking phenomenon of ceramic.

## 1. Introduction

Ceramic is prone to crack under severe thermal shock condition because of its inherent brittleness [1], and its mechanical properties will be greatly damaged by cracks [2]. As a result, more than one-third of the rejections of ceramic components are caused by thermal shock [3]. Therefore, the determination of thermal shock cracking for ceramic is always required for engineering applications.

Numerous theoretical studies on thermal shock crack propagation and crack length hierarchy phenomena have been reported, including the principle of energy [4], the energy release rate [5], the energy minimization [6,7], the non-local failure model [8], the meso-damage mechanics [9], and the variational model etc [10,11]. These works verified and complemented to each other, much promoted the studies on thermal shock cracking phenomenon of ceramic. However, all theoretical models are only proved by the final results of the tests, rather than the whole process. So, there is still a challenge for quantitative study on the process of cracking. To overcome this difficulty and to bridge the gap between theoretical prediction and experimental data, we developed a real-time observation of thermal shock cracking method [12], where the crack propagation is successfully captured, and the crack growth rate is calculated from the images. The goal of this paper is to find a theoretical method which can be utilized to predict the thermal-shock crack growth of ceramic.

For this purpose, we experimentally reveal the crack propagation speed of the semi-transparent ceramic sheet during the real-time thermal shock process. By comparing the crack growth rate with the numerical result based on meso-damage mechanics, we verify the feasibility of this method. In addition, we further point out the influence of quenching temperature difference and specimen size on the propagation speed of thermal shock crack.

## 2. Experimental procedure

### 2.1. Materials processing

The translucent ceramic was made of high purity 99.5% $Al_2O_3$ powder (particle size 0.5 μm; Xiongdi Material Co., Ltd., Jiyuan, China), which was tape casting and subsequently sintered at 1850 °C for 2 h in hydrogen. The bulk density of the ceramic was about 3.96 g/cm$^3$ by measuring its dimension and weight. The mean grain size at the surface was about 18.9 μm by using the mean linear intercept method.

### 2.2. Thermal shock test

To ensure the formation of a two-dimensional penetrating crack, ceramic sheets with dimensions of 0.4 mm in thickness, 5, 10 or 20 mm in width, and 50 mm in length were employed to investigate the crack patterns during water quenching. To prevent access of the coolant to the side faces, the sheet was stacked with two quartz glass slabs and was bound up with inconel wires, as shown in Fig. 1. The specimen was heated to a preset temperature at a rate of 10°C/min and held for

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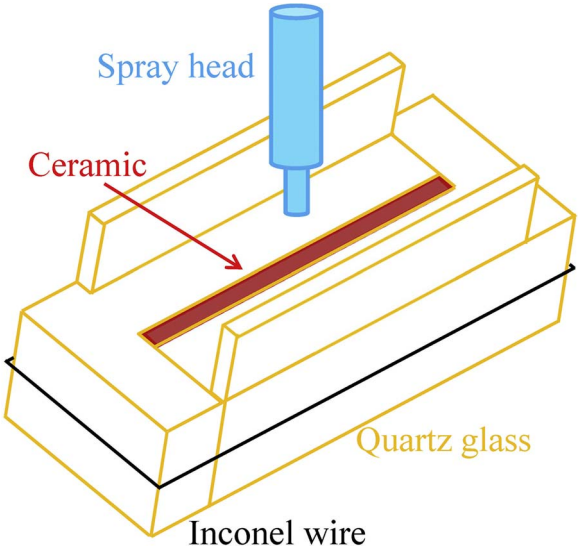


**Fig. 1.** Relative position of stacked sample and spray head for thermal shock.

30 min. After that, the sample was quickly taken out and put in a prefocused position on a table within 5s, then the spray head upon the sample began to spray deionized water of 20°C at a rate of about 5ml/s. Water flowed through the flume on quartz slabs, so the test sheet with the narrow upper surface (0.4 mm × 50 mm) was subjected to water quenching. The high-speed camera (Fastcam SA-X2, Photron, Tokyo, Japan) was used to capture images during the thermal shock process at 10,000 frames per second with a resolution of 1024 × 512 Pixels. From the series of recorded images, the crack speed could be obtained by the slope of the crack length curves per millisecond. The details are given elsewhere [12].

## 3. Numerical simulations

Here we use meso-damage mechanics to calculate the extent of crack growth. The FEM is used to evaluate the temperature and stress distribution in the specimen during water quenching. In the simulation, a statistical model of a heterogeneous elastic-brittle medium is used, and the damage criterion is used to check whether the elements fail or not.

### 3.1. Finite element model for temperature and stress simulation

A 2D plane stress FE model is introduced to depict the above water quenching test of ceramic sheet, along with the appropriate boundary conditions. In the beginning, a ceramic sheet with a uniform initial temperature $T_0$ is suddenly exposed to water with a uniform temperature $T_\infty$, as shown in Fig. 2a.

The specimen dimensions are $L = 50$ mm along the X-axis, and $H = 5$, 10 or 20 mm along the Y-axis, respectively. The right 1/2 area of the specimen is shown in Fig. 2a, the length of the finite element is 0.05mm and the size of the time increment is $t = 0.5$ms. The input parameters of alumina used in the calculation are listed in Table 1. It is assumed that the presence of the cracks that have formed do not influence the temperature distribution in the sheet under quenching, which can easily be calculated by Fourier's law of heat conduction. Then, the strain and stress distributions within the body are calculated from the temperature distribution at any given time by thermo-elastic theory, as well as strain energy density.

### 3.2. Mesoscopic heterogeneity of ceramics

According to experimental results, the statistic of fractures in ceramics follows Weibull distribution [3]. Therefore, in the presented numerical model, both strength and elastic modulus of ceramic are assumed to follow a Weibull distribution, whose probability density function is given as [9]:

$$f(\sigma) = \frac{m}{\zeta_0}\cdot\left(\frac{\zeta}{\zeta_0}\right)^{m-1}\cdot\exp\left[-\left(\frac{\zeta}{\zeta_0}\right)^m\right] \quad (1)$$

where $\zeta$ is the strength or elastic modulus of the element, $\zeta_0$ is the initial strength or elastic modulus of materials, and $m$ is the shape parameter or Weibull modulus which is set to be 15 [9]. In addition, the strength and elastic modulus of each element are considered as [9]:

$$\zeta_i = \zeta_0(-\ln\omega_i)^{1/m},\ i = 1...N \quad (2)$$

Where $\zeta_i$ is the strength/elastic modulus of the element $i$. $\omega$ is a random distributed number ranging from 0 to 1.

### 3.3. Meso-damage evolution

Continuum damage mechanics is used to describe the mechanical behavior of mesoscopic elements in the brittle material. Only tensile stress is considered in this study because most of the thermal shock failures occur in the tensile mode. The relation can be expressed as

$$\sigma_T(i, t) = [1 - D(i, t)]E(i, 0)\varepsilon_T(i, t) \quad (3)$$

where $\sigma_T(i,t)$, $\varepsilon_T(i,t)$ and $D(i,t)$ are the equivalent tensile stress, equivalent tensile strain and damage variable of the $i$th mesoscopic element under tensile mode. $E(i,0)$ is the initial elastic modulus. The stiffness of elements degrades gradually as damage progresses, and the elastic modulus of the $i$th damaged mesoscopic element can be defined as follows

$$E(i, t) = [1 - D(i, t)]E(i, 0) \quad (4)$$

As the $i$th mesoscopic element is in the damage mode, the damage evolution equation can be expressed as (Fig. 2b)

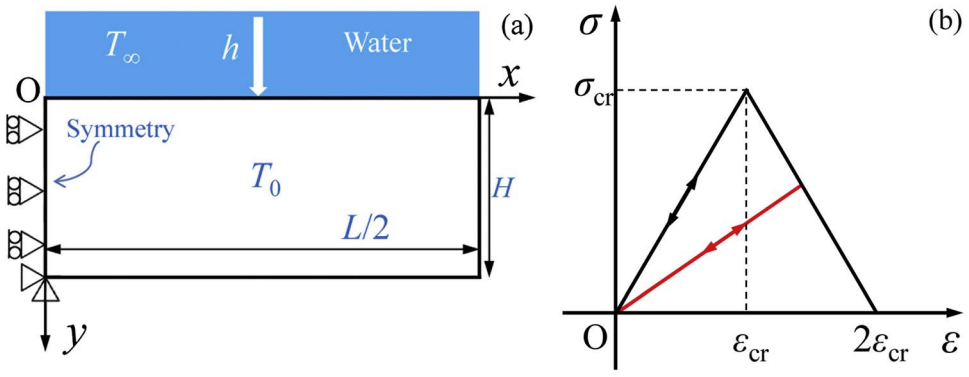


**Fig. 2.** (a) Finite element model used to determine the temperature and stress distribution in the specimen, (b) Damage constitutive model of the mesoscopic element.