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Quenching crack patterns of the ultra-high temperature ceramic in shapes of leading edge or alike

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ABSTRACT

Thermal shock behaviors of ultra-high temperature ceramic in shapes of sharp leading edges (SLE) or alike were investigated by water quenching and finite element methods. Distinct differences in the crack patterns among different test groups were observed, which were the result of the different SLE size and boundary effect and explained by the simulation results. Several interesting phenomena of the thermal shock crack patterns were presented. Effects of dimension and temperature difference (ΔT) on damage characteristics, such as the cracking mode, crack number and crack length during the thermal shock, were also revealed and discussed.

1. Introduction

ZrB_2-based composites, known as ultra-high temperature ceramics (UHTC), have an excellent combination of thermal (high melting point and thermal conductivity), physical (high strength and hardness) [1,2], chemical (good chemical stability) and oxidation-resistance properties [3,4]. These outstanding properties make them particularly attractive in hypersonic flight applications, especially for nose tips and sharp leading edges (SLEs) [5]. UHTC SLEs help reduce vehicle's drag, enhance maneuverability and performance [6,7]. In recent years, researchers have focused on their oxidation [4,8] and ablation performance [9,10], and significant progress has been made. However, poor thermal shock resistance is still a fatal weakness in engineering applications of UHTC SLEs. They are susceptible to catastrophic thermal stress failure from sharp thermal gradients under extreme aerodynamic conditions.

The cooling tests are wildly used for the evaluation of thermal shock resistance of ceramics compared with the heating ones because the heating thermal shock process always involves their oxidation or ablation [4,9]. In the reported studies on cooling thermal shock, Al_2O_3 samples with simple shapes, i.e. bars for quenching tests [11–15], were used most widely, because the bar was the most basic shape and Al_2O_3 material was the most basic ceramic that necessary to be investigated. In fact, from the viewpoint of experimental operation, the Al_2O_3 bar is also a very good choice for thermal shock investigation since the entire crack patterns on the white specimen are easier to detect, compared with the ceramics with dark color, such as ZrB_2-based ceramics and the Al_2O_3 ceramic is difficult to machining into special shapes due to its poor electric conduction and high hardness. However, the damage mode of many components in actual engineering applications differs significantly from that of test bars, because the geometry (shape and size) effects on thermal shock damage are great. Unfortunately, limited investigations have reported on the geometry effects of material components on their thermal shock behaviors [16,17] and even less on the structural damage resistance of their components, especially on the complete crack patterns observation of the entire sample in saturate color in a slight damage level.

In this paper, thermal shock behaviors of ZrB_2-SiC-G (ZSG) SLE-shaped samples were investigated by traditional water quenching and finite element analysis (FEA). The entire crack distribution (even in a slight damage level) on the specimens in the gray color

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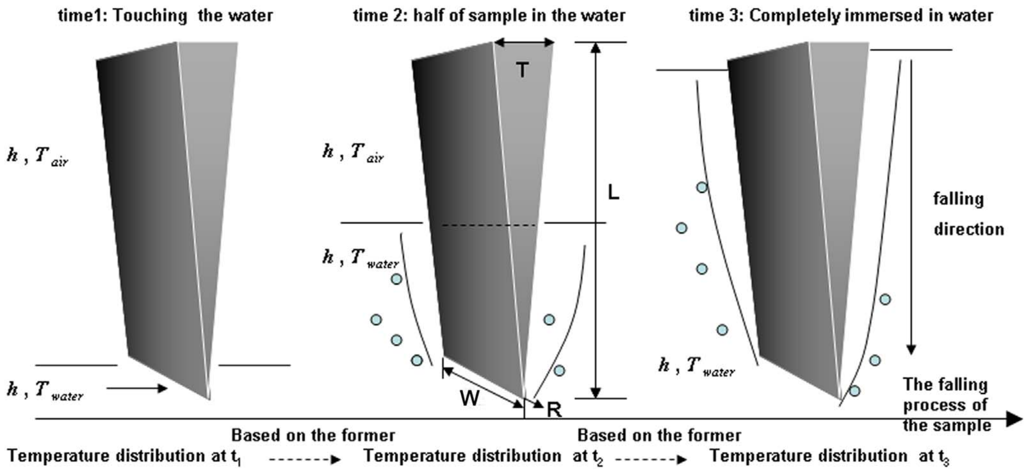

Fig. 1. Geometries for SLEs and heat transfer model: boundary and initial conditions during water quenching (L: length, W: width, T: thickness, R: radius; *h*: thermal convection coefficient, T_{air} and T_{water}: temperature of air and water, respectively).

were observed successfully and recorded. The influence of sample dimensions and test temperature differences on the thermal crack patterns as well as the relationship between stress distribution and crack characteristics was analyzed and discussed. Several interesting phenomena of the thermal shock crack patterns were also presented. These results are very useful for the theoretical and experimental investigations of thermal shock cracking and would lay the foundation for thermal shock failure analysis of the complicated components in actual engineering application.

2. Experimental procedure and models

The herein preparation of ZSG ceramics (ZrB_2-20 vol% SiC-15 vol% graphite) was as the same as that described elsewhere [18]. ZSG SLE-like specimens with different dimensions for subsequent thermal shock tests were cut from the hot-pressed billet using electric discharge machining (see Fig. 1):

D1: L = 60, T = 5.0, W = 20, R = 0.5 mm;
D2: L = 25, T = 2.5, W = 20, R = 0.5 mm;
D3: L = 25, T = 2.5, W = 60, R = 0.5 mm;
D4: L = 25, T = 5.0, W = 60, R = 0.5 mm;
D5: L = 25, T = 5.0, W = 60, R = 1.0 mm.

The specimens for thermal shock tests were put into a Muffle furnace preheated to the desired temperature (325, 350, 375, 400, 425, 525, 625 or 725 °C) and held for 15 min before water quenching. Higher temperatures were not attempted to avoid material oxidation [19]. The temperature of the water bath was 25 °C. A minimum of five specimens were tested for each experimental condition.

Fig. 1 also shows the whole quenching process. All specimens were dropped vertically into the water and the process was artificially divided into three stages, including 'touching', 'half in' and 'immersed', corresponding to times 1, 2 and 3, respectively. The total time of this process was approximately 0.02 s if the process was consider as a free fall (the distance from the specimen-drop position to the water surface was measured about 0.43 m), thereby we roughly assumed time 1 = 0 s (in the actual FEA calculation, we took a value of 0.001 which close to 0 s), time 2 = 0.01 s and time 3 = 0.02 s. The heat transfer between the water and ZSG [12] was reported very severe, thus it could cause significant differences in temperature and stress distributions on the SLE-like specimens at different stages, especially for the specimens with large scale. Hence, herein, different boundary and initial conditions were imposed on the specimens at different actual times, instead of imposing the boundary conditions directly to the specimen at the same initial time as many investigations did before [12], to obtain more accurate temperature and stress distributions. The calculation included two cooling boundary conditions, heat sinks temperature of 25 °C for both the water and air, and heat transfer coefficients of 130 $kW/m^2 \cdot °C$ [12] and 110 $W/m^2 \cdot °C$ for the parts of the specimens contacting with the water and air, respectively. First, the temperature and stress at time 1 were calculated according to the boundary and initial conditions illustrated in Fig. 1. Then FEA was conducted at time 2 using the calculated temperature distribution at time 1 as the initial condition with accompanying the boundary conditions. The FEA at time 3 was conducted by analogy. Some of the main properties of the ZSG ceramic required for FEA are listed

Table 1
Some of the main properties of ZSG ceramic used for FEA.

Material	k W/(m·°C)	ρ kg/m³	*c* J/kg·°C	*E* GPa	*α* /°C	*ν*
ZSG	62.91	5514	828.19	417.67	5.37E-6	0.164