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A novel and convenient temperature dependent fracture strength model for the laminated ultra-high temperature ceramic composites

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ABSTRACT

At present, no suitable and convenient model has been developed to predict variation tendencies of fracture strength of laminated ceramic composites with temperature. In this paper, a novel and quite simple temperature dependent fracture strength model for the laminated ultra-high temperature ceramic composites was developed based on energy theories—the Griffith energy criterion and a concept of energy storage capacity. The complicated problems of characterization of combined effects of temperature, change in critical flaw size and laminated structure parameters on fracture strength are solved by using primary and simple method. The model prediction agreed well with the experimental value. The novel model can be used to determine both fracture strength and change in critical flaw size of laminated composite at elevated temperature. It should be noted that the model has no any fitting parameter, which is an easy-to-use method for the engineering.

1. Introduction

The design of laminated structure of ultra-high temperature ceramic composites (UHTCCs) could improve the fracture toughness of materials significantly [1–4]. This promotes the applications of the ceramic composites for extreme environments.

Fracture behavior of laminated UHTCCs at elevated temperature has attracted wide attention. Wei et al. reported that the strength of laminated ZrB_2–SiC with BN layer decreases from 381 MPa at 20 °C to 111 MPa at 1500 °C, yet the composite with graphite layer still has great strength of 377 MPa at 1500 °C owing to the healing of surface microcracks and pores by the SiO_2 glass phase formed under high temperature oxidation [5]. Wei et al. tested the fracture properties of laminated ZrB_2–SiC–BN composite and laminated ZrB_2–SiC–graphite composite at 20 °C, 1300 °C and 1500 °C for 0.5 h, 2 h and 5 h in air [6]. The fracture strength of the laminated ZrB_2–SiC–graphite composite was reported to be always higher than that of the laminated ZrB_2–SiC–BN composite within the temperature and time range. And the changing trends of fracture strength of the two kinds of laminated composites with temperature showed great difference. This was caused by the difference of changes in microstructures with increase of temperature. For example, the healing of surface flaws by the glassy phase SiO_2 after oxidation and the viscous bridging of ZrO_2 and SiO_2 occurred in the laminated ZrB_2–SiC–graphite composite, leading to the beneficial effect on the improvement of fracture strength [6]. The experimental studies indicated that the temperature dependence of fracture strength and the effect of change in microstructure should be considered. However, it can also be observed that the existing experimental measurements are quite dispersed. On the theoretical side, Wang et al. developed a fracture strength model for laminated ZrB_2 based composites considering effect of temperature [7], which is an only theoretical model that can be found for predicting temperature dependence of strength of laminated ceramic composites. Yet the derivation process of the model is quite complicated, especially for the determination of the stress distributions on the crack surface and the stress concentration in the extreme environments. This leads to the hardly understanding and inconvenience of the model prediction for the engineering. Additionally, the fracture of laminated ceramic composites is a quite complicated process, especially at elevated temperatures. It involves the microstructures in the each layer such as micro and macro voids or

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cracks, clusters and the interface between two phases, the laminated structure and the temperature [5–7]. The characterization of effects of temperature, microstructures and laminated structures and their changes with temperature on the fracture strength of materials is very difficult. Typical of brittle fracture, the fracture strength of the laminated ceramic composites can be thought to be controlled by the critical flaw size in the materials. The critical flaw size is the value of the strength limiting flaw i.e. critical flaw in the materials, which is related to the microstructures such as grain, cluster, pores and the interface conditions and the laminated structures. In this work, for simplicity, the critical flaw size and its change with temperature are introduced to show the effects of microstructures and laminated structures on the fracture strength of the laminated ceramic composites at elevated temperatures.

In this paper, a novel and simple temperature dependent fracture strength model for laminated UHTCCs was developed just by using the primary and simple method. The theoretical method could describe critical flaw size evolution and laminated structure dependencies of fracture strength of materials. The model prediction agreed well with experimental measurement.

2. Theoretical model

The fracture of laminated composite is related to a layer having greatest fracture strength, which is determined by inherent strength of the layer and the surface compressive stress or weak phases. Here the solid model is a symmetrical laminated structure, which has two certain materials (as shown in Fig. 1). The layers of the first component are designated as material 1; the layers of the second component are designated as material 2. The thermal expansion coefficient of even layer is higher. In the case of the laminated structure, the number of layers designated as material 1 is n+1, and the number of layers designated as material 2 is n. In this work, the temperature dependence of fracture behavior of laminated ceramic composites is developed by using Griffith energy method and a concept of energy storage capacity.

According to the Griffith energy criterion, the change of strain energy of a specimen unit thickness due to the presence of a crack can be calculated from the expression

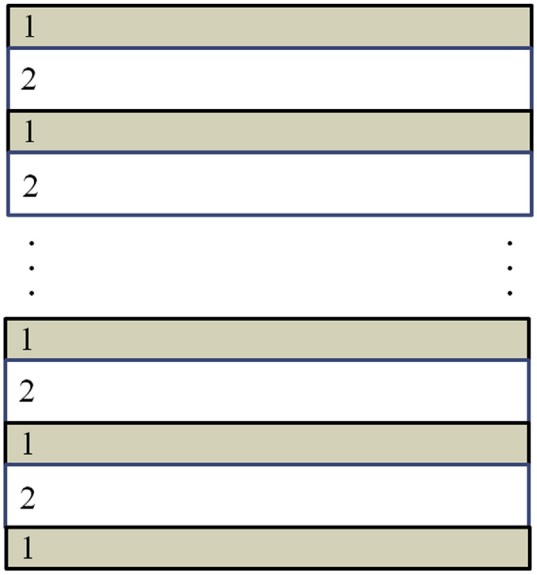

Fig. 1. Solid model of laminated structures.

$$W_c = \frac{-\pi s^2 \sigma^2}{E} \tag{1}$$

where s is crack size; E is Young's modulus; σ is applied stress. Then the strain energy for breaking the bonds of unit cracking area can be expressed as [8].

$$W_\sigma = -\frac{\partial W_c}{\partial(2s)} = \frac{\pi s \sigma^2}{E} \tag{2}$$

As described by the Griffith fracture theories, the fracture strength of brittle materials is generally thought to be controlled by the critical flaw size. The critical flaw size of materials is determined by the microstructures such as grain, cluster, pores and the interface conditions. For the laminated ceramic composites, the fracture strength is governed by the critical flaw size of the layer having greatest strength. Under such circumstance, in Eq. (2) W_σ is the critical strain energy release rate; s becomes the critical flaw size of the layer; σ includes external applied stress and compressive stress. Then W_σ can be expressed as

$$W_\sigma = \frac{\pi s_c (\sigma_a + \sigma_{res1})^2}{E_1} \tag{3}$$

where s_c is the critical flaw size; σ_a is the external applied stress which is equal to fracture strength; σ_{res1} is the compressive residual stress; E_1 is the Young's modulus of the layer designated as material 1.

For the compressive residual stress generated according to the symmetrical laminated structure can be expressed as

$$\sigma_{res1} = -\frac{nE_1E_2d_2(\alpha_2 - \alpha_1)(T_s - T_r)}{n(1-\nu_1)E_2d_2 + (n+1)(1-\nu_2)E_1d_1} \tag{4}$$

where T_s is the sintering temperature; T_r is the room temperature; d_1 and d_2 are the thickness of the layers designated as material 1 and material 2 respectively; and other parameters including Young's modulus E, thermal expansion coefficient α and poisson's ratio ν are material parameters of material 1 and material 2.

In this work, a concept of a maximum storage of energy of brittle materials during fracture is employed to develop the temperature dependence of fracture strength. The energy can be expressed by both elastic energy and quantity equivalent heat energy [9], which can be expressed as

$$W_{TOTAL} = W_\sigma(T) + kW_T(T) \tag{5}$$

where W_{TOTAL} is energy storage capacity unit volume; $W_T(T)$ is the heat energy per volume; $W_{\sigma_{th}}(T)$ is temperature dependent critical strain energy release rate; k is the ratio coefficient between the strain energy and the heat energy.

Considering effects of temperature, the critical strain energy release rate can be expressed as

$$W_\sigma(T) = \frac{\pi s_c(T)\left(\sigma_f(T) + \sigma_{res1}(T)\right)^2}{E_1(T)} \tag{6}$$

where $s_c(T)$ is the critical flaw size of materials at temperature T; $\sigma_f(T)$ is the fracture strength of materials at temperature T; $E_1(T)$ is the Young's modulus of the layer designated as material 1 at temperature T. In Eq. (6) the effects of temperature dependent fracture strength and critical flaw size are included. The temperature dependent compressive residual stress $\sigma_{res1}(T)$ can be expressed as