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Feature article

Temperature dependent first matrix cracking stress model for the unidirectional fiber reinforced ceramic composites

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ABSTRACT

Based on a kind of equivalence between heat energy and fracture energy, assuming that there is a constant maximum storage of energy that includes both heat energy and fracture energy, a new temperature dependent fracture surface energy model is developed. Using the new model and the classical ACK theory, a temperature dependent first matrix cracking stress model is obtained for the fiber reinforced ceramic composites. According to the model, the temperature dependent first matrix cracking stress of materials can be easily predicted using some basic material parameters such as matrix fracture surface energy and Young's modulus. The model is verified by comparison with experimental data of SiC fiber reinforced reaction-bonded Si_3N_4 composites at different temperatures. Good agreement is obtained between predicted and experimental data of first matrix cracking stress. The dependency of first matrix cracking stress on fracture surface energy and interfacial shear strength is systematically analyzed.

1. Introduction

Ceramic materials are the prime candidates for high-temperature applications such as turbine engine and thermal protection systems [1–4], owing to their low density, high porosity and high temperature capability. But their high degree of brittleness and low toughness render them highly susceptible to catastrophic failure during service, which limit their wide use [5,6]. The addition of fiber has been considered as the most promising approach to overcome the inherent shortcomings of monolithic ceramics [7,8]. Fiber reinforced ceramic matrix composites (CMCs) not only provide the ability for retaining the great properties of monolithic ceramics but also improve their mechanical behavior such as toughness and strength [5,9,10]. Therefore, they have received a great deal of consideration for practical use in high-temperature structural applications. In generally, fiber reinforced CMCs display damage associated with the interface or matrix well before final fracture due to the relatively low strain capability of matrix [10]. When the composite material is subjected to a stress along the fiber direction, a critical stress at which the composites exhibit first evidence of matrix cracking is defined as first matrix cracking stress (FMCS) [11]. If the applied stress exceeds the FMCS, it will cause irreversible damage to composite especially at high temperature [11]. For instance, air infiltrates to interfacial regions through matrix cracking will result in enhanced oxidation of oxidizable fibers or fiber/matrix interface [5,11–14]. Therefore, FMCS is a crucial parameter for fiber reinforced CMCs during service, and it is also considered as a design stress of fiber reinforced CMCs for thermostructural applications.

In the past, both theoretical and experimental investigations have been carried out by many investigators to understand the matrix cracking behavior of the unidirectional fiber reinforced CMCs [14]. For the theoretical research, based on the energetics of multiple fracture associated with a brittle matrix composites, Aveston, Cooper and Kelly (ACK theory) [15] derived an equation which could be used to predict the FMCS in materials. Another equation was developed by Marshall and Cox [16] to predict the FMCS according to the crack closure pressure and linear elastic fracture mechanics method, and their equation was similar to those of ACK. The energy balance approach and the fracture theory were used by Bernard, Hutchinson and Evans (BHE) [17] to study the critical conditions for the onset of widespread matrix cracks composites, which the residual thermal stress was included in their model. Based on the BHE model, M. Sutcu and W. Hillig [18] further

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studied the effect of fiber-matrix bonding on the matrix cracking strength. In the aspect of experimental research, Yih-Cherng Chiang [19] investigated the fiber volume fraction on the matrix cracking stress. The effect of some microstructural factors on the FMCS was studied at the microstructural level by Michel W. Barsoum [20] to obtain a better understanding of the matrix cracking mechanisms. In the contemporary researches, the proportional limit obtained by a traditional stress-strain curve is widely regarded as the initiation of matrix cracking, while Ran Y. Kim [10] found out that the proportional limit overestimated the value of FMCS, it is hard to determine the FMCS accurately through stress-strain curve at some extent. Most of the previous studies concentrated on describing or studying the factors and mechanisms influencing the FMCS of fiber reinforced CMCs, which are very helpful to understand the matrix cracking behavior of composites, but much less attention has been directed to the quantitative effect of temperature on the FMCS of materials. Fiber reinforced CMCs are often inevitable to subject to extremely high temperature environment during service. In reality, temperature has significant influence on the mechanical behavior of materials [21–23].

However, for experimental studies, the test temperatures are hard to meet the demands of actual high-temperature applications. Also, experimental tests at high temperatures are technically difficulty to conduct and laborious as lots of specimens and time are needed, especially at ultra-high temperatures. For theoretical studies, most of the existing theoretical matrix cracking models for the fiber reinforced CMCs can only be used at normal temperature ranges, there are few first matrix cracking stress model for high temperatures. Thus, we decided to further investigate the effect of temperature on the matrix cracking behavior. The principal objective of the present study is to develop a temperature dependent FMCS model for the unidirectional fiber reinforced CMCs.

As the energy needed for the formation of crack at different temperature is different, the fracture surface energy is temperature dependent. In this paper, a new temperature dependent fracture surface energy model is developed. This model is based on a definition of maximum storage of energy. From the viewpoint of energy, the model reveals the quantitative relationship between temperature and fracture surface energy. Using the proposed model and the classical ACK theory, a temperature dependent first matrix cracking stress model is developed for the unidirectional fiber reinforced CMCs. The effects of temperature, matrix fracture surface energy, interfacial shear strength, Young's modulus and residual thermal stress on the FMCS are included in the proposed model. The model predictions are presented for SiC fiber reinforced reaction-bonded Si_3N_4 (SiC_f/RBSN) composites, which agree well with the experimental data. Besides, we study the sensitivity of FMCS to matrix fracture surface energy and interfacial shear strength by the model, the results show that the FMCS can be enhanced by improving the matrix fracture surface energy and interfacial shear strength. The paper will help us to explore those potential materials with the ultra-high temperature properties needed for extreme engineering applications.

2. Theoretical model

2.1. A new temperature dependent fracture surface energy model

Based on the Griffith fracture theory, Wang [24] proposed a temperature dependent fracture surface energy model for the first time, which is given as follow:

$$\gamma_m(T) = \gamma_m^o \left[1 - \frac{\int_0^T C_P(T)\,dT}{\int_0^{T_m} C_P(T)\,dT} \right] \tag{1}$$

where $\gamma_m(T)$ and $\gamma_m^o$are the fracture surface energy of materials at temperature T and at reference temperature, absolute zero, respectively;$C_p(T)$ is the specific heat capacity for constant p pressure and temperature T; T_m is the melting point.

This model could characterize the effect of temperature on the fracture surface energy well. According to the model, if γ_m^o is obtained, it is easy to predict the fracture surface energy of ceramics at different temperatures, because the heat capacity can be easily found in material handbook. However, in many cases, the fracture surface energy at absolute zero temperature,γ_m^o, is difficult to get by experiment. The reference temperature in Eq. (1) limits the use of this model. Therefore, a new temperature dependent fracture surface energy model with an arbitrarily reference temperature can be deduced as follows:

We assume that there is a maximum constant energy storage per unit volume which is associated with the onset of material fracture for a particulate material. This energy can be provided by both fracture energy and heat energy. It is assumed that there is a quantity equivalent relation between the fracture energy and the corresponding heat energy according to their contribution to fracture of material. Based on the above assumptions and the viewpoint of energy in our previous work [22], the maximum energy storage per unit volume has the form:

$$W_{\text{Total}} = W_F(T) + K s_o h_o W_T(T) \tag{2}$$

where W_{Total}(in J) is the maximum energy storage per unit volume;K(dimensionless), assumed constant, is the transformation coefficient between the fracture energy and the heat energy; s_o(in m^2)andh_o(in m) are unit area and unit thickness, respectively; $W_F(T)$(in J) is the fracture energy associated with the formation of crack surface at temperature dependent T, which can be expressed as:

$$W_F(T) = 2\gamma_m(T) s_o \tag{3}$$

where $\gamma_m(T)$ is the fracture surface energy of material at temperature T

$W_T(T)$ (inJ/m^3) is the heat energy per unit volume at temperature T,which can be expressed as:

$$W_T(T) = \int_0^T \rho C_P(T)\,dT \tag{4}$$

where $C_P(T)$ is the specific heat capacity for constant pressure and temperature T; ρ is the density (here, ρ is set as a constant due to its weak dependence of temperature).

When $T = T_m$, the melting point of the material, the fracture energy entirely transforms into the heat energy, thus,

$$W_F(T_m) = 0$$

$$W_{\text{Total}} = K s_o h_o W_T(T_m) = K s_o h_o \int_0^{T_m} \rho C_P(T)\,dT \tag{5}$$

When $T = T_o$in Eq. (2), where T_0 is an arbitrarily reference temperature, we can obtain that:

$$W_{\text{Total}} = 2\gamma_m(T_o) s_o + K s_o h_o \int_0^{T_o} \rho C_P(T)\,dT \tag{6}$$

The combination of the Eqs. (5) and (6) yields

$$K h_o = 2\gamma_m(T_o) / \int_{T_o}^{T_m} \rho C_P(T)\,dT \tag{7}$$

Substituting Eq. (7) into Eq. (2) yields

$$W_{\text{Total}} = 2\gamma_m(T) s_o + 2\gamma_m(T_o) s_o \int_0^T \rho C_P(T)\,dT / \int_{T_o}^{T_m} \rho C_P(T)\,dT \tag{8}$$

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