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Effects of particle size and matrix grain size and volume fraction of particles on the toughening of ceramic composite by thermal residual stress

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Abstract

Toughening by thermal residual stresses is one of the effective toughening mechanisms in ceramic composites when the coefficient of thermal expansion of the dispersed particles is larger than that of the matrix grains. Based on this toughening mechanism, exploration of factors affecting the toughening of ceramic composite by thermal residual stress is the focus of the investigation in the present study. Results are verified for the TiB_2/SiC ceramic composite. It is shown that particle size and matrix grain size and volume fraction of particles and the particle size ratio is closely related to the toughening increment. It suggests that the investigation will lead practically to actual applications of the findings in the composition design and the microstructural design of the particulate reinforced ceramic composites.

Keywords: B. Composites; C. Toughness and toughening; Thermal residual stress

1. Instruction

The intrinsic brittleness is a key problem in the widespread application of the ceramic materials. In order to reduce the brittleness and to increase the strength and the toughness, varieties of toughening mechanisms [1–6], such as the crack deflection, crack bridging, crack branching, crack bowing, crack pinning, microcracking, thermal residual stress toughening, transformation toughening and the synergism toughening, etc. have been proposed in the past decades. Furthermore, methods of the ceramic material design such as the interfacial stress design have been adopted to help solve the problem [7]. As a result, the mechanical properties and performances and the reliability of the composite ceramic materials have been significantly improved. However, the problem remains unscanned and the scope of the current researches still remains to be widened and deepened to achieve viable results in the selection and design of reinforcing phases and toughening mechanisms.

When the coefficient of thermal expansion of the dispersed phase is larger than that of the matrix material, thermal residual stress resulted from the mismatch between the coefficients of thermal expansion (CTEs) of the ceramic matrix and particulates will become the dominant toughening mechanism in ceramic materials. At first, Wei and Becher [8] considered the thermal residual stress which is induced by CTE mismatch as a major cause for the crack deflection although they have made no quantitative estimate of the increased toughness. Virkar et al. and Evans et al. [9–11] explained the toughening mechanism in ZrO_2–Zr composite material and cemented carbides with the periodic thermal residual stress model. Then, Taya et al. [12] studied the toughening mechanism of the particulate reinforced TiB_2/SiC ceramic material. They pointed out that the toughening effect of thermal residual stress is approximately three times higher than that of crack deflection. Results predicted from the analytical model based on the compressive thermal stress in the matrix in particulate

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reinforced ceramic matrix composite are in better agreement with the experiments.

On the other hand, a maximum volume fraction of the dispersed phase exists just because of the thermal residual stress [13,14]. When the content exceeds the maximum value, the material will fracture without any external load resulted from the overload in the tensile thermal stress and then mechanical properties of the materials will undoubtedly decrease. According to this, two models have been built for the determination of the maximum volume fraction of the dispersed phase in ceramic composites when the coefficient of thermal expansion of the dispersed phase is less than that of the matrix. These models are used well in the development of the Al_2O_3/TiB_2 [13] and Al_2O_3/SiC/(W, Ti)C [14] ceramics. Therefore, the determination of the maximum volume fraction of the dispersed phase is one of the significant parts in the composition design of the composite ceramic materials.

In the present study, effects of particle size and matrix grain size and volume fraction of particles and the particle size ratio on the toughening of ceramic composite are analyzed in detail with an example of TiB_2/SiC ceramic material based on the toughening mechanism of thermal residual stress.

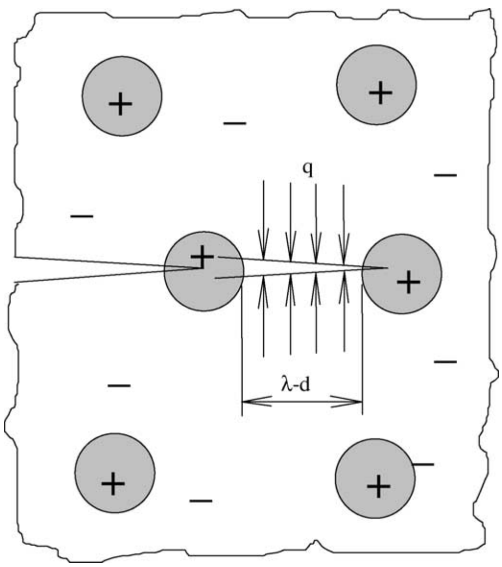

Fig. 1. Analytical model of the toughening mechanism by thermal residual stress [12].

2. Relationship between the toughening effect and volume fraction and particle size

2.1. Theoretical basis

According to Taya et al. [12], the thermal residual stress field in a TiB_2/SiC composite consists of two regions: the tensile stress region in the particulates and their vicinity in the matrix, and the compressive stress region in the bulk of the matrix, as shown schematically in Fig. 1. Consider a semi-infinite crack surrounded by a particulate reinforced ceramic matrix composite with a thermal residual stress distribution as shown in Fig. 1. For the purpose of fracture mechanics analysis, this residual compressive stress can be approximated by an averaged uniform compressive stress, acting normal to the crack plane ahead of a semi-infinite crack. The semi-infinite crack is assumed to advance from one concentrated tensile region to its nearest counterpart. Since the existence of the periodic thermal residual stress field in the particulate reinforced ceramic composite, the fracture toughness K_{IC} of the material is expressed as [11,12]:

$$K_{IC} = K_{I0} + 2q\sqrt{\frac{2D}{\pi}} \tag{1}$$

where K_{I0} is the critical stress intensity factor of the matrix, q is the local thermal residual compressive stress, D is the length of the compressive stress zone which in this case is the average particulate spacing. If the dispersed phase of the same grain size is distributed uniformly in the matrix, then $D = \lambda - d$, where the average distance between the particles of the dispersed phase is λ.

Eq. (1) is based on a stress intensity factor solution by Tada et al. [15] for a semi-infinite two-dimensional crack with a compressive stress zone of intensity q and length D. The compressive thermal residual stress in the matrix is generated when the CTE of the particulate exceeds that of the matrix. Indeed this is the case with the TiB_2-particulate/SiC-matrix [16–18] and TiC-particulate/SiC-matrix composites [17]. Both Cutler and Virkar and Chermant and Osterstock experimentally observed the $\sqrt{D}$ dependence of K_{IC} [10,19]. It was also found [10] that q is a strong function of the volume fraction of the second phase and larger values of q resulted in larger K_{IC}.

The existence of the local stress, q, for TiB_2/SiC composite example, decreases the stress intensity factor, ΔK_I. From Eq. (1) this decrease is

$$\Delta K_I = K_{IC} - K_{I0} = 2q\sqrt{\frac{2(\lambda - d)}{\pi}} \tag{2}$$

where [12]

$$\lambda = \frac{1.085d}{V_P^{1/2}} \tag{3}$$

$$q = \langle\sigma_m\rangle = \frac{2E_m V_P \beta \alpha_1^*}{A} \tag{4}$$

$$A = (1 - V_P)(\beta + 2)(1 + \nu_m) + 3\beta V_P(1 - \nu_m) \tag{5}$$

where $\langle\sigma_m\rangle$ is the average stress field in the matrix, V_P means the volume fraction of the dispersed phase, α_1^* indicates the strain inside the particulate resulted from the difference in the thermal expansion, $\alpha_1^* = \int_{T_P}^{T_R}(\alpha_P - \alpha_m)\,dT$, where T_R means the room temperature, T_P is the temperature where the