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Technical note

A thermal-shock-resistance model for laminated ceramics and its validation

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Abstract

A new thermal-shock-resistance (TSR) model for laminated ceramics was developed based on the TSR model for un-laminated ceramics. In the new model, the critical thermal shock temperature difference ΔT_c is directly correlative to the mechanical and physical properties of laminated ceramics. The ΔT_c of laminated ceramics with different compositions and structures were calculated and compared with the experimentally tested values to validate the new model. The results indicated that the calculated ΔT_c agreed well with the experimental results. It is concluded that the analytic TSR model for laminated ceramics could be used as a full qualitative or half quantitative analysis tool to explain and forecast the TSR of laminated ceramics.

Keywords: Thermal-shock-resistance; Laminated ceramics; Interface; ZrO_2; Al_2O_3

1. Introduction

Different theories for thermal-shock-resistance (TSR) evaluation fall into two broad categories: the thermal shock fracture theory and the thermal shock damage theory.[1–9] However, each theory has its own limitations and shortages to some extent. To overcome the situation, the author proposed an analytic TSR model for ceramics to unify the above two theories successfully.[10] According to the model, the critical thermal shock temperature difference ΔT_c of ceramics can be calculated using some basic property parameters.

Unfortunately, the above model is not applicable to laminated ceramics due to their special structures.

In this paper, we attempt to develop an improved TSR model for laminated ceramics from the model in.[10] Moreover, two sorts of laminated ceramics were prepared, and the critical thermal shock temperature difference ΔT_c tested in experiment were compared with the values predicted by the model. The results proved its effectiveness.

2. New TSR model for laminated ceramics

For laminated ceramics, inner interfaces exist among different layers with different compositions, residual stress occurs in these dissimilar layers after sintering because of their different linear coefficients of thermal expansion. Compressive residual stress is produced in the layers with lower linear coefficient of thermal expansion, while tensile residual stress in the layers with higher one.

2.1. New TSR model for three-layer ceramics

For convenience of model building, we consider the ceramics with only three layers first.

Generally three-layer ceramics are formed by two surface layers with the same composition and one center layer with another composition (see Fig. 1). Lower linear coefficient of thermal expansion in the surface layers but higher one in the center layer will lead to residual compressive stress in the surface and tensile stress in the center after sintering. The compressive stress will counteract part of the thermal stress caused by temperature difference in the interface. The existence of interfaces will conduce to cracks' deflexion and cracks' propagation. Therefore, laminated ceramics is superior to un-laminated ceramics in TSR behavior.

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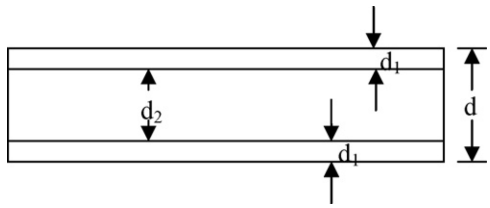

Fig. 1. Schematic of three-layer composite ceramic.

Compressive and tensile stresses are generated from the interaction between surface and center layers. According to the equilibrium of forces:

$$\frac{2d_1\sigma_1}{E_1} = -\frac{d_2\sigma_2}{E_2} \tag{1}$$

where d_i ($i = 1, 2$) is thickness; σ_i is stress; E_i is Young's modulus; and subscripts 1 and 2 denote surface and center layer, respectively.

According to Cleveland and Braett,[11] the strain ε induced from thermal mismatch between different layers is

$$\varepsilon = \Delta\alpha \ \ \Delta T \tag{2}$$

where $\Delta\alpha$ is linear coefficient of thermal expansion difference of layers.

By Hooke's law, considering the effect of layer thickness on stress, we obtain

$$\sigma_1 = -\frac{\varepsilon \cdot E_1 d_2}{d(1-\mu)} \tag{3}$$

where d is total thickness of specimen, and μ is Poisson's ratio of laminated composite.

Furthermore, we derived in[10] that (the deduction of Eq. (4) is shown in[10])

$$\frac{\sigma_H^2(1-\mu)V}{E} \geq \frac{\sigma_f^2(1-\mu)V}{E} + \frac{2ANK_{IC}^2}{2E} \tag{4}$$

Considering the effect of compressive stress on thermal stress, one has

$$\frac{(\sigma' + \sigma_1)^2 \cdot (1-\mu)V}{E} \geq \frac{\sigma_f^2(1-\mu)V}{E} + \frac{2ANK_{IC}^2}{2E} \tag{5}$$

where $\sigma_{\rm H}$ is thermal stress for un-laminated ceramics but σ_H' for laminated ceramics; V is volume of the material; N is number of cracks; A is half crack surface area; and E, σ_f, and K_{IC} are Young's modulus, fracture strength, and fracture toughness of laminated composites, respectively.

Therefore, the thermal shock temperature of three-layer ceramics is

$$\Delta T_{\rm c} \geq \left[\frac{b(1-\mu)K_{IC}^4 + (1-\mu)^2\sigma_f^4}{(E\alpha - E_1 \ \ \Delta\alpha(d_2/d))^2\sigma_f^2}\right]^{1/2} \tag{6}$$

$$\Delta T_{\rm c} \geq \left[\frac{b(1-\mu)\lambda^2 K_{IC}^4 + (1-\mu)^2\lambda^2\sigma_f^4}{\rho^2 c^2(E\alpha - E_1 \ \ \Delta\alpha(d_2/d))^2\sigma_f^2}\right]^{1/2} \tag{7}$$

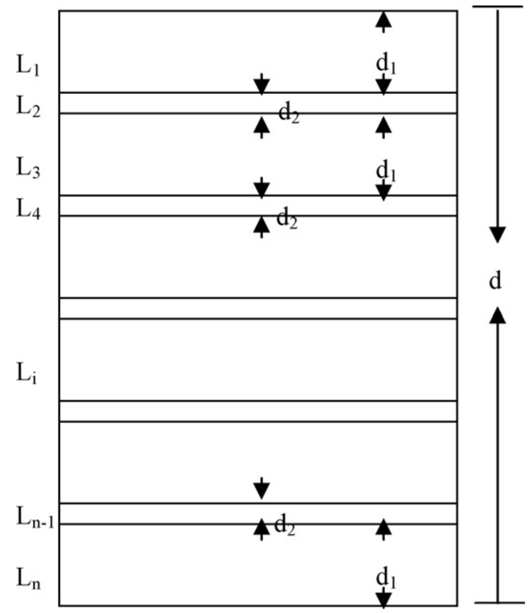

Fig. 2. Schematic of multi-layer composite ceramic.

where λ, ρ, c are coefficient of thermal conductivity, density, and thermal capacitance of laminated composites, respectively; and b is supposed a constant only correlative to the material. (See[10] for more details.)

Eqs. (6) and (7) give the critical thermal shock temperature difference $\Delta T_{\rm c}$ for three-layer ceramics under quick heating (or cooling) condition and at constant heating (cooling) rate, respectively. They reveal that the critical thermal shock temperature difference $\Delta T_{\rm c}$ of three-layer ceramics is correlative to its mechanical and physical properties.

2.2. *New TSR model for multi-layer ceramics*

Multi-layer structure usually contains tens to even hundreds of layers. According to the structure design of multi-layer ceramics, thin layers with low strength (i.e. weak layers) must be in between any two strong thick layers (see Fig. 2). When cracks extend to interfaces, they will deflex into the weak layers. After many similar deflexions, the expanding routes of cracks in laminated ceramics are remarkably prolonged, resulting in a higher toughness.[12]

In a similar way to Eq. (1), we obtain

$$\frac{(n+1)d_1\sigma_1}{E_1} = -\frac{(n-1)d_2\sigma_2}{E_2} \tag{8}$$

where n is the number of layers.

Through the same deduction as in Section 2.1, the final thermal shock temperature difference of multi-layer ceramics is derived as follows:

$$\Delta T_{\rm c} \geq \left[\frac{b(1-\mu)K_{IC}^4 + (1-\mu)^2\sigma_f^4}{(E\alpha - E_1 \ \ \Delta\alpha((n-1)d_2/2d))^2\sigma_f^2}\right]^{1/2} \tag{9}$$

$$\Delta T_c \geq \left[\frac{b(1-\mu)\lambda^2 K_{IC}^4 + (1-\mu)^2\lambda^2\sigma_f^4}{\rho^2 c^2 (E\alpha - E_1\ \Delta\alpha((n-1)d_2/2d))^2 \sigma_f^2} \right]^{1/2} \quad (10)$$

Eqs. (9) and (10) present the critical thermal shock temperatures difference ΔT_c of multi layers' ceramics under quick heating (or cooling) condition and at constant heating (cooling) rate, respectively. Note that when n is 3, Eqs. (9) and (10) turn into Eqs. (6) and (7), respectively. Therefore, Eqs. (6) and (7) can be regarded as a special case of Eqs. (9) and (10), respectively.

Similar to the model for un-laminated ceramics in,[10] the new model can also be used as a full qualitative or a half quantitative analysis tool for forecasting of the TSR of laminated ceramics.

3. Experimental

3.1. Materials preparation

To validate the new model, Al_2O_3–ZrO_2 three-layer ceramics with different compositions were prepared in experiments. The structure of the three-layer ceramics is shown in Fig. 1, where the center composition is always 5 wt%Al_2O_3 + ZrO_2 but the surface composition is 20, 30, or 40 wt%Al_2O_3 + ZrO_2. Besides, the thickness of the surface layer and the center layer is $d_1 = 0.3 \pm 0.1$ mm and $d_2 = 5.4 \pm 0.2$ mm, respectively, so the total thickness d is 6.0 ± 0.4 mm.

The composite powders were dry-pressing molded at room temperature. Then the compacts were pressureless sintered at 1620 °C.

The multi-layer ceramics as shown in Fig. 2 were prepared. The thin layers were 100% BN, and the thick layers were 20, 30, or 40 wt%Al_2O_3 + ZrO_2. The thickness ratio of thick to thin layers was controlled at 10:1, and the number of layers was 11.

The strong and weak interface layers were fabricated by flow cast process, and then hot pressing sintered at 1500 °C, 20 MPa in Ar conditions.

The Al_2O_3–ZrO_2 three-layer ceramics with the surface layers being 20, 30, and 40 wt%Al_2O_3 + ZrO_2 were marked samples 1–3, respectively. And the multi-layer ceramics with the strong interface layers being 20, 30, and 40 wt%Al_2O_3 + ZrO_2 were marked samples 4–6, respectively.

3.2. Apparatuses and methods of analysis

The fracture strength σ_f was tested by Japan JIS R 1601 test standard, and the fracture toughness was determined by the indentation method.[13]

For the three-layer ceramics, the critical thermal shock temperature difference ΔT_c under quick cooling condition was tested by the residual strength method.[14] Different temperatures (ΔT) from 150 to 800 °C with an interval of 50 °C were designed. Specimens were cut into 36 mm × 4 mm × 3 mm (the span is 30 mm), separately heated to the preset temperature point, and held at the constant temperature. Then the specimens were put into flowing cold water (which was supposed 0 °C) quickly till cooled down. The flexural strengths of the specimens before and after thermal shock were measured by three-point bend tests. In the $\sigma_b - \Delta T$ curve (Fig. 3), the temperature at the last point before the strength σ_b has an abrupt decline is defined to be the critical thermal shock temperature difference ΔT_c.

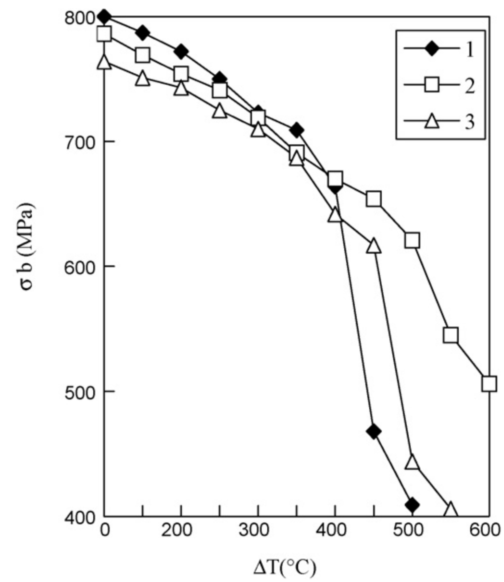

Fig. 3. Residual strength of three-layer ceramics after thermal shock for different temperature change.

The ΔT_c of the multi-layer ceramics under quick cooling condition was tested by the indentation method (early test results revealed that ΔT_c was hard to be determined in the $\sigma_b - \Delta T$ curve of the multi-layer ceramics). Specimens were polished and pre-cracks on the one surface were produced through indentation of 200 N load with a Vickers diamond. The crack lengths were measured by the optical microscope before and after thermal shock tests to calculate the crack extending rate R_e (i.e. the ratio of the extending cracks' length to the original cracks' length). The heating and cooling procedures are the same as those in the residual strength method. According to,[15,16] in $R_e - \Delta T$ curve (Fig. 4), the point before a crack length increases abruptly where the crack extending rate is less than 10% is defined as ΔT_c.

In our experiments, every value of ΔT_c was an average tested result from 5 specimens.

4. Results

The ΔT_c of two sorts of laminated ceramics are shown in Figs. 3 and 4. According to Figs. 3 and 4, the ΔT_c of samples 1–3 are 400, 500, and 450 °C, respectively; and the ΔT_c of samples 4–6 are 600, 650, and 550 °C, respectively.

5. Validation

For different layer of laminated ceramics, according to the basic theory of the composite materials, some parameters of bulk composites, such as Young's modulus, linear coefficient of thermal expansion, and Poisson's ratio, could be calculated (see Eqs. (19)–(23) in[10]).

Furthermore, based on the above calculating results, the E, α and μ of laminated composites and the volume fraction of

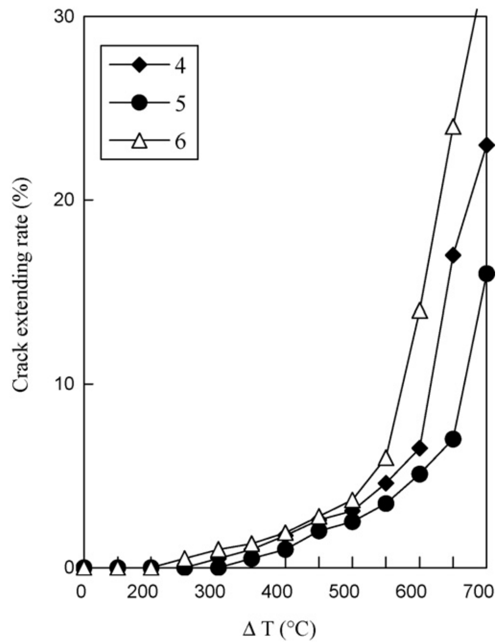

Fig. 4. Crack extending rate (R_e) of multi-layer ceramics after thermal shock for different temperature change.

different layers V_i are calculated by Eqs. (11)–(14).

$$E = \frac{n+1}{2} E_1 V_1 + \frac{n-1}{2} E_2 V_2 \tag{11}$$

$$\alpha = \frac{(n+1)\alpha_1 E_1 V_1 + (n-1)\alpha_2 E_2 V_2}{(n+1)E_1 V_1 + (n-1)E_2 V_2} \tag{12}$$

$$\mu = \frac{n+1}{2} \mu_1 V_1 + \frac{n-1}{2} \mu_2 V_2 \tag{13}$$

$$V_1 = \frac{(n+1)d_1}{2d}, \qquad V_2 = \frac{(n-1)d_2}{2d} \tag{14}$$

where subscripts 1 and 2, for three-layer ceramics, denote surface and center layers, respectively; but for multi-layer ceramics, denote strong and weak interface layers, respectively.

The mechanical properties and thermal physical properties of different samples are listed in Tables 1 and 2. The calculated ΔT_c and tested ΔT_c are listed in Table 3. (In Eq. (6), parameter b is supposed to be 1.6×10^7 m^{-2}, and the reason has been discussed in Ref.[10]).

The results show that the varying trend of the critical thermal shock temperature difference ΔT_c obtained by model and tests are similar, and the calculated ΔT_c is close to the tested ΔT_c on the whole. Therefore, it can be concluded that the TSR of the ceramics can be forecasted with their other mechanical properties.

Table 1
Mechanical properties of different laminated ceramics.

Sample	Fracture strength σ_f/MPa	Fracture toughness K_{IC}/MPa m$^{1/2}$
1	556	12.26
2	572	13.24
3	541	12.41
4	375	13.64
5	407	14.67
6	402	14.43

Table 2
Some physical properties of different laminated ceramics.

Sample	Young's modules E/GPa	Linear coefficient of thermal expansion $\alpha/10^{-6}$ K^{-1}	Poisson's ratio μ
1	235	9.4	0.32
2	237	9.4	0.32
3	239	9.4	0.32
4	265	9.0	0.30
5	284	8.9	0.29
6	297	8.8	0.28

Table 3
Comparison between calculated ΔT_c and tested ΔT_c for different laminated ceramics.

Sample	Calculated ΔT_c/°C	Tested ΔT_c/°C
1	409	400
2	516	500
3	471	450
4	637	600
5	654	650
6	585	550

6. Conclusions

(1) A new revised TSR model for laminated ceramics was established, which reveals that the critical thermal shock temperature difference ΔT_c is directly correlative to the mechanical and physical properties of the laminated ceramics.
(2) For validating the model, different Al_2O_3–ZrO_2 matrix three-layer and multi-layer ceramics were prepared, and the critical thermal shock temperature difference ΔT_c were tested. The results show that the ΔT_c of the multi-layer ceramics are higher than those of three-layer ceramics.
(3) The critical thermal shock temperature difference ΔT_c is calculated using the proposed model, and the calculated values appear close to the experimentally tested ΔT_c. Therefore, the new model may be used as a full qualitative or a half quantitative analysis tool for forecasting the TSR of the laminated ceramics.

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