The indentation thermal shock behavior of laminated ZrB₂-SiC ceramics with strong interfaces

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Abstract

The thermal shock behavior of laminated ZrB₂-SiC ceramics with strong interfaces has been investigated by indentation-quench method through experiments and modeling, and was compared with that of a reference monolithic ZrB₂-SiC ceramic. The residual stress formed in the layers of laminated ZrB₂-SiC ceramics was also quantified by indentation technique. Results obtained by indentation-quench tests show that the monolithic and laminated ZrB₂-SiC ceramics present a similar crack growth behavior with increasing temperature difference. Nevertheless, the critical temperature difference, ΔT_c , of laminated ZrB₂-SiC ceramics is much higher than that of the monolithic ZrB₂-SiC ceramic. A theoretical model considering all the stress intensity factors at the surface crack tip during thermal shock was established to analyze the mechanism of indentation thermal shock, which is in good agreement with the

experimental results. What's more, theoretical results show that the contribution of residual surface compressive stresses in laminated $\text{ZrB}_2\text{-SiC}$ ceramics to stress intensity make a negative contribution to the total stress intensity at the crack tips during thermal shock, which result in a better thermal shock resistance of laminated ceramics than monolithic ceramic.

Keywords: Indentation thermal shock behavior; Laminated ceramics; Stress intensity; $\text{ZrB}_2\text{-SiC}$; Residual stress

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1. Introduction

ZrB_2 -based ceramics have outstanding physicochemical properties, such as high melting point and hardness, low electrical resistivity, high thermal conductivity and good chemical and physical stability at high temperatures [1–4]. The unique combination of these properties makes them an attractive candidate for a variety of ultra-high temperature applications [5–7]. Although ZrB_2 -based ceramics have many excellent properties, the low mechanical and thermal reliability caused by the inherently low fracture toughness must be improved before the potential applications can be fully realized. The laminated structure with the introduction of surface compressive stresses is one of new and effective strategies to enhance the fracture toughness of brittle ceramics in recent years, which are significantly different from the

conventional approach to achieve “flaw tolerance” in opposition to the traditional “flaw elimination” approach of the dense ceramics [8,9]. Unfortunately, up to date the laminated structure with strong interfaces in the ZrB_2 -based ceramics have been rarely investigated.

Our previous works [10-12] related to laminated ZrB_2 -SiC ceramics with strong interfaces indicated that mechanical properties are significantly enhanced by the presence of residual surface compressive stresses [13,14]. The present work aims at investigating the effect of geometrical structure parameter of laminated structures on the thermal shock resistance and action mechanism of residual surface stresses on the thermal shock behavior of laminated ZrB_2 -SiC ceramics. The results were compared to those obtained by the same tests carried out on a reference homogeneous ZrB_2 -SiC composite material.

2. Experimental procedure

2.1 Material preparation and mechanical properties

Commercially available ZrB_2 (mean particle size 2 μm , Northwest Institute for Non-ferrous Metal Research, China) and SiC (mean particle size 0.5 μm , Weifang Kaihua Micro-powder Co. Ltd., China) were used as raw materials. The fabricating steps of the laminated ZrB_2 -SiC ceramics (namely LZS ceramics) included: ball milling of powders in certain proportions, stacking layers in alternated sequence in graphite mold and hot-pressed sintering. The mixtures of ZrB_2 powder plus 20 vol.% SiC or ZrB_2 powder plus 30 vol.% SiC were ball-milled for 10 h in a polyethylene bottle using ZrO_2 balls and ethanol as the grinding media, followed by rotating evaporation to remove the solvent. After drying, the milled powders were put into a graphite die according to a certain quality ratio. The laminated samples with the total thickness of ~4 mm were prepared by alternately stacking ZrB_2 +30vol.%SiC (namely

ZS30) and $\text{ZrB}_2+20\text{vol.}\%\text{SiC}$ (namely ZS20) layers. Because of the different coefficients of thermal expansion (CTEs) between ZrB_2 ($6.7\times 10^{-6} \text{ }^\circ\text{C}^{-1}$) and SiC ($4.3\times 10^{-6} \text{ }^\circ\text{C}^{-1}$), the different SiC contents in the layers result in a thermo-elastic mismatch between adjacent layers during sintering. The $\text{ZrB}_2+30 \text{ vol.}\% \text{ SiC}$ layer has a lower CTE than $\text{ZrB}_2+20\text{vol.}\% \text{ SiC}$ layer. As a result, a uniformly biaxial residual stress parallel to the layer plane appears in the laminate. The $\text{ZrB}_2+30\text{vol.}\%\text{SiC}$ layers are under compressive stress, while the $\text{ZrB}_2+20\text{vol.}\%\text{SiC}$ layers are under tensile stress. It should be noted that the upper and lower surfaces of laminated samples are set as $\text{ZrB}_2+30\text{vol.}\%\text{SiC}$ layers. The laminated sample was hot pressed at 1950°C for 60 min under a uniaxial load of 30 MPa in Ar atmosphere. For the purpose of comparison, an unstressed reference monolithic ceramic with the composition of $\text{ZrB}_2+30\text{vol.}\%\text{SiC}$ was also fabricated by hot-pressed sintering. The specimens for mechanical tests and thermal shock measurements were cut from the same hot-pressed tiles. The microstructures and macroscopic cross-section features of the ZrB_2 -based ceramics were observed by scanning electron microscopy and optical microscope, respectively.

According to ASTM-D790 standard, flexural strength (σ) was tested by three point bending on $3\text{mm}\times 4\text{mm}\times 36\text{mm}$ bars, using a 30-mm span and a crosshead speed of 0.5mm/min. Each specimen was ground and polished with diamond slurries down to a $1 \mu\text{m}$ finish. The edges of all the specimens were chamfered to minimize the effect of stress concentration due to machining flaws. Fracture toughness (K_{IC}) was evaluated by a single-edge notched beam (SENB) test, according to ASTM-C1421-01b standard, with a 16-mm span and a cross-head speed of 0.05 mm/min using $2 \text{ mm}\times 4 \text{ mm}\times 22\text{mm}$ bars, on the same jig used for the flexural strength. For the laminated specimens, the tips of the notches were located in the $\text{ZrB}_2+30\text{vol.}\%\text{SiC}$ layers. The elastic modulus was measured by three-points bending tests with a 30-mm span by using a calibrated

strain gauge to measure the relationship between strain and applied load with a cross-head speed of 0.5 mm/min using 3 mm×4 mm×36 mm bars. Hardness was determined by a Vickers pyramid diamond indenter (model HvS-5) through ASTM-E92 standard, using a load of 5kg and a dwell time of 15s on polished sections. All flexural and fracture bars were cut with the tensile surface perpendicular to the hot-pressing direction. A minimum number of five specimens were tested under same experimental condition and the standard deviation was calculated as error bars.

2.2 Indentation thermal shock

Indentation technique was used to measure thermal shock resistance by observing the propagation of pre-indented cracks around a Vickers indentation after single or repeated quenching. In the present work, Vickers indents were introduced into disc-shaped samples ($\Phi=6.5$ mm, $h=4$ mm) with parallel 1 μ m polished surfaces. Fig. 1 shows the schematic of Vickers indentation and its induced radial crack system of monolithic and laminated ZrB₂-SiC ceramics. As shown in Fig. 1, four indentations were made, using a load of 49 N, and uniformly distributed on a circle with radius of 3 mm. The upper and lower surfaces of samples for thermal shock tests are perpendicular to the hot-pressing direction. For laminated ZrB₂-SiC ceramic, the indentations were made on the polished surface of ZrB₂+30vol.%SiC layer (see Fig. 1a). So the Vickers indents for laminated ceramic sample were made into a continuous layer. The holding time of each indentation is 15 s and the interval between successive indentations is 60 s. Each indentation generated four cracks, so 16 cracks were made on each sample. After the indentation, the samples were heated in a vertical tube furnace in air to preset temperature for 30 min and then the specimens were rapidly dropped into a water bath of room temperature (~10 °C). The length of the cracks was measured using scanning electron microscopy before and after quenching. The initial crack length was defined as

the distance from the center of the indentation to the crack tip. And the final crack length after thermal shock is equal to the initial length plus crack length extended. In the present work, the initial crack length for laminated and monolithic ceramics is about 75μm and 100μm, respectively. Three specimens were tested for each preset temperature, namely, a total of 48 cracks were measured before and after each single quenching test. The procedure was repeated at increasing quenching temperatures ΔT , up to the critical value of ΔT_c at which no less than one radial crack became unstable and the specimen failed [15]. For the analysis of crack growth along the surface during thermal shock, two parameters, namely cracks propagated, % P , and crack extension, % E , are defined as follows:

$$\%P = \frac{\Delta N}{N} \times 100\% \quad (1)$$

$$\%E = \frac{\Delta c}{c} \times 100\%$$

Where N (=48) is the total number of available radial cracks around the indentation and ΔN is the number of radial cracks propagating after thermal shock loading; c is the indentation crack length before water quenching and Δc is the crack length extended after thermal shock.

3. Results and discussion

3.1 Microstructure

Two laminated ZrB₂–SiC ceramic samples with symmetric macrostructure and different layer thickness ratio were prepared by hot pressing. The layer thickness ratio is the ratio between the total thickness of the tensile layers and that of the compressive layers. The overall photographs and microstructure of laminated ZrB₂–SiC ceramics

(namely LZS-1 and LZS-2) are shown in Fig. 2. In these two LZS samples, five thinner layers are $\text{ZrB}_2+30\text{vol.\%SiC}$ layers, which are separated by four thicker $\text{ZrB}_2+20\text{vol.\%SiC}$ layers (Fig. 2a and Fig. 2c). The interfaces of the LZS ceramics are distinct and nearly straight as shown in Fig. 2b and Fig. 2d. According to Fig. 2b and Fig. 2d, the SiC grains homogeneously dispersed in the layers. In LZS-1, the thickness of $\text{ZrB}_2+30\text{vol.\%SiC}$ and $\text{ZrB}_2+20\text{vol.\%SiC}$ layers is about 400 μm and 500 μm respectively (Fig. 2a) and the layer thickness ratio is ~ 1 . For LZS-2 sample, the thickness of $\text{ZrB}_2+30\text{vol.\%SiC}$ and $\text{ZrB}_2+20\text{vol.\%SiC}$ layers is about 300 μm and 600 μm respectively (Fig. 2c) respectively, and the layer thickness ratio is ~ 2 .

3.2 Mechanical properties and residual stress

The mechanical properties of the LZS and ZS ceramics obtained by mechanical tests for theoretical calculation of indentation thermal shock are listed in Table 1. The measured fracture toughness values of LZS ceramics (more than $8.0 \text{ MPam}^{1/2}$) are much higher than that of monolithic ZS30 ceramic ($5.6 \text{ MPam}^{1/2}$). The flexural strength of the LZS ceramics are higher than 750 MPa, which is much higher than that of monolithic ZS30 ceramic (520 MPa). Moreover, both the hardness and elastic modulus of LZS ceramics are higher than those of monolithic ZS30 ceramic. The remarkable improvement in mechanical properties of laminated ceramic is due to the presence of residual compressive stresses in the tested specimens [10,11].

It is assumed that the stress in the outer layers of LZS ceramics is uniform. For this situation, the uniform residual stress, σ_s , can be calculated by [19,20]:

$$\sigma_s = K_{IC} \frac{1-(c_0/c_1)^{3/2}}{Yc_1^{1/2}} \quad (2)$$

Where K_{IC} is the intrinsic toughness of the top $\text{ZrB}_2+30\text{vol.\%SiC}$ layer of laminated

ZrB₂-SiC ceramic, c_0 and c_1 represent the indentation crack length in the unstressed and stressed surfaces, respectively. According to Eq. (2) the residual stress in the top surfaces of LZS-1 and LZS-2 was evaluated to be about -109 MPa and -126 MPa respectively, where the minus sign indicates that the residual stress is compressive stress. It can be inferred here that the different residual stress of LZS-1 and LZS-2 relate to different layer thickness resulted in the different mechanical properties, as shown in Table 1.

3.3 Thermal shock behavior

It should be noted here that in this study we only considered the condition of the crack propagating along the surfaces, and the crack extension in the depth direction was ignored for the simplicity of analysis and calculation. In addition, the effect of temperature on the residual stress in the laminated ZrB₂-SiC ceramic was also ignored during thermal shock test because the heating temperatures were only a few hundred degrees which would not significantly alter residual stress.

3.3.1 Indentation-quench tests

The crack extension after single quench into a bath of water at room temperature versus thermal-shock temperature difference for LZS and ZS30 ceramics is shown in Fig. 3. It should be noted that the reason for the scatter between the individual crack sizes is due to the variation in the microstructure at the tip of each crack. On top of that, the other reason may be considered is the stress release near the cracks extended that makes it possible to grow of the near cracks reduced during further quenching. Besides, the indentation thermal shock results of ZS30 ceramic reported in our previous work

[21] has been used as a reference to LZS ceramics in this study. As it can be seen from Fig. 3, both laminated and monolithic $\text{ZrB}_2\text{-SiC}$ ceramics show a similar pattern of crack growth: no crack growth at low ΔT , stable crack growth at medium ΔT and unstable crack growth over a certain ΔT . However, the monolithic ZS30 ceramic shows poor crack-growth resistance after a single thermal shock, in that $\%E$ are higher than for the LZS ceramics. The critical temperature differences for unstable crack growth of the LZS-1 and LZS-2 ceramics are 590°C , which are much higher than that of the monolithic $\text{ZrB}_2\text{-SiC}$ ceramic ($\Delta T_c=290^\circ\text{C}$). This indicates laminated $\text{ZrB}_2\text{-SiC}$ ceramics show better thermal shock resistance, comparing to monolithic ceramics. It is well known that the thermal shock resistance is related to mechanical and thermal properties, such as toughness, strength, elastic modulus, thermal expansion coefficient and thermal conductivity, etc. Furthermore, those material properties intrinsically depend on the chemical composition, microstructure and preparation process of materials. Both ZS30 and the surfaces of laminated $\text{ZrB}_2\text{-SiC}$ ceramics have the same chemical composition ($\text{ZrB}_2+30\text{vol}\%\text{SiC}$) and nearly the same microstructure due to the same hot-pressing parameters. Hence, the main reason why LZS ceramics have better thermal shock resistance than ZS ceramic is related to the ‘layers stacking’ in preparation process. As mentioned above, the surfaces of LZS ceramics are in the residual compressive stress state due to the ‘layers stacking’. The existence of residual compressive stress can shield the stress field intensity at the crack tip and enhance the crack growth resistance during thermal shock. Thus, cracks in ZS30 ceramic grow unstably at low temperature difference (290°C), but cracks in LZS ceramics grow

unstably until the temperature difference higher than 590°C.

As stated above, the presence of residual compressive stress can improve the thermal shock resistance of LZS ceramics. So, any factors that can affect the residual stress will affect the thermal shock resistance. LZS-1 and LZS-2 have the same chemical composition, total thickness and numbers of layer. Besides, they were prepared under same preparation parameters. However, it is important to note that they have different layer thickness ratio. The layer thickness ratio of LZS-1 and LZS-2 is 1 and 2, respectively. As reported in previous work [11], layer thickness ratio is a key factor that affects the residual stress arising from a mismatch in the thermal coefficient of expansion between the adjacent layers in laminated structures. The results described above (section 3.2) indicate that the difference in residual compressive stress on the surfaces between LZS-1 and LZS-2 is small, which will not change the thermal shock resistance of the material fundamentally. Hence, LZS-1 and LZS-2 show the same critical temperature difference, as shown in Fig. 3. Although the small difference of residual stress can not affect temperature difference range for stable or non stable propagation, it makes the cracks with lower tip stress intensity does not propagate at a certain temperature difference. This was confirmed by the results in Fig. 4, which is shows the percentage of cracks that have started to grow at each ΔT for LZS-1 and LZS-2. As it can be seen from Fig. 4, the fraction of cracks propagated increases with increasing temperature. But at the same temperature, the fraction of cracks propagated of LZS-1 is always higher than that of LZS-2 before cracks growing unstably. In other words, the number of cracks propagated in LZS-2 is less than that in LZS-1 attributing

to the small difference of residual compressive stresses.

If the indents are made into the cross section of laminated ceramics as shown in Fig. 1a, the crack-growth behavior will depend on the position of indents located in compressive or tensile layers. It is easy to infer that: (1) the cracks in tensile layers will propagate grow unstably at low temperature differences whereas the cracks in compressive layers are rather stable and don't propagate much at the same temperatures differences; (2) cracks in tensile layer will stop propagating when they reach the compressive layers [21].

3.3.2 Theoretical analysis of indentation thermal shock behavior

The stress intensity state at the indentation crack tips should be analyzed firstly for the mechanism analysis of indentation thermal shock. For the monolithic $\text{ZrB}_2\text{-SiC}$ ceramic, the total stress intensity (K_I) at an indentation crack tip subjected water quenching is the sum of the residual intensity (K_r) induced by indentation load and thermal stress intensity (K_{th}):

$$K_I = K_r + K_{th} \quad (3)$$

For indentation cracks, the residual stress intensity factor at the tip of a Vickers indentation flaw of length, c , formed due to an indentation load, P , is given by:

$$K_r = \chi_r P c^{-1.5} \quad (4)$$

Where the constant χ_r is approximated as $0.016(E/H)^{0.5}$ [22].

For a quenching thermal shock, the transient thermal stress intensity of the indentation crack system is only considered at the surface of the plate and can be calculated as [23]:

$$K_{th} = \sigma_{th} (\pi \Omega c)^{1/2} \quad (5)$$

where Ω is a geometrical factor for the stress intensity field of the crack and is usually estimated to be $4/\pi^2$ for a semi-elliptical surface crack. The thermal stress is defined by

[24,25]:

$$\sigma_{th} = f(\beta) \frac{E \cdot \alpha}{1 - \nu} \Delta T \quad (6)$$

where α and ν are the thermal expansion coefficient and the Poisson's ratio of the material, respectively. $f(\beta)$ stands for geometry and heat transfer conditions and is a function of the Biot modulus, $\beta = hd/\lambda$, and can be given by [26-28]:

$$f(\beta) = \left(A + \frac{B}{\beta} + C \cdot \exp\left(-\frac{D}{\beta}\right) \right)^{-1} \quad (7)$$

where d is a characteristic heat transfer length (half the thickness of the plate) [26], h is the surface heat transfer coefficient acting between the plate and the cooling medium, and λ is thermal conductivity. The constants A, B, C and D are 3.15, 1.33, -0.266 and 51.4, respectively for a cylindrical indentation specimen [26].

Hence, according to Eqs. (3)~(7), the total stress intensity of an indentation crack for ZS30 monolithic ceramic can be expressed as:

$$K_I = \frac{\chi_r P}{c^{3/2}} + f(\beta) \frac{E \cdot \alpha}{1 - \nu} \Delta T (\pi \Omega c)^{1/2} \quad (8)$$

With respect to the laminated ZrB₂-SiC ceramic, due to the presence of residual surface compressive stresses, the total stress intensity of an indentation crack subjected to quenching can be given as following:

$$K_I = K_r + K_{th} + K_s \quad (9)$$

The contribution of the residual surface compressive stresses, K_s , is defined by [29,30]:

$$K_s = Y \sigma_s c^{1/2} \quad (10)$$

where Y is a geometrical factor for the stress intensity field of the crack and is usually estimated to 1.29 for a semi-elliptical surface crack [19,20].

So, the total stress intensity of an indentation crack for LZS ceramic can be given as:

$$K_I = \frac{\chi_r P}{c^{3/2}} + f(\beta) \frac{E \cdot \alpha}{1 - \nu} \Delta T (\pi \Omega c)^{1/2} + Y \sigma_s \sqrt{c} \quad (11)$$

The value for K_I will determine whether the crack will grow or not and the crack grow stably or unstably. The crack will grow stably at the surface during thermal shock if

$$K_I \geq K_{IC} \quad (12)$$

and

$$\frac{dK_I}{dc} \leq \frac{dK_{IC}}{dc} \quad (13)$$

where K_{IC} is the fracture toughness of the material undergone quenching [26].

Fig. 5a shows the total stress intensity, K , vs crack length, c , calculated for a LZS-1 sample which has been quenched with seven different values of ΔT . The total stress intensity, K_I , at different ΔT are calculated according to Eq. (11). As can be seen from Fig. 5a, the total stress intensity increases with the temperature difference increasing. The K_I shows a trend of first decrease and then increase when quenching at every ΔT . That is to say, the K_I have a minimum, $K_{I,min}$, at every ΔT . The $K_{I,min}$ increases with the increase of temperature difference. When ΔT is less than 540 °C, the indentation crack growth is stable because of $K_{I,min}$ less than the fracture toughness, K_{IC} .

Fig. 5b shows the stress intensity vs crack length for a LZS-1 sample which has been quenched with $\Delta T=540$ °C and $\Delta T=590$ °C. The K_r , K_{th} , and K_s , for various ΔT are calculated according to Eqs. (4), (5) and (10), respectively. As can be seen from Fig. 5b, K_r and K_s decrease while K_{th} increases with the increasing crack length. When $\Delta T=540$ °C and the crack length is small ($c=c_0$), the total stress intensity will decrease because the reduction of K_r plus K_s is larger than the recruitment of K_{th} with the

increasing crack length. As long as K_I reduces to K_{IC} , crack growing will stop at $c=c_I$. The thermal shock temperature difference should be increased to keep crack growing. When ΔT are greater than or equal to 590 °C, K_I will be no less than K_{IC} all the time. So, cracks will grow unstably when ΔT no less than 590 °C. In other words, the critical temperature difference derived from theoretical calculation for LZS-1 is 590 °C, which is in good agreement with the experimental results.

The stress intensity, K , vs crack length, c , also was calculated for a LZS-2 ceramic sample quenched with several values of ΔT , and the results are shown in Fig. 6. It can be seen from Fig. 6 that LZS-2 shows the same patterns as LZS-1 in the curves of the stress intensity vs crack length. And the critical temperature difference derived from theoretical calculation for LZS-2 is also in good agreement with the experimental results.

The stress intensity, K , vs crack length, c , was also calculated for a ZS30 ceramic sample quenched with several values of ΔT , and the results are shown in Fig. 7. As can be seen from Fig. 7a, as the ΔT is less than 240 °C, the indentation crack grows stably due to $K_{I,min}$ less than K_{IC} . Nevertheless, the crack will propagate unstably when ΔT is no less than 290 °C. It can be seen from Fig. 7b that when $\Delta T= 240^\circ\text{C}$ and $c=c_0$, the reduction of K_r is larger than the recruitment of K_{th} during crack propagating. That makes the total stress intensity decrease with increasing crack length. As K_I reduce to K_{IC} , crack will get to c_I from c_0 and then stop propagating. In order to make the crack continue propagating, the thermal shock temperature difference should be increased. As long as ΔT is greater than or equal to 290°C, K_I will be no less than K_{IC} and cracks will grow unstably. That's to say, the critical temperature difference derived from theoretical calculation for ZS30 ceramic is 290°C, which is also in good agreement with the

experimental results.

Comparing the theoretical calculation results between laminated and monolithic $\text{ZrB}_2\text{-SiC}$ ceramics, it is confirmed that the contribution of residual surface compressive stresses to stress intensity will shield the thermal stress intensity and make a negative contribution to the total stress intensity at the crack tips during thermal shock. Thus, if cracks propagate from the initial length, c_0 , to the length of $c_0+\Delta c$, cracks in laminated $\text{ZrB}_2\text{-SiC}$ ceramic need a much higher thermal-shock temperature difference than that in monolithic $\text{ZrB}_2\text{-SiC}$ ceramics. This is why the laminated $\text{ZrB}_2\text{-SiC}$ ceramics show better thermal shock resistance than monolithic $\text{ZrB}_2\text{-SiC}$ ceramic.

4. Conclusions

The thermal shock resistance of laminated and monolithic $\text{ZrB}_2\text{-SiC}$ ceramics have been investigated by indentation-quench method through experiments and modeling. The curves of crack growth vs temperature difference for laminated and monolithic $\text{ZrB}_2\text{-SiC}$ ceramics are determined, respectively. The critical temperature difference of laminated $\text{ZrB}_2\text{-SiC}$ ceramic is much higher than that of monolithic ceramic, which suggests that the laminated $\text{ZrB}_2\text{-SiC}$ ceramics exhibit excellent resistance to thermal shock, comparable to that of monolithic $\text{ZrB}_2\text{-SiC}$ ceramics. The theoretical calculation shows that the theoretical results have a good agreement with the results of experiments. The contribution of residual surface compressive stresses in laminated $\text{ZrB}_2\text{-SiC}$ ceramics to stress intensity shield the thermal stress intensity and make a negative contribution to the total stress intensity at the crack tips during thermal shock, which is the reason why the laminated $\text{ZrB}_2\text{-SiC}$ ceramics have a better thermal shock resistance than monolithic $\text{ZrB}_2\text{-SiC}$ ceramic.

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Figure captions

Fig. 1. Schematic of the Vickers indentation (a) and its induced radial crack system (b) for monolithic and laminated $\text{ZrB}_2\text{-SiC}$ ceramics.

Fig. 2. The micrographs of cross-section for LZS-1 (a) and LZS-2 (c), and the microstructure images for LZS-1 (b) and LZS-2 (d).

Fig. 3. The percentage crack growth versus temperature difference (ΔT) for ZS30 and LZS ceramics: (a) shows the whole crack growth and (b) is a magnification image which only shows the percentage crack growth from 0 to 100%.

Fig. 4. The fraction of cracks propagated, $P\%$, versus temperature difference (ΔT) for laminated $\text{ZrB}_2\text{-SiC}$ ceramics.

Fig. 5. The stress intensity of Vickers indentation cracks at the surface as a function of the crack length after quenching for the LZS-1 laminated ceramic: the total stress intensity with various ΔT (a) and the stress intensity with $\Delta T=540^\circ\text{C}$ and $\Delta T=590^\circ\text{C}$ (b). K_{IC} denotes the static fracture toughness.

Fig. 6. The stress intensity of Vickers indentation cracks at the surface as a function of the crack length after quenching for the LZS-2 laminated ceramic: the total stress intensity with various ΔT (a) and the stress intensity with $\Delta T=540^\circ\text{C}$ and $\Delta T=590^\circ\text{C}$ (b). K_{IC} denotes the static fracture toughness.

Fig. 7. The stress intensity of Vickers indentation cracks at the surface as a function of the crack length after quenching for the ZS30 ceramic: the total stress intensity with various ΔT (a) and the stress intensity with $\Delta T=240^\circ\text{C}$ and $\Delta T=290^\circ\text{C}$ (b). K_{IC} denotes the static fracture toughness.

Table captions

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materials	Fracture toughness (MPa·m ^{1/2})	Flexural strength (MPa)	Hardness (GPa)	Young's modulus (GPa)	Poisson's ratio ^a	Thermal conductivity (W·m ⁻¹ ·K ⁻¹)	Thermal expansion coeff (×10 ⁻⁶)
ZS30	5.6±0.5	520±34	19.6±0.7	440±18	0.136	62 ^[16]	6.8 ^[16]
LZS-1	8.2±0.3	750±67	20.5±0.5	472±12	0.134	76.3 ^b	6.99 ^c
LZS-2	8.9±0.4	826±52	21.7±0.8	485±14	0.133	82.7 ^d	7.06 ^e

a, b, c, d, e —Calculated from composite rule, ν_{ZrB_2} =0.121 ^[17], ν_{SiC} =0.17 ^[17]; λ_{ZS30} =62 ^[16], λ_{ZS20} =99.2 ^[16]; α_{ZS30} =6.8 ^[16], α_{ZS20} =7.18 ^[18]

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