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ARTICLE

Inherent Relationship between Microstructure Parameters and Anti-impact Strength of Eutectic Composite Ceramic

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Abstract: The inherent relationship between the microstructure parameters and anti-impact strength is established by micromechanical strength and dynamic destruction criterion of eutectic composite ceramic. Firstly, in line with the microstructure characteristic of eutectic composite ceramic, the effective stress field of composite ceramic is computed by the interaction direct derivative estimate and sufficiently simplified calculation method. Secondly, according to equivalent inclusion method and Griffith micro-crack propagation theory, the micromechanical strength of eutectic ceramic composite is predicted. Thirdly, the dynamic destruction criterion of the comminuted zone is built by the unified pressure shear criterion. Finally, on account of the dynamic destruction criterion which is associative with microstructure, the calculated mode of anti-impact strength is obtained. The influence of microstructure parameters on anti-impact strength is quantitatively analyzed. Results show that decrease in interface defect size among eutectic grains and increase in eutectic grain stiffness will increase anti-impact strength.

Key words: interface defects; anti-impact strength; eutectic composite ceramic; micromechanical strength; dynamic destruction criterion

The anti-impact strength of eutectic composite ceramic is a subject of considerable importance. It is closely linked with its microstructure, especially the stiffness of eutectic grains and the size of interface defects among eutectic grains. It can be determined by the micromechanical strength and dynamic destruction criterion that depend on the microstructure features of eutectic composite ceramic.

There are some strength models for composite with different fracture properties, such as the Griffith's theory, the Mohr strength theory, the stress intensity factor and strain energy release rate criterion and statistical strength theory[1], in which the statistical feature of defects is took into account. Considering defects as damages, Budiansky and O'Connell[2] studied dispersed distributed defects with a self-consistent method, and Chaboche[3] proposed anisotropic damage theory. Most strength analyses are based on the presumption of non-defects in anisotropic composite, or assuming isotropic matrix when analyzing the influence of defects[4,5]. Fu established a microscopic strength model for eutectic composite ceramics with platelet defects[6]. However, eutectic grains around interface defects represent local anisotropy for eutectic composite ceramics. For interface defects in anisotropic material, the stress field and failure mechanism is more complex. However, there is some literature that can be used for reference. For example, G. C. Sih[7] and L. J. Willis[8] obtained microcrack tip stress field and stress intensity factor which provide the basic method for studying fracture mechanism of anisotropic material, and further analysis on the microcrack problem is discussed by V. S. Kirilyuk[9]. The above method is applied in studying the strength of uniform distribution fiber-reinforced composite material[10]. In 1987 Mura[11] elaborated the systematic theory of Eigen strain method to calculate the strength of

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anisotropic materials. C. R. Chiang[12,13] based on Eigen strain method and equivalent inclusion method, obtained the stress concentration factor of microcracks in the anisotropic material, and strength of anisotropic materials with microcracks. S. K. Kanaun[14] established a numerical model to compute the stress field in microcrack tips, and equation for the tensor of effective elastic constants of an anisotropic matrix containing a random set of elliptical micro cracks. The above study provides good references to research the micromechanical strength of eutectic composite ceramic.

The relation between micromechanical strength and anti-impact strength is built by dynamic destruction criterion. When composite ceramic is used for impact resistant protective material, there will be cracks, comminuting and cavity. The anti-impact model is the key of the problem. So far, many models were promoted, such as Sanchez-Galvez[15,16] model, centerline momentum balance model[17] and semi-analytical model[18]. Tate-Alekseevskii model and the cavity expansion theory are the primal models in ceramic anti-impact effect description and have been widely used[19,20]. The static penetration resistance of brittle materials and the penetration models of ceramic composite target were developed using the unified static cavity expansion theory[21,22]. The unified pressure shear criterion was used to analyze the stress field in the comminuted zone of ceramic material[23]. In these models, strength parameters of materials are dependent on the experimental test, but the experimental result is dispersed for the testing environment. To obtain the influence of microstructure on the anti-impact strength, a dynamic destruction criterion is needed to connect the micromechanical strength with anti-impact ultimate stress of eutectic composite ceramic.

In this research, the inherent relationship between the microstructure parameters and anti-impact strength is established by micromechanical strength and dynamic destruction criterion. Firstly, based on the microstructure feature of eutectic composite ceramic, the effective stress field is analyzed by the interaction direct derivative estimate[24]. Secondly, according to the equivalent inclusion method and Griffith micro-crack propagation theory, the micromechanical strength model of eutectic composite ceramic is established. Thirdly, the dynamic destruction criterion is built by the unified pressure shear criterion. Finally, the calculated mode of anti-impact strength is obtained.

1 Effective Stress Field of Eutectic Composite Ceramic

Eutectic composite ceramic is composed of rod-shaped eutectic grains in the majority and platelet crystals in the minority, and fibers are arranged in the same direction in eutectic grains, as shown in Fig.1. Eutectic grains are usually regularly arranged in a local region. In a local region, the micromechanical properties are transversely isotropic due to the parallelly arranged fibers[25-27]. A few interface defects are distributed among the eutectic grains, as seen in Fig.2.

The composite ceramic is simplified to a mesomechanical model, in which the random meso-cell is embedded in an equivalent medium. The mechanical property of the equivalent medium is the same as eutectic composite ceramic. In the meso-cell, equivalent matrix around an interface defect consists of the uniformly distributed rod-shaped eutectics which is transversely isotropic, and the interface defect is assumed as ellipsoid, as shown in Fig.3. The meso-cell consists of an interface defect and the eutectic grains. The equivalent medium possesses the mechanical property of eutectic composite ceramic. The rod-like eutectic grain is oriented along x axis and the normal of interface defects along y axis in the local coordinate system, as shown in Fig. 4.

The interface defect is considered to be an ellipsoid and defined by mathematical formalization.

$$\left(\frac{x}{a_1}\right)^2+\left(\frac{y}{a_2}\right)^2+\left(\frac{z}{a_3}\right)^2\le 1 \tag{1}$$

Where $a_2 \ll a_1$, a_3. The incremental compliance tensor of the meso-cell can be obtained by the interaction direct derivative estimate[24]:

$$\boldsymbol{H}_{\mathrm{m}}=[\boldsymbol{I}-\boldsymbol{H}_{\mathrm{c}}\boldsymbol{C}_{\mathrm{g}}(\boldsymbol{I}-\boldsymbol{M}_2)]^{-1}\boldsymbol{H}_{\mathrm{c}} \tag{2}$$

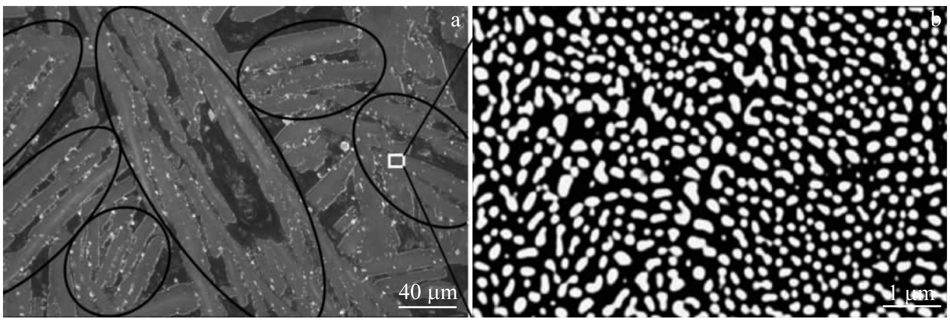

Fig.1 SEM Microstructures of the ceramic composites in different scales[28]: (a) eutectic composite ceramic and (b) rod-shaped eutectic grains with fibers

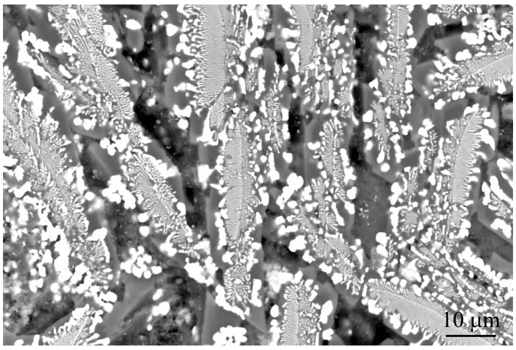

Fig.2 Microstructures feature in a local region

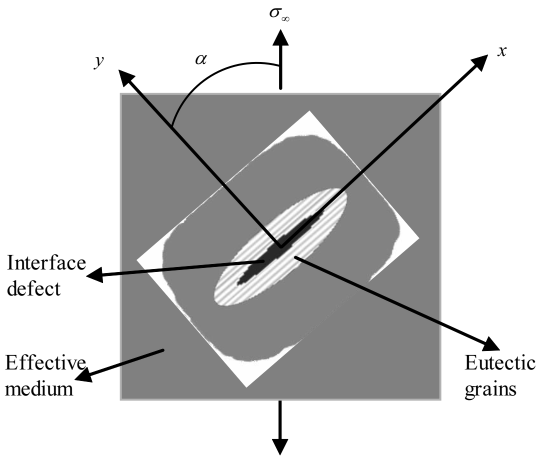

Fig.3 A meso-cell embedded in the equivalent medium

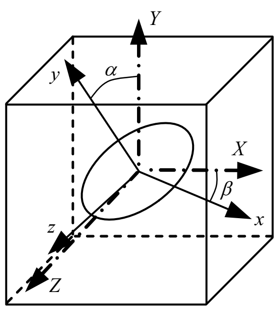

Fig.4 Relationship between local coordinates and global coordinates

Here, $\boldsymbol{H}_{\mathrm{c}} = f_2[\boldsymbol{I} + \boldsymbol{C}_{\mathrm{g}}(\boldsymbol{I} - \boldsymbol{M}_2)\boldsymbol{H}_2]^{-1}\boldsymbol{H}_2$. $\boldsymbol{I}$ is unit tensor, $\boldsymbol{C}_{\mathrm{g}}$ is the stiffness tensor of eutectic grains[29]. $\boldsymbol{M}_2$ is the Eshelby tensor of interface defects in the meso-cell, f_2 is the volume fraction of interface defects in the meso-cell, $\boldsymbol{H}_2$ is the incremental compliance tensor of interface defects. An interface defect can be regarded as an inclusion with zero stiffness, then $\boldsymbol{H}_{\mathrm{c}} = f_2[\boldsymbol{C}_{\mathrm{g}}(\boldsymbol{I} - \boldsymbol{M}_2)]^{-1}$, and Eq.(2) transforms into

$$\boldsymbol{H}_{\mathrm{m}} = (f_2^{-1} - 1)^{-1}[\boldsymbol{C}_{\mathrm{g}}(\boldsymbol{I} - \boldsymbol{M}_2)]^{-1} \tag{3}$$

So the effective stiffness of meso-cell is

$$\boldsymbol{C}_{\mathrm{m}} = (\boldsymbol{C}_{\mathrm{g}}^{-1} + \boldsymbol{H}_{\mathrm{m}})^{-1} \tag{4}$$

Considering meso-cells are randomly distributed inclusions in the equivalent medium, there is a complex integration for the random distribution of the inclusions. Based on the sufficiently simplified calculation[30], it is supposed that all the meso-cells have the same orientation firstly, and then the stiffness is averaged according to the orientation probability distribution function based on the Voigt approach. The effective stiffness tensor of composite with all the meso-cells located with the same orientation can be computed as follows

$$\boldsymbol{C}_{\mathrm{e}} = (\boldsymbol{C}_{\mathrm{p}}^{-1} + \boldsymbol{H}_{\mathrm{D}})^{-1} \tag{5}$$

Here, $\boldsymbol{H}_{\mathrm{D}} = (\boldsymbol{I} - K_{\mathrm{p}}H_{\mathrm{pm}}^{\mathrm{d}})^{-1}\boldsymbol{H}_{\mathrm{pm}}^{\mathrm{d}}$, $\boldsymbol{H}_{\mathrm{pm}}^{\mathrm{d}} = f_1(\boldsymbol{H}_{\mathrm{pm}}^{-1} + \boldsymbol{K}_{\mathrm{p}})^{-1}$, $\boldsymbol{K}_{\mathrm{p}} = \boldsymbol{C}_{\mathrm{p}}(\boldsymbol{I} - \boldsymbol{M}_{\mathrm{pm}})$, $\boldsymbol{H}_{\mathrm{pm}} = \boldsymbol{C}_{\mathrm{m}}^{-1} - \boldsymbol{C}_{\mathrm{p}}^{-1}$. $\boldsymbol{C}_{\mathrm{p}}$ is the stiffness tensor of particles among meso-cells, $\boldsymbol{M}_{\mathbf{pm}}$ is Eshelby tensor of meso-cells in particles. f_1 is the volume fraction of meso-cells in composite. Assuming random orientation of the meso-cells, the stiffness of the equivalent medium or composite has the following form[29]:

$$\boldsymbol{C}_{\mathrm{E}} = \begin{pmatrix} C_{11} & C_{12} & C_{12} & & & \\ C_{12} & C_{11} & C_{12} & & 0 & \\ C_{12} & C_{12} & C_{11} & & & \\ & & & \frac{C_{11}-C_{12}}{2} & & \\ & 0 & & & \frac{C_{11}-C_{12}}{2} & \\ & & & & & \frac{C_{11}-C_{12}}{2} \end{pmatrix} \tag{6}$$

Where,

$$C_{11} = \frac{1}{5}(C_{11}^{\mathrm{e}} + C_{22}^{\mathrm{e}} + C_{33}^{\mathrm{e}}) + \frac{2}{15}(C_{12}^{\mathrm{e}} + C_{13}^{\mathrm{e}} + C_{23}^{\mathrm{e}}) + \frac{4}{15}(C_{44}^{\mathrm{e}} + C_{55}^{\mathrm{e}} + C_{66}^{\mathrm{e}})$$

$$C_{12} = \frac{1}{15}(C_{11}^{\mathrm{e}} + C_{22}^{\mathrm{e}} + C_{33}^{\mathrm{e}}) + \frac{4}{15}(C_{12}^{\mathrm{e}} + C_{13}^{\mathrm{e}} + C_{23}^{\mathrm{e}}) - \frac{2}{15}(C_{44}^{\mathrm{e}} + C_{55}^{\mathrm{e}} + C_{66}^{\mathrm{e}})$$

Suppose the composite is subject to the simple tension σ_∞ as shown in Fig.3. Considering the spatial randomness of meso-cell distribution, the spatial relationships between local coordinate system and the global coordinate system are shown in Fig.4. Thereby, the applied stress tensor in the local coordinate system is

$$\boldsymbol{\sigma}_{\mathrm{g}} = \boldsymbol{g}\boldsymbol{\sigma}_\infty \tag{7}$$

Where, $\boldsymbol{g}$ is the transformation matrix between the global coordinate system and the local coordinate system in Fig.4. The effective stress tensor in the meso-cell is

$$\boldsymbol{\sigma}_{\mathrm{m}} = \boldsymbol{J}\boldsymbol{\sigma}_{\mathrm{g}} \tag{8}$$

Where, $\boldsymbol{J} = (\boldsymbol{I} + \boldsymbol{K}_{\mathrm{p}}\boldsymbol{H}_{\mathrm{pm}})^{-1}(\boldsymbol{I} - \boldsymbol{K}_{\mathrm{p}}\boldsymbol{H})^{-1}$, $\boldsymbol{H} = \boldsymbol{C}_{\mathrm{E}}^{-1} - \boldsymbol{C}_{\mathrm{m}}^{-1}$

2 Micromechanical Strength of Eutectic Ceramic Composite

The stress perpendicular to the interface defect in meso-cell can be obtained from Eq. (8).

$$\sigma_{yy}^{m} = J_{21}\sigma_{11}^{g} + J_{22}\sigma_{22}^{g} + J_{23}\sigma_{33}^{g} \tag{9}$$

The interface defect can be treated as a micro-crack in eutectic grains of parallel distribution. According to equivalent inclusion method, the boundary condition on the interface defect is[11, 31]

$$\sigma_{yy}^{m} + \sigma_{yy}^{*} = 0 \tag{10}$$

Where σ_{yy}^{*} is the stress disturbance of the interface defect along with y axis and can be computed by the equivalent inclusion method as follows:

$$\sigma_{yy}^{*} = \frac{a_1 a_2 a_3}{4\pi} C_{22kl}^{m} C_{pq22}^{m} \varepsilon_{22}^{*} \Gamma_{kplq} \tag{11}$$

In the above equation

$$\Gamma_{kplq} = \int_0^{2\pi} \frac{1}{(a_1\cos^2\theta + a_3\sin^2\theta)^{3/2}} d\theta \int_{-1}^{1} \frac{y}{(1-y^2)^{3/2}} \frac{\partial G_{kplq}(x,y,z)}{\partial y} dy$$

Where θ is angular coordinate of the interface defect, C_{22kl}^{m}, C_{pq22}^{m} are stiffness components of the meso-cell determined by Eq.(4). ε_{22}^{*} is eigen strain of the interface defect. Using Eq.(11), Eq. (10) transforms into

$$\sigma_{yy}^{m} + a_2 L_{2222}\varepsilon_{22}^{*} = 0 \tag{12}$$

Where, $L_{2222} = -\frac{a_1 a_3}{4\pi} C_{22kl} C_{pq22} \Pi_{kplq}$. The eigen strain is obtained

$$\varepsilon_{22}^{*} = \sigma_{yy}^{m} / (a_2 L_{2222}) \tag{13}$$

Then, the interaction energy of the interface defect is computed as follows

$$\Delta W = -\frac{2\pi}{3} a_1 a_2 a_3 \sigma_{yy}^{m} \varepsilon_{22}^{*} \tag{14}$$

Supposing the interface defect maintains self-similar propagation, Griffith micro-propagation theory can be expressed as

$$\frac{\partial(\Delta W + 2\pi a_1 a_3 \gamma)}{\partial a_1}\delta a_1 + \frac{\partial(\Delta W + 2\pi a_1 a_3 \gamma)}{\partial a_3}\delta a_3 = 0 \tag{15}$$

In above equation, γ is the surface energy. Interface defects among the eutectic grains propagating along axis 1 and axis 3 are equivalent. If the interface defect propagates along axis 1, there will be

$$\left[\gamma - \frac{\left(\sigma_{yy}^{m}\right)^2 P_{2222}}{L_{2222}^2}\right] \frac{\delta a_1}{a_1} = 0 \tag{16}$$

Here,

$$P_{2222} = \frac{a_1 a_3}{4\pi} \int_0^{2\pi} \frac{a_1^2 \cos^2\theta C_{22kl}^{m} C_{pq22}^{m}}{(a_1^2\cos^2\theta + a_3^2\sin^2\theta)^{5/2}} d\theta \int_{-1}^{1} \frac{y}{(1-y^2)^{1/2}} \frac{\partial G_{kplq}(x,y,z)}{\partial y} dy$$

Substituting Eq.(9) into Eq.(16), one has the micromechanical strength of interface cracking among the eutectic grains

$$\sigma_t = \frac{L_{2222}}{g_{12}J_{21} + g_{22}J_{22} + g_{32}J_{23}} \sqrt{\frac{\gamma}{P_{2222}}} \tag{17}$$

3 Dynamic Destruction Criterion of Eutectic Ceramic Composite

Based on static cylindrical expansion, we knew that there was a comminuted zone around impact cavity under the penetration of projectile body[32]. The stresses in the comminuted zone satisfied the dynamic destruction criterion. Under the impact load of the projectile, the stress field in the ceramic plate is axially symmetric. Choosing the impact point as the origin of the cylindrical coordinates system, equilibrium equation in cylindrical coordinate system is satisfied with the following expression:

$$\frac{d\sigma_r}{dr} + \frac{\sigma_r - \sigma_\theta}{r} = 0 \tag{18}$$

where σ_r is radial stress, and σ_θ is circumferential stress.

Taking the first order approximation of the strains, the radial strain ε_r and the circumferential strain ε_θ is calculated as follows

$$\varepsilon_r = \frac{\partial s}{\partial r}, \ \varepsilon_\theta = \frac{s}{r} \tag{19}$$

In the above equation, s is the radial displacement. Wang et al[21] considered the material in the comminuted zone obeyed the unified pressure shear criterion:

$$(1+\xi)[(\sigma_1 - \sigma_3) + b(\sigma_1 - \sigma_2)] = (1-\xi)[\sigma_1 + \sigma_3 + b(\sigma_1 + \sigma_2)] \tag{20}$$

Where σ_1, σ_2 and σ_3 are principal stresses and the compressive principal stress is positive, b is principle shear stress coefficient, and $\xi = \sigma_t / \sigma_C$. σ_t is determined by Eq.(20). For most of ceramic materials, the relation between tensile strength and compression strength can be expressed as σ_t=(0.2~0.4)σ_C. In different constraints, σ_1 and σ_3 have different effects on the anti-impact strength. Defining a stress coefficient ratio η to relate three principal stresses

$$\sigma_2 = \eta\sigma_1 + (1-\eta)\sigma_3 \tag{21}$$

In the above relation, $0 \leqslant \eta \leqslant 1$. Substituting Eq.(21) into Eq.(20), and it is simplified as

$$\sigma_1 - \sigma_3 = \frac{(1-\xi)(1+b)}{b(1-\eta)+1}\sigma_1 \tag{22}$$

Under the impact load of the projectile, we have $\sigma_1 = \sigma_r$ and $\sigma_3 = \sigma_\theta$. The dynamic destruction condition of the comminuted zone is

$$\sigma_r - \sigma_\theta = \zeta\sigma_r \tag{23}$$

Here $\zeta = (1-\xi)(1+b)/[2b(1-\eta)+1]$.

4 Anti-impact Strength of Eutectic Ceramic Composite

The XRD pattern of $TaSi_2$/SiC coated C/C composites indicates that the coating surface contains SiC, Si, $TaSi_2$, SiO_2 and Ta_2O_5 after oxidation in air at 1773 K. At high temperature, a few of reactions have happened as follows:

Substituting the dynamic destruction criterion (23) of comminuted zone into Eq.(18), we get

$$\frac{d\sigma_r}{dr}+\zeta\frac{\sigma_r}{r}=0 \tag{24}$$

Integrating the equation, one obtains

$$\sigma_r = Ar^{-\zeta} \tag{25}$$

Where, A is the integration constant. On basis of the cavity expansion theory[32], there are five zone around the impact point, i.e. cavity zone ($0\leqslant r\leqslant a_0$), comminuted zone ($a_0\leqslant r\leqslant a_1$), crack zone ($a_1\leqslant r\leqslant a_2$), elastic zone and undisturbed zone ($a_3\leqslant r\leqslant a_4$). At the cavity ($r=a_0$), the radial stress born by eutectic ceramic composite is defined as the anti-impact strength R_t

$$R_t = Aa_0^{-\zeta} \tag{26}$$

Then, $A=R_t a_0^{\zeta}$. So the stress field in comminuted zone can be expressed as

$$\sigma_r = R_t\left(\frac{a_0}{r}\right)^{\zeta} \tag{27}$$

In crack zone, the tensile stress vanish, equilibrium equation (18) transforms into

$$\frac{d\sigma_r}{dr}+\frac{\sigma_r}{r}=0 \tag{28}$$

Integrating Eq.(28), one has

$$\sigma_r = B/r \tag{29}$$

The integration constant B can be determined by stress continuous condition at $r=a_1$. Contrasting Eqs.(29) and (27), we have

$$B = R_t a_1\left(\frac{a_0}{a_1}\right)^{\zeta} \tag{30}$$

Therefore, the stress field in crack zone can be expressed as follows

$$\sigma_r = \frac{R_t a_1}{r}\left(\frac{a_0}{a_1}\right)^{\zeta} \tag{31}$$

Considering the boundary condition $\sigma_r=\sigma_C=\dfrac{\sigma_t}{\xi}$ at $r=a_1$, we obtain the anti-impact strength from Eq.(31)

$$R_t = \frac{\sigma_t}{\xi}\left(\frac{a_1}{a_0}\right)^{\zeta} \tag{32}$$

In order to determine a_1/a_0, we consider the mass conservation in the comminuted zone, i.e. $\rho_0\pi r^2=\rho\pi(r-s)^2$. Where ρ_0 and ρ are initial density and the comminuted density, respectively. The differential form is

$$\frac{d}{dr}(r-s)^2 = 2r\frac{\rho_0}{\rho} \tag{33}$$

The density is invariant for ceramic material, i.e. $\rho_0=\rho$. Integrating of Eq.(33) from a_0 to a_1, and ignoring the higher order term in the polynomial expansion of $s(a_1)$, Eq.(33) transforms to

$$\frac{(a_0/a_1)^2}{2} = s(a_1)/a_1 \tag{34}$$

On basis of Eqs. (18) and (19) and the displacement continuous condition, we have

$$s(a_1)=\frac{\sigma_t}{E}\left(\frac{a_1}{\xi}\ln\frac{a_2}{a_1}+\frac{(1-\upsilon)a_2^2}{a_2^2+a_3^2}[(1-2\upsilon)a_2+\frac{a_3^2}{a_2^2}]\right) \tag{35}$$

So

$$\frac{1}{2}(\frac{a_0}{a_1})^2=\frac{\sigma_t}{\xi E}\ln\frac{a_2}{a_1}+\frac{\sigma_t(1+\upsilon)a_2^2}{E(a_2^2+a_3^2)a_1}[(1-2\upsilon)a_2+\frac{a_3^2}{a_2^2}] \tag{36}$$

Considering $a_3 >> a_2 > a_1 > a_0$, the above expression is transformed as follows

$$\left(\frac{a_1}{a_0}\right)^2=\frac{2\sigma_t}{E}\left(\frac{1}{\xi}\ln\frac{a_2}{a_1}+1+\upsilon\right) \tag{37}$$

Substituted Eq.(37) into Eq.(32), the anti-impact strength of ceramic composite can be computed as following form

$$R_t=\frac{\sigma_t}{\xi}\left[\frac{2\sigma_t}{E}\left(1+\upsilon-\frac{\ln\xi}{\xi}\right)\right]^{-\zeta/2} \tag{38}$$

The anti-impact strength R_t of eutectic composite ceramic is determined by micromechanical strength and elastic constants. The two components of R_t are related to the microstructural feature of the composite ceramic, and mostly to the size of interface defect and stiffness of eutectic grains.

For composite ceramics mainly composed of Al_2O_3/ZrO_2 eutectic grains, the surface energy γ is 1.06 J/m^2. Based on the anti-impact strength R_t obtained by Eq. (38), Fig.5 illustrates typical relation curve between R_t and interface defect radius a_1. It reveals that anti-impact strength decreases with defect radius increasing. For small size defect, R_t is a strong function of defect radius, i.e. it decreases rapidly with increasing defect radius.

The stiffness of eutectic grains is related to the shape and size of inclusions in eutectic grains. The main parameters of the material properties are $E_{Al_2O_3}=402$ GPa, $E_{ZrO_2}=233$ GPa, $\upsilon_{Al_2O_3}=0.233$, and $\upsilon_{ZrO_2}=0.31$. Eutectic grains are transversely isotropic, and their maximum stiffness can be expressed as follows[29]:

$$\boldsymbol{C}_g=\begin{bmatrix} 4.07 & 1.64 & 1.41 & 0 & 0 & 0 \\ 1.32 & 4.57 & 1.32 & 0 & 0 & 0 \\ 1.41 & 1.64 & 4.08 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1.39 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1.38 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1.39 \end{bmatrix}\times 100\ \text{GPa} \tag{39}$$

The matrix of meso-cell is composed of parallel eutectic grains. The matrix stiffness (i.e. average stiffness of eutectic grains in the meso-cell) is determined $\boldsymbol{C}_m=m\boldsymbol{C}_g$, where m is the stiffness ratio. The role that matrix stiffness plays on an-

anti-impact strength is illustrated schematically in Fig.6. Clearly, the anti-impact strength increases with stiffness ratio increasing, and can increase threefold when stiffness ratio is maximal value.

The value of anti-impact strength R_t depends on the microstructure of composite ceramic, mainly on the size of interface defect and stiffness of eutectic grains. Decreases in defect size and increases in grains average stiffness will increase anti-impact strength.

We conducted anti-impact experiments into the eutectic composite ceramic plate with ogival nose kinetic energy projectiles. These plates were designed to be nearly a half space providing a relatively large depth and width. The plates were constructed in a steel culvert. All the experiments were conducted under "near" normal impact conditions, that is, angle-of-obliquity and angle-of-attack were less than 1 degree. The four experimental data of anti-impact strength were 1.01×104, 1.09×104, 0.85×104 and 1.71×104 MPa. The results of the calculation based on Eq.(38) are 1.038×104, 1.050×104, 0.878×104 and 1.768×104 MPa. The errors are 2.55%, 3.22%, 3.54% and 3.15%, respectively. The theoretical results correspond to experimental data essentially.

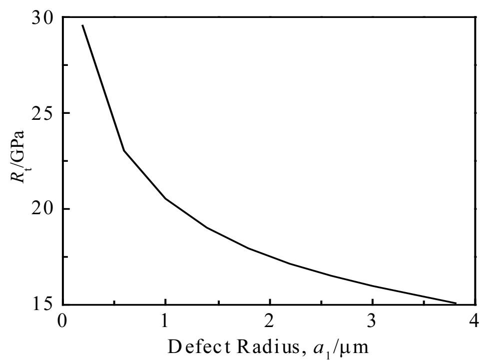

Fig.5 Anti-impact strength R_t of composite ceramic as a function of interface defect radius a_1

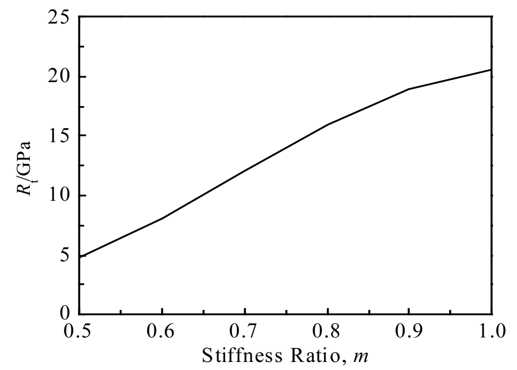

Fig.6 Relationship between anti-impact strength and stiffness ratio

5 Conclusions

1) Based on interaction direct derivative estimate, Griffith micro-crack propagation theory, unified pressure shear criterion and cavity expansion theory, the inherent relationship between the microstructure parameters and anti-impact strength is established. The anti-impact strength of eutectic composite ceramic is closely linked with the stiffness of eutectic grains and the size of interface defects among eutectic grains.

2) Anti-impact strength increases with average stiffness of eutectic grains, and can increase threefold when average stiffness is maximal value. To obtain higher anti-impact strength, the average stiffness of eutectic grains should be increased as far as possible. In the material preparation process, the size of fibers in eutectic grains should be decreased as far as possible and avoid plate-shaped defects.

3) Defect size significantly reduces the anti- impact strength especially under a small defect size because this variable sharply decreases the micromechanical strength of composite ceramics. When plate-shaped defects are inevitable, the smaller defect size should be required to enhance the safety of composite.

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共晶复相陶瓷细观结构对抗冲击强度的影响

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摘　要：通过共晶复合陶瓷的细观强度和动态破坏准则建立起微观结构参数与抗冲击强度间的内在关系。首先，根据共晶复合陶瓷的微观特征，用相互作用直推法和有效简化算法获得复合陶瓷的有效应力场。然后，应有等效夹杂法和 Griffith 微裂纹扩展理论预报了共晶复合陶瓷的细观力学强度。进而，应用统一压剪理论建立冲击区的动态破坏准则。最后，应用与微观结构相关的动态破坏准则建立冲击强度计算模型。定量分析了微观结构参数对冲击强度的影响，结果表明：共晶体间界面缺陷尺寸越小及共晶体刚度越大，抗冲击强度越大。

关键词：界面缺陷；抗冲击强度；共晶复合陶瓷；细观强度；动态破坏准则

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