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Development of new interface potential for evaluating strength of SiC/SiC composite joint

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Abstract

In order to examine mode-I and II type fracture behavior of ceramic joints, the interface element was proposed as one of the simple models which represent the mechanism of failure in an explicit manner. It was applied to the analyses of four point bending test and asymmetrical four point bending test for SiC/SiC composite specimen joined by ARCJoinT^{TM}. By using a new type interface potential, which is a coupled function of opening and shear deformations, both the bending and asymmetrical bending tests were simulated. From comparison with experiments, surface energy at the interface between the joint and composite was estimated to be about 30 N/m regardless of the fracture mode.

1. Introduction

Silicon carbide-based fiber reinforced silicon carbide composites (SiC/SiC composites) are promising candidate materials for high heat flux components because of their potential for low-activation, low-afterheat and their high-temperature properties [1–4]. For fabricating large or complex shaped parts of SiC/SiC composites, practical methods for joining simple geometrical shapes are essential. As a result of R&D efforts, an affordable, robust ceramic joining technology (ARCJoinT^{TM}) has been developed as one of the most suitable methods for joining SiC/SiC composites among various types of joining between ceramic composites [5]. To establish useful design databases, the mechanical properties of joints must be accurately measured and quantitatively characterized, where the bending and shear strength of joints are most basic and important mechanical properties. Therefore, the types of fracture behavior for each test configuration have to be precisely studied to measure those properties.

To describe deformation and fracture behavior more precisely, a new and simple computer simulation method has been developed [6–13]. The method treats the fracture phenomena as the formation of new surface during crack opening and propagation. Based on the fact that surface energy must be supplied for the formation of new surface, a potential function representing the density of surface energy is introduced to the finite element method (FEM) using cohesive elements [6] or interface elements [7–13]. So, in this research, to examine mode-I and II types of fracture behavior in SiC/SiC composite joint, the four point bending test and the asymmetrical four point bending test [14–17] were analyzed by using the interface element.

2. Interface potential

Essentially, the interface element is the distributed nonlinear spring existing between surfaces forming the interface or the potential crack surfaces as shown by Fig. 1. The relation between the opening of the interface δ and the bonding stress σ is shown in Fig. 2. When the opening δ is small, the bonding between two surfaces is maintained. As the opening δ increases, the bonding stress σ increases till it becomes the maximum value σ_{cr}

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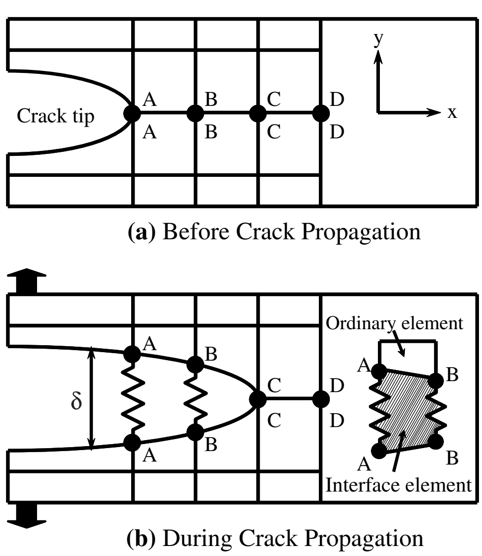

Fig. 1. Representation of crack growth using interface element.

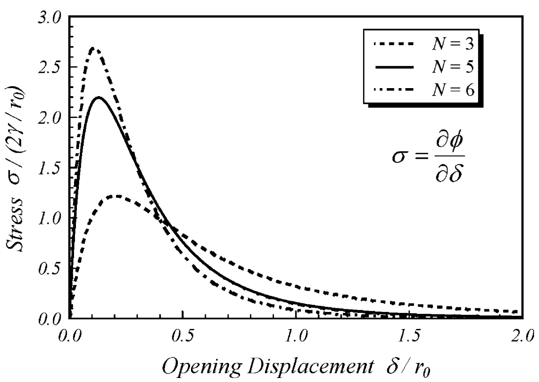

Fig. 2. Relation between crack opening displacement and bonding stress.

at the opening δ_{cr}. With further increase of δ, the bonding strength is rapidly lost and the surfaces are considered to be separated completely. Such interaction between the surfaces can be described by the interface potential. There are rather wide choices for such potential. The authors employed the Lennard–Jones type potential because it explicitly involves the surface energy γ which is necessary to form new surfaces. Thus, the surface potential per unit surface area ϕ can be defined by the following equation.

$$\phi(\delta) = 2\gamma \cdot \left\{ \left(\frac{r_0}{r_0 + \delta} \right)^{2N} - 2 \cdot \left(\frac{r_0}{r_0 + \delta} \right)^{N} \right\}, \tag{1}$$

where, constants γ, r_0 and N are the surface energy per unit area, the scale parameter and the shape parameter of the potential function. From the derivative of ϕ with respect to the opening displacement δ, the maximum bonding stress, σ_{cr}, is obtained as follows when the opening displacement is δ_{cr}.

$$\sigma_{cr} = \frac{4\gamma N}{r_0} \cdot \left\{ \left(\frac{N+1}{2N+1} \right)^{\frac{N+1}{N}} - \left(\frac{N+1}{2N+1} \right)^{\frac{2N+1}{N}} \right\},$$

$$\delta_{cr} = r_0 \cdot \left\{ \left(\frac{2N+1}{N+1} \right)^{\frac{1}{N}} - 1 \right\}. \tag{2}$$

By arranging such interface elements along the crack propagation path as shown in Fig. 1, the growth of the crack under the applied load can be analyzed in a natural manner. In this case, the decision on the crack growth based on the comparison between the driving force and the resistance as in the conventional methods is not necessary.

From the results of our previous researches using the interface elements, it was found that the failure mode and the stability limit depend on the combination of the deformability of the ordinary element in FEM and the mechanical properties of the interface element controlled by the surface energy γ and the scale parameter r_0 in Eq. (1); furthermore, the fracture strength in the failure problems of various structures might be quantitatively predicted by selecting an appropriate value for the scale parameter [12,13].

3. Model for analysis

SiC/SiC composite ceramic joints joined by ARC-JoinT™ were selected for this study. Fig. 3 shows a schematic of the four point bending and asymmetrical four-point bending tests. L_1 and L_2 are the inner and outer span lengths, respectively. According to our previous experimental results for $50^L \times 4^b \times 4^h$ mm^3, L_1 and L_2 were chosen to be 20 and 40 mm for the bending test and 12 and 44 mm for the asymmetrical bending tests, respectively [5,15,16]. The thickness of the joint was set to 100 μm, for a typical example of ARCJoinT™ [5]. Young's moduli and Poisson's ratios of SiC/SiC composite and the joint were assumed to be 300 GPa, 393 GPa, 0.3 and 0.19, respectively. Although the mechanical properties of SiC/SiC composites should be anisotropic, the properties were assumed to be isotropic since the difference between the properties of the composite and the joint material is significantly larger than those due to the composite anisotropy. Because of the brittleness of the ceramic materials, FEM calculations were conducted assuming linear elastic behavior in two-dimensional plain strain. The interface elements were arranged along both the interfaces between SiC/SiC composite and the joint because of the experimental observations [5,15,16].

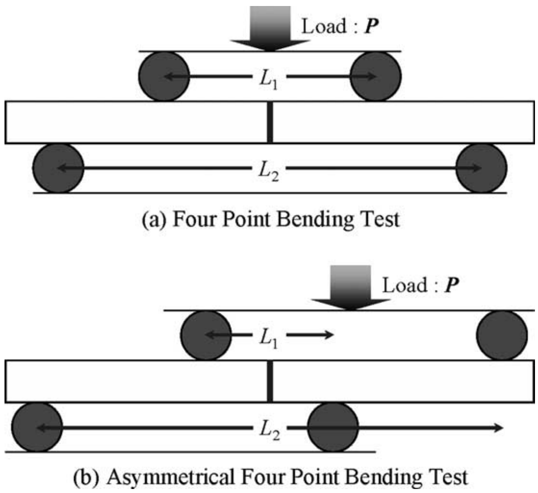

Fig. 3. Schematic illustration of bending and asymmetrical bending tests.

In order to examine the mode-I and II fracture behavior, the mechanical properties of the interface element need to be defined for both the opening and the shear modes since the mode of the failure is mixed mode. In this research, the interface potential ϕ was assumed to be a coupled function of the opening deformation δ_n and the shear deformation δ_t at the interface by using a constant value A as shown in the following equations.

$$\phi(\delta_n, \delta_t) \equiv \phi_a(\delta_n, \delta_t) + \phi_b(\delta_n), \tag{3}$$

$$\phi_a(\delta_n, \delta_t) = 2\gamma \cdot \left\{ \left(\frac{r_0}{r_0 + \delta} \right)^{2N} - 2 \cdot \left(\frac{r_0}{r_0 + \delta} \right)^{N} \right\},$$
$$\delta = \sqrt{\delta_n^2 + A \cdot \delta_t^2}, \tag{4}$$

$$\phi_b(\delta_n) = \begin{cases} \frac{1}{2} \cdot K \cdot \delta_n^2 & (\delta_n \leqslant 0), \\ 0 & (\delta_n \geqslant 0), \end{cases} \tag{5}$$

where a second term of Eq. (3) was introduced to prevent overlapping in the opening direction and K was a constant having a large value.

The bending strength of the composite joint was experimentally measured to be about 75 MPa, which is different from the shear strength obtained (about 30 MPa) [5,15,16], and it means that an effect of the interaction between the opening and the shear deformations seems not to be equal. The parameter A in Eq. (4), however, was assumed to be 1.0 because the fracture in the bending or the asymmetrical bending test would be controlled by only the opening or shear deformation at the joint interface, respectively. Then, by changing the scale parameter r_0 and the surface energy γ, both the bending and the asymmetrical bending tests were analyzed by using the finite element method with the interface element. The parameters r_0 and 2γ were varied from 0.1 nm to 100 μm and from 3.0×10^{-5} to 300 N/m, respectively. The shape parameter N was assumed to be 4 according to our previous researches [12,13].

4. Calculation results and discussions

The effects of scale parameter and the surface energy on the bending and shear strength of joint were summarized into Figs. 4 and 5, respectively. The experimental results are also shown in these figures. From the similarity of the interface element to the ordinary element, the predicted joint strength can be rearranged to a single curve [8,13]. As one example of a single curve, the predicted shear strength τ_f can be re-plotted as shown in Fig. 6 where τ_{cr} was a maximum shear strength at the interface calculated from Eq. (4). From this figure, the single curve was considered to be divided into three parts. From our previous research [12,13], it was found that the results in the middle part could be quantitatively compared with the experimental results, which were indicated by dotted lines in Figs. 4 and 5.

Fig. 7 shows the relationships between the surface energy and the scale parameter, where the predicted strength agreed with the experimental results. From the above discussions, a valid combination between 2γ and r_0 would be limited in the gray area shown in this figure. Especially, from the view point that the surface energy for the opening and shear deformations should be same, a most suitable surface energy of the interface was considered to be 30 N/m, which is as same as the fracture energy of porous SiC made by chemical vapor infiltration process [18]. Since the slopes of two lines in Fig. 7 was almost same, it was found that the correlation between the opening and shear deformations would have a fixed link, that means the parameter A in Eq. (4) can be

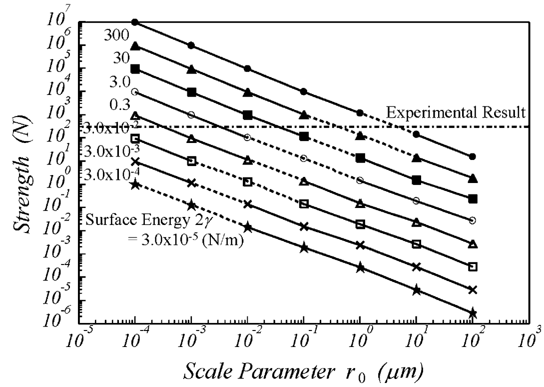

Fig. 4. Effect of scale parameter and surface energy on bending strength of SiC/SiC composite joint.

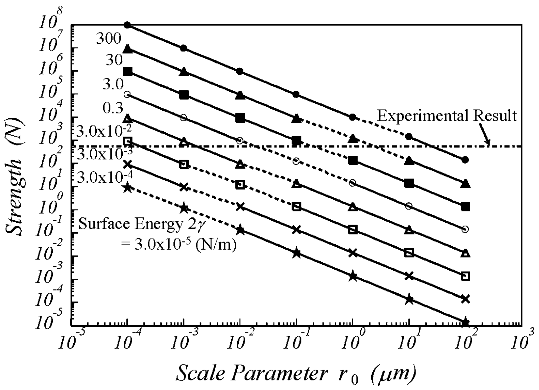

Fig. 5. Effect of scale parameter and surface energy on shear strength of SiC/SiC composite joint.

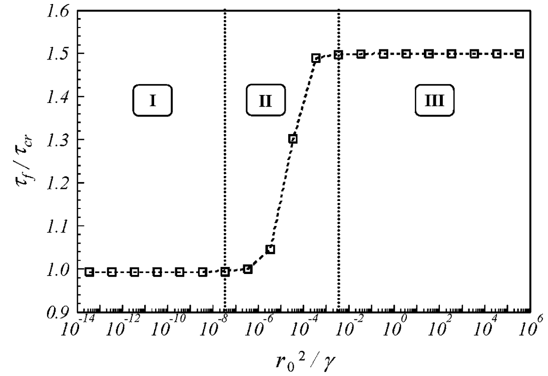

Fig. 6. Influence of r_0^2/γ on failure process in asymmetrical bending test.

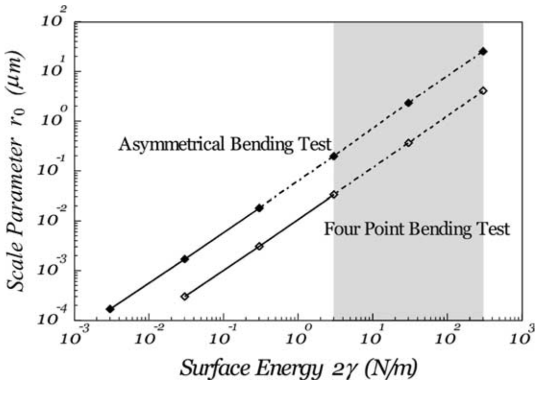

Fig. 7. Relationship between scale parameter and surface energy of interface element.

decided to be a fixed value regardless of the fracture mode. That is, the fracture behavior of mode-I and II might have a strong relationship. Moreover, from these results, this proposed method with the new interface potential was considered to have a great potential as a tool to study the failure problems whose fracture type was a mixture of mode-I and II.

5. Conclusions

The interface element was proposed as a simple model representing the mechanism of failure of a ceramic joint in an explicit manner. It was applied to the analyses of the fracture strengths of a SiC/SiC composite specimen jointed by ARCJoinT^{TM} under four-point and asymmetrical four-point bending tests. The conclusions can be summarized as follows.

(1) By using a new type interface potential, which is a coupled function of the opening and shear deformations, both the bending and asymmetrical bending tests were simulated.

(2) From the comparison with the bending and shear strengths experimentally obtained, the surface energy at the interface between the joint and composite was estimated to be about 30 N/m regardless of the fracture mode.

(3) The proposed method was considered to have a great potential as a tool to study the failure problems whose fracture type was a mixture of mode-I & II.

References

[1] R.H. Jones, C.H. Henager Jr., J. Nucl. Mater. 212–215 (1994) 830.
[2] R.H. Jones, C.A. Lewinsohn, G.E. Youngblood, A. Kohyama, Key Eng. Mater. 164&165 (1999) 405.
[3] H. Serizawa, C.A. Lewinsohn, G.E. Youngblood, R.H. Jones, D.E. Johnston, A. Kohyama, Ceram. Eng. Sci. Proc. 20 (4) (1999) 443.
[4] A. Kohyama, Y. Katoh, Ceram. Trans. 144 (2002) 3.
[5] M. Singh, Key Eng. Mater. 164-165 (1999) 415.
[6] A. Needleman, Int. J. Fract. 42 (1990) 21.
[7] Z.Q. Wu, H. Serizawa, H. Murakawa, Key Eng. Mater. 166 (1999) 25.
[8] H. Murakawa, H. Serizawa, Z.Q. Wu, Ceram. Eng. Sci. Proc. 20 (3) (1999) 309.
[9] H. Serizawa, M. Ando, C.A. Lewinsohn, H. Murakawa, J. Nucl. Mater. 283–287 (2000) 579.
[10] H. Serizawa, M. Ando, C.A. Lewinsohn, H. Murakawa, J. Nucl. Mater. 289 (2001) 16.
[11] H. Serizawa, C.A. Lewinsohn, H. Murakawa, Ceram. Eng. Sci. Proc. 23 (3) (2002) 825.
[12] H. Serizawa, H. Murakawa, C.A. Lewinsohn, Ceram. Trans. 144 (2002) 335.
[13] H. Murakawa, H. Serizawa, K. Miyamoto, I. Oda, in: Proceedings of the 2003 International Conference on Computational and Experimental Engineering and Sciences (ICCES'03), 6, 2003 (CD-ROM).
[14] Ö. Ünal, I.E. Anderson, S.I. Maghsoodi, J. Am. Ceram. Soc. 80 (5) (1997) 1281.

[15] C.A. Lewinsohn, M. Singh, T. Shibayama, T. Hinoki, M. Ando, Y. Katoh, A. Kohyama, J. Nucl. Mater. 283–287 (2000) 1258.
[16] C.A. Lewinsohn, M. Singh, T. Nozawa, M. Kotani, Y. Katoh, A. Kohyama, Ceram. Eng. Sci. Proc. 22 (4) (2001) 621.
[17] H. Serizawa, C.A. Lewinsohn, H. Murakawa, Ceram. Eng. Sci. Proc. 22 (4) (2001) 635.
[18] R.K. Bordia, D.H. Roach, S.M. Salamone, in: Proceedings of the 10th International Conference Computer Materials, IV, 1995 p. 711.