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Numerical analysis of mechanical testing for evaluating shear strength of SiC/SiC composite joints

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Abstract

As examples of the most typical methods to determine the shear strength of SiC/SiC composite joints, the asymmetrical four point bending test of a butt-joined composite, the tensile test of a lap-joined composite, and the compression test of a double-notched composite joint were analyzed by using a finite element method with the interface element. From the results, it was found that the shear strength in the asymmetrical bending test was controlled by both the surface energy and the shear strength at the interface regardless of their combination while the strength in the tensile test or the compression test was governed by the surface energy when both the surface energy and the shear strength were large. Also, the apparent shear strength of the composite joint obtained experimentally appeared to be affected by the combination of the surface energy and the shear strength at the interface.

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]. Practical methods for joining simple geometrical shapes are essential for fabricating large or complex shaped parts of SiC/SiC composites. To establish useful design databases, the mechanical properties of joints must be accurately measured and quantitatively characterized with the shear strength of the joint being one of the most basic and important ones.

The strength of a bonded joint is largely influenced by the geometry of the joint and the test method for evaluating the strength. Although, detailed information on the stress field is provided in previous studies, little information on the criteria of fracture is obtained [2]. To describe deformation and fracture behavior more precisely, a new and simple computer simulation method has been developed [3–7]. 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 [3] or interface elements [4–7]. So, in this research, examples are analyzed by using FEM with the interface

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element of the most typical methods to determine the shear strength of SiC/SiC composite joints. These methods are the asymmetrical four point bending test of butt-joined composites, the tensile test of lap-joined composites and the compression test of double-notched composite joints.

2. Interface element

Essentially, the interface element is the distributed nonlinear spring existing between surfaces forming the interface or the potential crack surfaces. The authors employed the Lennard–Jones type potential as the interface potential, which describes the interaction between the surfaces, 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:

$$\phi(\delta_n,\delta_t) \equiv \phi_a(\delta_n,\delta_t) + \phi_b(\delta_n), \tag{1}$$

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

$$\delta = \sqrt{\delta_n^2 + A\cdot\delta_t^2}, \tag{2}$$

$$\phi_b(\delta_n) = \begin{cases} \frac{1}{2}\cdot K\cdot\delta_n^2 & (\delta_n \leqslant 0) \\ 0 & (\delta_n \geqslant 0) \end{cases} \tag{3}$$

where, δ_n and δ_t are the opening and shear deformation at the interface, respectively. The constants γ, r_0 and N are the surface energy per unit area, the scale parameter and the shape parameter of the potential function. In order to prevent overlapping in the opening direction due to a numerical error in the computation, the second term in Eq. (1) was introduced and K was set to have a large constant value. Also, to model an interaction between the opening and the shear deformations, a constant value A was employed in Eq. (2). From the above equations, the maximum shear stress, τ_{cr}, under only the shear deformation δ_t is calculated as follows:

$$\tau_{cr} = \frac{4\gamma N\sqrt{A}}{r_0}\cdot\left\{\left(\frac{N+1}{2N+1}\right)^{\frac{N+1}{N}} - \left(\frac{N+1}{2N+1}\right)^{\frac{2N+1}{N}}\right\}. \tag{4}$$

By arranging such interface elements along the crack propagation path, the growth of the crack under the applied load can be analyzed in a natural manner. From the results of our previous work using the interface elements, it was found that the fracture strength of various structures might be quantitatively predicted by selecting the appropriate values for the surface energy γ, the scale parameter r_0, and the interaction constant A [4–7].

3. Model for analysis

Since, an affordable, robust ceramic joining technology (ARCJoinT$^{\mathrm{TM}}$) has been developed as one of the most suitable methods for joining SiC/SiC composites [8], SiC/SiC composite joints processed by ARCJoinT$^{\mathrm{TM}}$ were selected for this study. Fig. 1 shows schematic models of the test methods for measuring the shear strength of joint. L_1 and L_2 in Fig. 1(a) 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 12 and 44 mm, respectively [9]. The lap joint shown in Fig. 1(b) was made from two SiC/SiC composite plates, whose dimensions were 57.5 mm-long, 12.5 mm-wide and 2.125 mm-thick. The angle of the edge, θ, was assumed to be 161 degree according to our ongoing experiments. The size of the double-notched joint was set to 22 mm-long, 6 mm-wide and 6.1 mm-thick, and the width of notch and the notch separation were assumed to be 0.5 mm and 4.0 mm according to the experimental result [10]. In all the joints, the thickness of the joint was set to 100 μm, for a typical example of ARCJoinT$^{\mathrm{TM}}$ [8].

Young's moduli and Poisson's ratios of SiC/SiC composite and the joint were assumed to be 300 GPa, 350 GPa, 0.15 and 0.20, respectively [4,8,9]. Although, the mechanical properties of SiC/SiC composites should be anisotropic, the properties were assumed to be isotropic since the difference between the elastic 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 plane strain. Since, the fracture started from the interface between SiC/SiC composite and the joint, the interface elements were arranged along both the interfaces between the composite and the joint.

From previous FEM with the interface element studies of the four point and the asymmetrical four point bending tests of a butt-joined SiC/SiC composites via the ARCJoinT$^{\mathrm{TM}}$ method, the surface energy γ and the interaction parameter A in Eq.

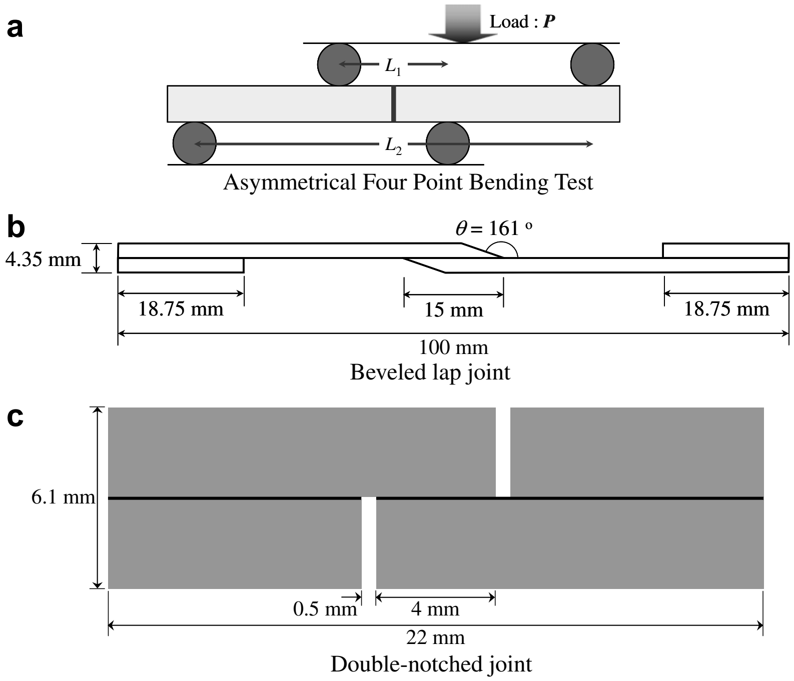

Fig. 1. Schematic illustrations of test methods for measuring shear strength.

(2) were estimated to be 30 N/m and 2.47×10^{-2}, respectively [7]. In this research, a constant K was set to 5.0×10^4 N/m. Then, by changing the scale parameter r_0 and the surface energy 2γ from 1.0×10^{-4} to 100 μm and from 3.0 to 300 N/m, respectively, the test methods for evaluating the shear strength of joint were analyzed. Also, the effect of the joint shape in the compression test of a double-notched joint was examined by changing the notch separation from 2 to 16 mm. The shape parameter N was assumed to be 4 according to our previous studies [4–7].

4. Calculation results

The tensile or compressive load was applied to the beveled lap joint or the double-notched joint through the horizontal displacement given on both ends of the joint. According to the experimental results, the maximum load computed was defined as the fracture load. The effects of the scale parameter and the surface energy on the fracture load under the asymmetrical bending test, the tensile test of the lap joint and the compression test of double-notched joint are summarized in Figs. 2–4, respectively. The experimental results for the asymmetrical bending test and the tensile test are also plotted in

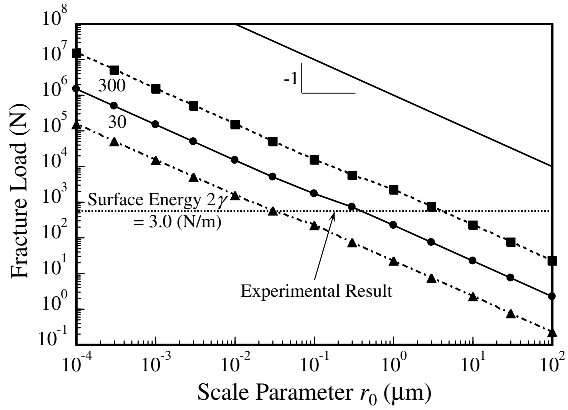

Fig. 2. Effect of scale parameter and surface energy on fracture load of butt-joined composite in asymmetrical four point bending test.

Figs. 2 and 3. In the case of the asymmetrical bending test, the fracture load increases with the surface energy 2γ and decreases with the scale parameter r_0 monotonically and the slopes of the curves are almost −1. On the other hand, in the other cases, all the curves can be divided into three parts with respect to the size of the scale parameter r_0. When r_0 is in the middle range, fracture load is almost independent of the scale parameter. The slopes of the curves become −1 when the scale parameter is

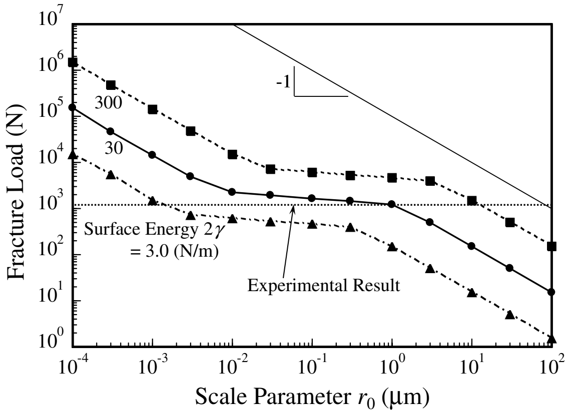

Fig. 3. Effect of scale parameter and surface energy on fracture load of beveled lap-joined composite in tensile test.

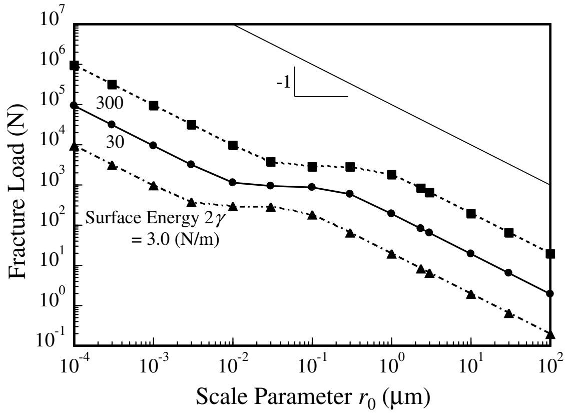

Fig. 4. Effect of scale parameter and surface energy on fracture load of double-notched composite joint in compressive test.

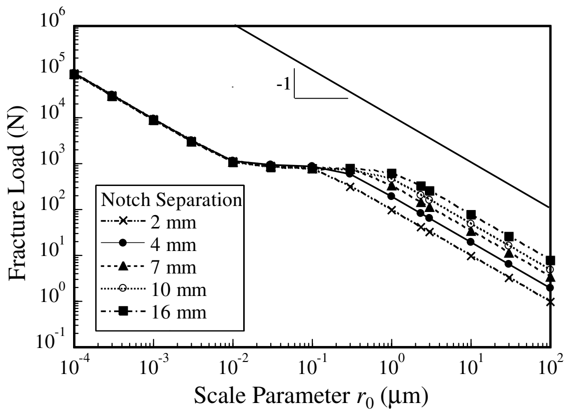

Fig. 5. Effect of scale parameter and notch separation on fracture load of double-notched composite joint in compressive test.

smaller or larger than this range. Fig. 5 shows the effect of the notch separation on the fracture load. All the curves also can be divided into three parts and the range of middle parts is widened with increasing notch separation.

5. Discussion

From the similarity of the interface element to the ordinary element, the predicted fracture load for the asymmetrical bending test can be rearranged to a single curve as shown in Fig. 6 [5], where τ_f is the predicted shear strength and τ_{cr} is the maximum shear strength at the interface element obtained from Eq. (4). As is clearly seen from this figure, this single curve also can be divided into three parts as in Figs. 3 and 4. From the close examination of the failure process, it was found that the composite and the joint were simply separated without significant deformation in the zone-III. In the zone-II, crack like localized sliding was observed at the center of the interface. The joint broke suddenly without significant shear deformation of the interface in the zone-I. These failure processes can be related to the shear strength of the interface element in the following way. Since, the shear deformation of the interface was dominant, the strength of the joint was almost the same as the maximum shear strength τ_{cr} in the zone-III. According to Eq. (4), both the stiffness and the shear strength of the interface were small in zone-III. Thus, the joint broke in the simple separation mode. On the other hand, when the scale parameter r_0 was small as in the zone-I, the shear strength became larger than the stress induced at the crack tip in FEM model. In this case, the crack like localized sliding was not formed and the failure occurred when the computed stress at the center of

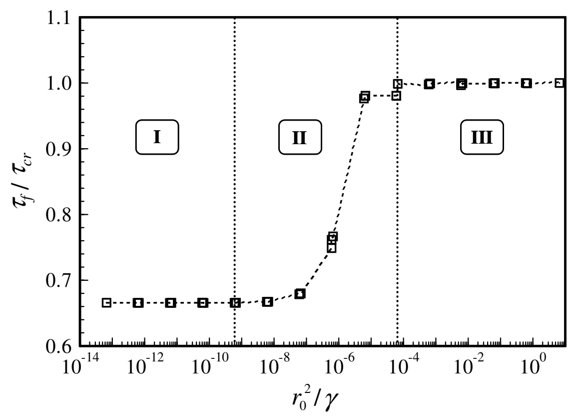

Fig. 6. Influence of r_0^2/γ on failure process in asymmetrical bending test.

the interface reached the critical shear stress τ_{cr}. Since, this phenomenon was caused by the coarseness of the mesh, it could be eliminated by using small enough mesh division. Therefore, it was found that the practical failure process was limited in the zone-II and III and the process was controlled by the combination of the surface energy and the shear strength of the interface element. Moreover, it was revealed that the fracture strength in the asymmetrical bending test was controlled by both the surface energy and the shear strength regardless of their combination although the strengths of lap and double-notched joints were governed by the surface energy in zone-II, in which the shear strength of the interface element was large.

From the comparison with the experimental result in the asymmetrical bending test, the scale parameter r_0 is estimated to be about 0.4 μm since the surface energy γ was estimated to be 30 N/m according to our previous study [7]. By using this value, the tensile strength of the joint is predicted to be 55 MPa while the strength obtained from our ongoing experiment was about 45 MPa. Although, the type of SiC/SiC composite is different from that for the asymmetrical bending test, those tensile strengths have reasonable agreement.

Using this same value for the scale parameter, the apparent shear strength, which is calculated from the fracture load divided by the area of joint, is 20, 19.1, 16.3, 12.4 and 7.88 MPa for the notch separation of 2, 4, 7, 10 and 16 mm, respectively. These results suggest that the apparent shear strength might be affected by the combination of the surface energy and the shear strength at the interface and the range of middle parts in Fig. 5 would be controlled by this combination. This effect could be revealed from the numerical analyses using FEM with the interface element.

6. Conclusions

As examples of the most typical methods to determine the shear strength of SiC/SiC composite joints, the asymmetrical four point bending test of a butt-joined composite, the tensile test of a lap-joined composite and the compression test of double-notched composite joint were analyzed by using the finite element method with the interface element. The conclusions can be summarized as follows:

(1) The shear strength in the asymmetrical bending test was controlled by both the surface energy and the shear strength at the interface regardless of their combination, although the strength of the lap or double-notched joint was governed by the surface energy when both the surface energy was large.
(2) The apparent shear strength of the ceramic composite joint obtained experimentally might be affected by the combination of the surface energy and the shear strength at the interface and this effect could be revealed from the numerical analyses using finite element method with the interface element.

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