Finite Element Analysis of Single Lap Joined Ceramic Composites by Using An Interface Element †

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Abstract

As one of the most typical test methods for determining the shear strength of joints, the effect of the joint shape on the tensile strength of a lap joined ceramic composite bonded by ARCJoinTTM was examined by using the finite element method with an interface element. Also, the influence of the mechanical properties of the interface element on the tensile strength was analyzed. From the effects of the surface energy and the bonding and shear strength of the interface element on the tensile strength, it was found that the tensile strength of a beveled lap joint was mainly governed by the surface energy at the interface and almost independent of the bonding and the shear strength. As the results of the joint shape effect, it was revealed that the joint shape slightly affected the tensile strength and this influence was caused by the order of singularity in the stress field at the edge of joint. Furthermore, it was considered that the shear strength measured by the tensile test of a lap joint might be different from that obtained by the asymmetrical four point bending test of a butt joined specimen.

KEY WORDS: (Shear Strength) (Lap Joint) (Interface Element) (Surface Energy) (Finite Element Method)

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 high-temperature properties, chemical stability and good oxidation and corrosion resistance[1-3]. 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[4].

To establish useful design databases, the mechanical properties of joints must be accurately measured and quantitatively characterized. A lap joint, in which two sheets are joined together with an overlay, is one of the most common joints encountered in practice and is the configuration most often used for testing adhesives. Also, in the practical use of lap joints, the edges of joint components are tapered to eliminate stress risers under loading and to reduce the tendency to peel. Although detailed information on the stress field of lap joints under tensile loading has been reported by using the analytical and numerical techniques[5-7], little information on the criteria of the fracture is available from these types of study. This comes from the fact that the physics of failure itself is not explicitly modeled.

On the other hand, to describe deformation and fracture behavior more precisely, a new and simple computer simulation method has been developed[8-12]. The method treats the fracture phenomena as the formation of new surfaces during crack opening and propagation. Based on the fact that surface energy must be supplied for the formation of a new surface, a potential function representing the density of surface energy is introduced into the finite element method (FEM) using cohesive elements[8)] or interface elements[9-12]. This method may have a potential capability not only to give insight into the criteria of the fracture but also to make the quantitative prediction of strength itself. In this research, the effect of the joint shape on the tensile strength of lap and beveled lap joined ceramic composites bonded by the ARCJoinT^{TM} was examined by using the finite element method with the interface element. Also, the influence of the interface element on the tensile strength was analyzed.

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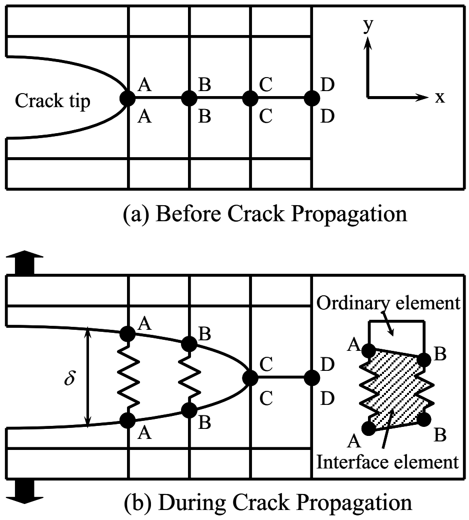

Fig.1 Representation of crack growth using interface element.

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}. 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 potentials. 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.

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

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

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

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

Where, δ_n and δ_t are the opening and shear deformations 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 value as a constant. 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 bonding stress, σ_{cr}, under only the opening deformation δ_n and the maximum shear stress, τ_{cr}, under only the shear deformation δ_t are calculated as follows.

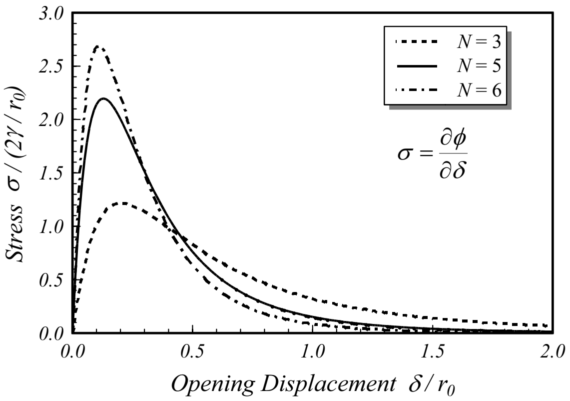

Fig.2 Relation between crack opening displacement and bonding stress.

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

$$\tau_{cr}=\frac{4\gamma N\sqrt{A}}{r_0}\cdot\left\{\left(\frac{N+1}{2N+1}\right)^{\frac{N+1}{N}}-\left(\frac{N+1}{2N+1}\right)^{\frac{2N+1}{N}}\right\} \tag{5}$$

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 about the crack growth based on the comparison between the driving force and the resistance as in the conventional methods is avoided.

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 as controlled by the surface energy γ, the scale parameter r_0 and the interaction parameter A in Eq.(2); furthermore, the fracture strength in the failure problems 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[11,12].

3. Model for Analysis

SiC/SiC composite ceramic joint joined by the ARCJoinT™ was selected for this study. **Figure 3** shows a model of the beveled lap joint for the tensile test. The joint was made from two SiC/SiC composite plates, whose dimensions were 57.5 mm-long, 12.5 mm-wide

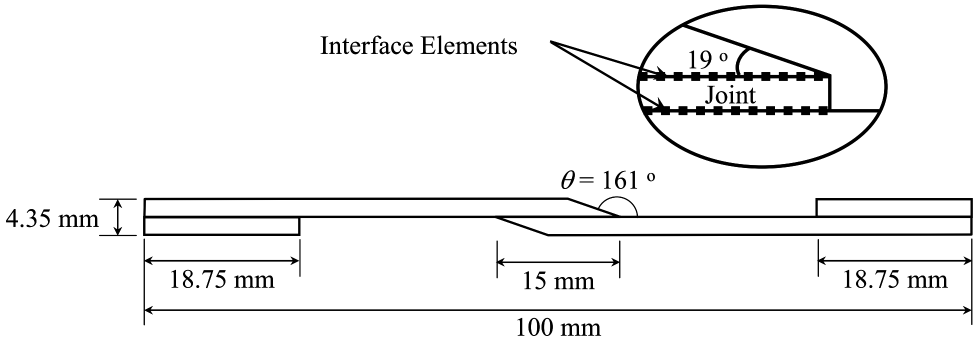

Fig.3 Schematic illustration of beveled lap joined ceramic composite.

and 2.125 mm-thick. The thickness of joint was set to be 100 μm for a typical example of ARCJoinT™ [4)] and the angle of the edge, θ, was assumed to be 161 degree according to our ongoing experiments. To prevent rotation of the joint due to a bending moment, the tabs were also joined to the ends of the joint via the ARCJoinT™ method. 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[10,12)]. 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 plain strain. Since the fracture started from the edge of the interface between the SiC/SiC composite and the joint where the load had a maximum value in the experiment, the interface elements were arranged along both interfaces between the composite as shown in Fig.3 and the joint and the mesh division near both the edges was set to fine. The total number of elements and nodes for the joint material were 17162 and 17521, respectively, and the element sizes were decided by continuously refining the mesh until approximate convergence with the numerical solution was achieved.

From the previous studies of the four point and the asymmetrical four point bending tests of a butt joined SiC/SiC composites via the ARCJoinT™ method by using FEM with the interface element, the surface energy γ and the parameter of the interaction between the opening and the shear deformations A in Eq.(2) were estimated to be 30 N/m and 2.47 x 10^{-2}, respectively[12)]. Also, in this research, a constant K was set to be 5.0 x 10^{4} N/m. Then, by changing the scale parameter r_0 in the range from 1.0 x 10^{-4} to 100 μm, the tensile strength of the beveled lap joint was analyzed. Also, the effect of the joint shape on the tensile strength of lap and beveled lap joints was examined by changing the thickness of the joint and the angle of the edge, θ. The shape parameter N was assumed to be 4 according to our previous researches[10-12)].

4. Effect of Mechanical Properties of Interface Element

The tensile load was applied to the beveled lap joint through the horizontal displacement given to both the ends of the joint. According to the experimental results, the maximum load obtained was defined as the fracture load. The effect of the scale parameter on the fracture load is summarized in **Fig.4** with a logarithmic scale where the surface energy was also changed in the range from 3 to 300 N/m to study the effect of the surface energy on the fracture load. As it is clearly seen from this figure, all the curves could be divided into three parts with respect to the size of the scale parameter r_0. When r_0 was 0.01 and 1.0 μm for $\gamma = 30$ N/m, the fracture load was almost independent of the scale parameter. On the other hand, the slope of the curve became -1 when the scale parameter was smaller or larger than this range. From our previous researches[11)], it was found that the results in the middle part, whose slopes were not -1, could be quantitatively compared with the experimental results. Namely, the appropriate value for the scale parameter r_0 was in this range. Also, from this figure, it was found that the tensile fracture strength of beveled lap joints was controlled by the surface energy γ and the strength was almost independent of r_0.

In order to study the effect of the interaction between the bonding and the shear strength of interface element, the influence of the interaction parameter A was analyzed and the result is summarized in **Fig.5**. This figure suggests that the fracture load was almost independent of the interaction between the bonding and the shear strength of interface element and only the range for the appropriate value of scale parameter was affected. From these results, it was concluded that the tensile strength of beveled lap joints is governed by the

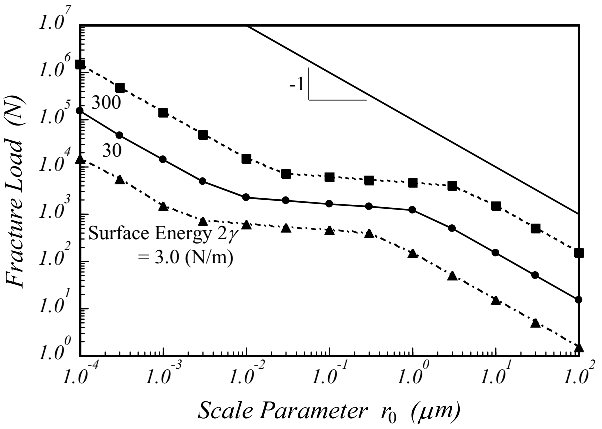

Fig.4 Effect of r_0 and γ on fracture load of lap joined SiC/SiC composite.

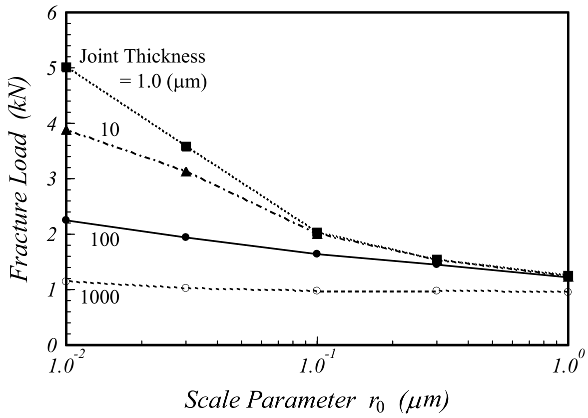

Fig.6 Effect of r_0 and joint thickness on fracture load of lap joined SiC/SiC composite.

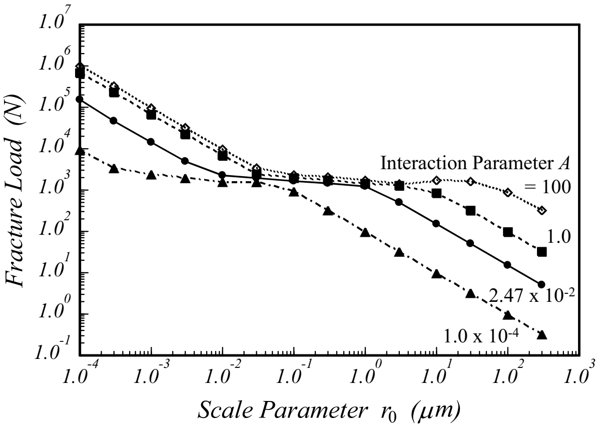

Fig.5 Effect of r_0 and A on fracture load of lap joined SiC/SiC composite.

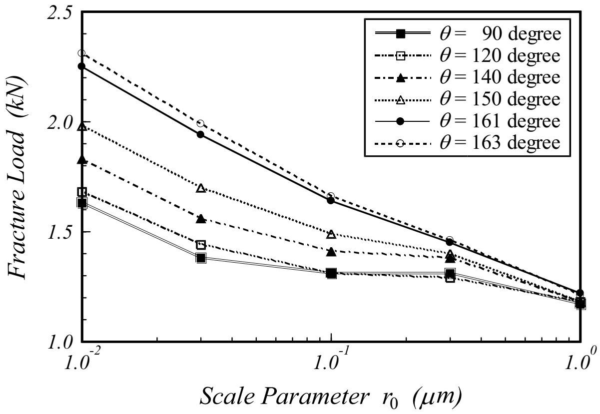

Fig.7 Effect of r_0 and θ on fracture load of lap joined SiC/SiC composite.

surface energy and almost independent of the bonding and the shear strength at the joint interface.

On the other hand, in our previous analyses about four point bending and asymmetrical four point bending tests of the butt joined ceramic composites, which are commonly used to measure the bonding and the shear strength of joint, the bonding and the shear strengths were controlled by not only the surface energy but also the strength at the joint[12]. Then, it can be considered that the shear strength measured by the tensile test of lap joint might be different from that obtained by the asymmetrical bending test of butt joined specimen.

5. Effect of Joint Shape

To examine the effect of the joint shape on the tensile strength of lap joints, the thickness of joint and the angle of edge were changed in the range from 1 to 1000 μm and from 90 to 163 degree, respectively. The results were summarized into **Figs.6 and 7** where the scale parameter was changed in the range from 0.01 to 1.0 μm according to the previous calculation. From these results, it was found that the tensile strength would be affected by the joint shape, though its effect was less than that of the surface energy at the joint. As for the joint thickness, the tensile strength monotonically decreases with increasing the joint thickness and this effect will be larger with decreasing scale parameter, which means that the bonding and the shear strengths at the joint increase as shown in Eqs.(4) and (5). In the case of the angle of edge, its influence on the tensile strength also becomes larger with increasing the bonding and the shear strengths at the joint. Furthermore, the stress distribution at the edge of joint was analyzed and the effects of the joint thickness and the angle of edge on the order of stress singularity were summarized into **Figs.8 and 9**. The tensile strengths were also plotted in this figure where the scale parameter was 0.1 μm. From these figures, it was found that there was a strong relationship between the tensile strength and the order of the singularity in the stress field at the interface although the strength was not determined by the order of the singularity.

Practically, the beveled lap joint was prepared by tapering the edge before or after joining SiC/SiC composite plates. In order to examine the effect of this preparation method, the influence of the angle of joint on

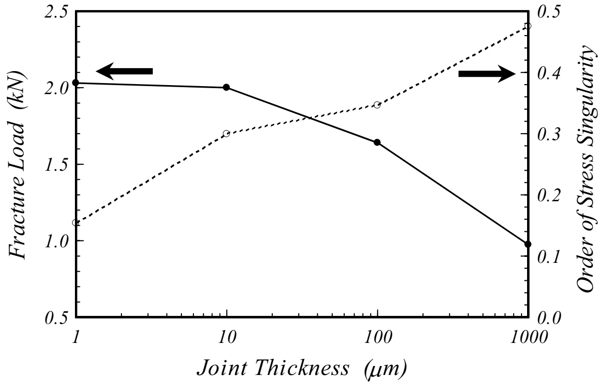

Fig.8 Effect of joint thickness on fracture load and order of stress singularity of lap joined SiC/SiC composite.

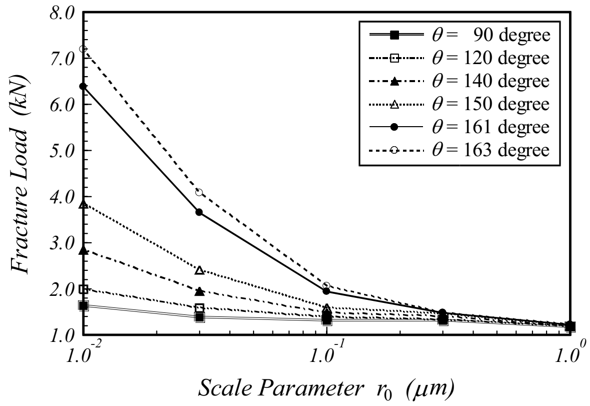

Fig.10 Effect of r_0 and θ on fracture load of lap joined SiC/SiC composite.

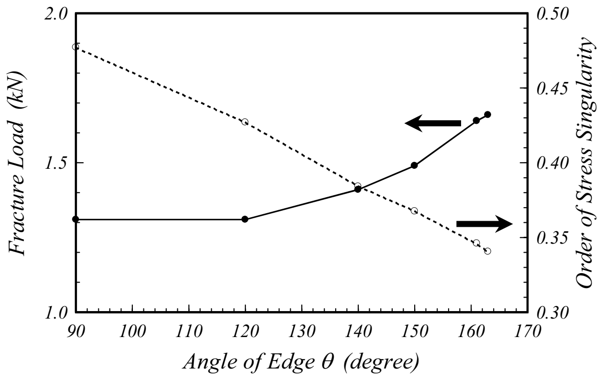

Fig.9 Effect of θ on fracture load and order of stress singularity of lap joined SiC/SiC composite.

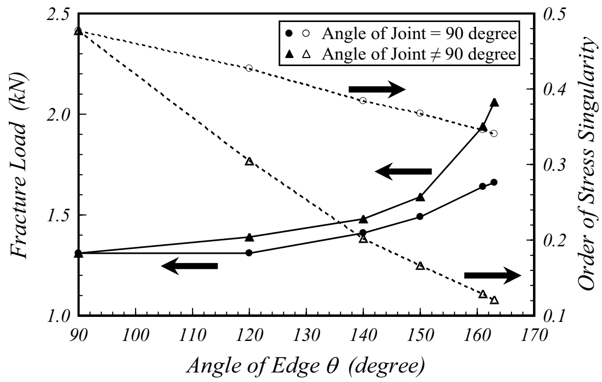

Fig.11 Effect of θ on fracture load and order of stress singularity of lap joined SiC/SiC composite.

the tensile strength was studied and the stress field at the edge of joint was also analyzed. **Figure 10** shows the effect of the angle of joint on the tensile strength as a function of the scale parameter. The relationship between the tensile strength and the order of stress singularity is summarized in **Fig.11** where the scale parameter was 0.1 μm and the results shown in Fig.9 were also plotted. From this figure, it was found that the tensile strength decreased with increasing the order of stress singularity at the edge of the interface. However, these changes in the tensile strength were much less than the effect of the surface energy at the interface. Namely, it was concluded that the tensile strength of lap or beveled lap joints was mainly governed by the surface energy at the interface and the effects of the joint of shape were small.

6. Conclusions

In order to examine the effect of joint shape on the tensile strength of single lap joined ceramic composites, the tensile test of lap and beveled lap joined SiC/SiC composites plates bonded by the ARCJoinT™ was analyzed by using the finite element method with an interface element. Also, the influence of the mechanical properties of the interface element on the tensile strength was analyzed. The conclusions can be summarized as follows.

(1) The tensile strength of a beveled lap joint is mainly governed by the surface energy at the interface and almost independent of the bonding and the shear strength at the interface.
(2) The joint shape slightly affected the tensile strength of lap and beveled lap joint and this influence was caused by the order of singularity in the stress field at the edge of joint.
(3) The shear strength measured by the tensile test of a lap joint might be different from that obtained by the asymmetrical four point bending test of a butt joined specimen.

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