ELSEVIER

Journal of Nuclear Materials 283–287 (2000) 579–583

journal of nuclear materials

www.elsevier.nl/locate/jnucmat

New evaluation method of crack growth in SiC/SiC composites using interface elements

H. Serizawa [a,*], M. Ando [b], C.A. Lewinsohn [c], H. Murakawa [a]

[a] *Joining and Welding Research Institute, Osaka University, 11-1 Mihogaoka, Ibaraki, Osaka 567-0047, Japan*
[b] *Graduate School of Engineering, Osaka University, 2-1 Yamada-oka, Suita, Osaka 565-0871, Japan*
[c] *Pacific Northwest National Laboratory, MSIN:P8-15, P.O. Box 999, Richland, WA 99352, USA*

Abstract

Crack propagation behavior in SiC/SiC composites was analyzed using a new computer simulation method that included time-dependent interface elements. The simulation method was used to describe the time-dependent crack growth in SiC/SiC composites under four-point bending of single-edge-notched beam bend-bars. Two methods were used to simulate time-dependent crack growth in SiC/SiC composites due to fiber creep. In one method, the creep property was introduced into the interface elements by the general method of finite element method (FEM) analysis. In the second method, a new technique making the best use of the potential function was used to represent crack closure tractions due to creeping fibers. The stage-II slow crack growth of a general creep deformation was simulated by both methods. Additionally, stage-III crack growth and the transition from stage-II to stage-III could be simulated by the new method. The new method has the potential to completely simulate time-dependent crack growth behavior in SiC/SiC composites due to fiber creep.

1. Introduction

Silicon carbide fiber-reinforced silicon carbide composites (SiC/SiC) are promising candidates as high-flux component materials, due to their potential of low-activation, low-afterheat and excellent high-temperature properties [1–4]. For safe design of fusion structures, it is very important to reliably estimate the fracture strength and deformation behavior of materials. The formation and propagation of cracks in SiC/SiC composites have been previously microscopically and statically analyzed [5–7]; however the macroscopic and dynamic deformations have not been sufficiently described.

To describe deformation and fracture behavior more completely, a new and simple computer simulation method [8,9] was developed. The method treats fracture phenomena as the formation of new surface during crack 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 proposed interface elements.

For SiC/SiC composites, matrix cracking precedes fiber failure. Following matrix cracking, intact fibers bridge the cracks and impose closure tractions behind the crack tip that reduce the driving force for further cracking (crack-tip shielding). Fracture is governed by creep of the bridging fibers, which relax the bridging tractions causing stress intensity at the crack tip to increase. Time-dependent crack growth of SiC/SiC composites in inert environments (slow crack growth) is controlled by the creep rate of the bridging fibers [6]. Therefore, a new, time-dependent interface element was developed to incorporate the creep behavior of fibers into FEM. This technique was then used to analyze the time-dependent crack growth of SiC/SiC composites.

2. Interface potential

For the case of ordinary crack propagation problems, a method using interface elements has been proposed [8,9]. In this method, the formation and

---

[*] Corresponding author. Tel.: +81-6 6879 8665; fax: +81-6 6879 8689.
E-mail address: serizawa@jwri.osaka-u.ac.jp (H. Serizawa).

0022-3115/00/$ - see front matter © 2000 Elsevier Science B.V. All rights reserved.
PII: S0022-3115(00)00214-2

propagation of a crack is governed by the interface potential energy function. The requirements of the interface potential energy function are:

1. It involves the surface energy necessary to form a new surface.
2. It is a continuous function of crack opening displacement, δ.

Among many functions satisfying these requirements, a Lennard–Jones type potential [10] may be employed where the potential energy $\phi(\delta)$ is defined by the following equation:

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

where δ is the crack opening displacement and γ, n and r_0 are material constants. In particular, 2γ is the surface energy per unit area. This form of the Lennard–Jones type potential function has been used to simulate peeling tests of metal plating on ABS resin. Since the agreement between the simulations and the experimental results were good [8], the same potential function was used to analyze the time-dependent crack growth of SiC/SiC composites.

The derivative of ϕ with respect to the crack opening δ, as shown in the following equation, gives the bonding strength per unit area of the crack surface:

$$\sigma = \frac{\partial\phi}{\partial\delta} = \frac{4\gamma n}{r_0}\left\{\left(\frac{r_0}{r_0+\delta}\right)^{n+1} - \left(\frac{r_0}{r_0+\delta}\right)^{2n+1}\right\}. \tag{2}$$

3. Modeling method

In this method, the bridging zone is analyzed macroscopically, not microscopically. One interface element is assumed to represent many fibers and the matrix in the bridging zone. The properties of the interface between the fiber and matrix are assumed to be invariant with respect to time or displacement, hence they are not explicitly included in the model. In other words, effective matrix properties are used to incorporate both the true matrix and the interface. Away from the cracked region, the composite is described by ordinary FEM elements.

Summation was used to characterize both fibers and matrices by one interface element. The interface potential $\phi(\delta)$ becomes

$$\phi \equiv \phi_{\mathrm{f}} + \phi_{\mathrm{m}}, \tag{3}$$

$$\phi_{\mathrm{f}} \equiv 2\gamma_{\mathrm{f}}\left\{\left(\frac{r_{\mathrm{f}0}}{r_{\mathrm{f}0}+\delta}\right)^{2n} - 2\left(\frac{r_{\mathrm{f}0}}{r_{\mathrm{f}0}+\delta}\right)^{n}\right\}, \tag{4}$$

$$\phi_{\mathrm{m}} \equiv 2\gamma_{\mathrm{m}}\left\{\left(\frac{r_{\mathrm{m}0}}{r_{\mathrm{m}0}+\delta}\right)^{2n} - 2\left(\frac{r_{\mathrm{m}0}}{r_{\mathrm{m}0}+\delta}\right)^{n}\right\}, \tag{5}$$

where subscripts f and m indicate fiber and matrix, respectively. Only ϕ_{f} was assumed to have a time dependency due to the creep effect of fiber. The effect of fiber creep was introduced by two methods: (1) the general method of FEM analysis using conventional elements with integral creep properties and, (2) a new method making the best use of a potential function.

4. Theoretical formulation

4.1. General method of FEM analysis

In the general method of FEM analysis for creep deformation, the total strain can be divided into elastic strain, plastic strain, creep strain and possibly other strains (e.g., thermal strain). Typically, due to the brittleness of SiC/SiC composites, their deformations may be limited to elastic and creep deformations. The strain of ordinary elements in FEM is equal to the increment of displacement in the interface element. For a fiber element, the increment of displacement, $\Delta\delta$, can be divided into an elastic increment, $\Delta\delta^{\mathrm{e}}$, and a creep increment, $\Delta\delta^{\mathrm{c}}$

$$\Delta\delta \equiv \Delta\delta^{\mathrm{e}} + \Delta\delta^{\mathrm{c}}. \tag{6}$$

The creep increment $\Delta\delta^{\mathrm{c}}$ was assumed to follow the classical Dorn formalism [11] for steady-state creep

$$\Delta\delta^{\mathrm{c}} \equiv A\sigma^{m}\Delta t, \tag{7}$$

where A, σ, m and Δt are a constant describing the structure of deformation, the applied stress of the interface element, the stress exponent and the time increment, respectively.

4.2. A new method

In Eq. (4), there are three material constants, which are γ_{f}, $r_{\mathrm{f}0}$ and n. Among these constants, only $r_{\mathrm{f}0}$ has the same dimension as the total displacement δ. As written in the previous section, in general, the displacement δ is controlled by Eq. (7) during creep. In this research, to make the best use of the potential function, the parameter $r_{\mathrm{f}0}$ was assumed to be time-dependent, and the increment of $r_{\mathrm{f}0}$ was defined by the following equation:

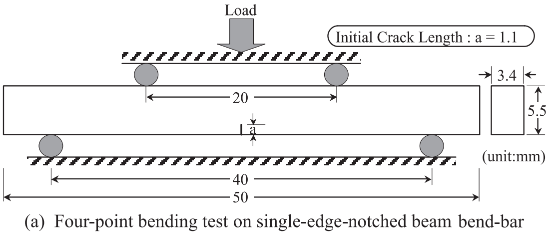
$$\Delta r_{\mathrm{f}0} = B\sigma^{m}\Delta t, \tag{8}$$

where B is a constant, and the other parameters are the same as those in Eq. (7). Thus, the interface potential energy of the fiber ϕ_{f} becomes a function of both opening displacement δ and time t, and is written as $\phi_{\mathrm{f}}(\delta, t)$. The total interface potential energy is also described as $\phi(\delta, t)$ while the interface potential energy of matrix ϕ_{m} is a function of only the opening displacement.

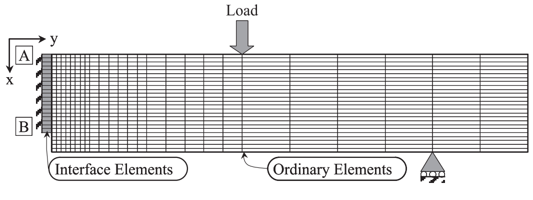
5. FEM model

In this report, the measured time-dependent slow crack growth in SiC/SiC composites was obtained by loading single-edge-notched beam bend-bar specimens in four-point bending (Fig. 1(a)). The reinforcements of the composites were 2-D plain-weave Hi–Nicalon fiber mats stacked in the direction of thickness, and the matrices were deposited by chemical vapor infiltration. The applied load varied from 540 to 570 N in the temperature range from 1100°C to 1200°C. The size of the specimens was approximately $50 \times 5 \times 4\ \mathrm{mm}^3$. The initial notch-to-depth ratio was approximately 0.2. The atmosphere was gettered Ar (<20 ppm O_2). In these tests, the crack propagated from the tip of the notch in a direction parallel to the applied load. Experimental details were published elsewhere [6].

To examine the validity of the proposed method using the time-dependent interface element for the analysis of slow crack growth, the model shown in Fig. 1(b) was analyzed as a plain strain problem. Due to the symmetry of the problem, only half the specimen was used. The time-dependent interface elements were arranged along the crack propagation path. In this analysis, only the mode-I type crack propagation parallel to the y-axis in Fig. 1(b) was taken into account. The results of previous calculations [8] using the interface element described here, indicated that a value of six for the parameter n in Eq. (1) was appropriate for the brittle fracture behavior such as the peeling test [8]. Therefore, in this analysis, the parameter n in Eqs. (4) and (5) was assumed to be six. The parameter m was assumed to be unity [12], since the test was performed at high-temperature.



(a) Four-point bending test on single-edge-notched beam bend-bar



(b) Model and mesh division for analysis

Fig. 1. Schematic illustration of bending test and FEM model for analysis.

6. Results and discussion

Fig. 2 shows typical experimental results for the time-dependent crack growth in SiC/SiC composites reported, where the temperature was 1200°C and applied load was 556 N [6]. In this paper, the proposed method with the time-dependent interface element was only compared with experimental results, where the displacement was more than 0.06 mm in the time–displacement curve. In this regime, the observed specimen behavior was almost steady-state and, hence, using a steady-state creep law to represent the interface elements (Eqs. (7) and (8)) was thought to be appropriate. Accurate modeling of all stages of crack growth behavior must include a time-dependent term.

Fig. 3 shows the experimental and calculated results using both the general and the new method. The parameters in Eqs. (4), (5), (7) and (8) were determined such that the calculated results fitted the quasi-steady-state experimental creep result in the displacement range from 0.06 to 0.10 mm as best as possible. Therefore, the parameters shown in Fig. 3 have no physical meaning. Nevertheless, the calculated results simulated the stage-II slow crack growth. Furthermore, the results using the

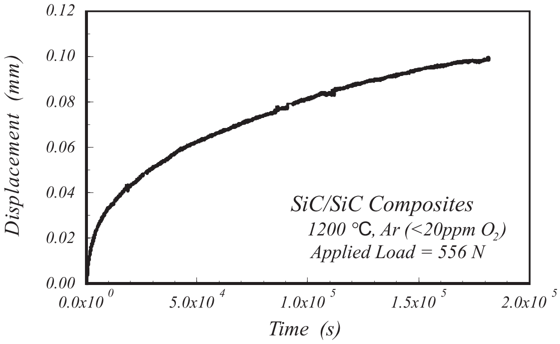


Fig. 2. Experimental displacement–time curve during time-dependent crack growth in SiC/SiC composites.

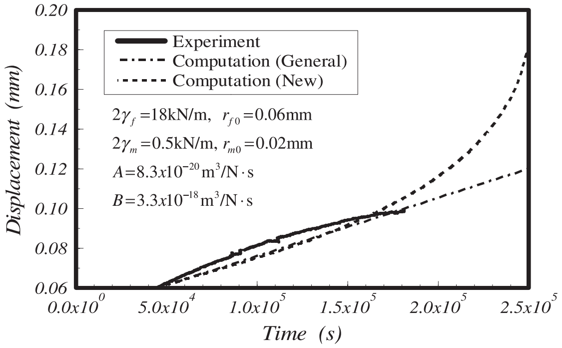


Fig. 3. Comparison between experiment and computation for time-dependent crack growth.

new method represented not only stage-II slow crack growth but also stage-III crack growth. Although stage-III crack growth is often not observed under conditions relevant to fusion devices, it may occur under other conditions. Therefore, the new method was used to calculate crack growth under various applied loads.

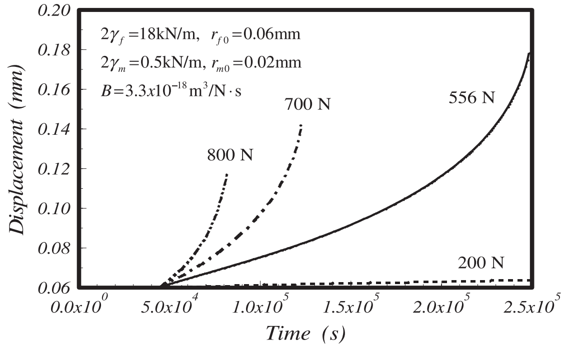


Fig. 4. Calculated displacement–time curves under various applied load for new method.

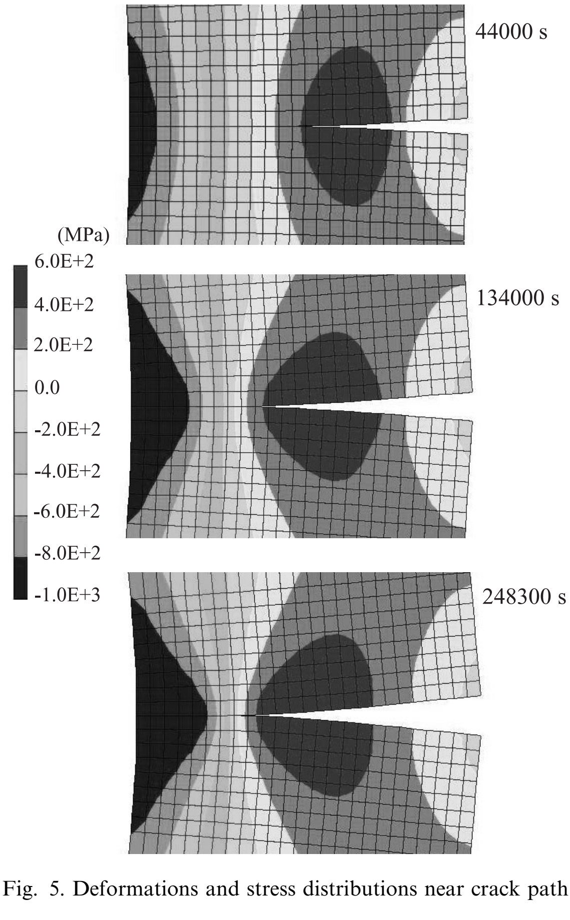


Fig. 5. Deformations and stress distributions near crack path.

The calculated results under various applied loads using the new method are shown in Fig. 4. The ends of curves indicate the fracture point of specimens. The transition time from stage-II to stage-III decreased with increasing applied load, similar to the general creep deformation. Therefore, the new method is considered to be useful for analyzing this transition. Fig. 5 shows the deformation and stress distribution during the time-dependent crack growth of SiC/SiC composites at 556 N applied load. The crack propagation behavior is clearly demonstrated and the stress relaxation behavior at the crack tip can also be calculated. From the definition of the interface potential, the stresses of the fiber and matrix in the interface element can be obtained. The changes in the stresses of the fiber and the matrix along the crack path are shown in Fig. 6. After the

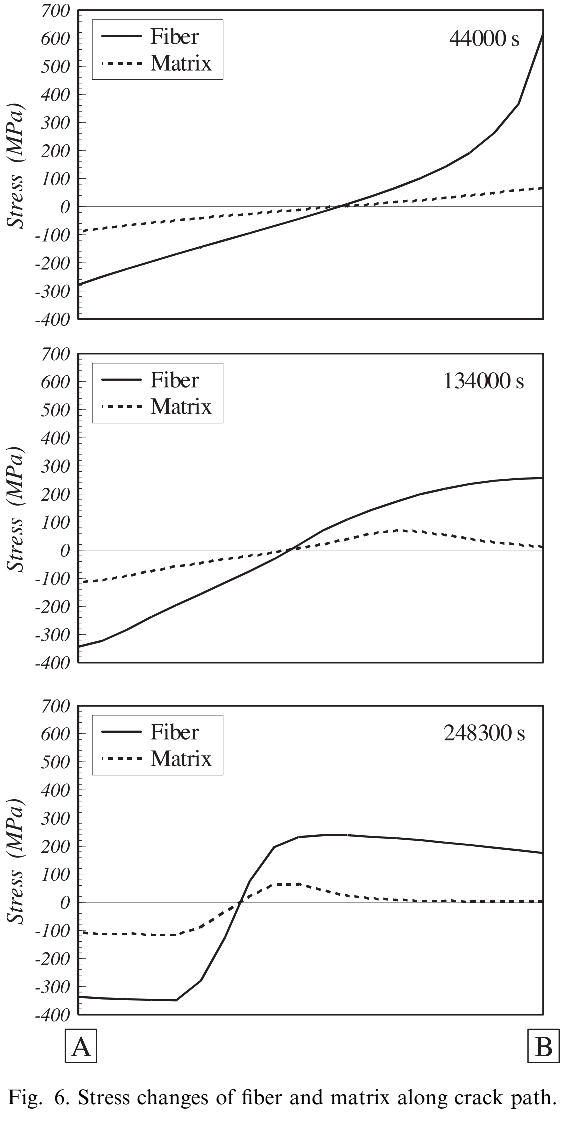


Fig. 6. Stress changes of fiber and matrix along crack path.

crack propagated, stress of both fiber and matrix decreased, and the stress of matrix became almost zero. On the other hand, the stress of fiber remained around 200 MPa after the crack propagated. In this research, as the first step for the calculation using the new method, the fiber was assumed as not to fracture but to continue to creep. Although the calculated results did not exactly represent the experimental behavior, the new method is considered to have the potential to demonstrate the time-dependent crack growth behavior in SiC/SiC composites. As a future work, the effect of fiber fracture and the effects of other parameters in Eqs. (4) and (5) will be examined.

7. Conclusions

In order to analyze crack propagation behavior in SiC/SiC composites, a new computer simulation method using time-dependent interface elements was developed and applied to time-dependent crack growth in SiC/SiC composites. The conclusions can be summarized as follows.

1. Two methods were used to simulate time-dependent crack growth in SiC/SiC composites due to fiber creep. In one method, the creep property was introduced into the interface elements by the general method of FEM analysis. In the second method, a new technique making the best use of the potential function was used to represent crack closure tractions due to creeping fibers. In both cases, the stage-II slow crack growth of a general creep deformation was simulated.
2. By using the new method, not only could the stage-III crack growth be simulated but also the transition from stage-II to stage-III. Therefore, the new method is considered to have the potential to model all stages of time-dependent crack growth behavior in SiC/SiC composites.

Acknowledgements

This work was maintained by the Core Research for Evolutional Science and Technology: Advanced Material Systems for Conversion of Energy. This work was also supported by Japan–US collaborative JUPITER program on fusion materials research.

References

[1] P.J. Lamicq, G.A. Bernhart, M.M. Dauchier, J.G. Mace, Am. Ceram. Soc. Bull. 65 (2) (1986) 336.
[2] J.R. Strife, J.J. Brennan, K.M. Prewo, Ceram. Eng. Sci. Proc. 11 (7–8) (1990) 871.
[3] R.H. Jones, C.H. Henager Jr., J. Nucl. Mater. 212–215 (1994) 830.
[4] R.H. Jones, C.A. Lewinsohn, G.E. Youngblood, A. Kohyama, Key Eng. Mater. 164&165 (1999) 405.
[5] C.H. Henager Jr., R.H. Jones, J. Am. Ceram. Soc. 77 (9) (1994) 2381.
[6] C.A. Lewinsohn, C.H. Henager Jr., R.H. Jones, Ceram. Trans. 74 (1996) 423.
[7] A.G. Evans, F.W. Zok, J. Mater. Sci. 29 (1994) 3857.
[8] Z.Q. Wu, H. Serizawa, H. Murakawa, Key Eng. Mater. 166 (1999) 25.
[9] H. Serizawa, H. Murakawa, Z.Q. Wu, in: Proceedings of the Eighth International Conference on Mechanical Behaviour of Materials, vol. 1, 1999, p. 261.
[10] A. Rahman, Phys. Rev. A 136 (1964) 405.
[11] G. Boitier, J.L. Chermant, J. Vicens, Key Eng. Mater. 164&165 (1999) 317.
[12] R. Bodet, J. Lamon, N. Jia, R.E. Tressler, J. Am. Ceram. Soc. 79 (10) (1996) 2673.