SWELLING AND TIME-DEPENDENT CRACK GROWTH IN SiC/SiC COMPOSITES—C. H. Henager, Jr. (Pacific Northwest National Laboratory)*

OBJECTIVE

Time-dependent and dose-dependent properties of SiC-composites include retained strength, dimensional stability, and creep-crack growth [1], which have been partly addressed by a dynamic crack growth model developed to predict composite lifetimes due to growth of internal cracks in these materials [2–4]. However, crack growth models have not been able to include dose-dependent swelling data until the development of a modified four-cylinder model [5]. The synthesis of these models will provide a more detailed understanding and improved predictive capabilities with respect to time-dependent mechanical properties of SiC-composites under neutron irradiation.

SUMMARY

Pacific Northwest National Laboratory (PNNL) was among the first to identify and study time-dependent bridging in ceramic composites [6–8] and we have proposed a crack growth mechanism map based on available experimental data as a function of temperature and oxygen partial pressure for continuous fiber composites with carbon interphases [4]. Once a relationship between crack-opening displacement and bridging tractions from crack-bridging elements is determined, a governing integral equation is obtained that relates the total crack opening, and the bridging tractions, to the applied load. The solution of this equation gives the force on the crack-bridges and the crack-opening displacement everywhere along the crack face [3]. This relation is rendered time-dependent by including appropriate bridging fiber creep laws and interface removal kinetics, if oxidation is an issue. For fusion environments, both thermal and irradiation-induced fiber creep are included but oxidation is not considered here. Since the frictional sliding stress, τ, is an input parameter for this dynamic model the results from our 4-cylinder model allow τ to be dose-dependent. The bridging model can be used to determine the effects of pyrocarbon type on composite mechanical properties in radiation environments.

A continuous fiber composite is simulated by four concentric cylinders [9]. The surrounding composite is the outermost cylinder, while the matrix, fiber coating, and fiber are the remaining cylinders, with the fiber being the innermost cylinder. The cylinders are subject to three independent boundary conditions; axisymmetric temperature change, $\Delta T(r)$, uniaxial applied stress, σ_{oz}, and biaxial applied stress, σ_{or}, where r and z are the radial and axial components referred to cylindrical coordinates (r, θ, z). Stress relaxation was not allowed during irradiation or during cooling from the fabrication temperature and all components remain elastic and perfectly bonded. The fiber, matrix, and surrounding composite were treated as isotropic materials, while the pyrocarbon coatings were considered to be transversely isotropic [10]. The boundary conditions for the four-cylinder problem and solution are presented in [9, 10] as the solution to eight simultaneous equations. Solution details when dose-dependent swelling terms are included in this model can be found in Ref. [5].

Several different cases were studied under simulated neutron irradiation at 1273K to 1473K using a dose rate of 10 dpa/year for a SiC-composite with SiC Type-S fibers. Time-dependent crack growth considering fiber creep under thermal and thermal plus radiation-induced was modeled under the assumptions of a constant sliding stress. This was then compared using the variable sliding stress results from the 4-cylinder model. For all models values of the domain radii for the 4-cylinder model were chosen to match microstructural information for CVI SiC/SiC composites. The fiber coating thickness was 100 nm, which is representative of pyrocarbon thicknesses. The stresses were computed out to 20 dpa, or 2 years of irradiation. Fiber thermal creep parameters for Hi-Nicalon Type-S SiC fibers were obtained from DiCarlo et al.†, while radiation-induced creep parameters were obtained from the work of Scholz and

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Youngblood [11] for Sylramic SiC fibers, which is a fine-grained SiC fiber comparable to the Type-S fiber. These creep parameters are shown in Table 1. The dynamic crack growth model reveals that Hi-Nicalon Type-S composites are thermal-creep resistant at 1273K but that using the assumed radiation-induced fiber creep law results in high crack growth rates, where the radiation-induced fiber creep is the dominant deformation mechanism. These crack growth results are shown in Fig. 1 for a composite bar in 4-point bending at 1273K to 1473K with an assumed crack in the bar loaded to 10 MPa√m and with an assumed sliding stress value of 20 MPa. The sliding stress is then allowed to vary according for both HDIC and LDIC pyrocarbon interfaces of 100-nm thickness. For both pyrocarbon materials there is a dose at which "turn around" occurs in their swelling and growth curves. Initially there is densification of the pyrocarbon and net radial shrinkage, which acts to reduce the sliding stress. At "turn around," pyrocarbon shrinkage stops and net radial swelling begins, which acts to put the fiber-matrix interface into compression and increase the sliding stress. The sliding stress begins at 20 MPa at $t = 0$ and decreases with increasing tensile σ_{rr} but is not allowed to decrease below 5 MPa. These predicted crack growth curves are shown in Fig. 2. Crack growth is initially more rapid compared to the constant sliding stress case when this detail is included, but then begins to decrease after "turn around" as the sliding stress begins to increase with increasing dose. Although the total crack length is longer for the variable sliding stress case, the crack growth rate has dropped below the rate for constant sliding stress after a dose of about 10 dpa.

Table 1. Properties used in calculations (typical values)

Materials	Young's Modulus (GPa)		Poisson's ratio		CTE ($10^{-6}C^{-1}$)	
	Axial E_L	Transverse E_T	Axial ν_L	In-plane ν_T	Axial α_L	Transverse α_L
Type-S SiC fiber	420	420	0.2	0.2	4.0	4.0
SiC matrix	460	460	0.22	0.22	4.5	4.5
HDIC*	80	80	0.23	0.23	5	5
LDIC**	80	80	0.23	0.23	5	5

*High-density isotropic carbon
**Low-density isotropic carbon

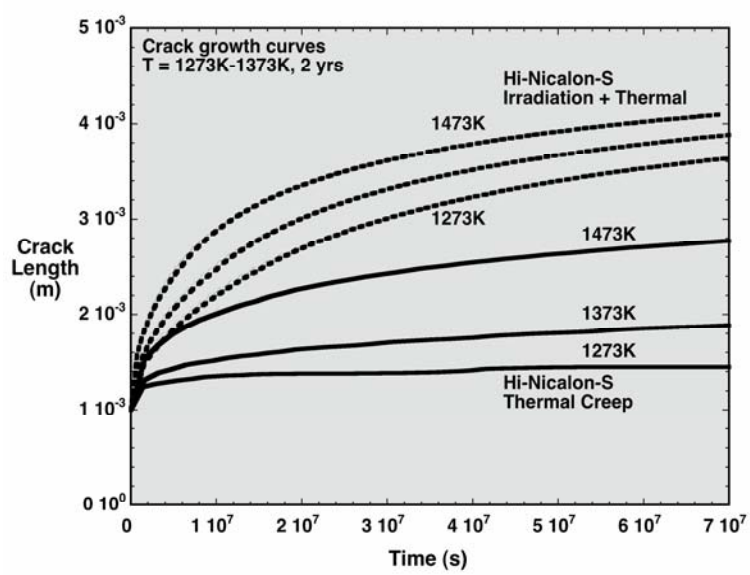

Fig. 1. Crack growth curves due to fiber thermal creep only (solid lines) or thermal plus radiation-induced creep (dashed lines) at 1273K to 1473K.

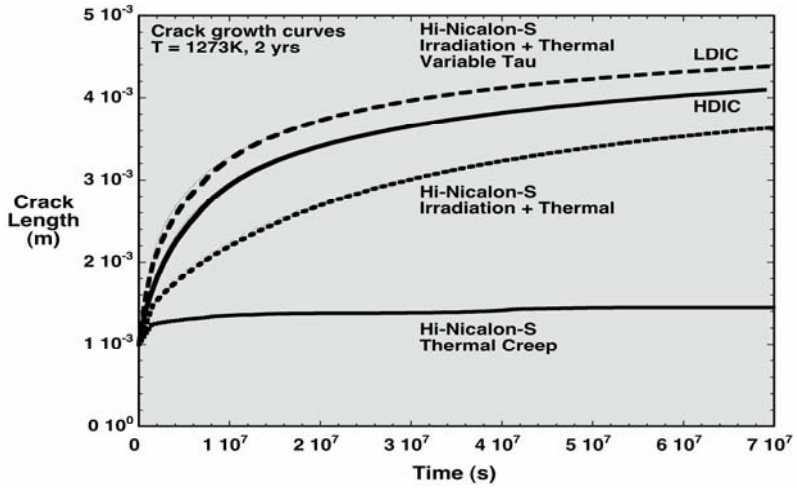

Fig. 2. Crack length as a function of time showing the effects of including a dose-dependent sliding stress in the dynamic crack modeling at 1273K. Total time in seconds is for 2 years or 20 dpa.

References

[1] L. L Snead, T. Inoki, Y. Katoh, T. Taguchi, R. H. Jones, A. Kohyama, and N. Igawa, Silicon carbide composites for fusion reactor application, 10th International Ceramics Congress 2002, Part D, Adv. Sci. Technol. 33 (2003) 129.

[2] C. H. Henager, C. A. Lewinsohn, and R. H. Jones, Subcritical crack growth in CVI SiCf/SiC composites at elevated temperatures: Effect of fiber creep rate, Acta Mater. 49 (2001) 3727.

[3] C. H. Henager, Jr., and R. G. Hoagland, Subcritical crack growth in CVI SiCf/SiC composites at elevated temperatures: Dynamic crack growth model, Acta Mater. 49 (2001) 3739.

[4] R. H. Jones and C. H. Henager, Jr., Subcritical crack growth processes in SiC/SiC ceramic matrix composites, J. Eur. Ceram. Soc. 25 (2005) 1717.

[5] C. H. Henager, E. A. Le, and R. H. Jones, A model stress analysis of swelling in SiC/SiC composites as a function of fiber type and carbon interphase structure, J. Nucl. Mater. 329–333 (2004) 502.

[6] C. H. Henager, Jr., R. H. Jones, C. F. Windisch, Jr., M. M. Stackpoole, and R. Bordia, Time dependent, environmentally assisted crack growth in Nicalon-fiber-reinforced SiC composites at elevated temperatures, Metall. Mater. Trans. A 27A (1996) 839.

[7] C. H. Henager, Jr., and R. H. Jones, Subcritical crack growth in CVI silicon carbide reinforced with Nicalon fibers: Experiment and model, J. Am. Ceram. Soc. 77 (1994) 2381.

[8] C. H. Henager, Jr., and R. H. Jones, High-temperature plasticity effects in bridged cracks and subcritical crack growth in ceramic composites, Mater. Sci. Eng. A 166 (1993) 211.

[9] Y. Mikata and M. Taya, Stress field in a coated continuous fiber composite subjected to thermo-mechanical loadings, J. Compos. Mater. 19 (1985) 554.

[10] C. M. Warwick and T. W. Clyne, Development of composite coaxial cylinder stress analysis model and its application to SiC monofilament systems, J. Mater. Sci. 26 (1991) 3817.

[11] R. Scholz and G. E. Youngblood, Irradiation creep of advanced silicon carbide fibers, J. Nucl. Mater. 283–287 (2000) 372.