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Postirradiation fiber debonding and pull-out in SiC–SiC composites *

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Abstract

The toughness of ceramic matrix composites is contributed by crack bridging, matrix crack deflection, fiber debonding and pull-out and other minor effects. Crack bridging relies on fibers being intact close to the crack tip, while pull-out toughening relies on the debonding and frictional characteristics of the fiber–matrix interface. The interface friction depends on the interface pressure (i.e., on misfit strains) and interface roughness. In this paper, a calculational model for postirradiation fiber debonding and pull-out toughness in SiC–SiC composites is presented. It is shown that fiber debonding and pull-out toughness in SiC–SiC composites vary significantly with neutron fluence and irradiation temperature, which is a direct consequence of the dependence of the misfit strain on these irradiation variables.

1. Introduction

SiC–SiC composites have been proposed for structural applications in fusion reactor first walls and blankets. The fracture toughness of these composites can be measured from work-of-fracture experiments, and can be theoretically determined by investigating the mechanisms of energy dissipation during composite failure. In addition to matrix toughness and matrix crack deflection, two other contributions are considered important in toughening SiC–SiC materials. First is the crack-tip bridging by intact fibers, which contributes a closure traction and lowers the stress intensity at the crack tip. This contribution is important in case of small cracks. The second contribution is caused by fiber debonding, fiber fracture and pull-out, which occurs at significant crack openings, thus involving energy dissipation by interface friction. Fiber bridging, debonding and pull-out depend on the composite mismatch stresses, i.e., on misfit strains.

Neutron irradiation alters the composite behavior in a complex fashion. In addition to basic property changes under irradiation, irradiation-induced swelling and creep change the mismatch stress state, which has a direct influence on the fracture strength and toughness of SiC–SiC composites. Detailed calculations of the time-evolution of mismatch stresses in SiC–SiC composites under high-temperature neutron irradiation are performed [1]. General inelastic constitutive equations for SiC fibers and SiC matrix, which are developed by the present authors [2] are used for that purpose. It is found that misfit strains change significantly during early irradiation, and that long-term changes depend on helium swelling and creep only, regardless of the initial thermal mismatch state. Accordingly, fiber debonding and pull-out behavior are expected to depend on the neutron fluence. In the present work, we calculate the postirradiation pull-out toughness and fiber debonding in SiC–SiC composites as functions of neutron fluence and irradiation temperature.

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2. Fiber debonding

Micromechanics of fiber pull-out and debonding makes use of the concentric cylinder model. It consists of a single fiber in a matrix with the outer radius determined such that the fractional cross sectional area of fiber is equal to fiber volume fraction. While approximate models for fiber debonding have been developed [3,4], a more accurate treatment is conducted by Gao et al. [5], which is followed in the present analysis. It relies on the principle of conservation of energy for debond crack extension with frictional sliding. The fiber debonding criterion is written as [5]

$$\frac{\gamma}{R_f} = -\frac{\sigma_f(0)}{4}\frac{\partial u_f(0)}{\partial L_d} - \frac{1}{2R_f}\int_0^{L_d}[\tau_0 - \mu q(z)]\frac{\partial u_r(z)}{\partial L_d}\,dz, \tag{1}$$

where γ is the interface fracture energy, R_f is the fiber radius, $\sigma_f(0)$ is the stress at the fiber's end, $u_f(0)$ is the fiber's end displacement, L_d is the debond length, μ is the friction coefficient, $q(z)$, is the interface pressure at $0 < z < L_d$, and τ_0 is a constant friction stress due to roughening of the interface under irradiation. In the original model of Gao et al. [5] the parameter τ_0 is not included. $u_r(z)$ is the relative displacement between fiber and matrix. Expressions for $u_r(z)$ and $u_f(0)$ are given in terms of the axial fiber and matrix strains, $\epsilon_f(z)$ and $\epsilon_m(z)$ by:

$$u_r(z) = \int_z^{L_d}[\epsilon_f(z) - \epsilon_m(z)]\,dz, \qquad u_f(0) = \int_0^{L_d}\epsilon_f(z)\,dz. \tag{2}$$

By representing the frictional shear stress at fiber–matrix interface as $\tau = \tau_0 - \mu q$ and following Gao et al. [5], the axial fiber stress, σ_f, the axial matrix stress, σ_m, and the interface pressure, q, can be written as

$$\sigma_f(z) = \sigma_f(0) + \frac{\mu q(0) - \tau_0}{\mu c}\left[\exp\left(\frac{2\mu cz}{R_f}\right) - 1\right],$$

$$\sigma_m(z) = -\frac{\mu q(0) - \tau_0}{\mu c}\left(\frac{f}{1-f}\right)\left[\exp\left(\frac{2\mu cz}{R_f}\right) - 1\right],$$

$$q(z) = \frac{\tau_0}{\mu}\left[1 - \exp\left(\frac{2\mu cz}{R_f}\right)\right] + q(0)\exp\left(\frac{2\mu cz}{R_f}\right), \tag{3}$$

in which f is the fiber volume fraction, and $q(0)$ is the interface stress at the fiber's end and is given by $q(0) = (c_q\sigma_f(0) + c_3\Delta\epsilon_{in})/c_4$. It can be shown that, by eliminating the terms containing τ_0 in Eq. (3), the expressions for $\sigma_f(z)$, $\sigma_m(z)$, and $q(z)$ reduce to those given in Ref. [5]. The constants c, c_1, c_3 and c_4, depend on the elastic constants of fiber and matrix and given by $c_1 = E_m(1-f)\nu_f$, $c_3 = E_m(1-f)E_f$, $c_4 = E_m(1-f)(1-\nu_f) + E_f[1 + \nu_m + f(1-\nu_m)]$, $c = (c_1 - fE_f\nu_m)/c_4$. Using stress–strain relationships, and Eq. (2), $u_r(z)$ and $u_f(0)$ can be found in terms of L_d and $\sigma_f(0)$. Then by employing Eq. (1), a transcendental equation for the debond length L_d in terms of $\sigma_f(0)$, γ and $\Delta\epsilon_{in}$ can be obtained. The interface debonding energy is then given by $\Gamma = 2\pi R_f L_d \gamma$.

In SiC–SiC composites, a graphite thin layer (~ 1 μm) is employed as a fiber–matrix interface. If the composite is heavily irradiated, the specific fracture energy of the interface is expected to change due to two effects; atomic mixing and helium bubble formation at the interface. Considering helium bubble formation alone, it can be shown that the irradiated interface fracture energy is given by $(1 - \Delta V/V)\gamma$, which does not deviate much from the unirradiated value since helium swelling, $\Delta V/V$, is only a few percent. Atomic mixing, on the other hand, can be the primary effect influencing the interface fracture energy, since the atomic composition in the interface layer will be altered. Specific experiments to measure the interface fracture energy as function of neutron fluence are not available at the present time. We will therefore consider the interface fracture energy as a parameter in our study.

3. Fiber pull-out

Fiber failure follows debonding if the crack opening displacement (COD) is significant. It is a statistical process, which is described by a Weibull-type analysis [3]. Usually fibers start to fail at COD of the order of R_f. Fibers then are pulled out of the matrix, with significant energy dissipation by frictional sliding. Detailed treatment of fiber pull-out, with statistical failure distribution, is given in Ref. [6]. At failure, the average fiber failure length, h, depends on the fiber stress state and in turn on the misfit strain. Statistical failure of fibers is not included in the present analysis, and hence the average failure length, h, is fixed.

Upon fiber failure, the fiber stress at the failure location drops to zero. Using the first of Eqs. (3), the relationship between $\sigma_f(0)$ and the crack opening displacement, Δ, can be written as

$$\sigma_f(0) = \frac{2c_4(h-\Delta)}{2\mu c_1(h-\Delta) + c_4 R_f}\left[\tau_0 - \frac{\mu c_3\Delta\epsilon_{in}}{c_4}\right], \tag{4}$$

where $\exp(2\mu cz/R_f)$ is approximated by $1 + 2\mu cz/R_f$. The steady state pull-out toughness is then determined by

$$W_p = f\int_0^h \sigma_f(0)\ d\Delta$$

$$= \frac{2f(c_4\tau_0 - \mu c_3 \Delta\epsilon_{in})R_f}{2\mu c_1} H(h/R_f), \qquad (5)$$

where $H(h/R_f)$ is a dimensionless function given by

$$H(h/R_f) = \frac{(h/R_f)^2}{(h/R_f)+a} - a\ \log_e\left(\frac{a}{(h/R_f)+a}\right) + a^2\left(-a^{-1} + \frac{1}{(h/R_f)+a}\right), \qquad (6)$$

where $a = c_4/2\mu c_1$.

4. Misfit strain history

As shown in Eqs. (4) and (5), the stress distribution in fiber and matrix, the interface pressure, and the pull-out toughness depend on the misfit strain, $\Delta\epsilon_{in}$. Viscoelastic analysis of the evolution of the misfit strain conducted in Ref. [1] has shown that the misfit strain can be represented as a function of irradiation time, t, by

$$\Delta\epsilon_{in}(t) = g(t)\Delta\epsilon_{th} + \int_0^t g(t-t')\frac{d\Delta\epsilon_s(t')}{dt'}dt', \qquad (7)$$

in which $g(t)$ is a function of the relaxation moduli of fiber and matrix, $\Delta\epsilon_{th}$ is the initial thermal misfit strain, and $\Delta\epsilon_s(t)$ is the differential swelling strain. The thermal misfit decays quickly as irradiation proceeds. A differential swelling of 10% of matrix swelling is considered. The latter consists of two components; lattice (loop) swelling which saturates early during irradiation and the long term helium swelling component [2]. Calculations are performed for the ARIES IV fusion reactor first-wall conditions [7]. By defining the following set of constants,

$$a_1 = c_4,$$
$$a_2 = -2[E_m(1-f)\nu_f + fE_f\mu_m],$$
$$b_1 = f\nu_m E_f - (1-f)\nu_f E_m, \qquad (8)$$
$$b_2 = (1-f)E_m + fE_f,$$
$$f_e = E_f E_m(1-f)\frac{b_2 - b_1}{a_1 b_2 - a_2 b_1},$$

the function $g(t)$ is then given by $g(t) = f_v(t)/f_e$, where $f_v(t)$ has the same expression as f_e with the elastic constants E_f and E_m being replaced by the time-dependent relaxation moduli $E_f(t)$ and $E_m(t)$, respectively.

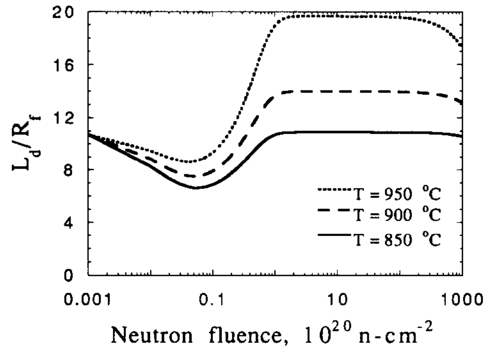

Fig. 1. Debonding length as function of neutron fluence and irradiation temperature ($\sigma_f(0) = 100$ MPa, $\tau_0 = 2$ MPa, $\mu = 0.1$).

5. Discussion

Calculations of debond length and pull-out toughness are carried out for SCS-6 fibers and CVD SiC matrix. The fibers and matrix properties are: $E_f = 420$ GPa, $\nu_f = 0.3$, $E_m = 380$ GPa and $\nu_m = 0.2$. In ceramic matrix composites the interface fracture energy has been always designed to be less than 20% of the fracture energy of the matrix [8]. Therefore, the specific fracture energy of interface, γ, is taken to be one tenth of CVD SiC surface energy which is 1 J m^{-2} [2]. Nicalon fibers are excluded since they spontaneously debond from the matrix at low fluence, which has been shown theoretically [1] and confirmed experimentally [9]. Such behavior is attributed to the significant shrinkage of Nicalon fibers under irradiation. The temperature effect on the spontaneous debonding of Nicalon fibers from CVD SiC matrix has not been experimentally investigated.

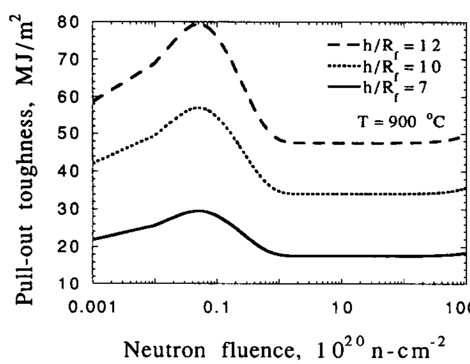

Fig. 2. Pull-out toughness as function of neutron fluence and pull-out length ($T = 900$°C, $\tau_0 = 2$ MPa, $\mu = 0.1$).

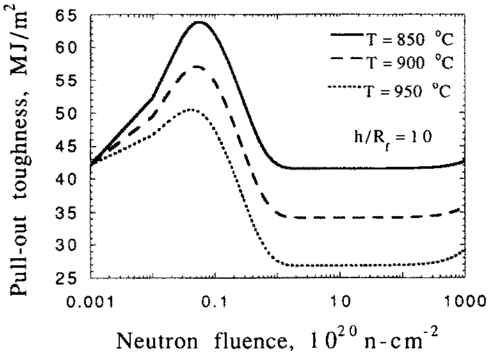

Fig. 3. Pull-out toughness as function of neutron fluence and irradiation temperature ($h/R_f = 10$, $\tau_0 = 2$ MPa, $\mu = 0.1$).

Fig. 1 shows the debond length as a function of fluence and and temperature at $\sigma_f(0)$ of 100 MPa. At very low fluences, the debond length decreases since lattice swelling dominates relaxation by creep. After lattice swelling saturates, the misfit strain relaxes which reduces the interface pressure, thus allowing more debonding to occur. At large fluences, slower evolution of the debond length occurs since helium swelling and irradiation creep fairly balance each other. The saturation level depends on the misfit strain at the end of the loop swelling phase. The latter increases as the irradiation temperature decreases. Therefore, the debonding energy, which is proportional to L_d, depends on the irradiation temperature.

Fig. 2 shows the dependence of pull-out toughness on neutron fluence and the pull-out length, h. At low fluences, a sharp decrease is observed. This is caused by the fast relaxation of the misfit strain, which controls the interface friction. At higher fluences, however, a slow recovery is observed due to the recovery of misfit strain. The pull-out length, h, depends on the fiber Weibull parameters and the misfit, with the latter controlling the axial fiber stress state. However, larger values of pull-out length are favorable. Fig. 3 shows the trends of the pull-out toughness with irradiation temperature. At lower temperatures, since the saturation level of misfit strain is higher, friction at the interface is enhanced and the pull-out resistance is higher. The calculated pull-out toughness for SiC–SiC composites is within the range of pull-out toughness of typical ceramic matrix composites. For example, experimental measurements have shown a pull-out toughness of 80 MJ/m^2 for silicon nitride matrix reinforced by carbon fibers [10].

The present calculations give first order estimation for the debonding and pull-out behavior of irradiated SiC–SiC composites. In principle, it has been shown that fiber–matrix interface debonding and pull-out depend on the irradiation history (neutron fluence and temperature). To obtain more accurate results for pull-out toughness, fiber failure statistics must be included to avoid the assumption of a fixed pull-out length. Since misfit strains change dramatically due to irradiation-induced creep and differential swelling between fibers and matrix, it is necessary to consider these changes in optimizing SiC–SiC composites for fusion first wall and blanket applications. Although postirradiation calculations are considered in the present work, modeling of in-service fiber debonding and pull-out toughness for SiC–SiC composites requires consideration of thc viscoelastic response of both fibers and matrix under neutron irradiation. Viscoelastic energy dissipation during fiber pull-out can be an important contribution to composite toughness.

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References

[1] A. El-Azab and N.M. Ghoniem, Viscoelastic analysis of residual mismatch stresses in ceramic matrix composites under high-temperature neutron irradiation, Mech. Mater., submitted.
[2] A. El-Azab and N.M. Ghoniem, Phenomenological inelastic constitutive equations for SiC–SiC composites under irradiation, Fusion Technol., submitted.
[3] L.S. Sigl and A.G. Evans, Mech. Mater. 8 (1989) 1.
[4] J.W. Hutchinson and H.M. Jensen, Mech. Mater. 9 (1990) 139.
[5] Yu-Chen Gao, Yiu-Wing Mai and Brian Cotterell, J. Appl. Math. Phys. 39 (1988) 550.
[6] M.D. Thouless and A.G. Evans, Acta Metall. 36 (1988) 517.
[7] F. Najmabadi, R.W. Conn and the ARIES Team, The ARIES II and ARIES IV Second Stability Tokamak Reactor Study - Final Report, UCLA-PPG 1461, in preparation.
[8] A.G. Evans, J. Am. Ceram. Soc. 73 (1990) 187.
[9] L. Sneed, D. Steiner and S.J. Zinkle, J. Nucl. Mater. 191-194 (1992) 566.
[10] T. Suzuki, M. Sato and M. Sakai, J. Mater. Res. 7 (1992) 2869.