Research Article

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Temperature-dependent proportional limit stress of SiC/SiC fiber-reinforced ceramic-matrix composites

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Abstract: In this paper, the temperature-dependent proportional limit stress (PLS) of SiC/SiC fiber-reinforced ceramic-matrix composites (CMCs) is investigated using the micro-mechanical approach. The PLS of SiC/SiC is predicted using an energy balance approach considering the effect of environment temperature. The relation between the environment temperature, PLS, and composite damage state is established. The effects of the fiber volume, interface properties, and matrix properties on the temperature-dependent PLS and composite damage state of SiC/SiC composite are analyzed. The experimental PLS and interface debonding length of 2D SiC/SiC composites with the PyC and BN interphase at elevated temperatures are predicted. The temperature-dependent PLS of SiC/SiC composite increases with the fiber volume, interface shear stress and interface debonding energy, and the matrix fracture energy and decreases with the interface frictional coefficient at the same temperature.

Keywords: ceramic-matrix composites (CMCs), proportional limit stress (PLS), matrix cracking, interface debonding

1 Introduction

Continuous SiC/SiC fiber-reinforced ceramic-matrix composites (CMCs) have excellent properties such as high specific strength, high specific modulus, wear resistance, oxidation resistance, corrosion resistance, radiation resistance, and insensitivity to cracks and noncatastrophic fracture, which make it a new type of thermal

structural material in the application prospects of aviation, aerospace, and energy [1–3]. SiC/SiC composites are mainly used for hot section components of high-performance aeroengines and industrial gas turbines and have potential applications in nuclear fusion reactors and fission reactors [4–9]. Solar Turbines Company uses SiC/SiC as the combustion chamber lining of Solar's Centaur 505 engine. In the 35,000-h test run, the NO_x and CO content of the exhaust gas is lower than that of the ordinary engine [10]. A comparative test of fiber-reinforced CMCs combustor lining was carried out in Germany. The results show that after a 10-h test in the gas engine, the delamination and debonding between the substrate and the coating appeared in the CVD-SiC coated C/SiC combustor; however, the SiC/SiC combustor did not suffer any damage after a 90-h test [11]. In cooperation with SNECMA to develop fiber-reinforced CMC nozzle seals for the F100-PW-229 aero engine, P&W is, also using CMC nozzle flaps and seals, validated under the IHPTET program to improve the F119 aeroengine, which powered the world's most advanced fighter F-22. With the new flaps, the durability of the aeroengine is improved significantly while the quality and the cost are reduced. GE has signed a multiyear development contract with Goodrich to develop C/SiC nozzle flaps and seals for the higher temperature F414 engine. Goodrich is responsible for providing lightweight and long-life CMCs, and GE is responsible for testing and evaluation. Now, GE has conducted production and flight testing of CMC standard parts. GE also developed and demonstrated the CMC combustion chamber under the support of the TECH56 program. The CMC combustion chamber can provide high temperature rise and possess a long life and need few cooling airs.

The nonlinear stress-strain behavior of fiber-reinforced CMCs under tensile loading is mainly due to the internal damages of matrix cracking and the fiber/matrix interface debonding [12]. The proportional limit stress (PLS) of fiber-reinforced CMCs corresponds to the first matrix cracking stress [13]. Below the PLS, the composite

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stress-strain response is linearly elastic and without macroscopic damage. Above the PLS, the matrix cracking occurs, leading to the exposure of the fibers to the application atmosphere/environment. The macro-tensile curves of fiber-reinforced CMCs can be divided into three stages: (1) the linear-elastic stage till the proportional limit stress, (2) the nonlinear stage of matrix cracking propagation and interface debonding stage till the saturation of the matrix cracking, and (3) the fibers failure stage after the saturation of matrix cracking [14–17]. Among the three stages mentioned above, the proportional limit stress is a key parameter for composite structure or component design. To ensure the safety of CMCs components, the design safety factor should satisfy $\sigma_{\text{PLS}}/\sigma_d > 1$ (i.e., σ_d is the design stress). The theoretical analysis of PLS can be divided into two cases, i.e., the energy balance approach, including the ACK model [18], BHE model [19], SH model [20], and Chiang model [21–23], and the stress intensity factor approach, including MCE model [24], MC model [25], and Chiang model [26]. Pavia et al. [27] predicted the PLS in micro/nanohybrid brittle matrix composites based on the ACK shear-lag model. It was found that the presence of a small function of strong stiff nanotubes provides significant enhancements in the PLS. Acoustic emission and electrical resistance can be used to monitor the matrix cracking behavior of fiber-reinforced CMCs [17]. The micromatrix cracking first occurred in the matrix-rich region due to the thermal residual stress which can be monitored using the acoustic emission or electrical resistance method that does not affect the linear behavior of fiber-reinforced CMCs. When this short matrix cracking propagates into the long steady-state matrix cracking, the tensile stress-strain curve begins to deflect. The steady-state matrix cracking stress corresponds to the PLS. Li [28] investigated the interface properties on the evolution of multiple matrix cracking of fiber-reinforced CMCs. Low interface shear stress leads to the low matrix cracking density. Singh et al. [29] investigated the effect of interface shear stress on the PLS of SiC/Zircon composite. With increasing interface shear stress (ISS), the PLS increases. At elevated temperatures, the ISS changes with temperature due to the thermal expansion coefficient mismatch between the fiber and the matrix. However, the relation between the temperature, ISS, and the PLS of SiC/SiC composites has not been established [30,31].

In this paper, the temperature-dependent PLS of SiC/SiC composite is investigated using the energy balance approach. The effect of environment temperature on the fiber and matrix elastic modulus, fiber/matrix

interface shear stress and interface debonding energy, and the matrix fracture energy is considered. The effects of the fiber volume, fiber/matrix interface properties, and matrix properties on the temperature-dependent PLS and composite internal damages are analyzed. The experimental PLS and fiber/matrix interface debonding length of 2D SiC/SiC composites with different interphase at elevated temperatures are predicted.

2 Theoretical analysis

The energy balance relation to evaluate the PLS of fiber-reinforced CMCs can be determined by equation (1) [19]:

$$\begin{aligned} & \frac{1}{2} \int_{-\infty}^{\infty} \left\{ \frac{V_f}{E_f(T)} [\sigma_{fu}(T) - \sigma_{fd}(T)]^2 \right. \\ & \quad \left. + \frac{V_m}{E_m(T)} [\sigma_{mu}(T) - \sigma_{md}(T)]^2 \right\} dx \\ & + \frac{1}{2\pi R^2 G_m(T)} \int_{-l_d(T)}^{l_d(T)} \int_{r_f}^R \left[\frac{r_f \tau_i(x, T)}{r} \right] 2\pi r dr dx \\ & = V_m \zeta_m(T) + \frac{4V_f l_d(T)}{r_f} \zeta_d(T) \end{aligned} \quad (1)$$

where V_f and V_m are the fiber and matrix volume fraction, respectively; $E_f(T)$ and $E_m(T)$ are the temperature-dependent fiber and matrix elastic modulus, respectively; $\zeta_m(T)$ and $\zeta_d(T)$ are the temperature-dependent matrix fracture energy and interface debonding energy, respectively.

$$\sigma_{fu}(T) = \frac{E_f(T)}{E_c(T)} \sigma \quad (2)$$

$$\sigma_{mu}(T) = \frac{E_m(T)}{E_c(T)} \sigma \quad (3)$$

$$\sigma_{fd}(x, T) = \begin{cases} \frac{\sigma}{V_f} - \frac{2\tau_i(T)}{r_f} x, & x \in [0, l_d(T)] \\ \frac{E_f(T)}{E_c(T)} \sigma, & x \in \left[l_d(T), \frac{l_c(T)}{2} \right] \end{cases} \quad (4)$$

$$\sigma_{md}(x, T) = \begin{cases} 2 \frac{V_f}{V_m} \frac{\tau_i(T)}{r_f} x, & x \in [0, l_d(T)] \\ \frac{E_m(T)}{E_c(T)} \sigma, & x \in \left[l_d(T), \frac{l_c(T)}{2} \right] \end{cases} \quad (5)$$

$$l_d(T) = \frac{r_f V_m E_m(T) \sigma}{2V_f E_c(T) \tau_i(T)} - \sqrt{\frac{r_f V_m E_f(T) \zeta_d(T)}{E_c(T) \tau_i^2(T)}} \quad (6)$$

where

$$\tau_i(T) = \tau_0 + \mu \frac{|\alpha_{rf}(T) - \alpha_{rm}(T)|(T_m - T)}{A} \quad (7)$$

Substituting the upstream and downstream temperature-dependent fiber and matrix axial stresses of equations (2), (3), (4), and (5) and the temperature-dependent fiber/matrix interface debonding length of equation (6) into equation (1), the energy balance equation leads to the following equation:

$$\alpha\sigma^2 + \beta\sigma + \gamma = 0 \quad (8)$$

where

$$\alpha = \frac{V_m E_m(T) l_d(T)}{V_f E_f(T) E_c(T)} \quad (9)$$

$$\beta = -\frac{2\tau_i(T)}{r_f E_f(T)} l_d^2(T) \quad (10)$$

$$\gamma = \frac{4}{3} \left[\frac{\tau_i(T)}{r_f} \right]^2 \frac{V_f E_c(T)}{V_m E_f(T) E_m(T)} l_d^3(T) - \frac{4V_f \zeta_d(T)}{r_f} - V_m \zeta_m(T) \quad (11)$$

3 Discussion

The ceramic composite system of SiC/SiC is used for the case study and its material properties are given by [32]: $V_f = 30\%$, $r_f = 7.5 \mu\text{m}$, $\zeta_m = 25 \text{ J/m}^2$ (at room temperature), $\zeta_d = 0.1 \text{ J/m}^2$ (at room temperature), $\alpha_{rf} = 2.9 \times 10^{-6}/\text{K}$, and $\alpha_{lf} = 3.9 \times 10^{-6}/\text{K}$.

The temperature-dependent SiC matrix elastic modulus $E_m(T)$ can be determined by equation (12) [33]:

$$E_m(T) = \frac{350}{460} \left[460 - 0.04T \exp\left(-\frac{962}{T}\right) \right], \quad T \in [300-1773 \text{ K}] \quad (12)$$

The temperature-dependent SiC matrix axial and radial thermal expansion coefficient of $\alpha_{lm}(T)$ and $\alpha_{rm}(T)$ can be determined by equation (13) [33]:

$$\alpha_{lm}(T) = \alpha_{rm}(T) = \begin{cases} -1.8276 + 0.0178T & T \in [125-1, 273 \text{ K}] \\ -1.5544 \times 10^{-5}T^2 \\ + 4.5246 \times 10^{-9}T^3, \\ 5.0 \times 10^{-6}/\text{K}, & T > 1, 273 \text{ K} \end{cases} \quad (13)$$

The temperature-dependent interface debonding energy $\zeta_d(T)$ and the matrix fracture energy $\zeta_m(T)$ can be determined by equations (14) and (15) [34]:

$$\zeta_d(T) = \zeta_{do} \left[1 - \frac{\int_{T_0}^T C_p(T) dT}{\int_{T_0}^{T_m} C_p(T) dT} \right] \quad (14)$$

$$\zeta_m(T) = \zeta_{mo} \left[1 - \frac{\int_{T_0}^T C_p(T) dT}{\int_{T_0}^{T_m} C_p(T) dT} \right] \quad (15)$$

where T_0 denotes the reference temperature; T_m denotes the fabricated temperature; and ζ_{do} and ζ_{mo} denote the interface debonding energy and matrix fracture energy at the reference temperature of T_0 .

$$C_p(T) = 76.337 + 109.039 \times 10^{-3}T - 6.535 \times 10^5 T^{-2} - 27.083 \times 10^{-6}T^2 \quad (16)$$

The effects of the fiber volume, interface properties, and matrix properties on the temperature-dependent PLS of SiC/SiC composite are discussed.

3.1 Effect of the fiber volume on temperature-dependent interface debonding and PLS

The PLS and the fiber/matrix interface debonding length versus the temperature curves for different fiber volume (i.e., $V_f = 25, 30$, and 35%) are shown in Figure 1. When the temperature increases from $T = 873$ to $1,273 \text{ K}$, the PLS and fiber/matrix interface debonding length decrease with increasing temperature. At the same temperature, the PLS increases with the fiber volume, and the fiber/matrix interface debonding length decreases with the fiber volume. When the fiber volume increases, the stress transfer between the fiber and the matrix increases, the stress carried by the matrix increases, leading to the increase of the PLS and the decrease of the fiber/matrix interface debonding length.

When the fiber volume is $V_f = 25\%$, the PLS decreases from $\sigma_{PLS} = 103 \text{ MPa}$ at an elevated temperature of $T = 873 \text{ K}$ to $\sigma_{PLS} = 87 \text{ MPa}$ at an elevated temperature of $T = 1,273 \text{ K}$; and the fiber/matrix interface debonding length decreases from $l_d/r_f = 6.1$ at $\sigma_{PLS} = 103 \text{ MPa}$ to $l_d/r_f = 5.0$ at $\sigma_{PLS} = 87 \text{ MPa}$. When the fiber volume is $V_f = 30\%$, the PLS decreases from $\sigma_{PLS} = 117 \text{ MPa}$ at an elevated temperature of $T = 873 \text{ K}$ to $\sigma_{PLS} = 99 \text{ MPa}$ at an elevated temperature of $T = 1,273 \text{ K}$; and the fiber/matrix interface debonding length decreases from

Figure 1: Effect of the fiber volume on (a) the PLS versus temperature curves and (b) the fiber/matrix interface debonding length versus temperature curves of SiC/SiC composite.

$l_d/r_f = 5.3$ at $\sigma_{PLS} = 117$ MPa to $l_d/r_f = 4.4$ at $\sigma_{PLS} = 99$ MPa. When the fiber volume is $V_f = 35\%$, the PLS decreases from $\sigma_{PLS} = 130$ MPa at an elevated temperature of $T = 873$ K to $\sigma_{PLS} = 110$ MPa at an elevated temperature of $T = 1,273$ K; and the fiber/matrix interface debonding length decreases from $l_d/r_f = 4.6$ at $\sigma_{PLS} = 130$ MPa to $l_d/r_f = 3.9$ at $\sigma_{PLS} = 110$ MPa.

3.2 Effect of the ISS on the temperature-dependent PLS and interface debonding

The PLS and the fiber/matrix interface debonding length versus the temperature curves for different ISS (i.e., $\tau_i = 15, 20$, and 25 MPa) are shown in Figure 2. When the temperature increases from $T = 873$ to $1,273$ K, the PLS and fiber/matrix interface debonding length decrease

Figure 2: Effect of the interface shear stress on (a) the PLS versus temperature curves and (b) the fiber/matrix interface debonding length versus temperature curves of SiC/SiC composite.

with the increasing temperature. The PLS increases with the ISS, and the fiber/matrix interface debonding length decreases with the ISS at the same temperature. When the ISS increases, the stress transfer between the fiber and the matrix increases, leading to an increase in the PLS and a decrease in the interface debonding length.

When the fiber/matrix ISS is $\tau_i = 15$ MPa, the PLS decreases from $\sigma_{PLS} = 89$ MPa at an elevated temperature of $T = 873$ K to $\sigma_{PLS} = 81$ MPa at an elevated temperature of $T = 1,273$ K; and the fiber/matrix interface debonding length decreases from $l_d/r_f = 6.8$ at $\sigma_{PLS} = 89$ MPa to $l_d/r_f = 5.9$ at $\sigma_{PLS} = 81$ MPa. When the fiber/matrix ISS is $\tau_i = 20$ MPa, the PLS decreases from $\sigma_{PLS} = 104$ MPa at an elevated temperature of $T = 873$ K to $\sigma_{PLS} = 90$ MPa at an elevated temperature of $T = 1,273$ K; and the fiber/matrix interface debonding length decreases from $l_d/r_f = 5.9$ at $\sigma_{PLS} = 104$ MPa to $l_d/r_f = 5$ at $\sigma_{PLS} = 90$ MPa. When the fiber/matrix ISS is $\tau_i = 25$ MPa, the PLS decreases from

$\sigma_{\text{PLS}} = 117$ MPa at an elevated temperature of $T = 873$ K to $\sigma_{\text{PLS}} = 99$ MPa at an elevated temperature of $T = 1,273$ K; and the fiber/matrix interface debonding length decreases from $l_d/r_f = 5.3$ at $\sigma_{\text{PLS}} = 117$ MPa to $l_d/r_f = 4.4$ at $\sigma_{\text{PLS}} = 99$ MPa.

3.3 Effect of the interface frictional coefficient on temperature-dependent PLS and interface debonding

The PLS and the fiber/matrix interface debonding length versus the temperature curves for different interface frictional coefficient (i.e., $\mu = 0.02, 0.03$, and 0.04) are shown in Figure 3. When the temperature increases from $T = 873$ – $1,273$ K, the PLS and fiber/matrix interface debonding

Figure 3: Effect of the interface frictional coefficient on (a) the PLS versus temperature curves and (b) the fiber/matrix interface debonding length versus temperature curves of SiC/SiC composite.

length decrease with the increasing temperature. At the same temperature, the PLS decreases with the interface frictional coefficient, and the fiber/matrix interface debonding length increases with the interface frictional coefficient. When the interface frictional coefficient increases, the ISS decreases at the same temperature, leading to a decrease in the PLS and an increase in the interface debonding length.

When the fiber/matrix interface frictional coefficient is $\mu = 0.02$, the PLS decreases from $\sigma_{\text{PLS}} = 117$ MPa at an elevated temperature of $T = 873$ K to $\sigma_{\text{PLS}} = 99$ MPa at an elevated temperature of $T = 1,273$ K, and the fiber/matrix interface debonding length decreases from $l_d/r_f = 5.3$ at $\sigma_{\text{PLS}} = 117$ MPa to $l_d/r_f = 4.4$ at $\sigma_{\text{PLS}} = 99$ MPa. When the fiber/matrix interface frictional coefficient is $\mu = 0.03$, the PLS decreases from $\sigma_{\text{PLS}} = 113$ MPa at an elevated temperature of $T = 873$ K to $\sigma_{\text{PLS}} = 98$ MPa at an elevated temperature of $T = 1,273$ K, and the fiber/matrix interface debonding length decreases from $l_d/r_f = 5.5$ at $\sigma_{\text{PLS}} = 113$ MPa to $l_d/r_f = 4.4$ at $\sigma_{\text{PLS}} = 98$ MPa. When the fiber/matrix interface frictional coefficient is $\mu = 0.04$, the PLS decreases from $\sigma_{\text{PLS}} = 109$ MPa at an elevated temperature of $T = 873$ K to $\sigma_{\text{PLS}} = 97$ MPa at an elevated temperature of $T = 1,273$ K, and the fiber/matrix interface debonding length decreases from $l_d/r_f = 5.7$ at $\sigma_{\text{PLS}} = 109$ MPa to $l_d/r_f = 4.5$ at $\sigma_{\text{PLS}} = 97$ MPa.

3.4 Effect of the interface debonding energy on temperature-dependent PLS and interface debonding

The PLS and the fiber/matrix interface debonding length versus the temperature curves for different interface debonding energy (i.e., $\zeta_d = 0.1, 0.2$, and 0.3 J/m²) are shown in Figure 4. When the temperature increases from $T = 873$ – $1,273$ K, the PLS and fiber/matrix interface debonding length decrease with the increasing temperature. At the same temperature, the PLS increases with the interface debonding energy, and the fiber/matrix interface debonding length decreases with the interface debonding energy. When the interface debonding energy increases, the resistance for the interface debonding increases, leading to an increase in the PLS and a decrease in the interface debonding length.

When the interface debonding energy is $\zeta_d = 0.1$ J/m², the PLS decreases from $\sigma_{\text{PLS}} = 117$ MPa at an elevated temperature of $T = 873$ K to $\sigma_{\text{PLS}} = 99$ MPa at an elevated temperature of $T = 1,273$ K, and the fiber/matrix interface debonding length decreases from $l_d/r_f = 5.3$ at $\sigma_{\text{PLS}} = 117$ MPa to $l_d/r_f = 4.4$ at $\sigma_{\text{PLS}} = 99$ MPa. When the fiber/matrix interface debonding energy is $\zeta_d = 0.2$ J/m², the PLS decreases from $\sigma_{\text{PLS}} = 121$ MPa at an elevated temperature of $T = 873$ K to $\sigma_{\text{PLS}} = 101$ MPa at

Figure 4: Effect of the interface debonding energy on (a) the PLS versus temperature curves; (b) the fiber/matrix interface debonding length versus temperature curves of SiC/SiC composite.

an elevated temperature of $T = 1,273$ K, and the fiber/matrix interface debonding length decreases from $l_d/r_f = 4.8$ at $\sigma_{PLS} = 121$ MPa to $l_d/r_f = 4.1$ at $\sigma_{PLS} = 101$ MPa. When the fiber/matrix interface debonding energy is $\zeta_d = 0.3$ J/m², the PLS decreases from $\sigma_{PLS} = 125$ MPa at an elevated temperature of $T = 873$ K to $\sigma_{PLS} = 103$ MPa at an elevated temperature of $T = 1,273$ K, and the fiber/matrix interface debonding length decreases from $l_d/r_f = 4.5$ at $\sigma_{PLS} = 125$ MPa to $l_d/r_f = 3.9$ at $\sigma_{PLS} = 103$ MPa.

3.5 Effect of the matrix fracture energy on temperature-dependent PLS and interface debonding

The PLS and the fiber/matrix interface debonding length versus the temperature curves for different matrix fracture energy (i.e., $\zeta_m = 15, 20$, and 25 J/m²) are shown

Figure 5: Effect of the matrix fracture energy on (a) the PLS versus temperature curves and (b) the fiber/matrix interface debonding length versus temperature curves of SiC/SiC composite.

in Figure 5. When the temperature increases from $T = 873$ – $1,273$ K, the PLS and fiber/matrix interface debonding length decrease with the increasing temperature. At the same temperature, the PLS and the fiber/matrix interface debonding length increase with the matrix fracture energy. When the matrix fracture energy increases, the energy needed for the matrix cracking increases, leading to an increase in the PLS and the interface debonding length.

When the matrix fracture energy is $\zeta_m = 15$ J/m², the PLS decreases from $\sigma_{PLS} = 117$ MPa at an elevated temperature of $T = 873$ K to $\sigma_{PLS} = 99$ MPa at an elevated temperature of $T = 1,273$ K, and the fiber/matrix interface debonding length decreases from $l_d/r_f = 5.3$ at $\sigma_{PLS} = 117$ MPa to $l_d/r_f = 4.4$ at $\sigma_{PLS} = 99$ MPa. When the matrix fracture energy is $\zeta_m = 20$ J/m², the PLS decreases from $\sigma_{PLS} = 132$ MPa at an elevated temperature of $T = 873$ K to $\sigma_{PLS} = 110$ MPa at an elevated temperature of $T = 1,273$ K,

and the fiber/matrix interface debonding length decreases from $l_d/r_f = 6.2$ at $\sigma_{PLS} = 132$ MPa to $l_d/r_f = 5$ at $\sigma_{PLS} = 110$ MPa. When the matrix fracture energy is $\zeta_m = 25$ J/m², the PLS decreases from $\sigma_{PLS} = 145$ MPa at an elevated temperature of $T = 873$ K to $\sigma_{PLS} = 119$ MPa at an elevated temperature of $T = 1,273$ K; and the fiber/matrix interface debonding length decreases from $l_d/r_f = 6.9$ at $\sigma_{PLS} = 145$ MPa to $l_d/r_f = 5.5$ at $\sigma_{PLS} = 119$ MPa.

4 Experimental comparisons

Guo and Kagawa [35] investigated the tensile behavior of 2D SiC/SiC composites with the PyC and BN interphase at elevated temperatures. The experimental tensile stress–strain curves of NicalonTM SiC/PyC/SiC and Hi-NicalonTM SiC/BN/SiC composites at room and elevated temperatures are shown in Figures 6 and 7. For the NicalonTM SiC/PyC/SiC composite, the PLS decreases from $\sigma_{PLS} = 65$ MPa at an elevated temperature of $T = 298$ K to $\sigma_{PLS} = 33$ MPa at an elevated temperature of $T = 1,200$ K; and for the Hi-NicalonTM SiC/PyC/SiC composite, the PLS decreases from $\sigma_{PLS} = 75$ MPa at $T = 298$ K to $\sigma_{PLS} = 45$ MPa at $T = 1,400$ K. The experimental and predicted PLS versus temperature curves of NicalonTM SiC/PyC/SiC and Hi-NicalonTM SiC/PyC/SiC are shown in Figure 8.

For the 2D NicalonTM SiC/SiC composite with the PyC interphase, the ISS of SiC/C/SiC composite decreases at an elevated temperature of $T = 800$ K from that of $T = 298$ K and then increases again at an elevated temperature of $T = 1,200$ K [35]. When the ISS decreases, the stress transfer between the fiber and the matrix decreases, leading to a decrease of the PLS [1]. The PLS decreases from $\sigma_{PLS} = 65$ MPa at an elevated temperature of $T = 298$ K to $\sigma_{PLS} = 33$ MPa at an elevated temperature of $T = 1,200$ K, and the fiber/matrix interface debonding length decreases from $l_d/r_f = 12.8$ at $\sigma_{PLS} = 65$ MPa to $l_d/r_f = 7.3$ at $\sigma_{PLS} = 33$ MPa.

For the 2D Hi-NicalonTM SiC/SiC composite with the BN interphase, the interface shear stress of SiC/BN/SiC at room and elevated temperatures is much lower than those of the SiC/C/SiC composite, due to the better oxidation resistance of BN-coating on the Hi-NicalonTM fiber surface than C-coating on the NicalonTM fiber surface [35]. The PLS decreases from $\sigma_{PLS} = 75$ MPa at an elevated temperature of $T = 298$ K to $\sigma_{PLS} = 45$ MPa at an elevated temperature of $T = 1,400$ K, and the fiber/matrix interface debonding length decreases from $l_d/r_f = 7.3$ at $\sigma_{PLS} = 75$ MPa to $l_d/r_f = 2.9$ at $\sigma_{PLS} = 45$ MPa.

Figure 6: Experimental tensile stress–strain curves of NicalonTM SiC/C/SiC at (a) $T = 298$ K, (b) $T = 800$ K, and (c) $T = 1,200$ K.

Figure 7: Experimental tensile stress–strain curves of Nicalon™ SiC/C/SiC at (a) $T = 298$ K, (b) $T = 1,200$ K, and (c) $T = 1,400$ K.

Figure 8: Experimental and predicted PLS versus the temperature curves of (a) SiC/SiC composite with the PyC interphase and (b) SiC/SiC composite with the BN interphase.

5 Conclusion

In this paper, the temperature-dependent PLS of SiC/SiC composite is investigated using the energy balance approach. The effects of the fiber volume, interface properties, and matrix properties on the temperature-dependent PLS and interface debonding length are analyzed. The experimental PLS and interface debonding length of 2D SiC/SiC composites with the PyC and BN interphase at elevated temperatures are predicted.

- (1) When the fiber volume, ISS, and interface debonding energy increase, the PLS increases and the interface debonding length decreases at the same temperature.
- (2) When the interface frictional coefficient increases, the PLS decreases and the fiber/matrix interface debonding length increases at the same temperature.

- (3) When the matrix fracture energy increases, the PLS and the interface debonding length increase at the same temperature.

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