

# Fatigue Life Prediction of Carbon Fiber-Reinforced Ceramic-Matrix Composites at Room and Elevated Temperatures. Part I: Experimental Analysis

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**Abstract** This paper presents an experimental analysis on the fatigue behavior in C/SiC ceramic-matrix composites (CMCs) with different fiber preforms, i.e., unidirectional, cross-ply and 2.5D woven, at room and elevated temperatures in air atmosphere. The experimental fatigue life S–N curves of C/SiC composites corresponding to different stress levels and test conditions have been obtained. The damage evolution processes under fatigue loading have been analyzed using fatigue hysteresis modulus and fatigue hysteresis loss energy. By comparing the experimental fatigue hysteresis loss energy with theoretical computational values, the interface shear stress corresponding to different peak stress, fiber preforms and test conditions have been estimated. It was found that the degradation of interface shear stress and fibres strength caused by oxidation markedly decreases the fatigue life of C/SiC composites at elevated temperature.

**Keywords** Ceramic-matrix composites (CMCs) · Fatigue · Life prediction · Hysteresis loops · Matrix multicroacking · Interface debonding

## 1 Introduction

Ceramic materials possess high strength and modulus at elevated temperatures. But their use as structural components is severely limited because of their brittleness. Continuous fiber-reinforced ceramic-matrix composites (CMCs), by incorporating fibers in ceramic matrices, however, not only exploit their attractive high-temperature strength but also reduce the propensity for catastrophic failure. Carbon fiber-reinforced silicon carbide ceramic-matrix composites (C/SiC CMCs) are one of the most

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promising candidates for many high temperature applications, particularly as aerospace and aircraft thermostructural components [1]. The CMC flaps for exhaust nozzles of SNECMA M53 and M88 aero engines have been used for more than one decade [2]. The CMC turbine vanes have been designed and tested in the aero engine environment under the implementation of Ultra Efficient Engine Technology (UEET) program [3]. A CMC turbine blade has been tested for 4 h by General Electric in a modified GE F414 engine, which represents the first application of CMC material in a rotating engine part. Incorporating CMC turbine blades on a GE90-sized engine, the overall weight can be reduced by 455 kg, which represents approximately 6 % of dry weight of full sized GE90-115 [4]. The CMC combustion chamber floating wall tiles have also been tested in the aero engine environment for 30 min, with the temperature range of 1047–1227 °C and the pressure of 2 MPa [5].

CMCs are subject to fatigue upon cyclic mechanical and thermal loading. Understanding the mechanisms of fatigue represents an important step in the use of these materials [6–8]. Many researchers experimentally investigated the fatigue behavior of fiber-reinforced CMCs. Holmes and Cho [9] investigated the fatigue hysteresis loops evolution characteristics of unidirectional SiC/CAS-II composite under cyclic loading at room temperature. At the initial stage, the fatigue hysteresis modulus decreases rapidly, and the fatigue hysteresis loops area increases, due to matrix multicracking, fiber/matrix interface debonding and interface wear. When cycle number approaches a critical value, the fatigue hysteresis modulus remains constant. However, the fatigue hysteresis loops area continually decreases with the increase of cycle number. Upon approaching fatigue failure, the fatigue hysteresis loops area increases rapidly. Zhu et al. [10] investigated the tension–tension fatigue behavior of 2D SiC/SiC composite at an elevated temperature of 1000 °C in argon atmosphere. The fatigue hysteresis loops, moving to the right along strain axis with the increase of cycle number, prove the fatigue and creep damage mechanisms operating simultaneously, which decreases the fatigue life of 2D SiC/SiC composite at elevated temperature. Fantozzi and Reynaud [11] investigated the fatigue hysteresis loops evolution of 2.5D SiC/[Si–B–C] and 2.5D C/[Si–B–C] composites at an elevated temperature of 1200 °C in air atmosphere under tension–compression and static fatigue loading. The fatigue hysteresis loops area of 2.5D SiC/[Si–B–C] composite decreases with the increase of cycle number due to interface wear; the hysteresis loops area of 2.5D C/[Si–B–C] composite decreases significantly after 144 h static fatigue loading attributed to PyC interface recession by oxidation or by a beginning of carbon fibers recession. There exists an intermediate temperature (800 to 1000 °C) regime where significant, time-dependent, strength degradation or fatigue life decreased of non-oxide CMCs can occur [12–14]. The carbon interphase is easy to be oxidized at intermediate temperatures, which is called “pest” phenomenon since fatigue life is markedly reduced [15].

In this paper, the fatigue behavior of unidirectional, cross-ply and 2.5D C/SiC composites at room temperature and 800 °C in air atmosphere has been investigated. The fatigue hysteresis modulus and fatigue hysteresis loss energy versus the cycle number have been analyzed. The relationships between the fatigue hysteresis loss energy, fatigue hysteresis loops, interface frictional slip and interface shear stress of C/SiC composite with different fiber preforms have been established. By comparing the experimental fatigue hysteresis loss energy with theoretical computational values,

the interface shear stress corresponding to different peak stress, fiber preforms and test conditions have been estimated.

## 2 Materials and Experimental Procedures

The T-700<sup>TM</sup> carbon (Toray Institute Inc., Tokyo, Japan) fiber-reinforced silicon carbide matrix composites were provided by Shanghai Institute of Ceramics, People's Republic of China. The fibers have an average diameter of 7  $\mu\text{m}$  and come on a spool as a tow of 12 k fibers. The unidirectional and cross-ply C/SiC composites were manufactured by hot-pressing method, which offered the ability to fabricate dense composites via a liquid phase sintering method at a low temperature. The volume fraction of fibers was approximately 40 %. The low pressure chemical vapor infiltration was employed to deposit approximately 5~20 layer PyC/SiC with mean thickness of 0.2  $\mu\text{m}$  in order to enhance desired non-linear/non-catastrophic tensile behavior.

The dog-bone shaped specimens, with dimensions of 120 mm length, 3.2 mm thickness and 4.5 mm width in the gage section of unidirectional C/SiC composite, with dimensions of 123 mm length, 3.8 mm thickness, and 10 mm width in the gage section of cross-ply C/SiC composite, were cut from 150 mm $\times$ 150 mm panels by water cutting. The specimens were further coated with SiC of about 20  $\mu\text{m}$  thick by chemical vapor deposition to prevent oxidation at elevated temperature. These processing steps resulted in a material having bulk density about 2.0  $\text{g}/\text{cm}^3$ , and an open porosity below 5 %.

The fatigue experiments at room temperature and 800 °C in air atmosphere were conducted on an MTS Model 809 servo hydraulic load-frame (MTS Systems Corp., Minneapolis MN) equipped with edge-loaded grips. The fatigue experiments were in a sinusoidal wave form and a loading frequency of 10 Hz. The fatigue load ratio was 0.1. The maximum number of cycles was defined to be 1,000,000 cycles. Under fatigue loading, the gage-section strains were measured using a clip-on extensometer (Model No. 634.12 F-24 at room temperature and Model No. 632.53 F-11 at 800 °C temperature, MTS systems Corp.; modified for a 25 mm gage-length). The fatigue tests were conducted under the load control in accordance with the procedure in ASTM standard C 1360 at room and 800 °C elevated temperatures in air environment.

The stress levels in fatigue tests of unidirectional C/SiC composite were 260 MPa (96 % tensile strength), 240 MPa (88 % tensile strength), 200 MPa (74 % tensile strength), 180 MPa (66 % tensile strength) and 140 MPa (51 % tensile strength) at room temperature, and 250 MPa (78 % tensile strength), 210 MPa (65.6 % tensile strength), 180 MPa (56 % tensile strength), 140 MPa (43.7 % tensile strength) and 120 MPa (37.5 % tensile strength) at an elevated temperature of 800 °C in air atmosphere.

The stress levels in fatigue tests of cross-ply C/SiC composite were 112 MPa (90 % tensile strength), 105 MPa (85 % tensile strength), 99.2 MPa (80 % tensile strength) and 87 MPa (70 % tensile strength) at room temperature, and 105 MPa (70 % tensile strength), 97.5 MPa (65 % tensile strength) and 90 MPa (60 % tensile strength) at an elevated temperature of 800 °C in air atmosphere.

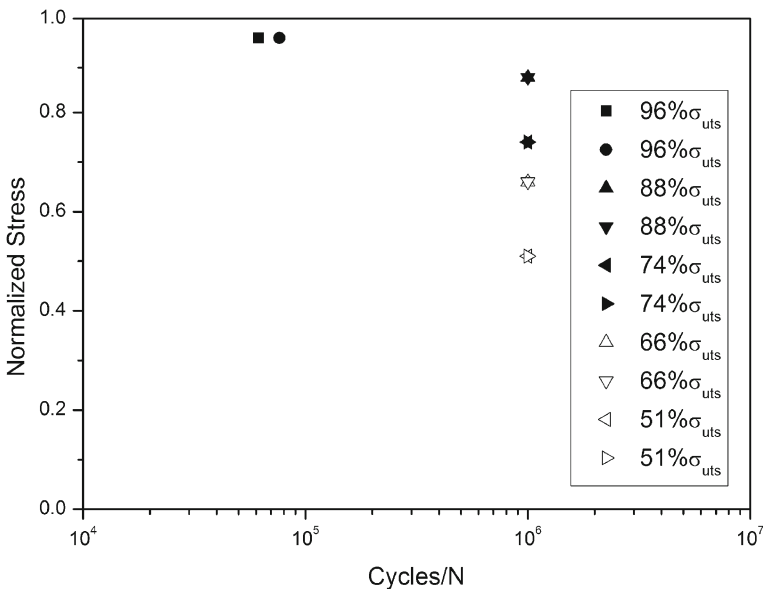
### 3 Experimental Results

#### 3.1 Unidirectional C/SiC Composite

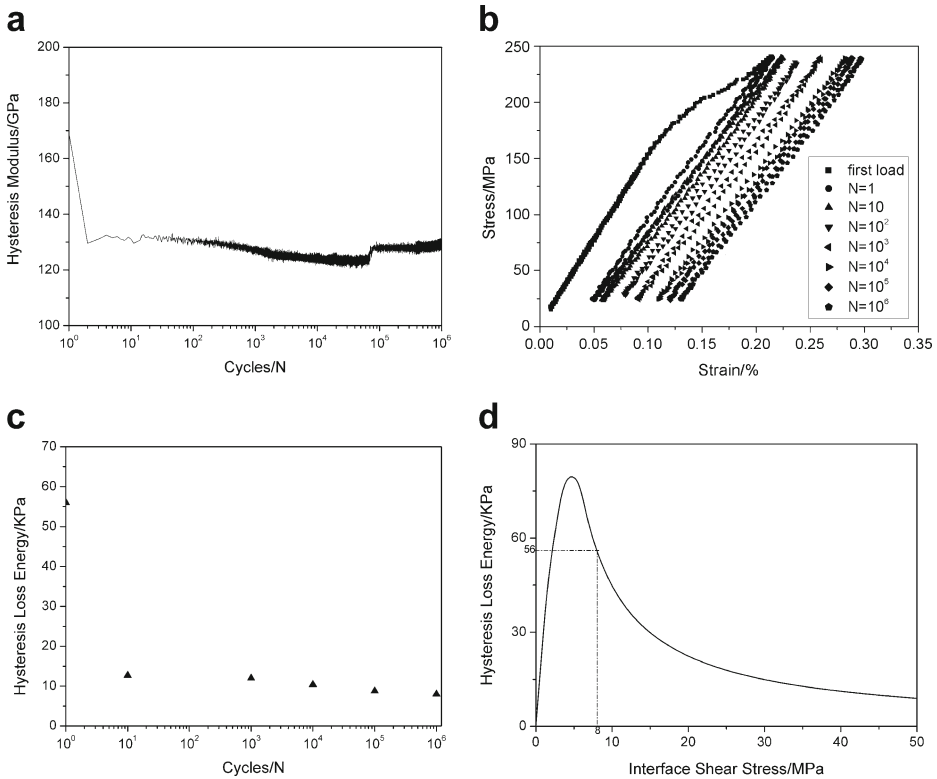
##### 3.1.1 Room Temperature

The tensile experiments of unidirectional C/SiC composite were conducted at room temperature. The tensile strength is approximately  $270 \pm 5$  MPa. The fatigue peak stresses were 260 MPa (96 % tensile strength), 240 MPa (88 % tensile strength), 200 MPa (74 % tensile strength), 180 MPa (66 % tensile strength) and 140 MPa (51 % tensile strength), respectively. The fatigue life S–N curve is illustrated in Fig. 1.

Under fatigue peak stress  $\sigma_{max}=240$  MPa, the fatigue hysteresis modulus decreases rapidly at the beginning of cyclic loading, as shown in Fig. 2a. The fatigue hysteresis modulus decreases from 169 GPa to 128 GPa at the first 10 cycles, which is mainly attributed to matrix multicracking and fiber/matrix interface debonding. The fatigue hysteresis loops corresponding to the 1st, 10th, 100th, 1000th, 10000th, 100000th and 1000000th cycles are shown in Fig. 2b. The experimental fatigue hysteresis loss energy degrades from 56 KPa at the 1st cycle to 8 kPa at the 1000000th cycle, as shown in Fig. 2c. The theoretical fatigue hysteresis loss energy as a function of interface shear stress is given in Fig. 2d. The fatigue hysteresis loss energy first increases with the decrease of interface shear stress to the maximum value of 79.5 kPa (the corresponding interface shear stress is  $\tau_i=4.7$  MPa), and then decreases with the decrease of interface shear stress to zero kPa (the corresponding interface shear stress is  $\tau_i=$  zero MPa). By comparing the experimental fatigue hysteresis loss energy with theoretical computational values, the interface shear stress of different number of applied cycles can be estimated, as shown in Table 1. The experimental fatigue hysteresis loss energy of the 1st, 3rd,



**Fig. 1** The fatigue life S–N curve of unidirectional C/SiC composite at room temperature



**Fig. 2** **a** the fatigue hysteresis modulus versus applied cycles; **b** the fatigue hysteresis loops of different number of applied cycles; **c** the experimental fatigue hysteresis loss energy versus applied cycles; and **d** the theoretical fatigue hysteresis loss energy versus interface shear stress of unidirectional C/SiC composite under fatigue peak stress of  $\sigma_{max}=240$  MPa at room temperature

7th, 10th, 100th, 10000th, 100000th and 1000000th cycles are 56, 45, 30, 12.7, 12, 10.4, 8.8 and 8 kPa, respectively; the corresponding interface shear stress estimated from fatigue hysteresis loss energy are 8, 1.5, 1, 0.4, 0.38, 0.35, 0.32 and 0.3 MPa, respectively. Under fatigue loading of  $\sigma_{max}=240$  MPa, the fatigue hysteresis loss energy of the 1st cycle lies in the right part of the fatigue hysteresis loss energy versus the interface shear stress curve. The fatigue hysteresis loop of the 1st cycle corresponds to interface slip Case 2, i.e., the interface partially debonds and fiber partially slips relative to matrix in the interface debonded region upon unloading/reloading. When the interface completely debonds, the interface shear stress degrades rapidly due to interface radial thermal residual tensile stress. The fatigue hysteresis loop of the 100th cycle corresponds to interface slip Case 4, i.e., the interface completely debonds and fiber completely slips relative to matrix in the interface debonded region upon unloading/reloading.

### 3.1.2 Elevated Temperature

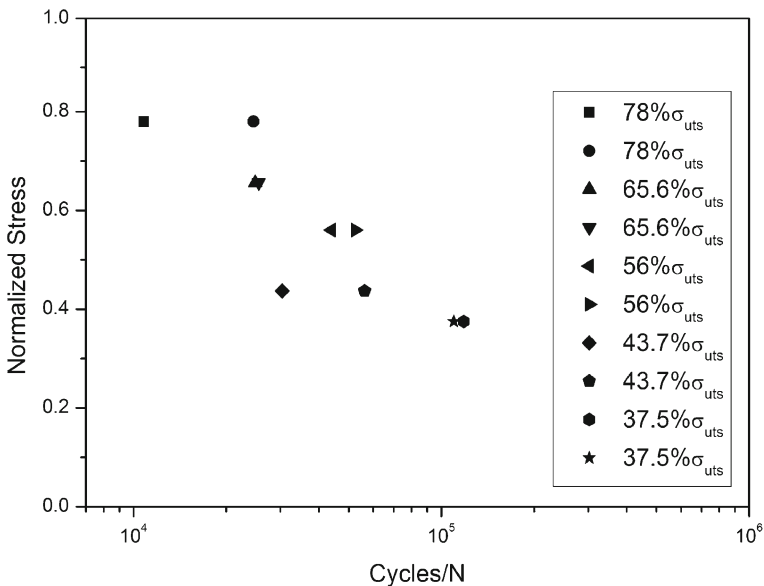
The tensile experiments of unidirectional C/SiC composite were conducted at an elevated temperature of 800 °C in air atmosphere. The tensile strength is approximately  $320\pm 3$  MPa.

**Table 1** The interface shear stress of unidirectional C/SiC composite corresponding to different number of applied cycles under fatigue peak stress of  $\sigma_{max}=240$  MPa at room temperature

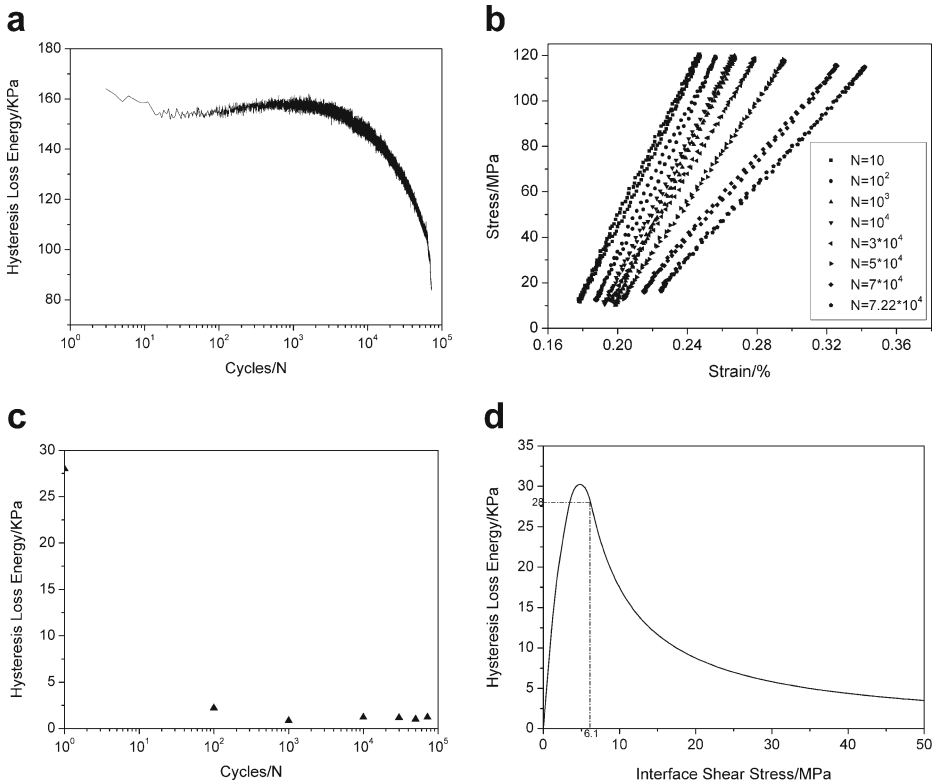
Cycles	Experimental hysteresis loss energy/KPa	Interface shear stress/MPa
1	56	8
10	12.7	0.4
100	12	0.38
10,000	10.4	0.35
100,000	8.8	0.32
1,000,000	8	0.3

The fatigue peak stresses were 250 MPa (78 % tensile strength), 210 MPa (65.6 % tensile strength), 180 MPa (56 % tensile strength), 140 MPa (43.7 % tensile strength) and 120 MPa (37.5 % tensile strength), respectively. The fatigue life S–N curve is illustrated in Fig. 3.

Under fatigue peak stress of  $\sigma_{max}=120$  MPa, the fatigue hysteresis modulus versus cycle curve can be divided into three regions, i.e., (1) at the beginning of fatigue loading, fatigue hysteresis modulus decreases rapidly due to matrix multicracking and interface debonding; (2) when matrix cracks approach saturation, fatigue hysteresis modulus decreases slowly due to interface shear stress degradation; and (3) at the final 2000 cycles, fatigue hysteresis modulus decreases rapidly for large amounts of fibers failure, as shown in Fig. 4a. The fatigue hysteresis loops corresponding to the 10th, 100th, 1000th, 10000th, 50000th, 70000th and 72200th cycles are given in Fig. 4b. The fatigue hysteresis loss energy degrades from 28 kPa at the 1st cycle to 1.22 kPa at the 72200th cycle, as shown in Fig. 4c. The theoretical fatigue hysteresis loss energy as a function of interface shear stress



**Fig. 3** The fatigue life S–N curve of unidirectional C/SiC composite at 800 °C in air atmosphere



**Fig. 4** **a** the fatigue hysteresis modulus versus applied cycles; **b** the fatigue hysteresis loops of different number of applied cycles; **c** the experimental fatigue hysteresis loss energy versus applied cycles; and **d** the theoretical fatigue hysteresis loss energy versus interface shear stress of unidirectional C/SiC composite under fatigue peak stress of  $\sigma_{max}=120$  MPa at an elevated temperature of 800 °C in air atmosphere

is given in Fig. 4d. The fatigue hysteresis loss energy first increases with the decrease of interface shear stress to the maximum value of 30.2 kPa (the corresponding interface shear stress is  $\tau_i=4.75$  MPa), and then decreases with the decrease of interface shear stress to zero kPa (the corresponding interface shear stress is  $\tau_i=$ zero MPa). By comparing the experimental fatigue hysteresis loss energy with theoretical computational values, the interface shear stress of different number of applied cycles can be estimated, as shown in Table 2. The experimental fatigue hysteresis loss energy of the 1st, 100th, 10000th and 72200th cycles are 28, 2.2, 1.4 and 1.2 kPa, respectively; the corresponding interface shear stress estimated from fatigue hysteresis loss energy are 6.1, 0.3, 0.22 and 0.2 MPa, respectively. Under fatigue loading of  $\sigma_{max}=120$  MPa, the fatigue hysteresis loss energy of the 1st cycle lies in the right part of the fatigue hysteresis loss energy versus the interface shear stress curve. The fatigue hysteresis loop of the 1st cycle corresponds to interface slip Case 2, i.e., the interface partially debonds and fiber partially slips relative to matrix in the interface debonded region upon unloading/reloading. When the interface completely debonds, the interface shear stress degrades rapidly due to interface radial thermal residual tensile stress. The fatigue hysteresis loop of the 100th cycle corresponds to interface slip Case 4, i.e., the interface completely debonds and fiber completely slips relative to matrix in the interface debonded region upon unloading/reloading.

**Table 2** The interface shear stress of unidirectional C/SiC composite corresponding to different number of applied cycle under fatigue peak stress of  $\sigma_{max}=120$  MPa at an elevated temperature of 800 °C in air atmosphere

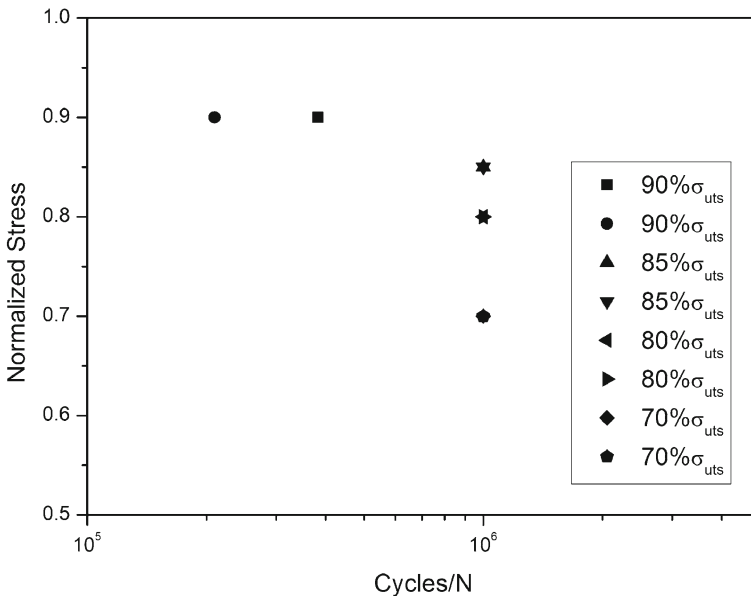
Cycles	Experimental hysteresis loss energy/KPa	Interface shear stress/MPa
1	28	6.1
100	2.2	0.3
10,000	1.4	0.22
72,200	1.2	0.2

### 3.2 Cross-ply C/SiC Composite

#### 3.2.1 Room Temperature

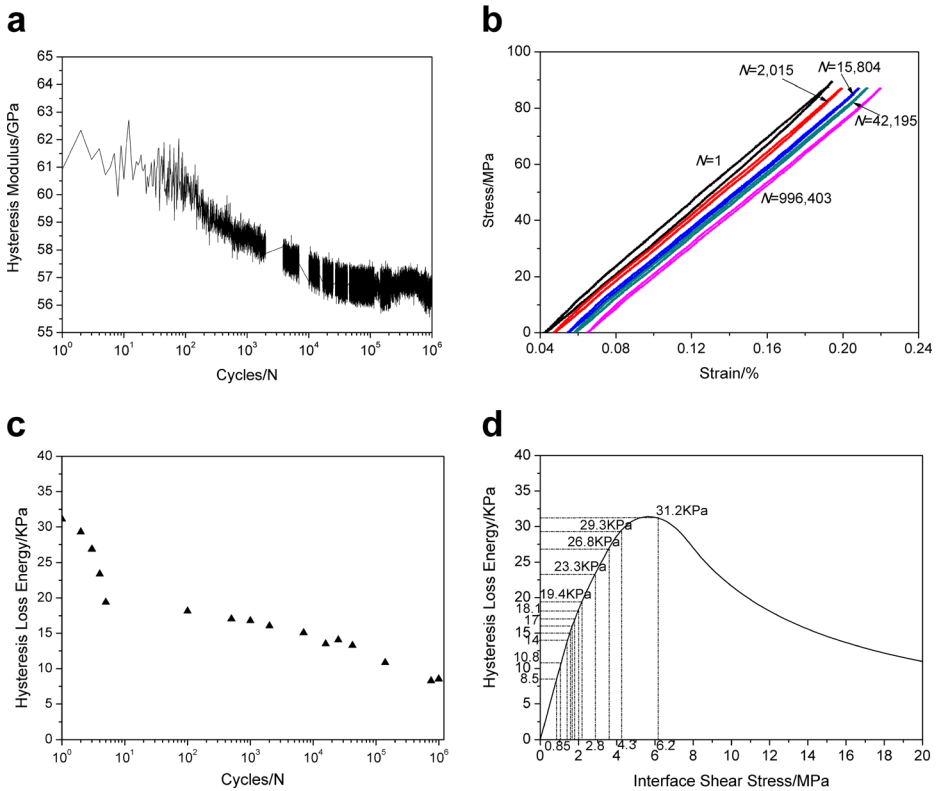
The tensile experiments of cross-ply C/SiC composite were conducted at room temperature. The tensile strength is about  $124\pm3$  MPa. The fatigue peak stresses were 112 MPa (90 % tensile strength), 105 MPa (85 % tensile strength), 99.2 MPa (80 % tensile strength) and 87 MPa (70 % tensile strength), respectively. The fatigue life S–N curve is shown in Fig. 5.

Under fatigue peak stress of 87 MPa, the fatigue hysteresis modulus decreases from 62 GPa at the 1st cycle to 56 GPa at the 1000000th cycle, as shown in Fig. 6a. At the initial stage of cyclic loading, fatigue hysteresis modulus decreases due to transverse multicracking in the 90° plies and matrix multicracking, fiber/matrix interface debonding in the 0° plies. With cycles increasing, fatigue hysteresis modulus decreases slowly due to interface wear. The fatigue hysteresis loops corresponding to the 1st, 2015th, 15804th, 42195th, 996403th cycles are shown in Fig. 6b. The experimental fatigue hysteresis loss energy versus applied cycles curve is shown in Fig. 6c. The theoretical fatigue hysteresis loss energy as a function of interface shear stress is given in Fig. 6d. The fatigue hysteresis loss energy first increases with the



**Fig. 5** The fatigue life S–N curve of cross-ply C/SiC composite at room temperature





**Fig. 6** **a** the fatigue hysteresis modulus versus applied cycles; **b** the fatigue hysteresis loops of different number of applied cycles; **c** the experimental fatigue hysteresis loss energy versus applied cycles; and **d** the theoretical fatigue hysteresis loss energy versus interface shear stress of cross-ply C/SiC composite under fatigue peak stress of  $\sigma_{max}=87$  MPa at room temperature

decrease of interface shear stress to the maximum value of 31.3 kPa (the corresponding interface shear stress is  $\tau_i=5.6$  MPa), and then decreases with the decrease of interface shear stress to zero kPa (the corresponding interface shear stress is  $\tau_i=$ zero MPa). By comparing the experimental fatigue hysteresis loss energy with theoretical computational values, the interface shear stress of different number of applied cycles can be estimated, as shown in Table 3. The experimental fatigue hysteresis loss energy of the 1st, 100th, 500th, 2015th, 25098th and 996403th cycles are 31.2, 18.1, 17, 16, 14 and 8.5 kPa, respectively; the corresponding interface shear stress estimated from fatigue hysteresis loss energy are 6.2, 2, 1.8, 1.7, 1.4 and 0.85 MPa, respectively. Under fatigue loading of  $\sigma_{max}=87$  MPa, the fatigue hysteresis loss energy of the 1st cycle lies in the right part of the fatigue hysteresis loss energy versus the interface shear stress curve. The fatigue hysteresis loop of the 1st cycle corresponds to interface slip Case 2, i.e., the interface partially debonds and fiber partially slips relative to matrix in the interface debonded region upon unloading/reloading. When the interface completely debonds, the interface shear stress degrades rapidly due to interface radial thermal residual tensile stress. The fatigue hysteresis loop of the 100th cycle corresponds to interface slip Case 4, i.e., the interface completely debonds and fiber completely slips relative to matrix in the interface debonded region upon unloading/reloading.

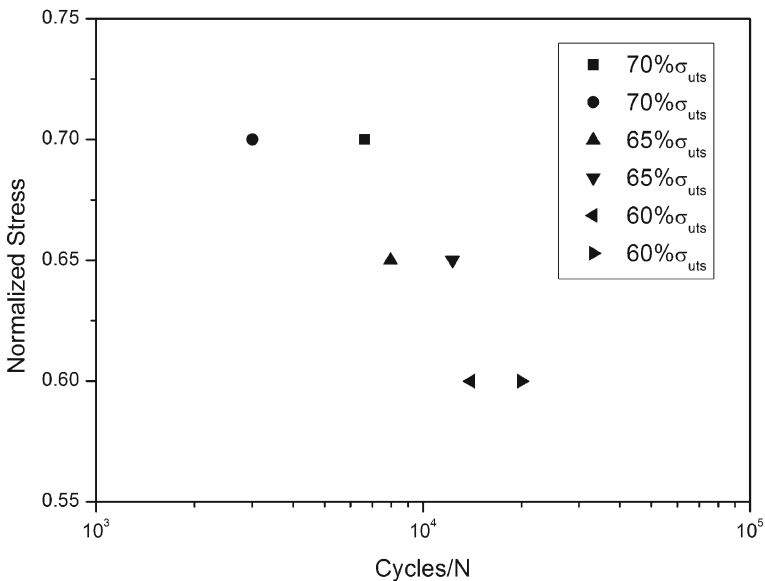
**Table 3** The interface shear stress of cross-ply C/SiC composite corresponding to different number of applied cycles under fatigue peak stress of  $\sigma_{max}=87$  MPa at room temperature

Cycles	Experimental hysteresis loss energy/kPa	Interface shear stress/MPa
1	31.2	6.2
100	18.1	2
500	17	1.8
2015	16	1.7
25,098	14	1.4
996,403	8.5	0.85

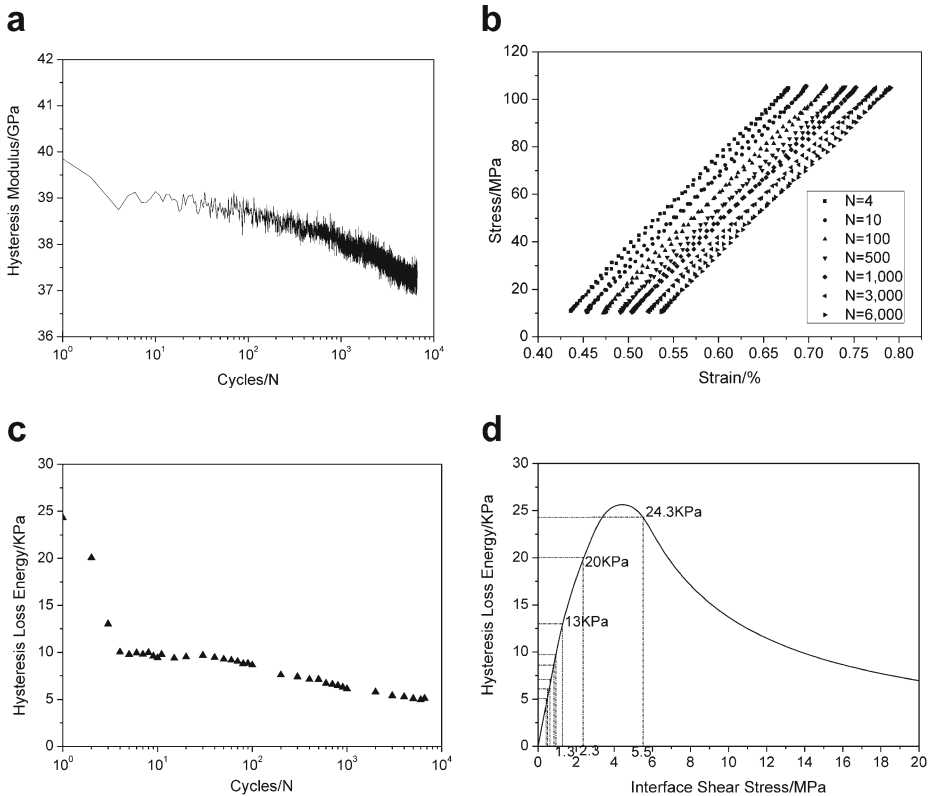
### 3.2.2 Elevated Temperature

The tensile experiments of cross-ply C/SiC composite were conducted at an elevated temperature of 800 °C in air atmosphere. The tensile strength is approximately 150±2 MPa. The fatigue peak stresses were 105 MPa (70 % tensile strength), 97.5 MPa (65 % tensile strength) and 90 MPa (60 % tensile strength), respectively. The fatigue life S–N curve is illustrated in Fig. 7.

Under fatigue peak stress of 105 MPa, the fatigue hysteresis modulus versus applied cycles curve is given in Fig. 8a, which can be divided into three regions, i.e., (1) at the beginning of cyclic loading, fatigue hysteresis modulus decreases rapidly due to transverse multicracking in the 90° plies, matrix multicracking and interface debonding in the 0° plies; (2) when matrix cracks approach saturation, fatigue hysteresis modulus decreases slowly due to interface shear stress degradation for interface oxidation; (3) at the final cyclic loading, fatigue hysteresis modulus decreases rapidly due to fibers failure. The



**Fig. 7** The fatigue life S–N curve of cross-ply C/SiC composite at 800 °C in air atmosphere



**Fig. 8** **a** the fatigue hysteresis modulus versus applied cycles; **b** the fatigue hysteresis loops of different number of applied cycles; **c** the experimental fatigue hysteresis loss energy versus applied cycles; and **d** the theoretical fatigue hysteresis loss energy versus interface shear stress of cross-ply C/SiC composite under fatigue peak stress of  $\sigma_{max}=105$  MPa at 800 °C in air atmosphere

fatigue hysteresis loops corresponding to the 4th, 10th, 100th, 500th, 1000th, 3000th and 6000th cycles are given in Fig. 8b. The experimental fatigue hysteresis loss energy versus applied cycles curve is shown in Fig. 8c. The fatigue hysteresis loss energy degrades from 24.3 kPa at the 1st cycle to 5.1 kPa at the 6600th cycle. The theoretical fatigue hysteresis loss energy as a function of interface shear stress in the 0° plies is illustrated in Fig. 8d. The fatigue hysteresis loss energy first increases with the decrease of interface shear stress to the maximum value of 25.6 kPa (the corresponding interface shear stress is  $\tau_i=4.4$  MPa), and then decreases with the decrease of interface shear stress to zero kPa (the corresponding interface shear stress is  $\tau_i=0$  MPa). By comparing the experimental fatigue hysteresis loss energy with theoretical computational values, the interface shear stress of different number of applied cycles can be estimated, as shown in Table 4. The experimental fatigue hysteresis loss energy of the 1st, 2nd, 3rd, 4th, 10th, 100th, 500th, 1000th, 3000th, 6000th and 6600th cycles are 24.3, 20, 13, 12, 9.7, 8.6, 7.1, 6.1, 5.4, 5.2 and 5.1 kPa, respectively; the corresponding interface shear stress estimated from the fatigue hysteresis loss energy are 5.5, 2.3, 1.3, 1.2, 0.9, 0.8, 0.6, 0.5, 0.45, 0.43 and 0.4 MPa, respectively. Under fatigue loading of  $\sigma_{max}=105$  MPa, the fatigue hysteresis loss energy of the 1st cycle lies in the right part of the fatigue hysteresis loss energy versus the interface shear stress curve. The fatigue hysteresis loop of the 1st cycle corresponds to interface

**Table 4** The interface shear stress of cross-ply C/SiC composite corresponding to different number of applied cycles under fatigue peak stress of  $\sigma_{max}=105$  MPa at 800 °C in air atmosphere

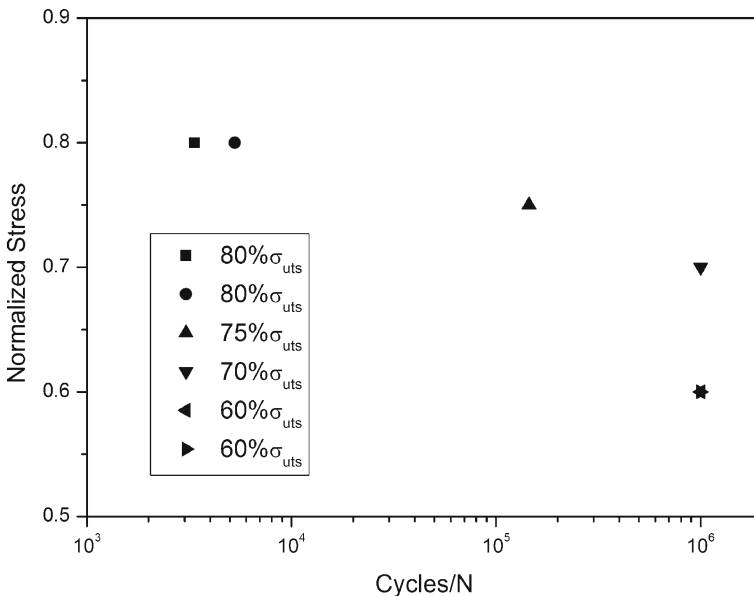
Cycles	Experimental hysteresis loss energy/kPa	Interface shear stress/MPa
1	24.3	5.5
100	8.6	0.8
500	7.1	0.6
1000	6.1	0.5
3000	5.4	0.45
6600	5.1	0.4

slip Case 2, i.e., the interface partially debonds and fiber partially slips relative to matrix in the interface debonded region of the 0° plies upon unloading/reloading. When the interface completely debonds, the interface shear stress degrades rapidly due to interface radial thermal residual tensile stress. The fatigue hysteresis loop of the 100th cycle corresponds to interface slip Case 4, i.e., the interface completely debonds and fiber completely slips relative to matrix in the interface debonded region of the 0° plies upon unloading/reloading.

### 3.3 2.5D C/SiC Composite

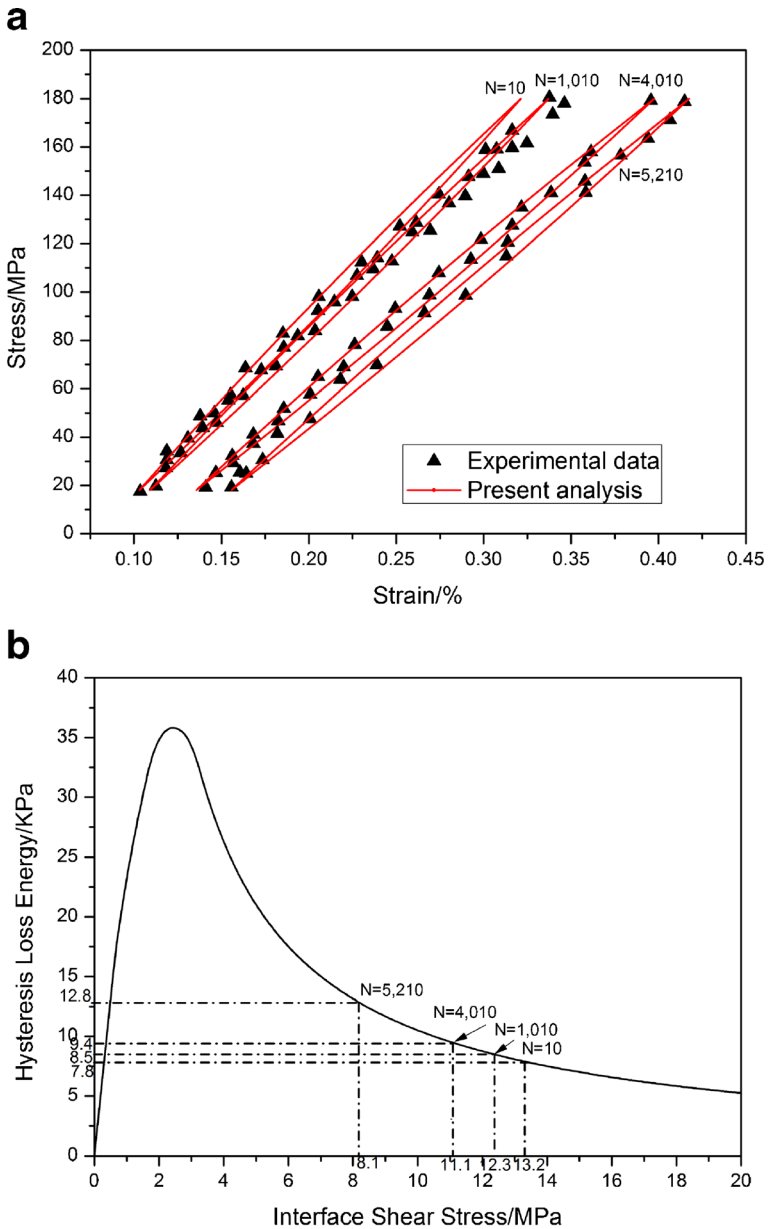
#### 3.3.1 Room Temperature

Yang [16] investigated the fatigue behavior of 2.5D C/SiC composite at room temperature. The fatigue stress ratio was 0.1 and loading frequency was  $f=10$  Hz. The



**Fig. 9** The fatigue life S–N curve of 2.5D C/SiC composite at room temperature

tensile strength was  $225 \pm 2$  MPa. The fatigue peak stresses were 135 MPa (60 % tensile strength), 157.5 MPa (70 % tensile strength), 168.7 MPa (75 % tensile strength) and 180 MPa (80 % tensile strength), respectively. The fatigue life S–N curve is illustrated in Fig. 9.

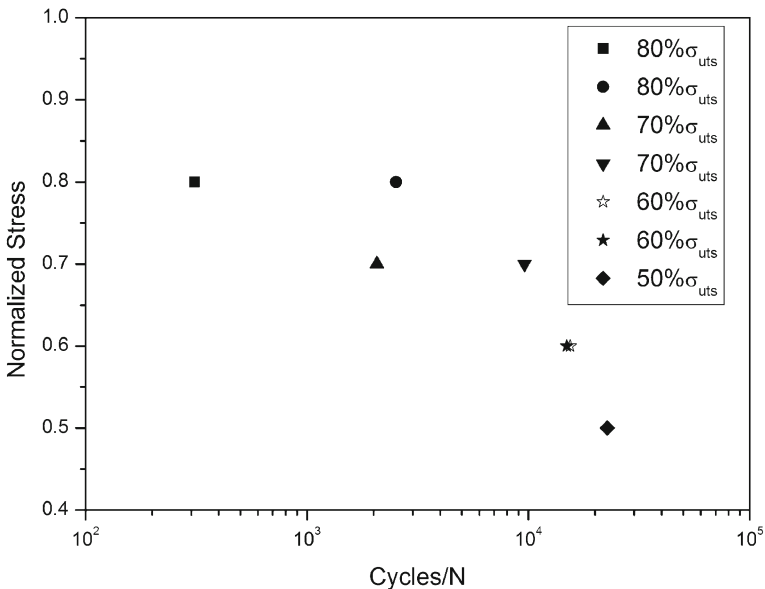


**Fig. 10** a the experimental and predicted fatigue hysteresis loops; and b the theoretical fatigue hysteresis loss energy as a function of interface shear stress of 2.5D C/SiC composite under fatigue peak stress of  $\sigma_{max} = 180$  MPa at room temperature

**Table 5** The interface shear stress of 2.5D C/SiC composite corresponding to different number of applied cycles under fatigue peak stress of  $\sigma_{\max}=180$  MPa at room temperature

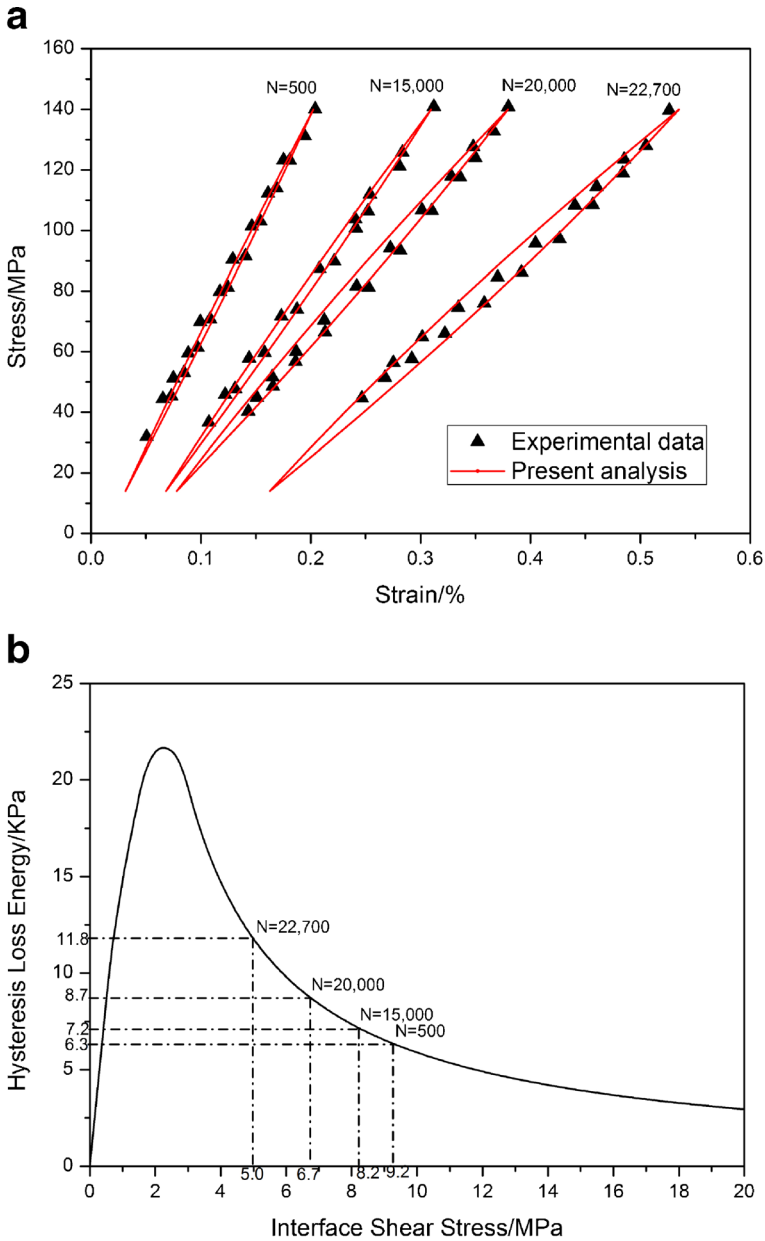
Cycles	Experimental hysteresis loss energy/kPa	Interface shear stress/MPa
10	7.8	13.2
1010	8.5	12.3
4010	9.4	11.1
5210	12.8	8.1

Under fatigue peak stress  $\sigma_{\max}=180$  MPa, the fatigue hysteresis loops corresponding to the 10th, 1010th, 4010th and 5210th cycles are shown in Fig. 10a. The specimen experienced 5281 cycles and fatigue failed. The theoretical fatigue hysteresis loss energy as a function of interface shear stress in the longitudinal yarns is illustrated in Fig. 10b. The fatigue hysteresis loss energy first increases with the decrease of interface shear stress to the maximum value of 35.8 kPa (the corresponding interface shear stress is  $\tau_i=2.4$  MPa), and then decreases with the decrease of interface shear stress to zero kPa (the corresponding interface shear stress is  $\tau_i=$  zero MPa). By comparing the experimental fatigue hysteresis loss energy with theoretical computational values, the interface shear stress corresponding to different number of applied cycles can be estimated, as shown in Table 5. The experimental fatigue hysteresis loss energy of the 10th, 1010th, 4010th and 5210th cycles are 7.8, 8.5, 9.4 and 12.8 kPa, respectively; the corresponding interface shear stress estimated from fatigue hysteresis loss energy are 13.2, 12.3, 11.1 and 8.1 MPa, respectively. Under fatigue loading of  $\sigma_{\max}=180$  MPa, the fatigue hysteresis loss energy increases with the increase of the number of applied cycles. The fatigue hysteresis loops from the 1st cycle to 5210th cycle all correspond to interface slip Case 2, i.e., the interface partially debonds and fiber partially slips relative to matrix in the interface debonded region of the longitudinal yarns upon unloading/reloading. The theoretical predicted



**Fig. 11** The fatigue life S–N curve of 2.5D C/SiC composites at 800 °C in air atmosphere

hysteresis loops corresponding to the 10th, 1010th, 4010th and 5210th cycles using the hysteresis loops models and estimated interface shear stress agreed with experimental data, as shown in Fig. 10a.



**Fig. 12** a the experimental and predicted fatigue hysteresis loops; and b the theoretical fatigue hysteresis loss energy as a function of interface shear stress of 2.5D C/SiC composite under fatigue peak stress of  $\sigma_{max} = 140$  MPa at 800 °C in air atmosphere

**Table 6** The interface shear stress of 2.5D C/SiC composite corresponding to different number of applied cycles under fatigue peak stress of  $\sigma_{\max}=140$  MPa at 800 °C in air atmosphere

Cycles	Experimental hysteresis loss energy/kPa	Interface shear stress/MPa
500	6.3	9.2
15,000	7.2	8.2
20,000	8.7	6.7
22,700	11.8	5

### 3.3.2 Elevated Temperature

Yang [16] investigated the fatigue behavior of 2.5D C/SiC composite at an elevated temperature of 800 °C in air atmosphere. The fatigue stress ratio was 0.1 and loading frequency was  $f=10$  Hz. The tensile strength was  $280\pm 3$  MPa. The fatigue peak stresses were 140 MPa (50 % tensile strength), 168 MPa (60 % tensile strength), 196 MPa (70 % tensile strength) and 224 MPa (80 % tensile strength), respectively. The fatigue life S–N curve is illustrated in Fig. 11.

Under fatigue peak stress of  $\sigma_{\max}=140$  MPa, the fatigue hysteresis loops corresponding to the 500th, 5000th, 20000th and 22700th cycles are shown in Fig. 12a. The specimen experienced 5281 cycles and fatigue failed. The fatigue hysteresis loss energy as a function of interface shear stress in the longitudinal yarns is shown in Fig. 12b. The fatigue hysteresis loss energy first increases with the decrease of interface shear stress to the maximum value of 21.7 kPa (the corresponding interface shear stress is  $\tau_i=2.25$  MPa), and then decreases with the decrease of interface shear stress to zero kPa (the corresponding interface shear stress is  $\tau_i=$  zero MPa). By comparing the experimental fatigue hysteresis loss energy with theoretical computational values, the interface shear stress of different number of applied cycles can be estimated, as shown in Table 6. The experimental fatigue hysteresis loss energy of the 500th, 15000th, 20000th and 22700th cycles are 6.3, 7.2, 8.7 and 11.8 kPa, respectively; the corresponding interface shear stress estimated from the fatigue hysteresis loss energy are 9.2, 8.2, 6.7 and 5 MPa, respectively. Under fatigue loading of  $\sigma_{\max}=140$  MPa, the fatigue hysteresis loss energy increases with the increase of the number of applied cycles. The fatigue hysteresis loops from the 500th cycle to 22700th cycle all correspond to interface slip Case 2, i.e., the interface partially debonds and fiber partially slips relative to matrix in the interface debonded region of the longitudinal yarns upon unloading/reloading. The theoretical predicted fatigue hysteresis loops corresponding to the 500th, 15000th, 20000th and 22700th cycles using the hysteresis loops models and estimated interface shear stress agreed with experimental data, as shown in Fig. 12a.

## 4 Conclusions

The fatigue behavior of unidirectional, cross-ply and 2.5D woven C/SiC composites at room temperature and 800 °C in air atmosphere has been investigated. At room temperature and 800 °C in air atmosphere, the fatigue hysteresis modulus and fatigue hysteresis loss energy decrease with applied cycles increasing due to matrix multicracking, fiber/matrix interface debonding and interface shear stress degradation for interface wear or interface oxidation. The



fatigue limit stresses of unidirectional, cross-ply and 2.5D C/SiC composites at room temperature were 88, 88 and 70 % of tensile strength, respectively. However, there was no apparent fatigue limit stress for unidirectional, cross-ply and 2.5D C/SiC composites under fatigue loading at 800 °C in air atmosphere due to interface oxidation or carbon fibers oxidation.

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### Compliance with Ethical Standards

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**Conflict of Interest** The author declares that he has no conflict of interest.

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