Tension-tension Fatigue Behavior and Residual Strength of 2.5D SiO_{2f}/SiO_2 at High Temperature

Ma Yan[1], Zhang Peiwei[1*], Xu Peifei[1], Liu Jian[2], Fei Qingguo[1]

1. School of Mechanical Engineering, Southeast University, Nanjing 211189, China;
2. Beijing Aerospace Technology Institute, Beijing 100074, China

Abstract

2.5D SiO_{2f}/SiO_2 is extensively utilized in the aerospace industry. The performance under high-temperature cyclic fatigue is paramount importance for potential applications. This study examines the fatigue behavior at service temperatures, alongside the residual strength. Findings reveal that temperature elevation enhances both the tensile strength and fatigue resistance. Under reduced fatigue loads, specimens exhibited signs of fatigue strengthening, demonstrating augmented strength and stiffness compared to their initial state. However, the interfacial bond strength in these specimens decreased, leading to a shift in fracture behavior from purely brittle to a combined fracture mode.

Introdution

Quartz fiber reinforced silica composite (SiO_{2f}/SiO_2) is widely used in antenna covers in the aerospace field [1]. During flight, the antenna cover is subjected to the combined effects of high temperature, high pressure, vibration. It is necessary to comprehensively analyze the influence of thermodynamic coupling load on the material's performance [2].Scholars have conducted a series of studies on the thermal and mechanical properties of 2.5D SiO_{2f}/SiO_2 [3], [4]. The bending performance [5], shear performance [6], and ablation performance [7] at high temperatures have been studied, which reveal that high temperature can form a glassy SiO_2 film on the material surface, affecting the fracture mode [8]. In summary, the physical and mechanical properties of 2.5D SiO_{2f}/SiO_2 have strong temperature dependence. However, there have been few reports on the high temperature fatigue performance.

In this study, fatigue performance tests were carried out on 2.5D SiO_{2f}/SiO_2 at elevated temperatures. The influence of temperature and fatigue load on fatigue behavior, and the influence of fatigue load on residual strength were investigated. A residual stiffness degradation model was used. The damage mechanism of the material under high temperature fatigue was discussed in combination with fracture morphology.

Material and Method

Fatigue temperature:	800°C, 900°C, 1000°C	high-temperature furnace:	HTF06-1400
Frequency:	5Hz	Stress ratio:	0.1
Upper limit:	10^5cycles	Loading rate of static strength test:	0.5mm/min
Scanning electron microscope:	Navo Nano SEM-450	3D X-ray microscope:	Zeiss Xradia 510 Versa
Fatigue test and tensile strength equipment:	SDS-100 electro-hydraulic servo fatigue testing machine		

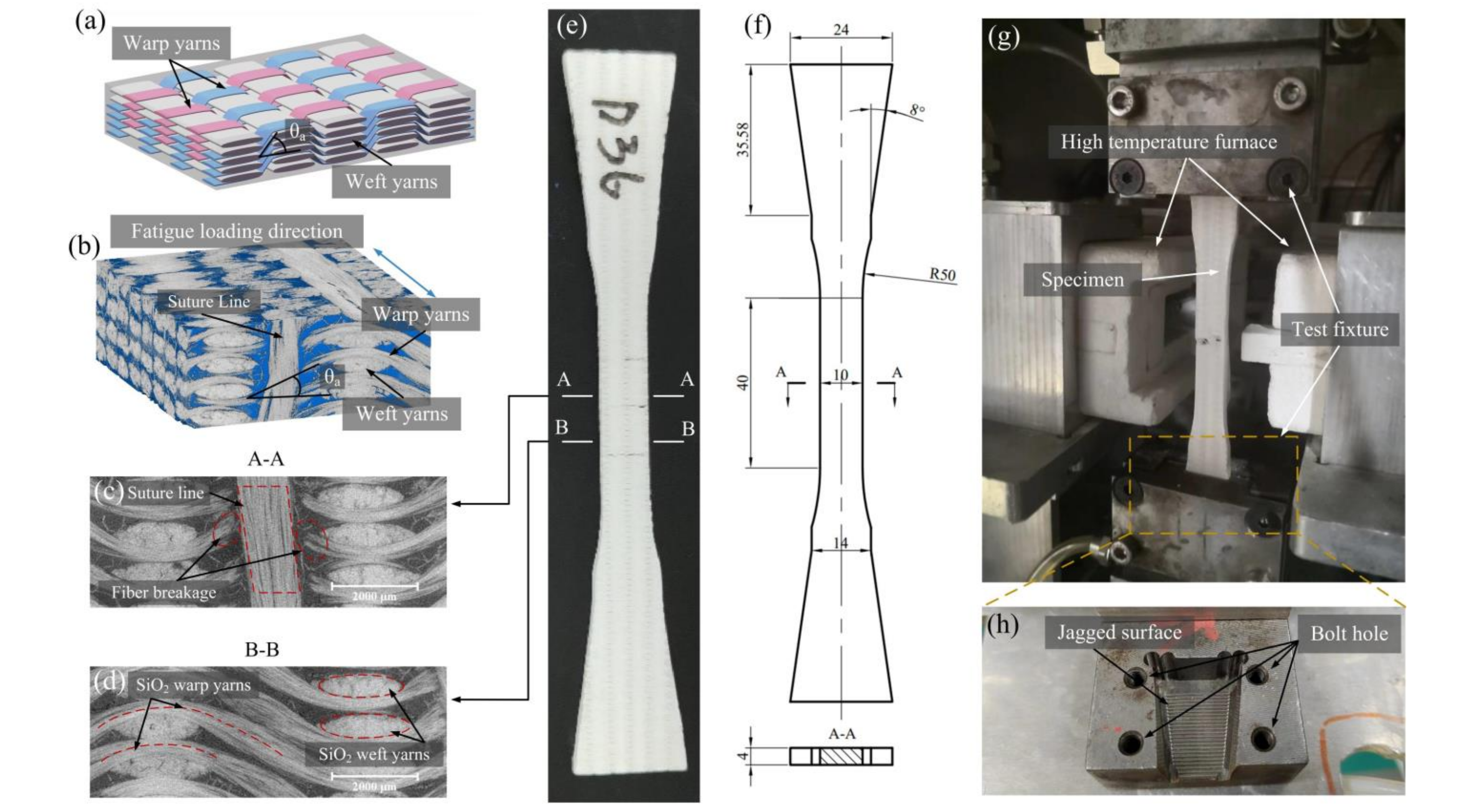

Figure 1. Microstructure and specimen diagram of 2.5D SiO_{2f}/SiO_2. (a) Schematic of fiber preform. (b) CT reconstruction diagram. (c) Longitudinal section of the specimen (with sutural line). (d) Longitudinal section of the specimen (without sutural line). (e) Photo of the specimen. (f) Size of the specimen. (g) Fatigue test equipment. (h) Test fixture.

Results

1. Effect of temperature on mechanical properties of materials

Considering the service temperature of the radome, along with the long-term service temperature of SiO_{2f}/SiO_2 being 1000°C, this study selected the range of 800°C to 1000°C for the investigation of fatigue behavior and residual strength. A set of six static tensile strength tests were performed ,listed in Table 1.

Table 1. Tensile strength at different temperatures

T/°C	RT	800	1000
Average strength	24.46	30.87	34.23

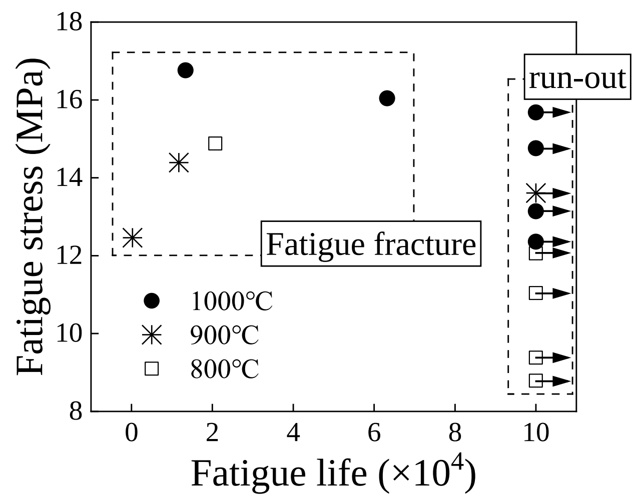

Figure 2. Fatigue life of material at different temperatures and stress levels

2. Typical hysteresis loops and residual stiffness at elevated temperature

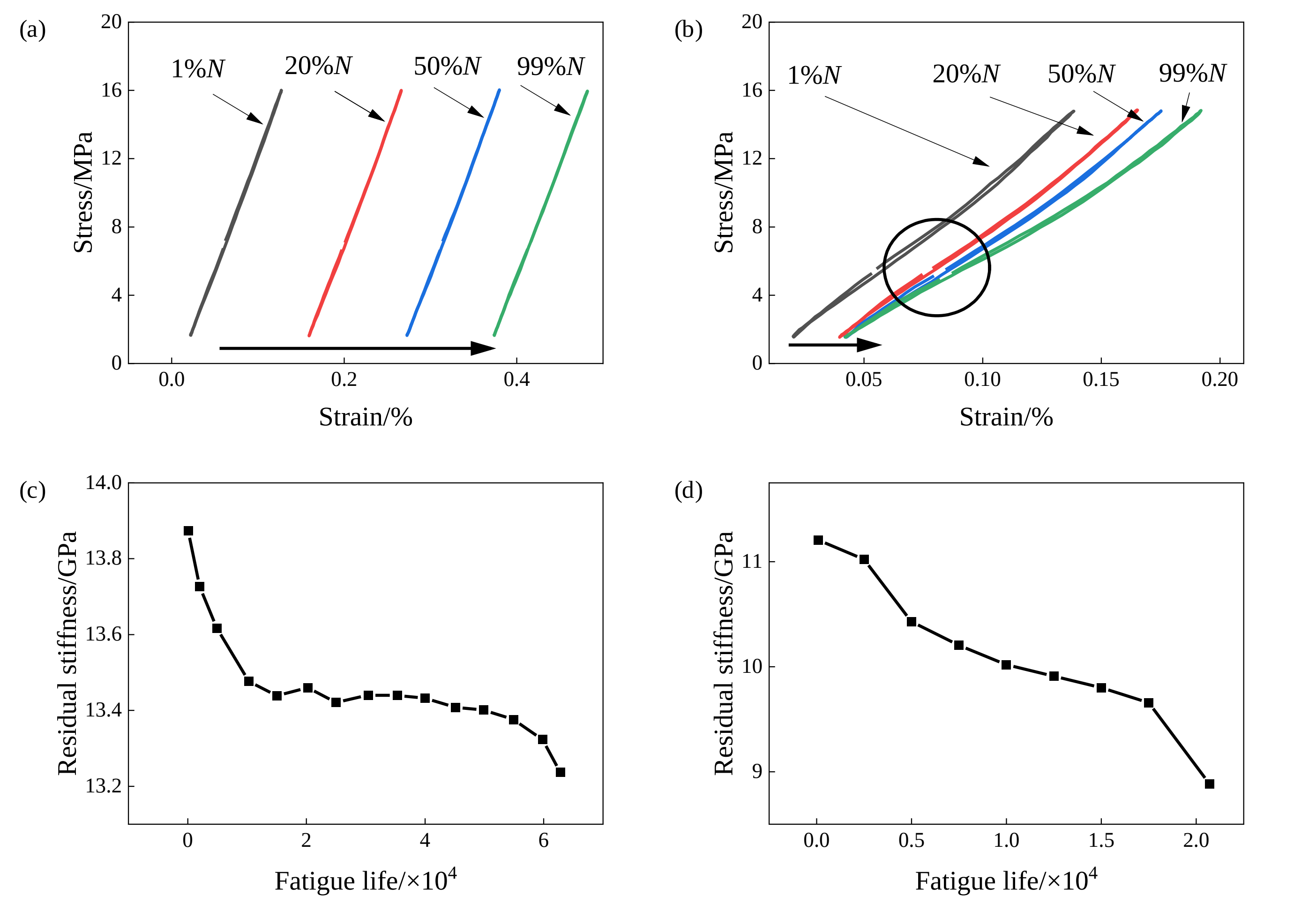

Figure 3. Hysteresis curve evolution and stiffness degradation at different temperatures at 48% stress level. (a) Hysteresis loop at 800°C; (b) Hysteresis loop at 1000°C; (c) Stiffness degradation curve at 800°C; (d) Stiffness degradation curve at 1000°C

3. Residual stiffness degradation model

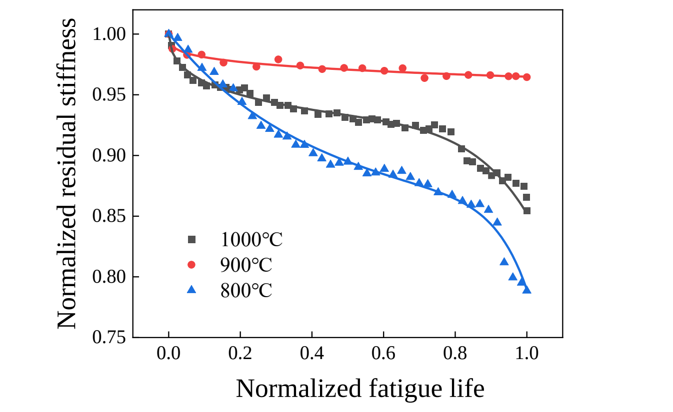

Figure 4. Stiffness test value and model curves of specimens

$$\frac{E_n}{E_0}=1-\left(1-\frac{E_{rc}}{E_0}\right)\left\{1-\frac{1-(n/N)^a}{1+b(n/N)^c}\right\} \quad (1)$$

Table 2. Fitting parameters and goodness-of-fit

T/°C	Stress level	a	b	c	R^2
1000	50%	7.047	1.155	0.5075	0.975
900	45%	0.2598	-0.0102	-0.2723	0.9429
800	48%	12.48	2.086	1.068	0.9858

4. Effect of fatigue load on residual performance

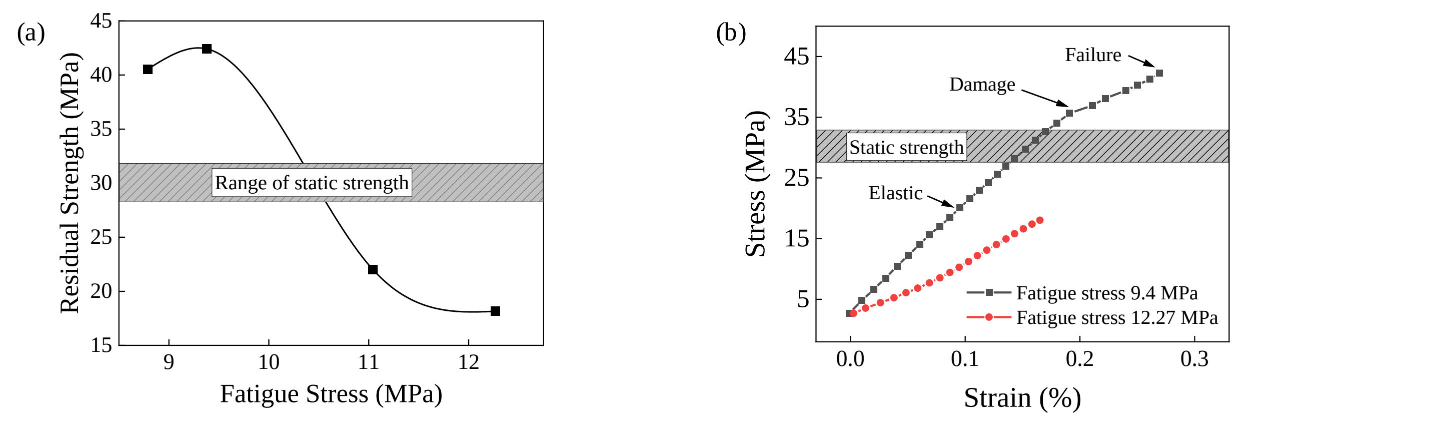

Figure 5. Residual tensile strength result. (a) Residual strength variation curve with fatigue load; (b) Stress-strain curve

5. Damage mechanisms

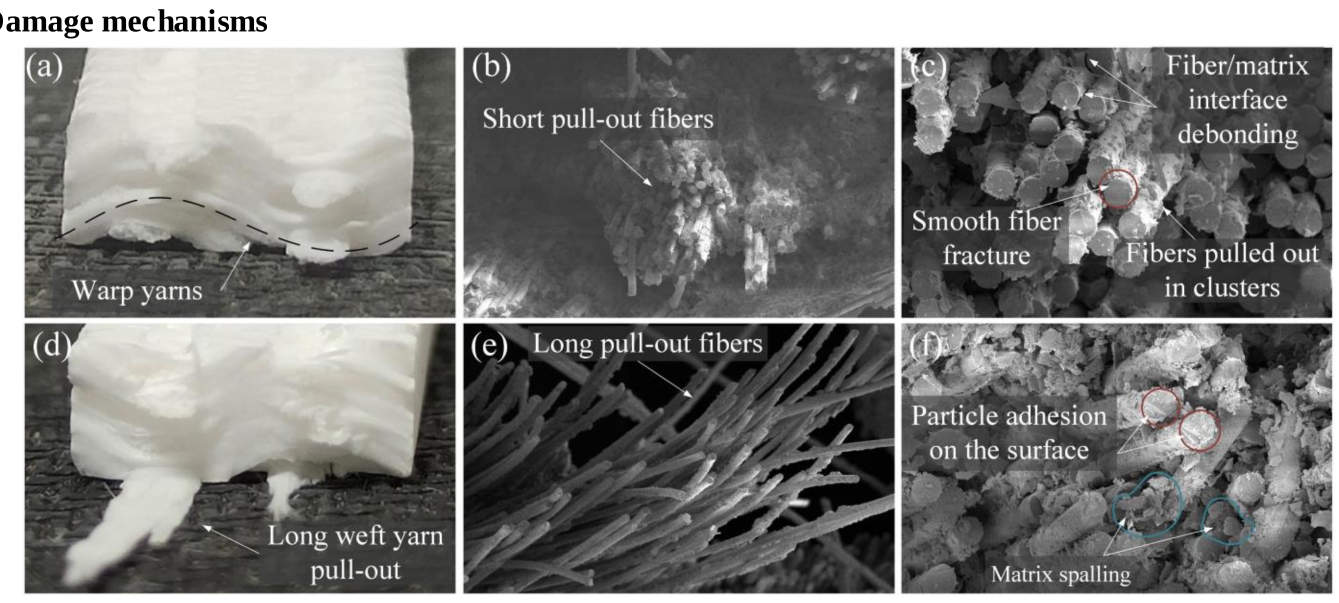

Figure 7. Fracture morphologies. (a) The virgin specimen; (b) The virgin specimen (1000×); (c) The virgin specimen (4000×); (d) The pre-fatigue specimen ; (e) The pre-fatigue specimen (1000×); (f) The pre-fatigue specimen (4000×).

Conclusion

Fatigue tests and strength evaluations were conducted on 2.5D SiO_{2f}/SiO_2 at elevated temperatures. Finding reveals that:

- Within the experimental temperature range, both the static strength and the fatigue limit under specified conditions gradually increased.
- The material exhibited increased strength under lower fatigue load due to the fatigue strengthening mechanism. The experimental results from 800°C ~ 1000°C show good agreement with the stiffness degradation model.
- The fracture mechanism of the virgin specimen exhibited brittle fracture, and the pre-specimen demonstrated a combination of brittle and ductile fracture mechanisms.

Reference

[1] Q. An, "Machining of SiC ceramic matrix composites: A review," Chinese Journal of Aeronautics, vol. 34, no. 4, pp. 540–567, 2021.
[2] Ş. Saliha Fidan and R. Ünal, "A survey on ceramic radome failure types and the importance of defect determination," Engineering Failure Analysis, vol. 149, p. 107234, Jul. 2023.
[3] S. A. Han, K. H. Jiang, and J. W. Tang, "Studies on Preparation and Property of 2.5D SiO_{2f}/ SiO_2 Composites," AMR, vol. 79–82, pp. 1767–1770, Aug. 2009.
[4] Y. Zhang, W. Liu, Z. Gui, S. Zhou, and Z. Ren, "Damage mechanisms of 2.5D SiO_{2f}/SiO_2 woven ceramic matrix composites under compressive impact," Ceramics International, vol. 49, no. 6, pp. 9203–9218, Mar. 2023.
[5] Y. Liu, Z. Zhu, Y. Jiang, and B. Li, "Mechanical properties and mechanical behavior of $(SiO_2)_f/SiO_2$ composites with 3D six-directional braided quartz fiber preform," Science and Engineering of Composite Materials, vol. 19, no. 2, pp. 113–117, Jun. 2012.
[6] Y. Liu et al., "Mechanical properties and microstructure of 2.5D (shallow bend-joint) $quartz_f$/silica composites by silicasol-infiltration-sintering," Science and Engineering of Composite Materials, vol. 19, no. 1, Jan. 2012.
[7] C. Zou et al., "Ablation behavior and mechanism of SiO_{2f}/SiO_2, SiO_{2f}/BN and Si3N4f/BN radar wave transparent composites," Corrosion Science, vol. 139, pp. 243–254, Jul. 2018.
[8] X. Yang, W. Qing, P. Zhi-hang, and C. Feng, "High-temperature properties of 2.5D SiO_{2f}/SiO_2 composites by sol–gel," Ceramics International, vol. 42, no. 11, pp. 12802–12806, Aug. 2016.