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Low cycle fatigue behavior of a 3D braided KD-I fiber reinforced ceramic matrix composite for coated and uncoated specimens at 1100 °C and 1300 °C

Duoqi Shi *, Xin Jing, Xiaoguang Yang

School of Energy and Power Engineering, Beihang University, Beijing 100191, China

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ABSTRACT

Stress-controlled low cycle fatigue tests of a three-dimensional KD-I fiber reinforced ceramic matrix composites were conducted with a sine wave form at 1100 °C and 1300 °C in air. Fatigue stress level ranged from 40 MPa to 136 MPa. The influences of temperature, coating and loading frequency on fatigue performance were considered. The strain ratcheting and modulus drop were observed, and their relation with damage evolution and ultimate failure were studied. Damage and failure mechanisms were also investigated. Oxidation embrittlement controlled the damage and failure of the composites in fatigue tests.

1. Introduction

Ceramic matrix composites (CMCs), particularly those containing braided or woven fiber preforms, are under development for high temperature applications as e.g. in aero engine components, rocket nozzles, and re-entry thermal protection systems. To be utilized into these areas, the composites should exhibit superior long-term mechanical properties under high temperature and oxygen environment. A thorough understanding of high temperature mechanical performance of the composites is necessary for structure design and durability evaluation.

Fatigue is responsible for the majority of failure in structural components. The fatigue mechanisms in CMCs are complex and involved a multitude of spatially distributed and interacting mechanisms [1,2]. The mechanism responsible for the fatigue damage in SiC/SiC composite appeared to be related to degradation of the sliding stress along the fiber/matrix, which might lead to long debonding of interfaces and lower fiber's failure stress [3]. Additionally, the most significant problem for SiC/SiC composites is oxidation embrittlement [4]. Once the matrix cracking occurs, oxygen infiltrates into the composites and leads to the degradation of fibers and fiber/matrix interface. Under fatigue loading, the embrittlement would be accelerated [5]. To improve oxidation resistance, several approaches have been developed including self-healing multilayered matrix [6,7], glass sealant [8] and anti-oxidation coating [9].

Several recent researches investigated fatigue performance of SiC/SiC at elevated temperatures. Zhu investigated creep and fatigue behavior of SiC fibers (Nicalon and Hi-Nicalon) reinforced CVI derived SiC matrix composites in air and argon at temperatures ranging from 1000 °C to 1300 °C [10]. Both creep and fatigue resistance of Hi-Nicalon/SiC [11] are similar to that of enhanced SiC/SiC [12], but much better than standard SiC/SiC [13]. Improving fiber and matrix properties are the routines to enhance the composites performance during fatigue and creep tests at elevated temperatures. The failure mechanism was due to slow crack propagation in the matrix of the SiC/SiC composite. The crack propagation of the composite is controlled by both the bridged fibers and the matrix. Morscher [14] studied fatigue and creep properties of a melt-infiltrated SiC matrix Sylramic-iBN fibers reinforced composite. Tow regimes of strength degradation were analyzed. At higher stress level, oxidation-induced unbridged crack growth in matrix dominates the failure. At relative lower stress level, the failure was attributed to fiber degradation. The fatigue properties of polymer derived crystalline [$SiC+Si_3N_4$] matrix reinforced with Sylramic type fibers composites [15], CVI derived SiC matrix reinforced with Hi-Nicalon fibers composites and SiC [16] and B_4C multilayered matrix reinforced with Hi-Nicalon fibers composites [7] were evaluated in air and in steam at elevated temperatures to investigated the environment effect on fatigue. Results revealed that the presence of steam can cause noticeable degradation for the fatigue properties.

* Corresponding author. Tel./fax: +86 10 82316362.
E-mail address: shdq@buaa.edu.cn (D. Shi).

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Recently, the National University of Defense Technology (NUDT) and Beihang University conducted a program to develop 3D CMC based on the SiC/SiC composite system for aerospace application. The CMC consists of KD-I (Si–C–O) fibers and polymer-derived ceramic (Si–C–O) matrix. Polymer infiltration and pyrolysis (PIP) is an attractive processing method because of its relative lower cost and allowance of near-net-shape molding and fabrication. The monotonic tension, creep properties have been evaluated [17–19]. In this paper, the fatigue behavior is investigated with a sine wave form under stress control at elevated temperature. The effect of temperature, frequency and anti-oxidation coating are considered to understand the fatigue behavior. The damage and failure mechanisms during the fatigue test are discussed.

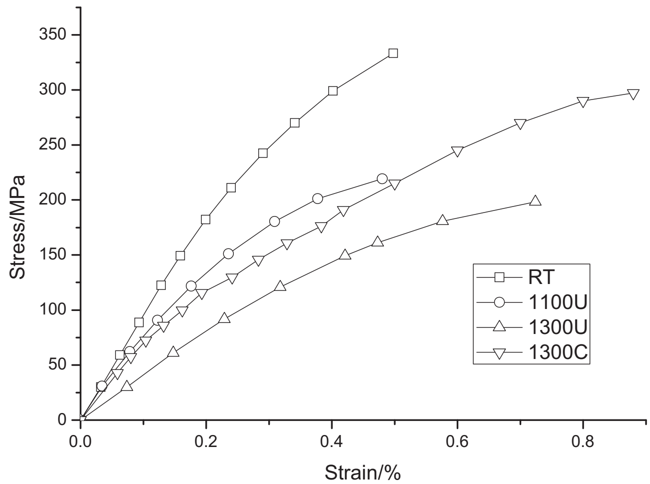

Fig. 1. Stress–strain response of the CMCs under monotonic tension (C means the coated specimen and U means the uncoated specimen).

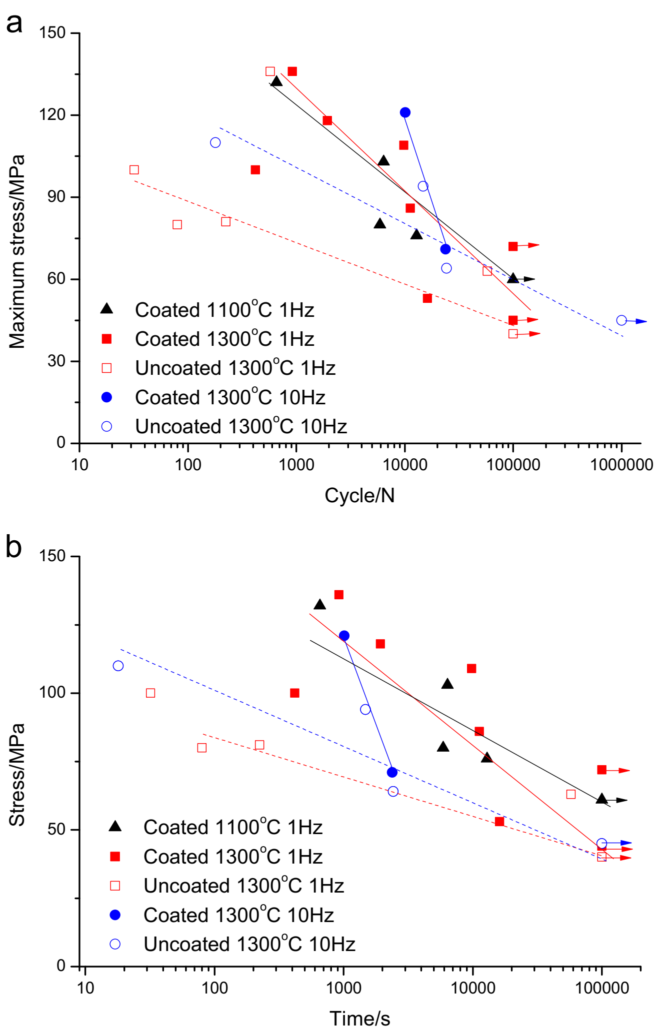

Fig. 2. (a) Maximum stress vs cycles to failure plot and (b) maximum stress vs time to failure plot for KD-I/SiC composites at elevated temperatures. *Arrow* indicates that failure of specimen did not occur when the test was terminated.

2. Materials and experimental procedure

2.1. Material

The CMCs, provided by National University of Defense Technology (NUDT), were chosen for this study because of their potential use in high temperature structural applications as hot section components in advanced jet engines. The composites are based on the SiC/SiC system with KD-I fibers as reinforcement. The yarns consisting 1.2 K fibers were braided into a 3D four directional preform. The fiber volume fraction was approximately 45%. The preform was surrendered to a chemical vapor deposition (CVD) process to prepare a ~200 nm thick pyrolysed carbon (PyC) layer. Polymer impregnation and pyrolysis (PIP) process with a polymer precursor of liquid polyvinycarbosilane (LPVCS) was adopted to densify the matrix [15]. Totally, 14 cycles of impregnation and pyrolysis were repeated to reduce the composites porosity. The original densified preform was a flat plate with dimension of 130 mm × 60 mm × 4 mm. Then, tensile test specimens were cut by water-jet cutting machine. The overall specimen dimensions were roughly 127 mm × 14 mm × 4 mm and the central reduced

Table 1
Summary of fatigue results for KD-I/SiC composites at elevated temperatures.

Max stress (MPa)	Coatings	Cycle to failure	Time to failure (h)	Failure strain (%)
Fatigue at 1 Hz				
1300 °C				
45	Yes	100,000[a]	27.8[a]	0.173[a]
53	Yes	16,185	4.5	0.187
72	Yes	1,00,000[a]	27.8[a]	0.515
86	Yes	11,271	3.13	0.369
109	Yes	9811	2.73	0.475
100	Yes	420	0.12	0.852
118	Yes	1930	0.54	0.555
136	Yes	920	0.26	0.540
40	No	1,00,000[a]	27.8[a]	0.408
63	No	57,765	16.05	0.930
81	No	224	0.06	0.360
80	No	80	0.02	0.608
100	No	32	0.01	–
136	No	576	0.16	1.209
1100 °C				
60	Yes	1,00,000[a]	27.8[a]	0.330[a]
76	Yes	12,899	3.58	–
80	Yes	5910	1.64	0.400
103	Yes	6372	1.77	0.144
132	Yes	655	0.18	0.620
Fatigue at 10 Hz				
1300 °C				
45	No	1,000,000[a]	27.8[a]	0.767[a]
64	No	24,267	0.67	0.658
94	No	14,752	0.41	0.453
110	No	180	0.005	0.343
71	Yes	23,801	0.66	0.842
121	Yes	10,125	0.28	1.196

'–' Abnormal strain recorded by extensometer.

[a] Run-out, failure of specimen did not occur when the test was terminated.