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Fundamental issues of applications of C/SiC composites for re-entry vehicles

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Carbon fiber reinforced silicon carbide ceramic matrix composite materials (C/SiCs) are being tested for hot structures and thermal protection systems (TPS) of launch vehicles and spacecraft, and also for advanced friction system of aircraft and racing cars. A number of tribological and joining components are required in these applications, such as bushing and rolling contact bearings, nuts and bolts, which require excellent mechanical, physical and chemical properties at temperatures higher than 1650 °C. This study summarizes preparation of C/SiC load-carrying bearings for hinge by the Chemical Vapor Infiltration (CVI) method and C/SiC bolts for joints by the CVI + PIP (Polymer Impregnation and Pyrolysis) methods. The hinge bearing and bolts were examined in a simulated re-entry environment. Stress-oxidation was investigated under different stress levels from 0 to 200 MPa up to 1800 °C. The friction behavior of the hinge bearing system was studied under high loads (up to 25 kN) and low rotating velocities. The mechanical properties of the bolts with a thread connection were conducted under tensile and shear fatigue at both room temperature and elevated temperature. The results show that the stress-oxidation behavior of 2D-C/SiC composites in a combustion environment is a combined effect of extremely high load, high temperature, and oxidation. The load and temperature influenced the crack openings and thus the oxidation of carbon fibers in the pre-cracked composites. The combustion environment mainly determined the time to failure of the specimens by oxidation damage under a high applied stress. Reliable thermal load-carrying ability and stable friction performance of the hinge bearing is demonstrated in high-temperature combustion environments with extremely high loads. The oxidation products of SiO_2 at high temperatures between surfaces played an important role to modifies the friction by providing a protective layer. The room temperature tensile and shear strength of the bolts made of needled C/SiC are 139 MPa and 83 MPa, respectively. Even at 1800 °C in a combustion environment, the strengths still retained about 116 MPa with a maximum decrease of 13%. More importantly, the bolts did not suffer significant mechanical degradation after tension-tension fatigue at 1 Hz for 24 h.

Key words: C/SiC, Hinge bearing, Bolts, Stress-oxidation, Tribological behavior, Joining.

Introduction

Ceramic matrix composite materials (CMCs), mainly those consisting of a SiC-based matrix reinforced with either carbon or SiC-fibers, are being considered the primary materials for hot structures of future reusable launch vehicles [1-3]. In these applications, C/SiC composites will be subjected to a service cycle that includes mechanical or thermal loading under complex environments [4]. CMC hot structures are load-carrying structures of lightweight construction and are able to sustain high operational temperatures and thermo-mechanical loads without failure. The successful utilization of these materials has been demonstrated in the integral design concept of thermal protection and hot structure systems, and also in an advanced friction system for aircraft [5-8]. Besides these, spacecraft and satellites require a number of tribological components, such as bushing and rolling contact bearings in components. Sliding contacts are found in brakes, clutches, hinges, deployment devices, etc [8, 9]. Many of these tribological devices must operate with minimum friction both in air and in space.

For instance, during re-entry, large amounts of energy are set free near the surface due to the high entry velocity. These re-entry conditions must be simulated in ground test facilities to qualify the necessary heat protection materials. The high thermal and mechanical loading effects demand excellent high temperature mechanical properties such as against the stress-oxidation of hot structures [4]. Furthermore, the high temperature joining strength and especially the high temperature tribological behaviors of some hot structures are becoming new important issues [10]. One of the problems such as stress-oxidation, hot joining, and high load friction may be involved in many hot structures during re-entry, such as for the leading edge segments, rudders, nose cap, and chin panel. However, all the above problems should be simultaneously considered in the hinge bearing of the body flaps. An important challenge has been to investigate the friction and wear behavior of CMCs as load-carrying structures under high loads at high temperatures and in oxidizing atmospheres (combustion gas). To control the atmosphere when simulating conditions for the end use requirement is rather important. It may be possible to achieve a degree of simulation by evaluating specimens in vacuum or in a dry argon or dry nitrogen

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atmosphere [9]. However, this will neglect the important effect that the high temperature, the oxygen and water vapor have on the mechanical properties and also on the friction and wear processes.

A fundamental evaluation of the role of the environment on damage mechanisms of materials subjected to mechanical loading is needed to assess the applicability of C/SiC composites [11, 12]. Furthermore, previous studies on frictional applications of these CMCs were mainly focused on the friction and wear resistance as brake disks under controlled conditions [13, 14]. However, there is little knowledge on the friction of C/SiC bearing contact structures under high loads and low sliding velocities in an oxidizing atmosphere. This paper investigates the stress-oxidation and hot joining of C/SiC composites, as well as the friction behavior of a C/SiC hinge bearing in a self-built experimental simulation environment. This environment would facilitate testing under coupled stress in air and at high temperature up to 1800 °C in an oxidizing atmosphere.

Experimental Procedure

The two dimensional carbon/silicon carbide matrix (2D-C/SiC) composites were prepared by a chemical vapor infiltration (CVI) method, and the detailed manufacturing process is described as follows. Step 1: The preform with a fiber content of 40 vol.% was shaped by lamination of 2D-carbon cloth with a plain weave. The carbon preform was first infiltrated with pyrolytic carbon (PyC) with a thickness of 200 nm to produce the carbon/carbon (C/C) composites. The C/C samples were then heat-treated with a graphitization process at 1800 °C for two hours. Step 2: The C/SiC composites were prepared by chemical vapor infiltration of SiC into C/C composites at 1000 °C. Methyltrichlorosilane (MTS, CH_3 $SiCl_3$) was used as the SiC precursor. MTS vapor was carried by bubbled hydrogen. Step3: The C/SiC samples were machined to the final shape. Then a SiC coating was further deposited on the composite surface with a thickness of about 80~100 μm by chemical vapor deposition (CVD).

The hinge bearing system for friction tests are made of 2D-C/SiC ceramic composites. The stress-oxidation behavior tested in a high temperature combustion environment was applied to these 2D-C/SiC composites. Considering the shear strength limits of 2D-C/SiC composites, the 3D needled C/SiC bolts were manufactured by a CVI process combined with a PIP method for qualification of joining tests in combustion.

All the tests of stress-oxidation, joining, and friction of the C/SiC hinge bearing were conducted in a high temperature combustion environment, which is to simulate the re-entry environment with a high temperature and oxidizing atmosphere. The high temperature combustion environment was simulated in a self-built integrated system. This system can facilitate testing in a simulated condition by controlling the thermal environment and coupled stress environment. The high temperature gas-combustion wind

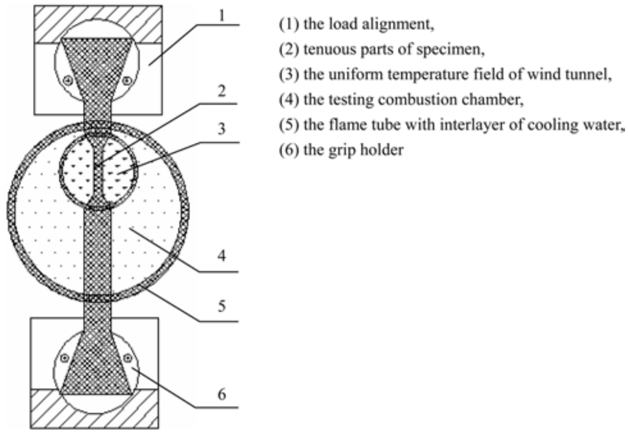

Fig. 1. Schematic diagram of the stress-oxidation tests and tensile tests of C/SiC composites in high temperature combustion environment.

tunnel ensured a thermal environment up to 1800 °C. The gas produced in the combustion chamber was a mixture of oxygen, water vapor, carbon dioxide, with the balance nitrogen. The combined mechanical loading system and rotating servo-driver promised a coupling stress environment. Detailed information has been given in reference [15].

Fig. 1 shows a schematic diagram of the stress-oxidation tests and tensile tests of C/SiC composites in the combustion environment. Stress-oxidation tests were carried out in the combustion environment under an applied stress of 200 MPa at three temperatures: 1300 °C, 1500 °C and 1800°C. To investigate the influence of load on the stress-oxidation behavior, the tests were controlled at five stress levels of 40 , 80, 120, 160, and 200 MPa at 1500 °C with an exposure time of 10 minutes. The residual strength described in this paper was measured under a tensile load at a set temperature after the stress-oxidation tests. The tensile strength tested in the combustion environment at 1300 °C ~1800 °C is marked as TSCE in the following. Tensile tests were conducted with a loading rate of 0.2 mm/minute.

Fig. 2 shows a test schematic of the friction behavior of the C/SiC hinge bearing, which was tested at room temperature in air and at high temperature in a combustion

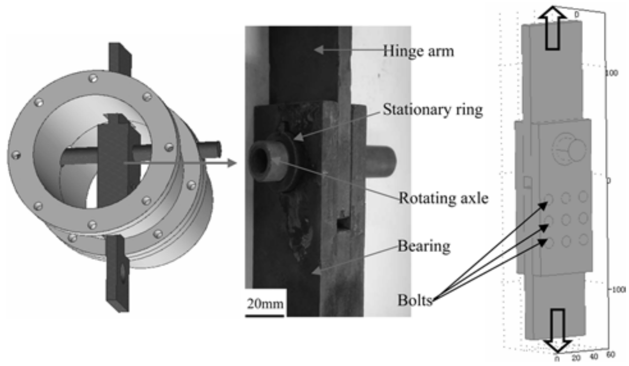

Fig. 2. Test schematic of friction behavior of C/SiC composites hinge bearing sample in high temperature combustion environment.

environment. The friction couples contain a rotating axle and a stationary ring. Both the ring and axle go through the hinge arm and bearing. The stationary ring is fixed in the hinge arm. The rotating axle is driven by the shaft coupling at one end and connected with a fixing device at the other end. Equal up-loads and down-loads were applied during the tests. The lower hinge arm is connected by several C/SiC bolts with the other two side-plates. Both the upper and lower hinge arms are located in an instrument (Instron 8801) to perform the loading function. The load, sliding velocity, friction torque, and friction force can be controlled well and measured during tests. The friction behavior of the C/SiC hinge bearing was tested under a cyclic loading condition up to 25 kN. The axle is controlled under constant rotating velocity of 32 rpm (sliding velocity of 0.033 m/s) during the framework of the tests. Fig. 3 shows a schematic of joining tests of 3D needled C/SiC bolts in combustion environments. The strength of the C/SiC pin/bolt is measured by a servo-hydraulic machine (Model Instron 8801). To investigate the effect of fatigue on the strength of C/SiC bots, a frequency of about 1 Hz was applied during the fatigue within a loading range of 1000~2500 N and tested for 24 h. The tensile tests were conducted with the same loading rate of 0.2 mm/minute.

Worn surfaces of rotating axle were examined by optical microscopy (Nikon SMZ1000) and scanning electron microscopy (SEM, HITACHI-S-2700, Japan). Fracture surfaces of tested stress-oxidation specimens were also observed by scanning electron microscopy. The roughness of contact surfaces was measured by atomic force microscopy (AFM, Molecular Imaging, USA).

Results and Discussion

Stress-oxidation of C/SiC composites

The stress-oxidation behavior of C/SiC composites under an applied stress of 200 MPa at three temperatures 1300 °C, 1500 °C, and 1800 °C was investigated as listed in Table 1. It was found that, the specimen tested at 1300 °C under an applied stress of 200 MPa (80% of the initial TSCE) fractured ahead of a set holding time of 10minutes, compared with that tested at 1500 °C and 1800 °C. The stress-oxidation life of C/SiC composites in the combustion environment under a stress of 200 MPa is less than 10minutes at 1300 °C, but more or less than 10minutes at 1500 °C and 1800 °C. The average residual strength of the specimens which survived was about 227 MPa and 231 MPa at 1500 °C and 1800 °C, which indicated a strength retained ratio of about 91~93% after stress-oxidation at 200 MPa. It is concluded that, the temperature influenced the stress-oxidation life of C/SiC composites when the same stress is applied. The time to failure was dependent on both the applied stress and temperature in the combustion environment.

Fig. 4 shows the influence of the applied stress on the residual strength and weight loss of C/SiC composites after exposure for 10 minutes at 1500 °C in a combustion environment. The residual strength decreased and the weight loss increased with an increase in the applied stress in the stress-oxidation testing construction. As the initial tensile strength of C/SiC composites in the combustion environment (TSCE) tested at 1300 °C ~1800 °C was about 250 MPa, it is seen from Fig. 4 that the strength

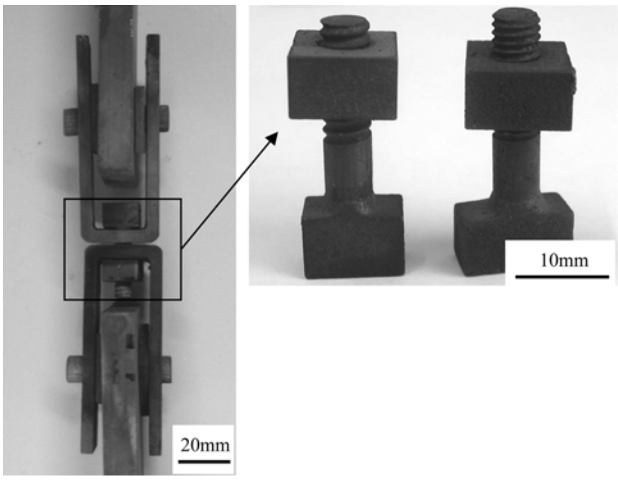

Fig. 3. Clamping fixture for tensile tests of 3D needled C/SiC bolts at high temperatures in combustion environments.

Table 1. The stress-oxidation tests and results of C/SiC composites in a combustion environment

Appliedstress (MPa)	Tem. (°C)	Exposure time (s)	Life (minutes)	Residual strength at temperature (MPa)
200	1300	430	< 10	All fractured
		490		
		550		
	1500	580	< 10	fractured
		860	> 10	225
		820	> 10	229
	1800	580	< 10	fractured
		860	> 10	228
		820	> 10	233

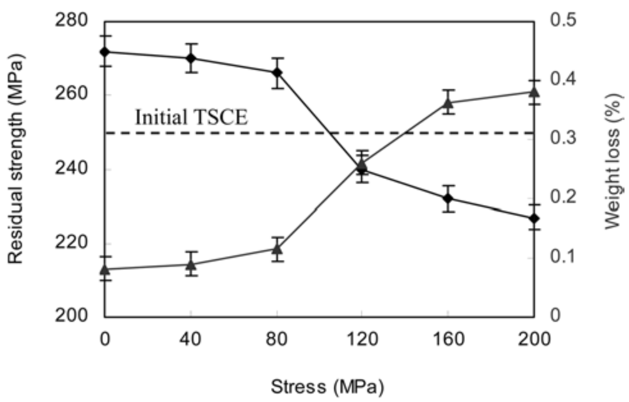

Fig. 4. The residual strength and weight loss of C/SiC composites after exposure for 10 minutes at 1500 °C under different applied stresses in a combustion environment.

retained ratio is about 110%, 108%, 106%, 96%, 94%, and 91% after exposure for 10 minutes at 1500 °C under applied stresses of 0, 16%, 32%, 48%, 64%, and 80% of the initial TSCE. An applied stress below 80 MPa resulted in no strength degradation and no obvious influence on the weight loss. However, an applied stress of about 120~200 MPa caused significant strength degradation and an increase of weight loss.

Fig. 5 shows the morphological changes of fibers on fracture surfaces of C/SiC composites tested at 1800 °C in a combustion environment. The oxidation regions are found along the opening cracks perpendicular to the coating surface. The oxidation of fibers is selective, and it occurs more rapidly in the near-surface zone on a pre-cracked surface. The diameter of a fiber cluster dramatically oxidized in the near-surface zone at a facing-flux site was about 40~50 μm (Fig. 5(a)). Furthermore, severe oxidation of both the PyC interface and carbon fibers was observed in the near-surface region in all failed samples. The damage to C/SiC composites caused by oxidation is also related to a notch-like partial degradation of carbon fibers located near the matrix crack tips as shown in Fig. 5(c). However, almost no oxidation occurred in the center of a fracture surface. Examination of the failed specimens indicated that oxidation of the carbon fibers was the primary damage mode for specimens tested under a high load in a combustion environment.

The influence of the load on the stress-oxidation behavior of C/SiC composites is mainly related to the influence on the matrix cracking. Either the weight loss or the strength reduction is primarily dependent on oxidation damage of the composites caused by matrix cracking. The fiber damage is enhanced due to the increased matrix cracking caused by the increased load. Thereby, an increase of the applied load accelerated material failure due to oxidation by development of cracking.

The stress-oxidation behavior of C/SiC composites in a combustion environment is a combined effect of an extremely high load, high temperature, and oxidation. The load and temperature influenced the crack opening and thus the oxidation of carbon fibers in the pre-cracked composites. The combustion environment mainly determined the time-to-failure of the specimens by oxidation damage under a high applied stress. An oxidizing atmosphere enhanced the failure of composites by decreasing the load-carrying ability of fibers. The residual strength of composites decreased and the weight loss increased with an increase in the applied stress. A combustion environment and a high applied stress above 80 MPa accelerated the material failure and lead to a strength reduction after exposure for 10 minutes at 1500 °C. At an applied stress below 80 MPa, no strength degradation was observed, however, at a higher strength a retained ratio of 106~110% was obtained.

Friction behavior of C/SiC hinge bearing

The friction behavior of a C/SiC hinge bearing was tested at 1800 °C gas-temperature in a combustion environment, and compared with that at room temperature in air. Fig. 2

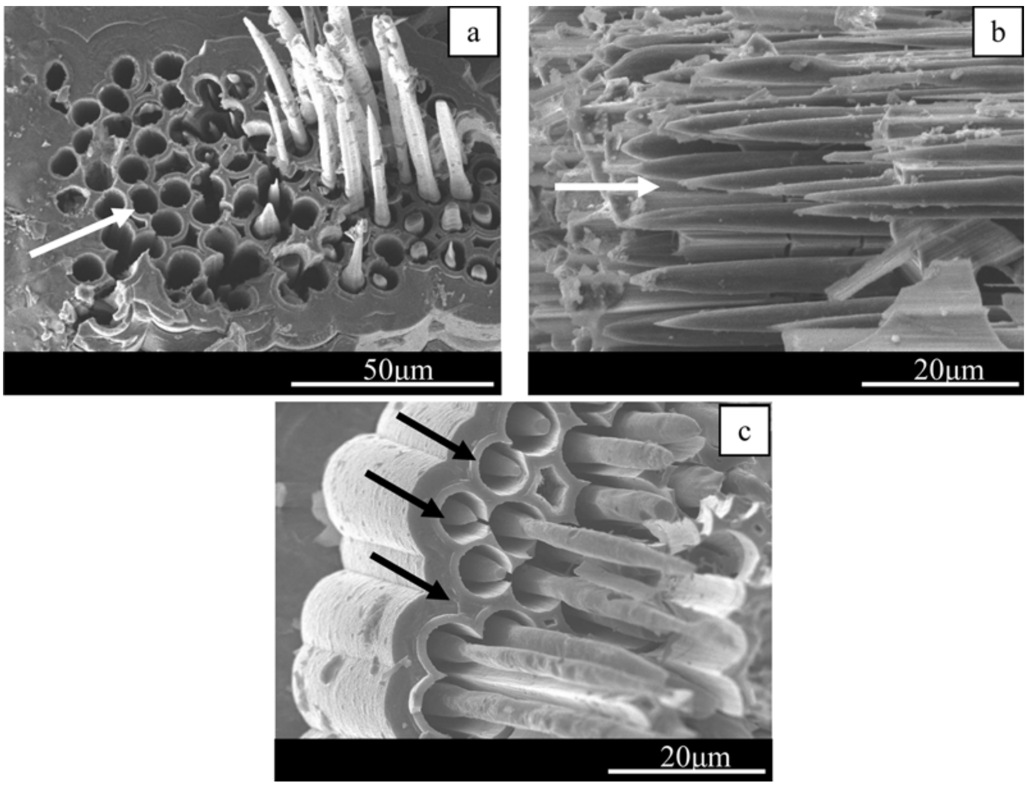

Fig. 5. The morphology of oxidized fibers on fracture surfaces of C/SiC composites tested at 1800 °C in a combustion environment (the direction of the heat flux is marked by an arrow).

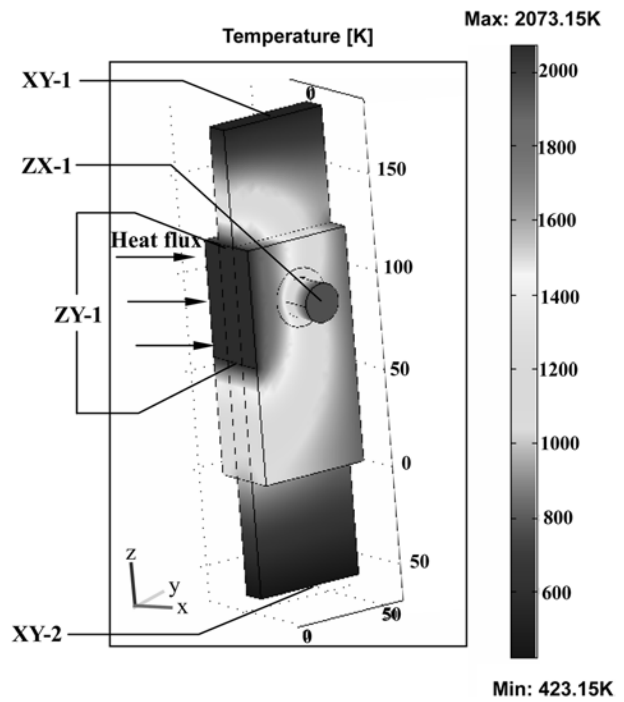

Fig. 6. Temperature distribution in a C/SiC composite hinge bearing when tested at a gas-temperature of 1800 °C in a combustion environment.

shows a schematic of the friction tests of a C/SiC hinge bearing in the wind tunnel with a combustion environment. As shown in Fig. 6, when the gas-temperature in a combustion environment is controlled at 1800 °C, the temperature distribution in the hinge bearing is not uniform. This indicates that, the temperature in the friction couple of a stationary ring and a rotating axle is in the range 800~1300 °C.

To simulate some frictional components under cyclic mechanical/thermal loading conditions during their sliding contact, the friction behavior of the C/SiC hinge bearing under cyclic loading conditions was tested both at room temperature in air (RT) and at high temperature in a combustion environments (HTCE).

At room temperature, the C/SiC hinge bearing presented friction degradation under cyclic loading conditions during the friction between rotating axle and stationary ring. The friction torque followed a sine-wave pattern under the same sine-wave change of the applied load between 5 kN and 15 kN (as shown in Fig. 7(a)). A quick rise of the friction torque to the peak value in the first cycle, followed by a decrease within 4~6 cycles, and it finally approached a stable range of 0-10 N·m was observed (Fig. 7(b)). After a friction process for about 30 minutes, the applied load elevated up to 15 kN~25 kN (Fig. 7(d)) at a

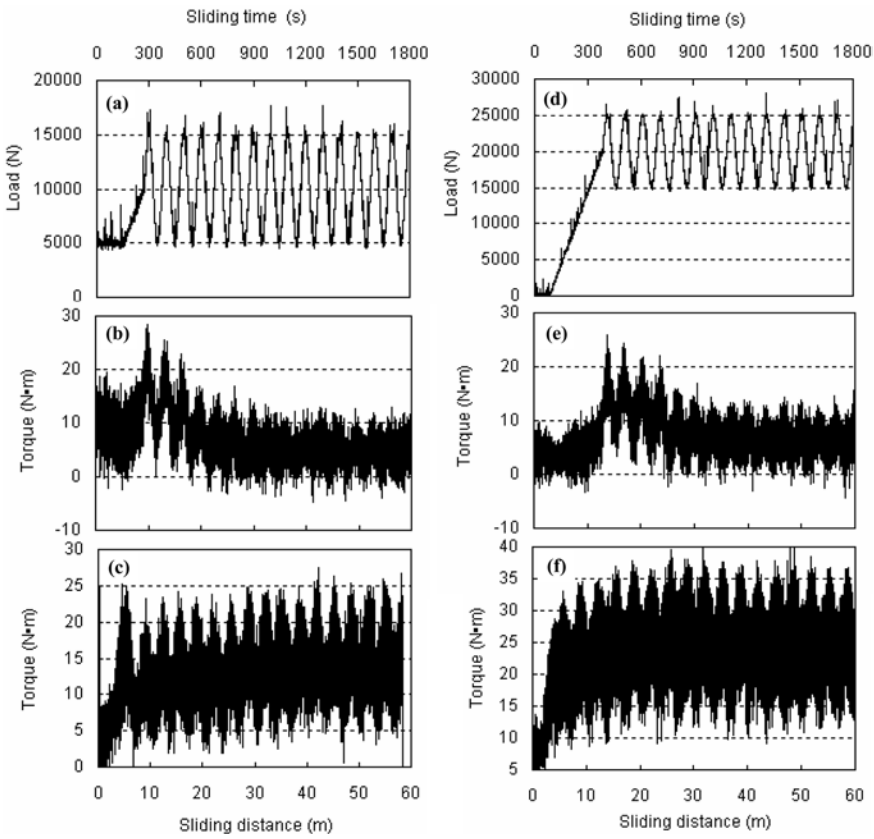

Fig. 7. The relationship of friction torque versus sliding time of the C/SiC composites axle under a cyclic loading condition at a gas-temperature of 1800 °C in a combustion environment, comparing with that at room temperature. (a) 5~15 kN loading condition, (b) torque at room temperature in air, (c) torque in a combustion environment, (d) 15~25 kN loading condition, (e) torque at room temperature in air, (f) torque in a combustion environment.

constant sliding speed does not reveal any significant effect on the friction torque (Fig. 7(e)). This is related to the change of contact configuration and reduced roughness of surfaces during sliding wear. The friction of the C/SiC hinge bearing both under cyclic loading conditions of 5~15 kN and 15~25 kN exhibited significant frictional degradation versus the sliding distance.

However, friction of the C/SiC hinge bearing was modified at high temperatures in a combustion environment. As shown in Fig. 7(c), a quick rise of the friction torque to the first peak value, followed by a non-decrease and stable range of friction torque was observed at HTCE under the same loading conditions (5~15 kN). A small increase of the friction torque after the first cycle to reach a stable range is mainly related to the process of developing a tribo-chemical layer caused by adhesion and plastic deformation of surface materials. The difference is that, the friction torque is stable at HTCE, however, it sharply decreased within 4~6cycles to half of the peak value at RT. As expected, the C/SiC composites demonstrated their stable load-carrying ability and the friction resistance at high temperatures in a combustion environment, due to the stable range of friction torque during the tests. The increase of the applied load to 15~25 kN at HTCE revealed its influence on the friction torque. As shown in Fig. 7(f), an elevated but stable friction torque is observed under this higher applied load. It is concluded that, the friction behavior of the hinge bearing at HTCE is stable and reliable for long operational durations. The friction torque at HTCE is insensitive to the sliding time/distance but greatly sensitive to the applied load.

Microstructural observations revealed that, the worn surfaces tested at room temperature are mainly related to the applied load that determined the asperity fracture on surfaces at different scales. At low loads, smooth surfaces with few shallow grooves and soft wear debris were observed. When the load was increased, a tribo-layer was gradually formed. The surface became more compact and smoother. When the load became large, the surfaces are covered with a large amount of wear debris (Fig. 8(a) and (b)). The EDS analysis (Fig. 8(c)) revealed no tribo-

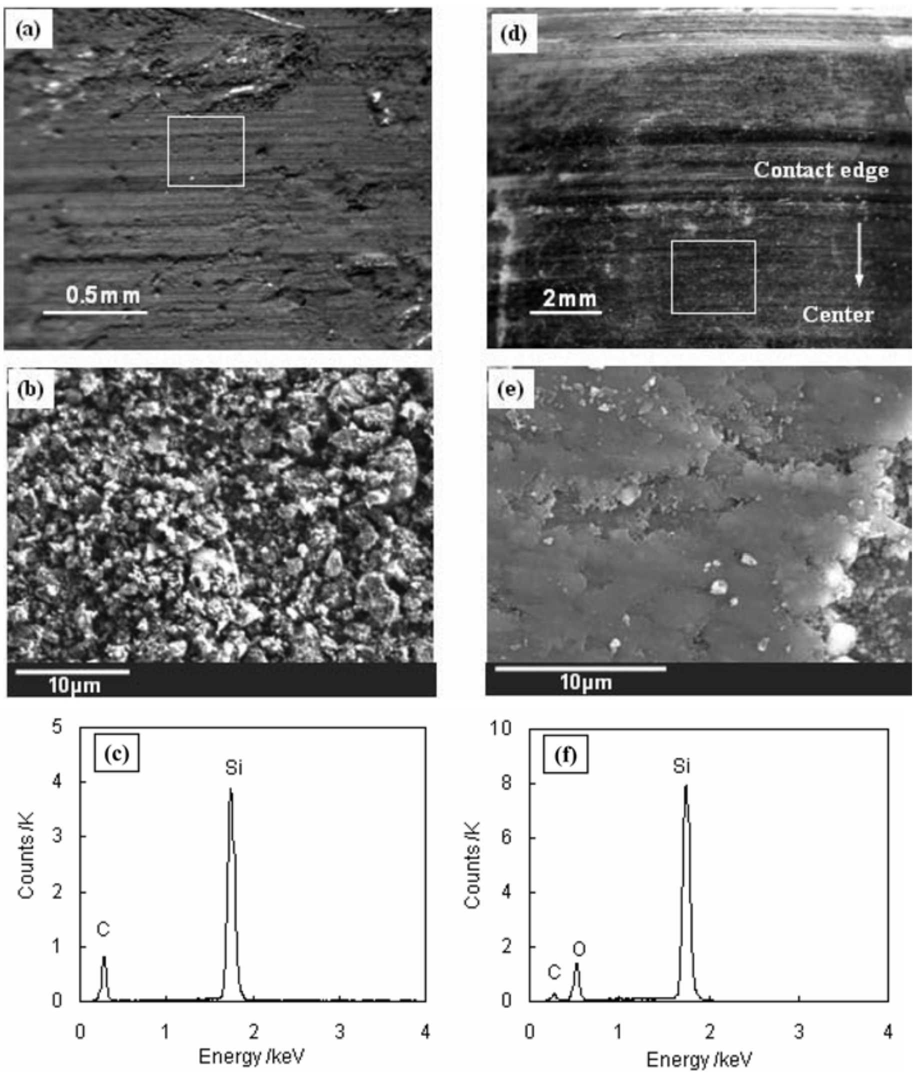

Fig. 8. SEM microstructure and EDS analysis of the worn surfaces of the C/SiC hinge bearing tested at room temperature in air (as shown in (a)-(c)) and at high temperatures in a combustion environment (as shown in (d)-(f)).

chemical product under the framework of this given testing condition due to the low sliding speed of only 0.033 m/s between surfaces. The wear debris between surfaces is derived from the macro-fracture of surface SiC materials (Fig. 8(b)).

The wear mechanisms of ceramics are predominantly dependent on the tribological contact stresses [16]. At low contact stress, the removal of material is controlled by plastic deformation-induced micro-fracture on the asperity contact scale. Wear debris is produced when the plastic deformation exceeds the plasticity limit of the material. However, the formation of wear debris is very sensitive to the environment (temperature, humidity) [17]. A smooth surface with compact material and metallic-like luster is observed after tests in a combustion environment (Fig. 8(d)). The surface roughness is about 0.08 μm (1/15 of the roughness 1 μm before tests). Fig. 8(e) presents the adhesion of the wear debris and plastic extension of the newly developed tribo-film due to the surface absorption of water molecules in a combustion environments. The EDS spectra (Fig. 8(f)) indicated oxidation products on the worn surface. The oxygen in the combustion environment is rich enough to react with SiC to produce SiO_2. Previous studies have reported that humidity has a strong influence on the wear and friction [18]. Ambient humidity causes adhesion between the wear debris which are compacted into layers that have sufficient adhesion to reduce wear. Wear mechanisms changed from fracture-controlled wear at room temperature to slight adhesive wear in combustion can be attributed to the change of wear transition due to the presence of an oxide layer. The friction in a combustion environment is significantly modified by the SiO_2 oxidation layer for wear protection.

Joining properties of C/SiC bolts

The joining of the C/SiC pin/bolts can be measured in an experimental simulation method as their application in many hot structures. As listed in Table 2, the mechanical properties of thread connection with needled C/SiC bolts were tested at room temperature. The tension-tension fatigue with a frequency at 1 Hz for 24 h leads to an increased tensile strength of the bolts by 8% when tested at room temperature. As listed in Table 3, the average shear strengths vertical to layers of 3D needled C/SiC bolts is about 83 MPa. However, after shear fatigue with a frequency at 1 Hz for 24 h, the shear strength of C/SiC bolts exhibited a little decrease. The shear strength after fatigue retained about 92% of the virgin shear strength.

Table 2. Effect of fatigue on tensile strength of bolts made of 3D needled C/SiC tested at room temperature

Item	Number	Load (N)	Average load	Strength (MPa)
Tensile strength	1	5690	4887	139
	2	4987		
	3	3983		
Tensile strength after fatigue	1	5105	5276	150 (108%)
	2	5705		
	3	5164		
	4	5086		

Table 3. Effect of fatigue on shear strength of bolts made of 3D needled C/SiC tested at room temperature

Item	Number	Load (N)	Average load	Strength (MPa)
Shear strength	1	8284	8377	83
	2	8198		
	3	8130		
	4	8428		
	5	8848		
Shear strength after fatigue	1	-	7668	76 (92%)
	2	7437		
	3	7795		
	4	7429		
	5	8011		

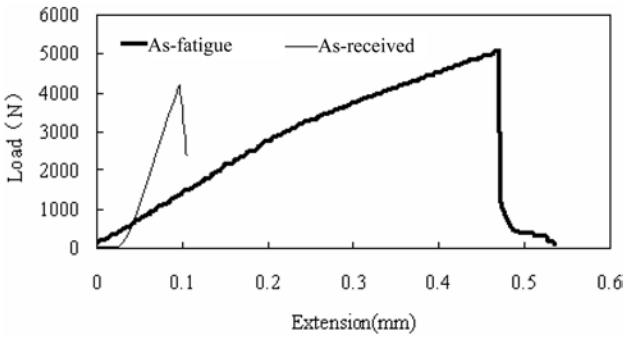

Fig. 9. Relation between load and extension of 3D-C/SiC bolts after a tensile test and a fatigue tensile test at room temperature.

Fig. 9 show the joining tests of the C/SiC bolts with a diameter of 6 mm by load-displacement curves tested before and after fatigue. A rapid brittle failure is observed for the C/SiC bolts during the tensile tests without fatigue. The average tensile strength of bolts made of needled C/SiC composites is 139 MPa. The fractured C/SiC bolts after tensile tests shown in Fig. 10(a) indicate the typical brittle behavior on a fracture surface with several fiber clusters pull-out. However, a maximum joining strength of about 150 MPa and a non-linear curve was obtained after fatigue, which indicated the non-brittle failure behavior of C/SiC bolts after fatigue. As shown in Fig. 10(b), more fibers are pulled out from the matrix on the fracture surface of the pre-fatigued bolts, and the pull-out fibers are longer than those tested after tension.

When tested at high temperature in a combustion environment, the effect of oxidation damage on the material results in a strength decrease of C/SiC bolts as listed in Table 4, and compared with the virgin strength at room temperature. However, as shown in Fig. 11, the strength conversation rate of C/SiC bolts increased with an increase in the temperature from 1300 °C

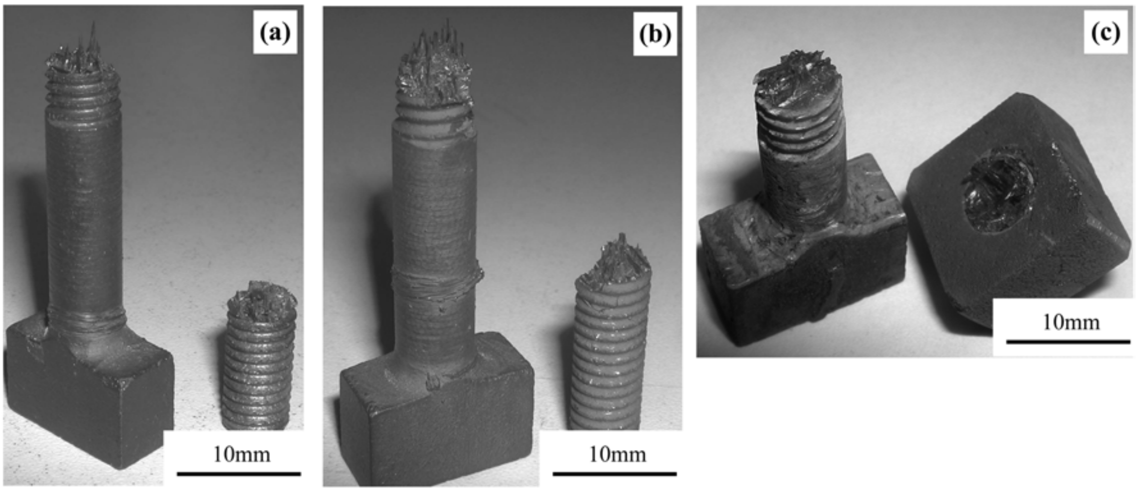

Fig. 10. The fractured 3D needled C/SiC bolts (a) after a tensile test at R.T., (b) after a fatigue tensile test at R.T., (c) after a tensile test at 1800 ºC in a combustion environment.

Table 4. Tensile strength of bolts made of 3D needled C/SiC tested in a combustion environment

Materials	Temperature (ºC)	Tensile strength (MPa)	Strength conversation (HT/RT)
3D needled C/SiC	RT	133	
	1300	100	75%
	1600	117	88%
	1800	116	87%

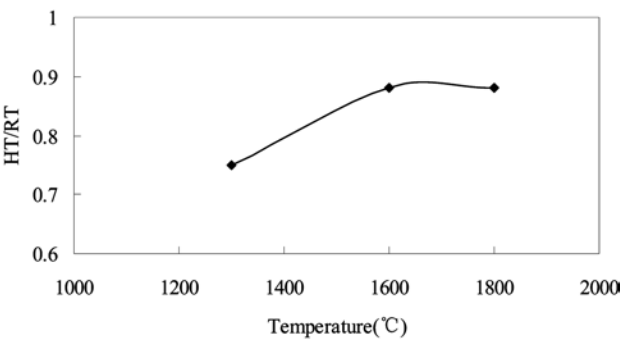

Fig. 11. Relationship between strength conversation rates of 3D-C/SiC bolts and test temperature in a combustion environment.

to1800 ºC. It is seen from Fig. 10(c) that, the C/SiC bolt fractured together with the C/SiC bolt cap when tested in a combustion environment due to the thermal expansion at high temperatures between the bolt and bolt cap. As the oxidizing atmosphere in the high-temperature combustion environment has an oxidation effect on C/SiC materials in the pre-fractured surfaces when tested under tensile condition, almost no obvious fiber pull-out can be observed on the fracture surface due to burn off by the heat flux. Therefore, the effect of an oxidizing atmosphere in the high-temperature combustion environment would be responsible for the 13% decrease of tensile strength of C/SiC bolts even tough it still retained about 116 MPa.

Conclusions

(1) The stress-oxidation behavior of C/SiC composites in a combustion environment is a combined effect of extremely high load, high temperature, and oxidation. The load and temperature influenced crack openings and thus the oxidation of carbon fibers in the pre-cracked composites. The combustion environment mainly determined the time-to-failure of the specimens by oxidation damage under a high applied stress. An oxidizing atmosphere in the combustion environment speeded and enhanced the failure of composites by decreasing the load-carrying ability of fibers which suffered from oxidation damage. The residual strength of composites decreased and the weight loss increased with an increase in the applied stress.

(2) The C/SiC hinge bearing showed good load-carrying ability and reliable friction performance under a high load and a low rotating velocity at high temperatures in a combustion environment. Even under coupled conditions of the cyclic loading up to 25 kN and a high temperature up to 1800 ºC, the C/SiC bearing retained a stable friction torque versus an increased sliding distance. The wear mechanism is dependent on the load, temperature, and especially atmosphere. The wear of the fracture-controlled mechanism at room temperature is transmitted to a slight adhesion in the combustion environment. The oxidation layer of SiO_2 in a combustion environment played an important role in modifing the friction for wear protection.

(3) The needled C/SiC bolts with a high tensile strength of 139 MPa and shear strength of 86 MPa were manufactured by the CVI + PIP process. As expected, the C/SiC bolts exhibited an increased tensile strength to 150 MPa and even a good non-brittle failure mode when tested under a post-fatigue tensile test with a frequency at 1 Hz for 24 h. However, the strength retained ratio of the shear strength after fatigue is about

92%. When tested at 1800 °C in a combustion environment, the tensile strength of the 3D needled bolts still retained about 87% of the initial strength (116 MPa) which increased with an increase in the temperature. The combustion environment played an important role in the strength decrease of C/SiC bolts due to fiber oxidation damage on the pre-cracked material.

Acknowledgments

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