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Effect of carbon fiber reinforcement on the tribological performance and behavior of aircraft carbon brake discs

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ABSTRACT

Two types of carbon fibers (CF-A, CF-B) with different mechanical properties as well as microstructure were used as the reinforcement to prepare carbon/carbon composites (C/C-A, C/C-B) for aircraft brakes. The deformation ability of carbon fiber determined the wear mode of itself and also influenced the wear resistance of the nearby pyrocarbon. In C/C-A, the fracture of CF-A at the wear surface was attributed to its hardness and indentation modulus being close to pyrocarbon as well as its weak interface bonding with pyrocarbon, which caused larger wear rate and thicker friction layer at the surface of C/C-A. Large deformation of the friction surface contributed to the larger contact area and higher friction coefficient of C/C-A but induced cracks between friction layer and the substrate, causing the unstable brake process under high energy brake. The enhanced interlaminar shear strength of the composites as well as better wear resistance of CF-B contributed to the lower wear loss of C/C-B. Brake discs reinforced by CF-B exhibited a lower friction coefficient but more stable curves under different braking conditions, which was mainly due to the higher hardness and indentation modulus of CF-B and steady friction surface of C/C-B during braking.

1. Introduction

Due to the better mechanical properties, light weight and high temperature tolerance, carbon fiber was widely used as reinforcement to manufacture carbon/carbon (C/C) composites [1–5]. The quality of the C/C composites could be improved by the choice of reinforcing fibers [6,7] as it was reported that the mechanical and tribological properties of carbon fiber reinforced composites were strongly affected by the fiber mechanical properties [8,9] as well as interfacial bonding strength between fiber and carbon matrix [3,10,11]. Literature has reported that the flexural modulus of C/C composites depends mainly on the type of reinforcing fibers [12]. Our previous study [13] found that the surface structure, for example, the microvoids existed near the fiber surface, would influence the interfacial bonding between carbon fiber and pyrocarbon matrix.

A large proportion of the C/C composites produced in the world were used in aircraft braking systems and the tribological behavior and wear mechanism of C/C composites were experimentally investigated for decades [10,14–17]. The friction behavior of C/C composites was affected by microstructure of the composites, friction parameters as well as experimental atmosphere [18]. As for the matrix microstructure, it was reported that C/C composites with high textured (rough laminar, RL) pyrocarbon would form a uniform compacted friction layer between the rubbing surfaces during braking [19] and satisfy the requirements of different braking conditions of aircraft brakes [20], which was mainly attributed to the lower hardness and easier deformation of the RL pyrocarbon matrix [21,22].

The tribological performance, such as friction coefficient and wear rate, and the tribological behavior were strongly dependent on the specific structure and elastic/plastic properties of the contact surfaces [10,18,23–25]. Research about the mechanical properties of individual constituent in C/C composites demonstrated that the carbon fibers and carbon matrix from different precursors or thermal treatments had varied values for indentation modulus and hardness [4,26–28]. During the friction process, the real contact at the macroscale actually comprised many small contacts at micro or nano scale which mainly acted as the asperities of the contact interface [23]. For contact interfaces consisting of components with differing shear moduli, disequilibrium deformations of the reinforcing fiber and carbon matrix existed at the friction surface

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Table 1
Braking parameters of different conditions for the carbon brake discs.

Condition	Tyre load (kN)	Braking pressure (MPa)	Energy (MJ)	Brake speed (km/h)
Normal landing	50	8	9	240
Overload landing	58	8	11	250
Rejected takeoff	80	8	17	260

[29,30]. It was suggested that the carbon fibers in a composite contributed to the large majority of the asperities and preferentially supported the most part of the applied load [31,32]. The difference of elastic modulus between the carbon fibers and the carbon matrix would change the load distributions in contact area of frictional surface [11,17,33,34], which would surely influence formation of wear debris as well as friction layer at the friction surface [5,30,35,36].

From these works, it was sufficient to consider that the crystallographic structure and nanomechanical properties of the fiber reinforcement would influence the tribological behavior of C/C composites. However, the wear mode of the reinforcing carbon fibers and their effects on the tribological performance and behavior of C/C composites need further research. In the present study, two different types of commercially available polyacrylonitrile (PAN)-based carbon fibers were used to manufacture the C/C composites of actual-sized aircraft brake discs. Dynamometer tests were conducted under real aircraft brake operations to obtain the braking performance under varied conditions. Our efforts focused on the investigation of the factors related to carbon fiber reinforcement that influenced the tribological properties, including the microstructure of carbon fibers as well as the fiber/pyrocarbon interface structure in C/C brake materials, the macroscopic and microcosmic mechanical properties of composites, the deformation of carbon fiber and pyrocarbon at the subsurface of the disc after braking and their relationship with the tribological behavior of the brake discs.

2. Experimental

2.1. Preparation of the materials

Commercially available 12K PAN-based carbon fiber CF-A (GQ4922-12K from Weihai Tuozhan Fiber Co. China) and CF-B (GQ3522-12K from Weihai Tuozhan Fiber Co. China), which corresponded to Chinese T700 grade and T300 grade carbon fiber, respectively, were used to prepare composites in this study. Quasi-three dimensionally needled carbon fiber preforms made of CF-A and CF-B were fabricated by alternatively stacked nonwoven fiber cloth and chopped fiber web by a needle-punching technique. C/C composites were manufactured by densifying the porous performs with chemical vapor infiltration, followed by furan resin impregnation-carbonization process to the ultimate density of ~1.80 g/cm^3. The final heat treatment temperature of the composites was 2300 °C. The prepared C/C composites were correspondingly labeled as C/C-A and C/C-B according to their carbon fiber types.

2.2. Mechanical properties

Compressive strength of the carbon brake materials was tested on specimens (ϕ10 mm × 20 mm) in the direction perpendicular to the friction surface on a testing machine Instron 3369. Rectangular bars of 36 × 10 × 6 mm^3 were cut from carbon brake materials for the interlaminar shear strength tests in a three-point bending rig over a span of 24 mm with a ϕ4 mm supporting roller and a ϕ6 mm loading roller. The fracture surface of the C/C samples was observed by scanning electron microscopy (SEM, Nova Nano SEM230).

The nanoindentation experiments were conducted at room temperature with a CSM Indentation Tester using a Berkovich-type diamond tip. Carbon fibers and pyrocarbon matrix in the perpendicular and parallel directions were indented for the mechanical characterization of the raw C/C carbon brake materials. Elastic modulus and hardness of individual component in the composites were calculated from the load displacement data obtained by nanoindentation at loads of 25 mN.

2.3. Brake dynamometer tests

Braking tests were performed on the HJDS-II simulation tester with actual size airplane brake discs as well as actual aircraft brake operations [15]. After running in, braking tests were conducted under aircraft normal landing (NL), overload landing (OL) and rejected takeoff (RTO) conditions. The braking parameters of different conditions were shown in Table 1.

Temperature at the middle of the stator was measured through a thermocouple located approximately 10 mm below the friction surface. During the braking tests, parameters such as braking time (s), braking torque (kN·m) and temperature of the stator disc (°C) were recorded automatically. The friction coefficients of the brake discs were calculated by the recorded braking torque. The average linear wear rate was determined by measuring thickness of the

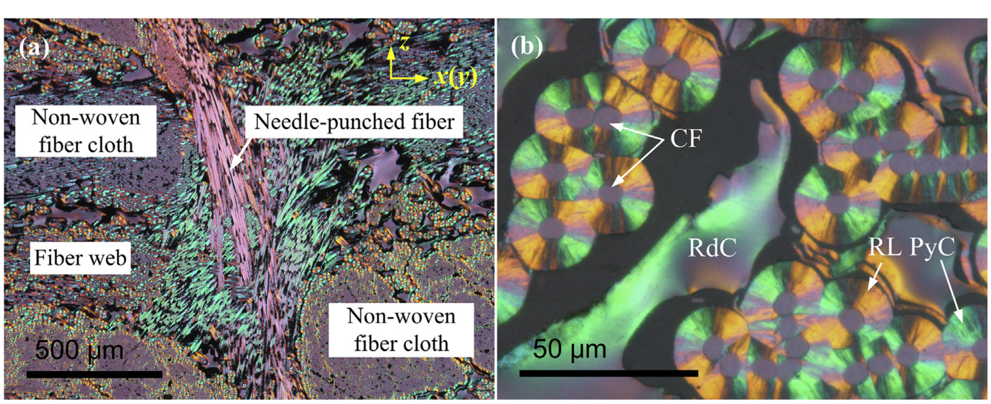

Fig. 1. (a) Optical microscopy image of the cross section structure of the carbon brake material; (b) microstructure of the carbon brake material. (A colour version of this figure can be viewed online.)