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Structural transformation of carbon/carbon composites for aircraft brake pairs in the braking process

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ABSTRACT

Amorphous structure discovered from both the wear debris and the friction layer of the carbon/carbon composites after the braking tests was attributed to the breakdown of crystallites in the graphitized bulk material. Graphite layers produced through interlayer shear deformation were found to be the basic units of the pyrocarbon during sliding while carbon fiber tended to be worn into small fragments along the fiber axis in the primary stage of rubbing. The transition of graphitic pyrocarbon in the friction process was described as four stages. Nano-scale carbon particles of onion-like structure were found in the fiction layer, which were likely to participate in the formation of friction layer and lubricate the friction process.

1. Introduction

Carbon/carbon (C/C) composites have been widely used as the brake material for aircrafts due to their light weight, exceptional friction performance, excellent thermal properties and dimensional stability at severe environment. The frictional properties and general wear mechanisms of C/C composites were investigated for decades [1–4].

Because of the complex microstructure, serious deformation as well as the atomic level interactions between the contact surfaces, the phenomenon of wear was defined as a dynamic process which was difficult to model [5]. Kasem et al. [6] presented that both physico-chemical action and mechanical interaction were responsible for the tribological transitions between the first body surfaces. In addition, the wear debris (third body) formation was mainly due to the abrasion and fatigue of the first bodies.

Researches about the wear debris of C/C composites showed that the debris comprised a much lower structural order phase compared with the well-graphitized parent matrix [7], which was revealed through X-ray diffraction (XRD) study [8,9] as well as transmission electron microscopy (TEM) analysis [10–12]. Friction layer of amorphous structure was also nonuniformly formed in the dynamic wear process [13]. It was widely accepted that disordered carbon layer formed on the friction surface protected the bulk composites from further wearing and degradation [12], however, how the disordered carbon in the friction layer was transformed in the braking process was barely reported. Molecular dynamics simulation of nanoscratching on multilayer graphene showed that graphene would partly turn to amorphous structure due to numerous cross-linking between neighbor-layer graphenes [14,15]. The transformation of 3D graphite into a 2D turbostratic phase constituting high degree of stacking interlayer disorder was considered to increase the friction coefficient of crystalline graphite at high loading range [16]. In general, the tribological property of carbon material was surely correlative with the structural transformation during the dynamic friction process.

This paper presented detailed microstructure information of the wear debris and friction layers of the C/C composites for aircraft brake discs after braking tests. The structural transformations from graphitic structure to amorphous type structure were explained and modeled. The wear-induced structural transition was briefly discussed.

2. Material and methods

2.1. Material preparation

The C/C composites used in this study were manufactured from quasi-three dimensionally needled polyacrylonitrile (PAN)-based carbon fiber preform which was fabricated by alternatively staked nonwoven fiber cloth and chopped fiber felt by a needle-punching technique. The preform was densified to ~1.60 g/cm^3 by chemical vapor infiltration in an atmosphere containing propylene as precursor and hydrogen as carrier gas followed by furan resin impregnation-carbonization process to the density of ~1.80 g/

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cm^3. The final heat treatment temperature of the composites was 2300 °C.

2.2. Material characterization

The optical microstructure of the C/C composites was observed using a polarized microscope. The graphitization degree was obtained by XRD analysis (Rigaku-3014). Compressive strength was tested on specimens (ϕ10 mm × 20 mm) in the direction perpendicular ($\perp$) to the friction surface. Flexural strength was tested on bar specimens (55 mm × 10 mm × 4 mm) using the three-point bending method with a span of 40 mm. Thermal diffusivity was measured according to ASTM E1461-11 (Standard Test Method for Thermal Diffusivity by the Flash Method) by a flash laser technique on a JR-3 property tester with samples (ϕ10 mm × 4 mm) at room temperature. Thermal conductivity was calculated according to

$$\lambda = 418.68 \rho \alpha C_p$$

where λ-thermal conductivity, W/(m K); ρ-density of the material, g/cm^3; α-thermal diffusivity, cm^2/s; C_p-the specific heat capacity. Usually, the value of C_p at room temperature is considered to be 0.171 cal/(g K).

2.3. Braking tests

Braking tests were performed on the HJDS-II simulation tester with actual size airplane brake discs as well as actual aircraft brake operations according to the National Aerospace Standards of China: HB 5434.4-2004 (Test methods for aircraft wheel friction materials-Part4: Dynamometer test method for brake performance). The dimensions of the rotator discs were 336 mm and 212 mm in outer and inner radius respectively, and 20 mm in thickness. The dimensions of the stator discs were 312 mm and 188 mm in outer and inner radius respectively, and 22 mm in thickness. After running in, braking tests were conducted under aircraft normal landing and overload landing conditions. Braking parameters of normal landing and overload landing 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. All the braking tests were exposed to atmosphere with a 40% relative humidity.

2.4. Wear debris and friction layer observation

Wear debris was collected from the friction surfaces of the rotor and stator discs (Fig. 1) after all the braking tests, of which the morphologies were observed by scanning electron microscopy (SEM, Helios Nanolab 600i) and TEM (Titan G2 60-300 with image corrector). Furthermore, friction layers for TEM observation were prepared according to the method described in the literature [12].

3. Results and discussions

3.1. Microstructure and properties of the C/C composites

Fig. 2a showed the optical microscopy micrograph of the C/C composites. The pyrocarbon (PC) deposited around the carbon fiber (CF) was mainly rough laminar texture and resin-derived carbon (RC) was filled in the interspace. There existed cracks (defects) between RC and PC, which was due to their different thermal expansion coefficients during the high temperature treatment process of the composites. The PC displayed a well-developed and continuous graphitic structure (Fig. 2b) while the CF had a partially crystalline structure with graphene layers

Table 1
Braking parameters of normal landing and overload landing conditions.

Test conditions	Braking pressure (MPa)	Kinetic energy (MJ)	Braking speed (km/h)
Normal landing	8	9.14	240
Overload landing		11.43	250

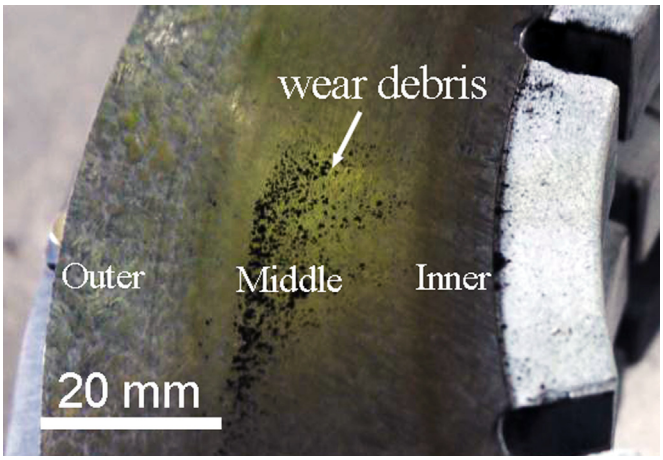

Fig. 1. Worn surface of the C/C brake disc after braking tests.

aligned basically along the fiber axis direction (Fig. 2c). The RC showed a glass-like carbon structure of entangled graphene layers (Fig. 2d) which was the less-ordered phase in the C/C composites.

In the real usage of braking, the discs are subjected to shear forces as well as impact loads. Resistance to failure under such conditions is very important for the stability of the brake material. The physical properties of the C/C composites in this study were listed in Table 2.

Fig. 3 showed the coefficient of friction (COF) and the temperature measured by thermocouple during every normal landing test. The COF stabilized at around 0.30 and the average measured temperature at the stator disc of all the normal landing tests was 570 °C. As listed in Table 2, the thermal conductivity perpendicular to the friction surface was lower than that parallel to the friction surface. Therefore, before the frictional heat was transferred to the measure point (10 mm below the friction surface), part of the heat was already conducted into the air along the direction parallel to the friction surface. Generally, the measured temperature was much lower than the true temperature of the friction interface.

The overload landing tests were arranged after the 10th, 18th and 26th normal landing tests. The average COF of overload landing tests was 0.32 and the average measured temperature was 680 °C. The average sliding distance of normal landing tests and overload landing were 440 m and 525 m, respectively.

Researches showed that higher speed would produce higher frictional heat which might influence the formation of friction film and the wear mechanism[17,18]. Overload landing tests of higher braking speed and kinetic energy produced higher frictional work and increased the temperature of the disc, which influenced the thermal stress distribution as well as the formation of friction layer at the contact surfaces. The structure in the friction layer might be rearranged and the thickness and size of the friction layer were changed under the overload landing, leading to a higher COF (0.32). It suggested that the steady wear surface formed through normal landing was severely damaged after the overload landing test. What is more, the structural damage of the wear surface also increased the COF of the normal landing tests following overload landing. As was seen from Fig. 3, it was noted