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# Microstructure and properties of needle punching chopped carbon fiber reinforced carbon and silicon carbide dual matrix composite

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ABSTRACT

Chopped carbon fiber preform reinforced carbon and SiC dual matrix composites (C/C–SiC) were fabricated by chemical vapor infiltration (CVI) combined with liquid silicon infiltration. The preform was fabricated by repeatedly overlapping chopped carbon fiber web and needle punching technique. A geometry model of the pore structure of the preform was built and reactant gas transportation during the CVI was calculated. The microstructure and properties of the C/C–SiC composites were investigated. The results indicated that the CVI time for densification of the preform decrease sharply, and the model showed the permeability of the preform decreased with the increase of its density. The C/C–SiC exhibited good mechanical characteristics, especially excellent compressive behavior, with the vertical and parallel compressive strength reached to 359($\pm$40) MPa and 257($\pm$35) MPa, respectively. The coefficient of friction (COF) decreased from 0.60 (at 8 m/s) with the increase of sliding velocity, and finally stabilized at $\sim$0.35 under the velocity of 20 m/s and 24 m/s, and the variations of COF were not sensitive to the sliding distance. The wear rates were between 0.012 $cm^3$/MJ and 0.024 $cm^3$/MJ under different velocities. These results showed that the chopped carbon fiber preform reinforced C/C–SiC are promising candidates for high-performance and low-cost friction composites.



## 1. Introduction

C/C–SiC, carbon fiber reinforced carbon and SiC dual matrices composites, have been proved to be ideal for the manufacture of ultrahigh performance brakes since the end of 20th century [1,2]. Comparison to the traditional friction composites, C/C–SiC composites show not only light weight, high thermal shock resistance, high and stable coefficient of friction (COF), deformation stability and wear-resistance, but also have lower sensibility to surroundings and greatly extended lifetime [3–6]. Up to now, the friction pairs of C/C–SiC disks mating with different pads have been successfully applied in many engineering fields. Krenkel et al. [1] have been investigating C/C–SiC composites for high performance automobile applications since the Middle of 1990s. After 20 years development, C/C–SiC composites with chopped carbon fiber as reinforcement and produced by combination of Hot Pressing and Liquid Silicon Infiltration (LSI), have already been established in the segment of sports cars, luxury sedans and sport utility vehicles (SUVs) since their first use in 2001 [2,7,8]. Zhang et al. [9–11] investigated the C/C–SiC aircraft brakes with 3D needle punching carbon fabric preform fabricated by Chemical Vapor Infiltration (CVI) combined with LSI, which were firstly installed on a certain airplane for a trial flight and achieved success in 2008. Xiao et al. [12,13] have been developing C/C–SiC composites with 3D needle punching carbon fabric preform for advanced brake systems from 2001, and have made significant progress in many areas, like high-speed train, special vehicle and engineering machinery.

Nowadays, although C/C–SiC composites have been demonstrated to be the top choice for the advanced brake systems, some shortcomings of the C/C–SiC friction composites limit their large-scale application. The main disadvantage is the cost of C/C–SiC which is more expensive than the traditional friction materials, like gray cast iron, Copper-based powder metallurgy materials, although the manufacturing cost have been reduced to a large extent in the past decade years. At one-fourth the cost of a Carbon/Carbon racing brake, the price tag for C/C–SiC disk is still high, especially to replace a metal disk of family car that costs less and has worked well for years [14]. The costs of chopped fiber reinforced C/C–SiC disks have been estimated in terms of materials,

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investments and personnel costs, and the cost analysis for a series production of internally ventilated brake disks showed the costs arise from auxiliary materials (34%), personnel (30%), raw materials (18%), investments (14%) and energy (4%) [15]. In this case if the costs of materials and manufacturing time could decrease on the premise of the excellent mechanical and tribological properties are maintained, the application of C/C–SiC will become more and more widespread.

The use of random chopped carbon fiber preform and CVI processing methods has the potential to satisfy these criteria. One of the advantages is the waste carbon fiber preform can be returned into the production line with a step of re-unwrapping process, thus significantly increase the material utilization efficiency. Peterson et. al [16] reported typical C/C–SiC parts (disk brakes, rocket nozzles, telescope mirrors, etc.) fabricated by the LSI process using random oriented chopped Carbon/Carbon (C/C) felt. Jacob et.al [17] investigated the crashworthiness of various random chopped carbon fiber reinforced epoxy composite materials and their strain rate dependence for automotive applications. Hence, we were interested in investigating the C/C–SiC friction composites with needle punching chopped carbon fiber preform as reinforcement because of the low costs involved in their manufacture thus making them cost effective for engineering applications.

In the present study, an attempt has been made to develop high-performance and low-cost C/C–SiC composites with chopped carbon fiber preform as reinforcement. The fabric preform was fabricated by repeatedly overlapping the chopped carbon fiber layers web and needle punching technique. A combination of CVI and LSI technique were used for densification of the C/C–SiC composites. A geometry model of the chopped carbon fiber preform was built and the reactant gas transportation during the CVI process was calculated. The microstructure and properties of the obtained chopped carbon fiber preform reinforced C/C–SiC composites were also characterized.

## 2. Experimental

### 2.1. Raw materials

Polyacrylonitrile (PAN) based carbon fiber (T700, 12 K) with a mean diameter of 10 μm was supplied by Toray Industries Inc. (Japan). According to the producer, the as-received fiber is coated with commercial polyurethane. Si powder with average particle size of 30–50 μm purity of 99.8% was employed, which contains 0.15–0.20 wt% Fe, 0.02–0.10 wt% Al and 0.02–0.10 wt% Ca, according to information supplied from the manufacturer of Da Di Zelin-silicon Co., LTD, Beijing, China.

### 2.2. Fabrication of the composites

The fabrication process of C/C–SiC composites consisted of four steps as shown in Fig. 1. The first step involved preparation of chopped carbon fiber web with the unwrapping and carding technique, in which carbon fiber with average fiber length of 20–80 mm have been dispersed in the form of monofilaments. The obtained random carbon fiber web was homogeneous with a weight per unit area of 10–40 g $m^{-2}$.

The second step was to generate the fabric preform by needle punching technique, which started with repeatedly overlapping the layers of chopped carbon fiber web. The needle punching density was 15 to 35 pin $cm^{-2}$. The fabric preform had a layer density of 12 to 15 layer $cm^{-1}$, and a bulk density of 0.18 g $cm^{-3}$.

The third step involved densification of the fabric preform and production of porous C/C material in an isothermal furnace with CVI process. The temperature for CVI was about 1000 °C for 120 h in an

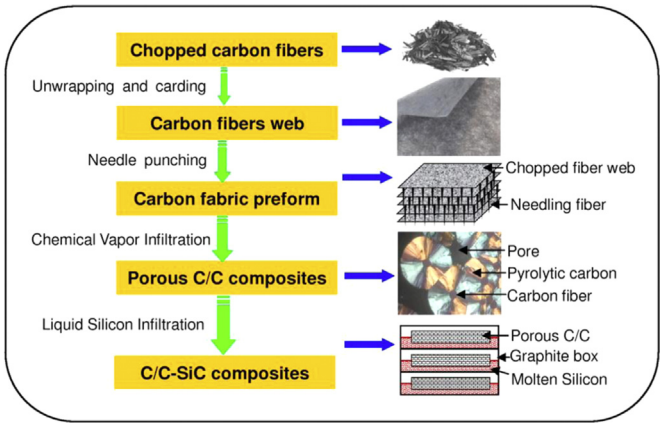


**Fig. 1.** Schematic representation of the manufacturing process for the C/C–SiC composites reinforced with needle punching chopped carbon fiber preform.

argon atmosphere of 0.1 MPa. $C_3H_6$ was use as a precursor and $H_2$ as a carrier and diluting gas ($C_3H_6/H_2$ = 10 ml $min^{-1}$:20 ml $min^{-1}$). The density of the porous C/C material was 1.36 g $cm^{-3}$.

The final step was a subsequent infiltration of the resulting porous C/C material with molten Si. The Si powder was put inside a graphite box, then the porous C/C material was put above the Si powder. Finally, the graphite boxes with Si powder and porous C/C material were stacked vertically in the furnace and heated up to the desired infiltration temperature. The desired infiltration temperature reached at a heating rate of 10 °C/min from 1400 °C. In this work, LSI process was conducted at high temperature (1650 ± 100 °C) for 0.5–2.0 h in vacuum (residual pressure 1 Pa). Thereby the liquid Si infiltrated the pores of C/C material with capillary force and reacted with a small amount of the carbon matrix to formed SiC matrix. The density and open porosity of the resulting C/C–SiC friction composites were about 2.14 g/$cm^3$ and 6.8%, respectively.

### 2.3. Analysis methods

The bulk density and open porosity of the composites were measured by Archimedes' method at room temperature, and the accuracy of the electronic balance was 0.1 mg. The compressive and flexural tests were conducted on Instron 1196 universal testing machine at a rate of 5 mm/min, and the test methods were according to the ASTM C1258-97 and ASTM C1341 standard, respectively. The impact-toughness test was carried out on a home-made pendulum impact tester, and the sample size was 50 × 10 × 10 $mm^3$. The thermal conductivity and thermal diffusivity were measured by a laser flash apparatus (Netzsch LFA 427, Germany) under an Ar atmosphere (100 mL/min), the sample size was φ12.7 × 2 $mm^3$.

The tribological property of the C/C–SiC composites was tested on a fix-velocity friction testing machine (Xian Shun-tong Institute of Electrical and Mechanical Application, model QDM150, China), with the C/C–SiC specimens acted as sliders in contact sliding against cast iron friction disk. Fig. 2 gives an schematic view of the slider-on-disk friction system used in the present study. The size of the cast iron disk was Φ300 × 25 mm, and the size of the C/C–SiC specimens was 25 × 25 × 10 $mm^3$. The kinetic energy was supplied by the cast iron disk, which was driven by a DC motor. The C/C–SiC sliders were mounted on a support holder, and the load between sliders and friction disk was applied by a lever system. The temperature of friction subsurface was measured with a thermocouple, which embedded within the slider at a point located on the face center and the pin at 1 mm beneath the friction surface. The test was according to the GB 5763–2008 standard of Brake